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ACCURACY OF TEMPERATURE MEASUREMENTS
WITH THE VACM

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TECHNICAL REPORT

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Preface

For the past five years the Buoy Group at Woods Hole Oceanographic Institution has included temperature as one of the variables recorded in its current meters. These measurements began with the first successful deployments of Vector Averaging Current Meters (VACMs) in 1971. Circuitry designed for making highly accurate temperature measurements has been included in all the Buoy Project's VACMs. During the past year we have begun to add similar circuitry to the EG&G 850 current meters. This report is intended to describe what we have learned about making water temperature measurements with VACMs.

Among the authors, K. Schleicher and A. Bradshaw are responsible for thermistor calibrations, J. Dean for quality control of VACM maintenance and calibration work, and R. Payne for data analysis.

Acknowledgments

We would like to mention the efforts of R. Koehler and J. McCullough who had the principal responsibility of designing the VACM. Ms. Sharrill D. Wood of the National Bureau of Standards very kindly calibrated a set of thermistors for us to provide an independent check of our calibration facilities.

1. Introduction

The Vector Averaging Current Meter (VACM) was designed several years ago by engineers at the Woods Hole Oceanographic Institution in response to the needs of scientists associated with the Buoy Project at that Institution. After the first few prototypes were built and tested the design was turned over to the AMF Electrical Products Division of Alexandria, Virginia which builds and sells the instrument. Included in the original design and in the standard instrument sold by AMF is circuitry capable of making accurate temperature measurements. This report describes calibration techniques we have found effective for both sensor and electronics as well as evaluations of the performance of the two components independently and as a system.

System description

A thermistor is mounted in the lower plate of a chassis assembly which, in turn, is mounted on the end plate of the pressure housing of the VACM. An electrical current through the thermistor is sensed by an electronic circuit which provides a series of pulses whose rate is proportional to the current. These pulses are summed, typically, over a 15 minute interval and the total recorded as part of the VACM data record on a magnetic tape cassette. This arrangement allows true time averaging of the thermistor resistance over the entire recording interval. For most oceanographic applications this is equivalent to a time average of temperature. This technique has been used since about 1971 and has proved to be quite reliable and accurate.

The standard VACM uses a Yellow Springs Instrument Corp. (YSI) thermistor, part #44032, with 0.1° C interchangeability. In addition to these we have recently been using in our routine operations some Thermometrics Corp. thermistors with quite similar characteristics developed for the Internal Wave Experiment (IWEX). This report will describe results on the YSI thermistors only since we have accumulated the most experience with them. The epoxy encapsulated thermistors are potted in an aluminum screw for attachment to the VACM chassis. The nominal resistance of the thermistor is 30,000 ohms at 25° C with a temperature coefficient of -4.5 %/° C.

The thermal time constant (time required for the thermistor to sense 63% of a step change in temperature) for the device when installed in a VACM end cap is a function of water current speed and has been measured to be approximately 100 seconds for an average current of 14 cm/sec.

We believe that the absolute accuracy of our temperature measurements in VACMs is better than .01° C. This has been substantiated by the intercomparisons described in this report and by analysis of the errors inherent in the the instrument (Section 6). Thermistor stability and the practical difficulties of making extremely precise temperature calibrations appear to be the limiting factors. Making a series of calibrations over several years and culling unstable thermistors are necessary for highest accuracy.

We might point out that making meaningful absolute temperature measurements with accuracies of .01° C requires stability and accuracy of depth which strains present day mooring techniques. In the main thermocline in the Atlantic Ocean the temperature gradient is of the order of 20 m° C/m. A temperature accuracy of 10 m° C there is equivalent to a depth accuracy of 50 cm.

There are other reasons for making precise calibration of sensors and associated circuitry. Currently many of our moorings are out for periods approaching 1 year. Much of the use made of temperatures, such as computing low frequency heat fluxes, depends more on the stability of temperature measurements than on their absolute accuracy. A drift of 20 m° C/year in a thermistor can make temperature measurements well below the main thermocline virtually meaningless unless it can be corrected for. Accuracy of drift rate estimates depends on the uncertainty in individual calibrations and the length of time over which the calibrations have been made. Doubling the uncertainty in accuracy of individual thermistor calibrations doubles the length of time over which calibrations must be made to achieve the same accuracy in drift rate estimates. We find that a minimum of 3 calibrations over 2 years are required to determine drift rates to our specifications. Although highly accurate calibrations are expensive, an increase in calibration period would leave us with virtually no certifiably stable thermistors.

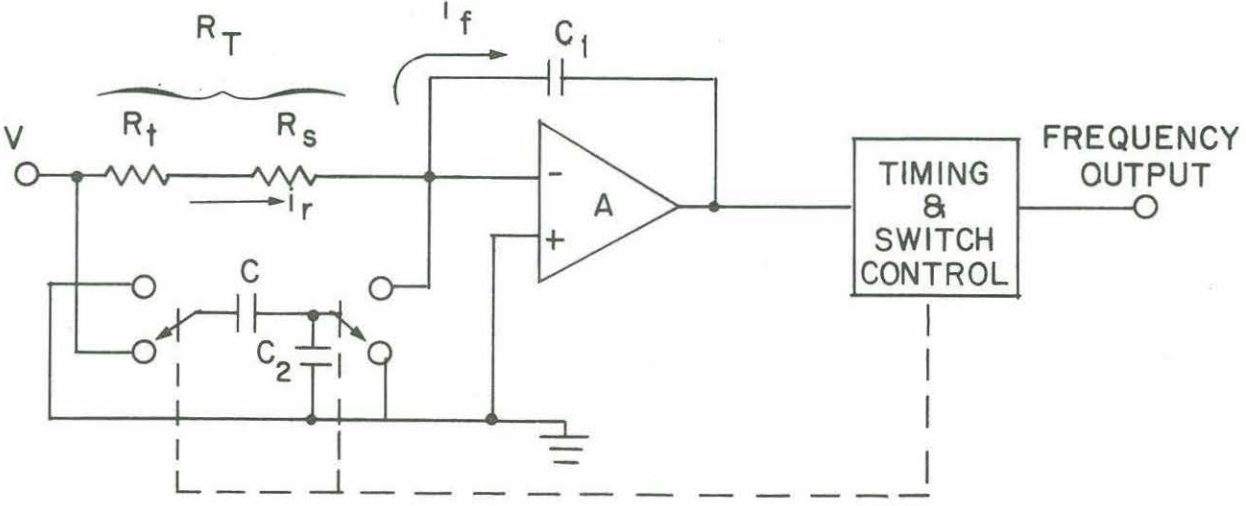
2. V/F Converter Operation

In the VACM the thermistor is used to vary the electrical current into a converter (called the voltage to frequency (V/F) converter). Since the period of the pulse train output of the converter is proportional to the input current, the average resistance (and therefore temperature) of the sensor over a precisely measured time interval can be obtained by counting the pulses in that interval. The pulses are summed, typically for 15 minutes. A technical discussion of the circuitry can be found in the VACM technical manual, AMF Publication #SLS 106-11419, Section 2.2.1. The technique described has been used since about 1971 and has proved to be quite precise and reliable.

Referring to Figure 1, operational amplifier (op amp), A, and feedback capacitor, C_1, form a current integrator. Ideally, an op amp has infinite gain, the input summing points (+ and -) have zero potential between them, and no current can flow into the input terminals. A stable, precise reference voltage, V, is applied to R_T, the series combination of thermistor R_t and a fixed precision resistor R_s, resulting in a current $i_r = V/R_T$. Since no current can flow into the op amp, current i_r must flow in C_1 and equal i_f.

Figure 1

V/F Converter



Periodically, a precise electrical charge, Q, is applied to the op amp input summing point and is transferred to capacitor C_1. This charge Q is dispensed by i_f, and the time period, P, required to remove the charge is a function of the current i_f.

The charge Q accumulated on the precision capacitor C by reference voltage V is

$$Q = CV.$$

The input current flowing in the thermistor is

$$i_r = V/R_T.$$

The discharge of Q by current i_f in time P is

$$i_f = Q/P = CV/P.$$

Since

$$i_f = i_r$$

then

$$V/R_T = CV/P, \text{ or}$$

$$P = R_T C = (R_t + R_s)C.$$

The period P is proportional to the total resistance R_T, hence related to the thermistor resistance R_t. R_t is converted to temperature by substitution into the calibration equation (see Section 5).

Solid state FET switches transfer the charge from C to C_1 via op amp A. After an appropriate interval (nominally 400 microseconds) the switches reconnect C to V to recharge C. C_1 continues to discharge and after time interval P, C_1 is discharged, the switches again transfer the charge on C to the integrator, and the cycle begins again. C and C_2 form a voltage divider to reduce the voltage at the input of A to prevent driving the op amp input into saturation where it would draw current.

Additional circuitry controls the switching and provides closed loop operation whereby the cycle is reinitialized as soon as the charge is dispensed. The circuit also provides a slight delay in the switching (about 10 micro-seconds) to allow break-before-make action of the switches to prevent loss of charge.

Since the frequency output is a function of the total resistance R_T and the capacitance of capacitor C ($P = R_T C$), the circuit is relatively insensitive to variations in components in the circuit except for R_s and C. The series resistor R_s is chosen to produce a nearly linear relationship between the current in the thermistor and its temperature. With this resistor value equal to 37,300 ohms, the current in the thermistor-resistor network is linear with temperature within 1.7% over the range of 0° C to 30° C. Although the network is somewhat non-linear temperature excursions in the ocean do not often cause biases in a 15 minute average. The output frequency of the converter is proportional to current input within .01%.

There is a slight error in the period (not exactly equal to $R_T C$) and is probably due to a finite reaction time of the op amp to the charge applied at its input. An empirical constant, K, can be determined from tests, resulting in a more nearly exact equation

$$P = R_T\, C + K.$$

K has been found to be about 0.5 microseconds for a typical instrument.

The expression for computing thermistor resistance from the period of the V/F converter output signal is straightforward to derive, if rather involved. One begins with the valid assumptions that the voltage across R_t and R_S in Fig. 1 is constant and that the frequency of the V/F converter is directly proportional to the current through R_t and R_S. The resulting expression is:

$$R_t = \frac{\left(\frac{1}{P} + K_2\right) R_S}{K_1 - K_2 - \frac{1}{P}}$$

where $P = T_S/N$ = period of V/F output

$$K_1 = \left(\frac{1}{P_2} - \frac{1}{P_1}\right)/D$$

$$K_2 = \left[\frac{R_1}{P_2(R_S + R_1)} - \frac{R_2}{P_1(R_S + R_2)}\right]/D$$

$$D = \frac{R_2}{R_S + R_2} - \frac{R_1}{R_S + R_1}$$

and R_1, R_2, P_1, P_2 are the input resistances and output periods of two V/F calibration points.

3. V/F Converter calibration

Since the V/F converter transforms the resistance changes of the thermistor into electrical signals it is essential that it be calibrated as carefully as the thermistor. Our calibration procedure is designed to monitor the long term behavior as well as provide a calibration for a specific setting of an instrument.

Before and after each deployment the V/F converter is calibrated at seven precise (.001%) input resistances corresponding to nominal thermistor resistance values at seven temperatures. The values are shown in Table 1. The period at the 5° C point is adjusted to read 1820.4 μs at 74434 Ω and the seven periods are recorded again, both at room temperature and in a cold room at ∿5° C. A record is made at the periods before and after adjustment which allows us to monitor the temporal stability of each converter. The cold room values are used in decoding most data since they correspond closely to the <u>in situ</u> conditions of the instruments in typical moorings.

Table 1

V/F Converter Calibration Results

Temperature	Input Resistance	Period (x 10^{-6} seconds
0° C	94972 Ω	2154.871 ± .075
5	74434	1820.412 ± .004
10	58747	1564.911 ± .056
15	46675	1368.2
20	37299	1215.640 ± .093
25	29998	1096.765 ± .109
30	24269	1003.464 ± .127

The period values in Table 1 are the means and standard deviations of the data points at each temperature for the 175 calibrations investigated. Only a nominal value has been included for the 15° C point because we discovered some of the calibrations were made with an incorrectly labeled precision resistor.

The period-resistance relationship is linear. In decoding the data from a current meter we use the 5° C and 25° C points to determine the relation. We checked the linearity for 175 calibrations of 45 instruments by comparing the actual calibration points and the values computed from the straight line determined by the 5° C and 25° C points. The result was that, in all but five calibrations, the error introduced by using the straight line was equivalent to 1 m° C and in those five it was equivalent to about 2 m° C inaccuracy in the decoded temperatures.

Using the 5° C and 25° C points from Table 1 the period-resistance relation is

$$\text{PER } (\mu s) = 608.243 + 0.01628515 * R.$$

A least squares fit of all but the 15° C point yields

$$\text{PER } (\mu s) = 608.231 + 0.01628516 * R.$$

The two equations fit the data equally well. The standard deviation of the first is 0.013 μsec, and of the second, 0.018 μsec. The accuracy in period required for ±1 m° C accuracy in temperature is ±0.08 μsec at 0° C, ±0.05 μsec at 10° C, and ±0.03 μsec at 20° C.

We have also fit an equation like the first of the preceding paragraph to the data of the 175 individual V/F calibrations. After solving each equation for R and subtracting the input resistances we computed an r.m.s. residual for each calibration. The mean of this residual over all the calibrations is 0.9 ohms. All but three of the residuals were less than 3 ohms. One ohm represents 0.22 m° C at 0° C and 0.99 m° C at 30° C for our standard thermistors.

The calibrations also show that the stability of the V/F converters is such that they will maintain 1 m° C accuracy over the period of one year, a stability of 3 parts in 10^5.

4. Thermistor Calibrations: Methods and Facilities

All of our thermistor calibrations have been made with the same variety of equipment: a constant temperature bath, a platinum resistance thermometer (PRT) and bridges to measure the resistance of both the PRT and the thermistor. Calibrations began in January 1973. In August 1973 (just prior to batch 11) there was a bath modification resulting in an improvement in accuracy. In December 1974 (just prior to Batch 45) most of the system was replaced for some improvement in accuracy and a large improvement in convenience and speed.

We will describe both calibration systems and the errors connected with them.

A. System 1. January 1973 - December 1974. Batches 1-10

Figure 2 shows a diagram of the first bath. It was one used previously (Bradshaw and Schleicher, 1970) but its precision of control was improved for this application. It consisted of an outer and an inner bath, both filled with a stirred water-ethylene glycol solution. The outer bath had heating and cooling coils. The inner bath was heated to maintain it 1-2° C above the temperature of the outer bath. Within the inner bath was a kerosene-filled aluminum vessel containing the thermistor mounting block (see Fig. 3). The kerosene was stirred.

The thermistor mounting block was made from a 10" length of aluminum hexagonal bar stock 1 1/4" across the flats. The thermistors were screwed into radial tapped holes in the flat sides, 4 to a side. The platinum resistance thermometer was mounted in a 3/8" diameter hole drilled to within 1/2" of the bottom. Mercury was used in the bottom of the well for good thermal contact.

A guarded Wheatstone bridge, Leeds and Northrup type 4737-A20, was used to measure thermistor resistance.

A Leeds and Northrup type 8163-C platinum resistance thermometer was used to measure the temperature of the thermistor mounting block. The resistance of the thermometer was measured with a Leeds and Northrup type 8068-B Mueller bridge using a nanovoltmeter as a null meter. The calibration of the PRT was checked periodically at the triple point temperature of water with a Trans-Sonic Equiphase type 130 triple point cell.

Up to 23 thermistors were mounted in the aluminum block. The thermistor leads were connected to cables going to the Wheatstone bridge via terminal strips. The 24th terminal pair of these strips was usually connected to a pair of bare wires immersed in the kerosene. The resistance of this open line was monitored with a megohmmeter as a check on any condition (contaminated oil, condensation, etc.) which could cause a significant shunting error in the thermistor resistance measurements.

Resistance of the thermistors was measured in sequence at a set of temperatures starting at approximately 0° C and increasing in 5° C steps to 30° C. Voltage across the thermistor was set to correspond to that appearing in the current meter to avoid differences in power dissipated in the thermistor. The whole sequence of measurements took 2 or 3 days.

Estimated Random and Systematic Errors of Measurements

During this period (January 1973 - January 1975) a change was made in the apparatus which affected the estimated precision of measurement. This occurred in August 1973 when a temperature gradient was discovered in the oil-filled vessel. From tests made at this time (by interchanging the thermistors in the highest and lowest position in a similar mounting block) the largest temperature difference from the top of the mounting block to the bottom appeared to be .004° C at a bath temperature of 0° C. After changing the oil level and introducing baffles inside the aluminum vessel, retesting showed that the difference, if any, was less than .001° C. The estimated random error prior to Batch 11 (September 7, 1973) includes a factor based on the larger gradient.

The temperature variation in the water bath due to the control cycle ($\simeq$ 1 cycle/min) was usually less than 1 m° C. The oil-filled vessel further reduced the cycling variation to the order of several tenths of a millidegree as measured by the platinum thermometer. The longer term temperature variation inside the mounting block could be followed by the thermistors and by the platinum thermometer and under typical conditions did not vary by more than 1 m° C over the time required to make all measurements at one temperature point (1 to 1 1/2 hour for 23 thermistors).

The values of the "α" and "δ" constants of the platinum thermometer are traceable to a NBS calibration (see NBS Monograph 126, 1973, for symbol nomenclature) and its resistance was checked regularly at the triple point of water. This resistance changed by the equivalent of about 2.5 m° C over the two year period. The Mueller bridge calibration corrections are traceable to a NBS calibration. This thermometer-bridge combination was checked in February 1975 against that of a newer Leeds and Northrup platinum thermometer and Guildline Current Comparator Resistance Bridge (see section B in this chapter). The temperatures indicated by the two systems differed by not more than 0.7 m° C at 30° C.

The warranted (uncorrected) accuracy of the type 4737 guarded Wheatstone bridge used to measure the thermistor resistances is ±100 ppm at 25° C (equivalent to ±2 m° C). The accuracy is derated by 10 ppm per °C difference from 25° C. Corrections to the bridge dial readings were found at 25° C using resistance ladders, one element of which had been measured to an accuracy of 5 ppm. The accuracy of the corrected guarded Wheatstone bridge readings at 25° C was then taken as about 5 ppm, equivalent to 0.1 m° C when applied to the measurement of thermistor resistance.

The corrections described above were used throughout the January 1973 to December 1974 period. In November 1974, they were checked by measuring the resistances of the Guarded Wheatstone Bridge using a Guildline Comparator Bridge and Guildline standard resistors. Differences of up to 20 ppm (0.4 m° C) were found. These could be accounted for by the temperature of the Guarded Bridge (23-24° C instead of 25° C) and by a drift in the Guildline standard resistors; however, this figure, 0.4 m° C, instead of 0.1 m° C as found earlier, is taken as the systematic error associated with the type 4737 bridge.

The first two columns of Table 2 sum up our estimates of the errors inherent in the VACM thermistor calibration for the calibration system in use until January 1975.

B. System II. January 1975 (Batch 45) to present

In January 1975 we began using a new set of thermistor calibration apparatus which has moderately improved the calibration accuracy and substantially increased the speed and convenience of making calibrations.

The new bath system consists of a Tronac Model 400 constant temperature bath with a Tronac Model 40 temperature controller. This is a single bath system making it easier to change the bath temperature rapidly.

The new thermistor mounting block (Fig. 4) was machined from an aluminum cylinder, 4 inch diameter by 4 inch long. Six lengthwise, 1 inch deep cuts around the cylinder allow recessed mounting of 4 thermistors per cut. The platinum thermometer is mounted in a 3/8 inch diameter hole drilled through the axis of the cylinder. The mounting block is enclosed in an aluminum housing which is purged with dry nitrogen and hermetically sealed before being placed in the bath.

The new platinum resistance thermometer is a Leeds and Northrup Model 8167-25B. Its resistance is measured with a Guildline Instruments Model 9975 thermometer bridge. As used in thermometry, the bridge determines the ratio of the platinum probe resistance and a high precision, stable resistor mounted in a temperature controlled air bath. As with the Mueller bridge, a four terminal measurement of the probe resistance is made and the effect of the thermal emf's is eliminated by current reversals. Readings can be made in far less time and with greater precision than with the Mueller bridge used previously.

The rest of the equipment, the Wheatstone bridge and null meter for measuring thermistor resistance, and the triple point cell, remains the same as before.

The calibration procedure is the same as before except that the amount of time required to calibrate a normal batch of 24 thermistors is now 12 hours or less.

Estimated Random and Systematic Errors of Measurements

During this period (January 1975 to the present) the random and systematic errors of measurements were estimated to be somewhat less than in the previous period. They are summarized in column 3 of Table 2.

The mounting block gradient, one of the main sources of error in precision during the previous period, was improved through the use of the newer apparatus. A test done in March 1976 which included a careful measurement of the vertical profile of the temperature along the axis of the platinum thermometer well as well as the exchange of thermistor position indicated a maximum variation of less than 0.6 m° C.

As a result of the improved temperature control of the new bath the error due to the short term temperature cycling of the mounting block was estimated to be not more than 0.1 m° C. Actually, much of the time, the temperature read by the platinum probe did not change during the scanning of 24 thermistors at one temperature (1/2 to 3/4 hours) by more than 0.1 or 0.2 m° C. When the drift was larger than this the tracking of the recorded thermistor temperature and platinum thermometer temperature was close enough so that the errors were still kept within the 0.1 m° C figure.

The largest source of error in precision with this new equipment was due to the drift of the platinum thermometer between triple point readings. Of course, most of this error can be corrected by interpolating linearly between check points but since this would have delayed the processing and reporting of the data it was not done. In the future it is planned to take more frequent triple point checks to reduce this source of error.

The random errors due to temperature effects on the bridge used to measure the thermistor resistances remain the same as in the previous period. There are no significant temperature effects (< 0.1 m° C) on the Guildline bridge.

The systematic error of the platinum resistance thermometer is estimated to be 0.5 m° C from information obtained from the manufacturer Leeds and Northrup (L&N).

The Guildline bridge error in ratio measurement is certified by the manufacturer not to exceed ±(2 parts in 10^7 of reading + 1 step of last dial). This would cause an insignificant sytematic error in the temperature (< .1 m° C).

The systematic errors associated with the type 4737 bridge and the triple point cell remain the same as before.

Table 2

Random and Systematic Errors of Measurements in m° C Equivalents

Time Period

	A. Jan. 1, 1973 to Jan. 1975		B. After Jan. 1975
	Before Sept. 7, '73	After Sept. 7, '73	
Random Errors Due to			
1) Mounting block gradient	2.0	0.5	0.3
2) Short term temperature cycling of bath	0.2	0.2	0.1
3) Uncorrected R(O) drift of platinum probe	0.1	0.2	0.8 (1)
4) Effect of room temperature changes on Type 4737 bridge	0.5	0.5	0.5
Sum of Random Errors	2.8	1.4	1.7
Root Sum Square Random Error	2.1	0.8	1.0
Systematic Errors Due to Inaccuracies of:			
1) Platinum probe calibration	1.0	1.0	0.5
2) Triple point	0.5	0.5	0.5
3) Mueller bridge	0.5	0.5	NA
4) Guildline bridge	NA (2)	NA	< 0.1
5) Type 4737 bridge	0.4	0.4	0.4
Sum of Systematic Errors	2.4	2.4	1.4

Note: (1) Includes drift, if any, of Guildline standard resistor

(2) NA - Not Applicable

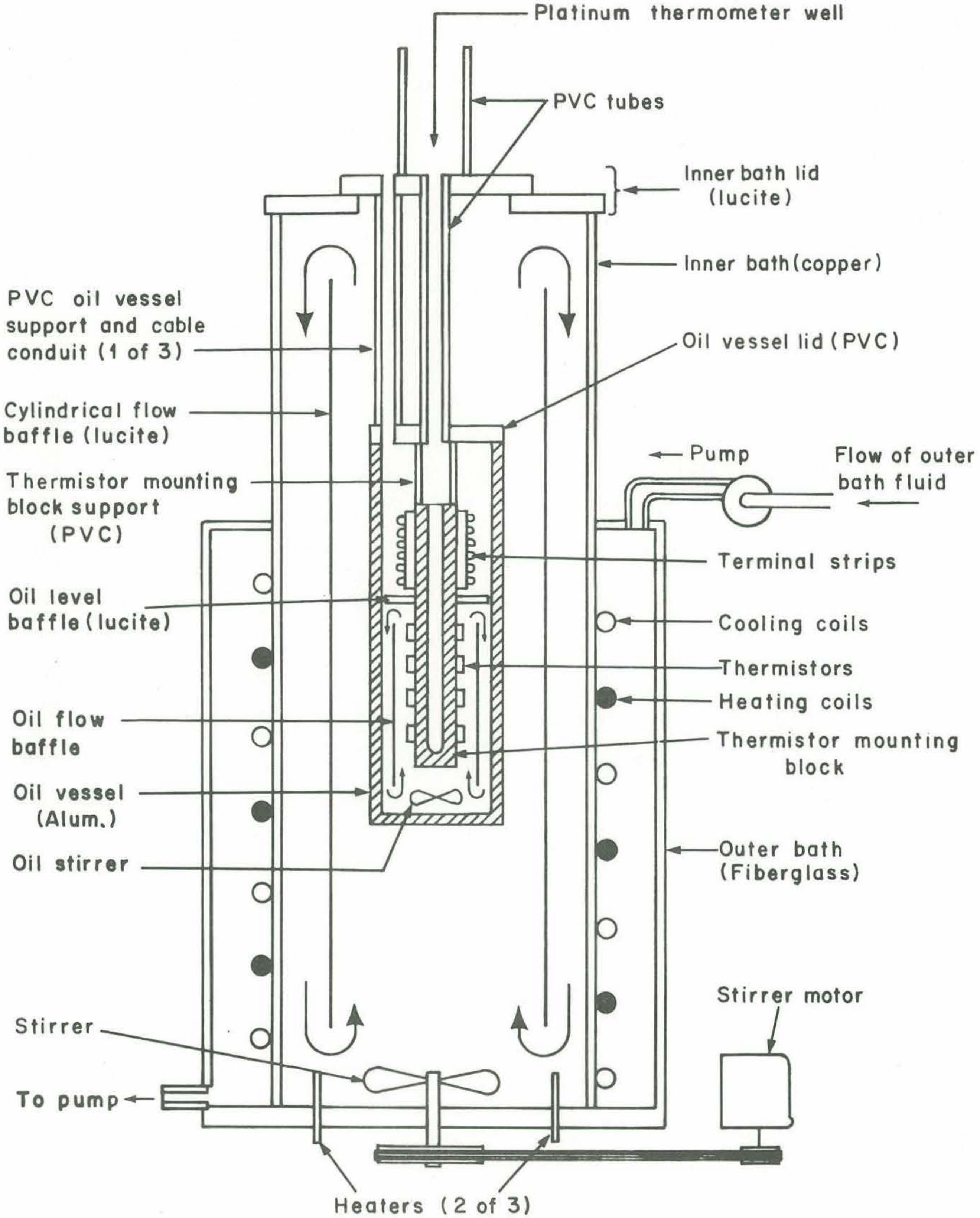


Figure 2

CONSTANT TEMPERATURE BATH
WITH THERMISTOR MOUNTING BLOCK

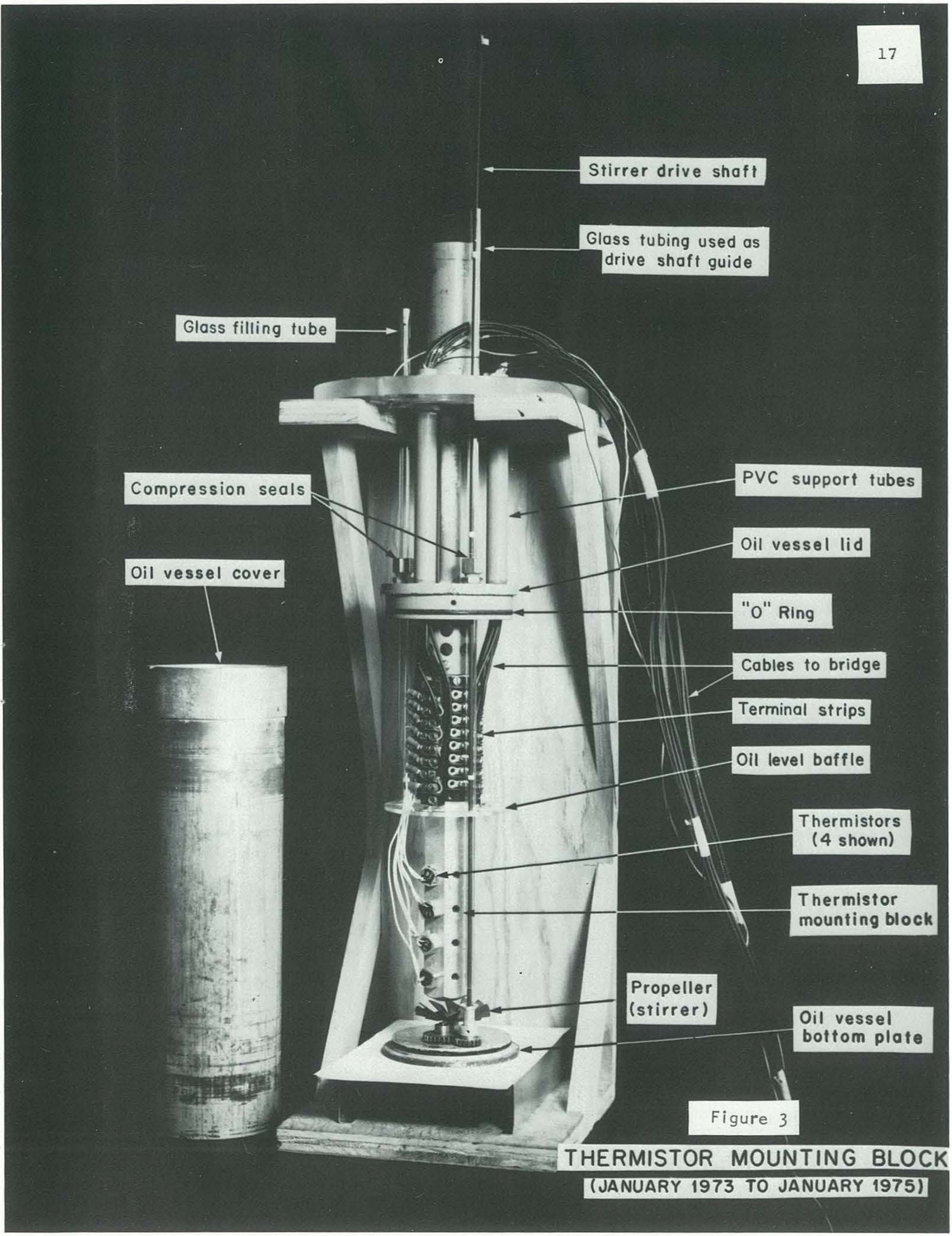


Figure 3

THERMISTOR MOUNTING BLOCK
(JANUARY 1973 TO JANUARY 1975)

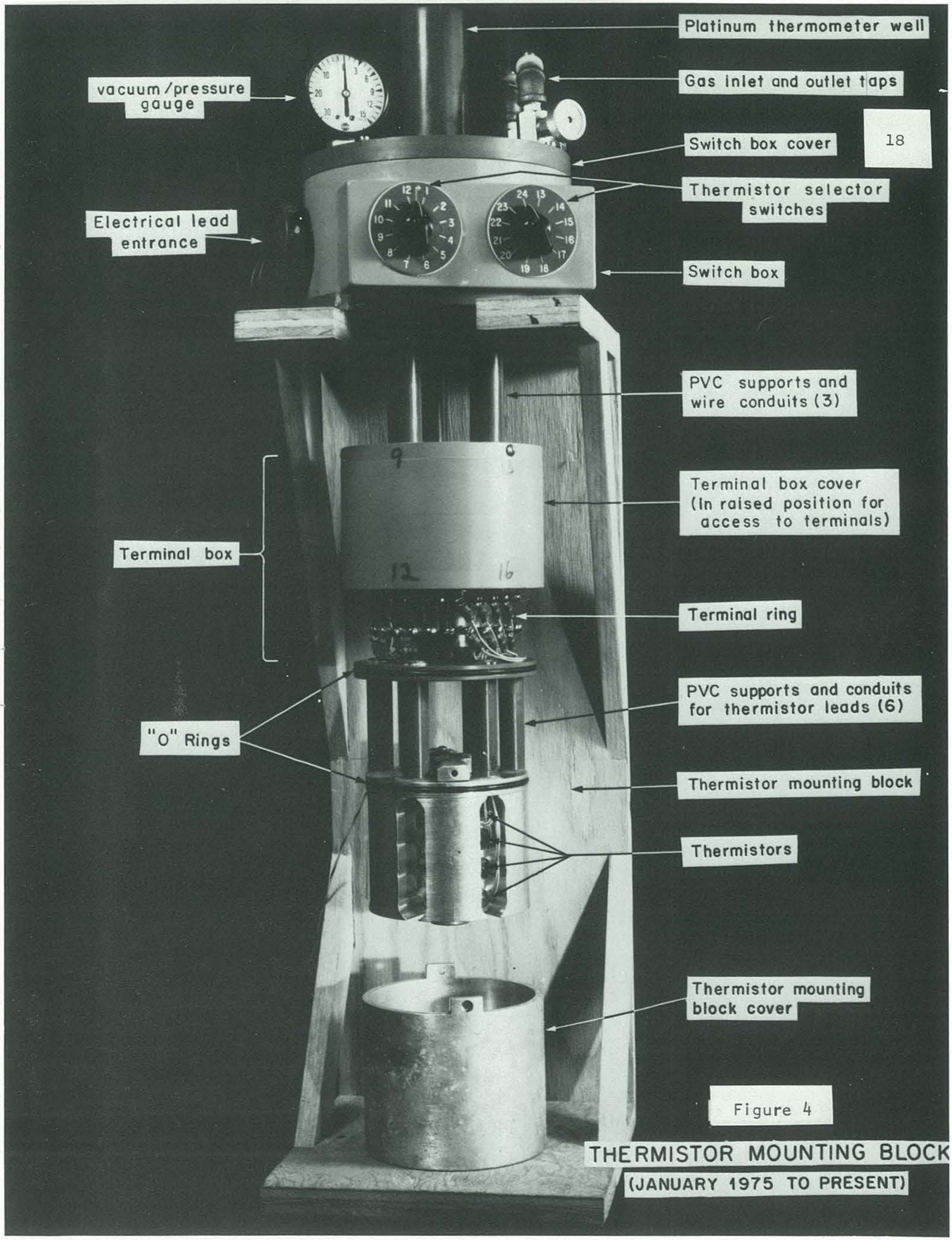


Figure 4

THERMISTOR MOUNTING BLOCK
(JANUARY 1975 TO PRESENT)

5. Thermistor Calibration Results

In this section we will describe what we have learned from calibrations to date of our YSI type 44032 thermistors.

We now own 163 YSI type 44032 thermistors which have each had at least one calibration. Of these, 69 meet the criteria for being included in this study, i.e., at least three calibrations over at least two years. We intend to continue regular calibrations of all our thermistors.

Our analysis of thermistor performance is based on the outputs of the computer programs CALIBB and CALCOLIN, described in Appendices II and III. CALIBB fits the resistance, temperature calibration data to the expression (Bennett, 1972, Steinhart and Hart, 1968)

$$T^{-1} = A + B\ell nR + C(\ell nR)^3$$

by a least squares technique. A residual is computed for each data point as the difference between the observed temperature and a temperature computed from the observed thermistor resistance and the A, B, C constants from that calibration. The r.m.s. value of this residual for the seven data points in a calibration is printed out in CALIBB and falls in the range 0-1 m° C for nearly all of our calibrations. The mean value for all our past calibrations is .2 m° C, which shows how well the above equation fits the data.

Using CALCOLIN we can estimate the rate at which the temperature indicated by a thermistor is changing relative to the true temperature of its environment. We should remember, however, that what is actually changing is the resistance of the thermistor at a given temperature.

Table 3 and Figure 5 sum up the calibration histories of the 69 thermistors with sufficient calibration history. Table 3 lists for each thermistor, in order of increasing drift rate magnitude, the total number of calibrations, the elapsed time in years between the first and latest calibration, the mean drift rate, and the standard deviation about the mean drift. The drift rate and standard deviation are means over the least squares fit at each of the seven calibration temperatures and are computed in CALCOLIN. In this table drift rate has the opposite sign from the number in the CALCOLIN output since it is the rate at which temperature would appear to change if the thermistor were kept immersed in a bath whose temperature was held constant. Positive drift rate indicates that thermistor resistance at constant temperature is decreasing with time.

The standard deviations listed in Table 3 show that our calibrations are consistent with each other to better than 1 m° C. Standard deviations are less than this, for the most part, except for the higher drift rates. There is other evidence for the repeatibility of our calibrations. Calibration batches 52 and 53 were done within 1 week of each other and 19 thermistors were common to both batches. The mean difference between the two calibrations for each of the 19 thermistors was .3 m° C. The r.m.s. difference was .97 m° C.

Figure 5 is a histogram of the mean drift rate magnitudes for the 69 thermistors in Table 3. The dividing line we have chosen between stable and unstable thermistors is arbitrary but can be rationalized. The absolute accuracy of our temperature measurements is no worse than ±10 m° C and may be as good as ±5 m° C. For a typical deployment of 9-12 months we would prefer that the thermistor drift be less than 5 m° C so that correction for drift is not necessary. The dip in the distribution around 3 m° C/year provides a natural place to draw the line.

Since the thermistors we use are standard off-the-shelf units with no preselection applied we would expect the distribution shown in Figure 5 to be typical. Thus, in any batch of thermistors we would expect 65-75% of them to have drift rates less than 5 m° C/year and about 10% of them to have drift rates greater than 10 m° C/year. A few of these would have drift rates high enough to make them unuseable for any scientific purpose. We should point out that high drift rates seem to decrease with time but we will need several more years of calibrations before we can elaborate on that topic.

Table 3

Thermistor Drift Rates

Thermistor Number	Number of Calibrations	Calibration Span (years)	Drift Rate (m° C/year)	Standard Deviation About Drift (m° C)
51	6	2.4	.00	1.19
60	6	2.4	-.02	1.13
122	5	3.0	+.02	1.20
58	7	2.4	-.06	1.54
72	4	2.3	-.07	.93
54	4	3.1	-.12	.85
111	5	3.0	+.13	1.19
69	7	3.0	-.14	1.29
61	5	3.1	+.15	1.39
113	5	2.4	-.18	.83
126	8	2.1	+.21	1.82
164	4	2.6	-.22	.94
162	4	2.3	-.25	1.23
152	5	2.1	-.26	.83
123	6	2.9	+.27	1.28
52	5	2.2	+.29	1.06
63	4	2.9	+.31	1.14
158	6	2.8	-.33	1.40
74	5	3.1	+.39	1.59
159	6	3.0	-.47	1.25
53	6	2.7	-.50	1.26
102	7	2.9	+.50	1.03
163	6	3.4	+.55	2.31
125	5	2.1	+.58	1.31
66	6	2.4	+.60	1.15
154	7	3.0	-.61	1.06
57	5	2.9	+.62	.94
32	7	2.7	-.74	1.02
114	7	3.1	+.78	1.58
7	7	3.4	-.83	3.03
130	6	2.4	-.83	1.12
70	6	2.3	+.94	1.70
106	4	2.2	-.95	1.10
167	5	2.3	-1.00	1.01
129	5	2.1	-1.01	1.28
170	4	2.8	-1.02	.95
247	4	2.2	+1.02	2.07
3	5	2.4	+1.08	1.81
160	3	2.2	-1.08	.57
67	5	2.7	-1.39	1.85
135	5	2.5	+1.43	1.56
246	4	2.2	-1.77	2.33
56	8	2.7	-1.79	1.99
157	6	3.0	+1.89	1.88
238	4	2.0	+1.91	1.77
156	5	3.4	+2.09	2.33
109	8	3.5	+2.15	2.59
166	5	3.0	-2.15	1.19
244	5	2.0	+2.17	2.94
242	6	2.0	-2.74	2.39
112	5	3.0	+3.18	1.50
240	5	2.0	-3.97	1.61
155	5	3.4	+4.19	2.57
189	5	2.1	+4.33	2.90
136	5	2.9	+5.08	3.63
76	8	3.5	+5.25	3.13
190	4	2.1	-5.29	2.01
134	4	2.7	+5.33	2.71
187	4	2.1	+5.60	2.60
188	4	2.2	+5.86	1.61
131	8	3.0	+6.51	2.90
169	3	3.1	+6.70	2.81
168	6	3.4	+11.60	4.85
239	5	2.0	-13.02	2.85
132	7	2.6	-16.53	3.91
121	4	2.5	-41.94	6.92
153	6	3.1	-129.33	13.30
133	7	2.9	-336.85	24.29
128	4	3.2	-503.19	31.06

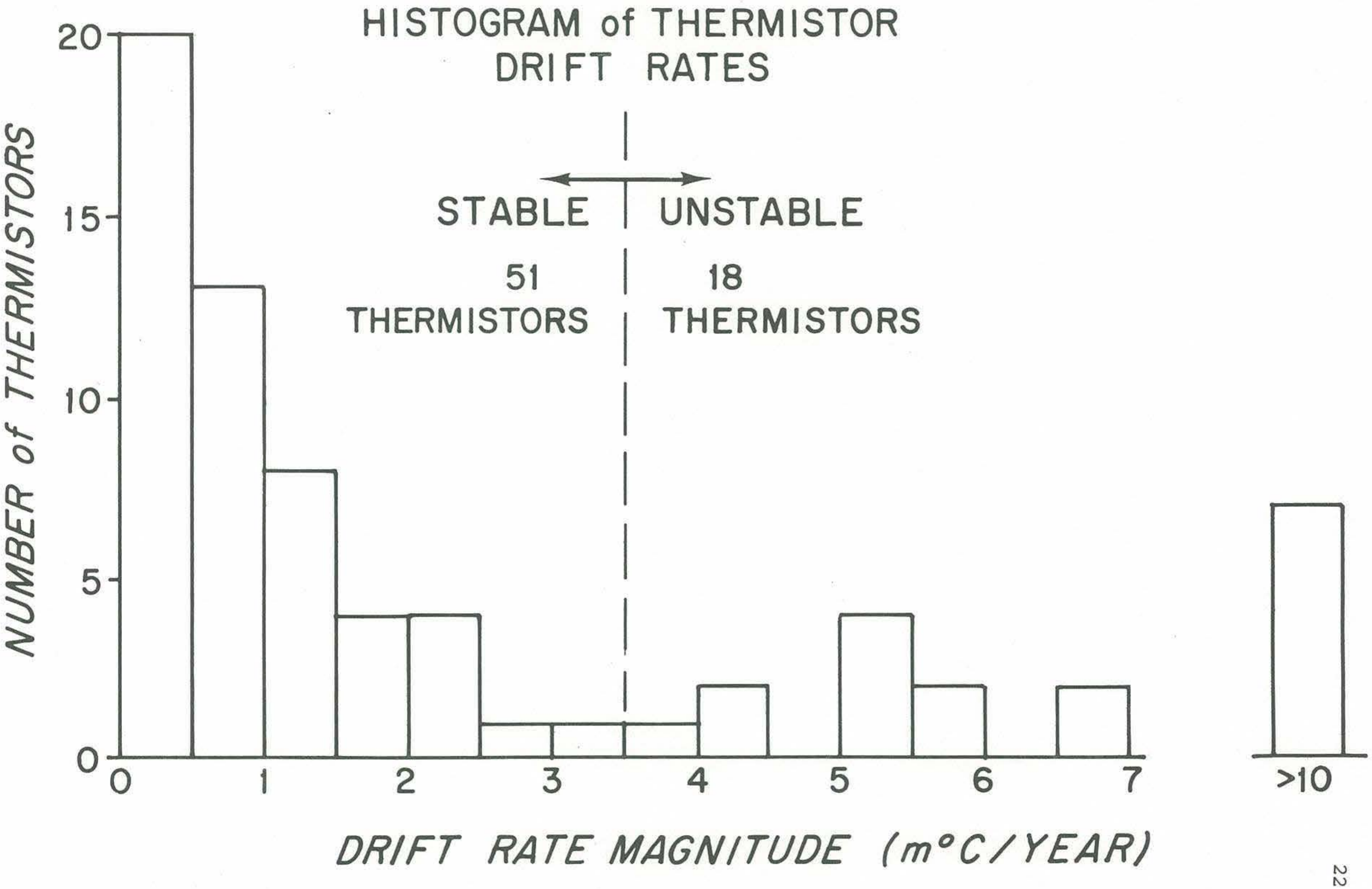

HISTOGRAM of THERMISTOR
DRIFT RATES
STABLE
51
THERMISTORS
UNSTABLE
18
THERMISTORS
NUMBER of THERMISTORS
20
15
10
5
0
0
1
2
3
4
5
6
7
>10
DRIFT RATE MAGNITUDE (m°C/YEAR)

Figure 5

6. Temperature Accuracy and Precision

6. A. NBS Intercomparison

In December 1973 we sent 17 thermistors to the National Bureau of Standards (NBS) where they were calibrated by Ms. Sharrill D. Wood. Upon their return to W.H.O.I. in April 1974 they were calibrated by Karl Schleicher. The results give us a comparison of the results of our calibration techniques vs. those at NBS.

The thermistors chosen for this intercomparison were of two types, both preselected by the manufacturer for stability and both purchased for a special application of the VACM. One type ("5000 series") has 4000 Ω resistance at 25° C and is used in a differential circuit to measure the difference in water temperature between the top and bottom of the VACM, thus giving local temperature gradient (See Section 6. B., IWEX). The other type ("6000 series") is different from our standard YSI thermistor in that it is pretested for stability and has a slightly different mechanical configuration. Their temperature-resistance specifications are the same as the standard VACM thermistors, having 30,000 Ω resistance at 25° C.

Normal W.H.O.I. calibrations are run with the same current passed through the thermistor as in the VACM at that temperature so that the self-heating will be quite similar. For this intercomparison, however, all resistance measurements at NBS and W.H.O.I. were made with 10 μa current through the thermistors, substantially lower than normal operating currents, to give a minimum amount of self-heating.

Table 4 shows the difference in resistance at several temperatures between the NBS and W.H.O.I. calibrations and the equivalent temperature difference. The resistances were calculated from the A, B, C constants (See Appendix II) at the indicated temperatures. The temperature difference was calculated by multiplying the resistance difference by dT/dR as calculated from the A, B, C constants with the expression

$$\frac{dT}{dR} = -\frac{Tabs^2}{R}\left[B + 3C(\ell nR)^2\right]$$

The individual temperature and resistance differences in Table 4 appear fairly random. For the most part the r.m.s. differences for each thermistor are within 5 m° C. The mean difference is -1.6 ± 3.1 m° C. This is probably what one should realistically expect for comparisons between two laboratories and may be indicative of the absolute accuracy of calibrations at any one laboratory. The standard deviation is consistent with the scatter we find between several calibrations of a stable thermistor.

Calibration results of two of the "6000 series" thermistors were omitted since later calibrations showed them to be drifting at a rate which would make comparison of the NBS and W.H.O.I. results meaningless. Four of the thermistors listed were destroyed for testing purposes after only two calibrations. These were 6003, 6017, 6046, 6118. These show some of the highest differences for the 6000 series thermistors in Table 4. Because of the limited number of calibrations we cannot be sure that the differences were not caused by drift.

TABLE 4

Comparison of NBS and WHOI Calibrations

		0C			5C			10C			15C			20C			25C			30C	
Thermistor	R_{NBS} Ohms	R_{WHOI} Ohms	ΔT mC	R_{NBS} Ohms	R_{WHOI} Ohms	ΔT mC	R_{NBS} Ohms	R_{WHOI} Ohms	ΔT mC	R_{NBS} Ohms	R_{WHOI} Ohms	ΔT mC	R_{NBS} Ω	R_{WHOI} Ω	ΔT mC	R_{NBS} Ω	R_{WHOI} Ω	ΔT mC	R_{NBS} Ω	R_{WHOI} Ω	ΔT mC
5013	11269.4	11268.9	1.0	9043.8	9043.2	1.5	7305.1	7304.7	1.2	5937.6	5937.3	1.2	4855.1	4854.9	1.0	3992.8	3992.8	0.0	3301.8	3301.9	-0.8
5017	11254.6	11256.8	-4.4	9038.3	9039.9	-4.1	7305.3	7306.5	-3.5	5941.1	5942.0	-3.7	4860.2	4861.0	-4.2	3998.7	3999.3	-3.9	3307.9	3308.4	-4.0
5026	11261.0	11262.9	-3.8	9041.4	9042.9	-3.8	7307.4	7308.6	-3.5	5943.3	5944.2	-4.1	4863.1	4863.8	-3.6	4002.5	4003.0	-3.3	3312.5	3312.8	-2.4
5051	11250.6	11254.8	-8.4	9035.4	9038.2	-7.2	7303.7	7305.8	-6.1	5940.8	5942.4	-6.6	4861.2	4862.6	-7.3	4000.7	4002.0	-8.5	3310.6	3311.9	-10.5
5095	11257.3	11260.0	-5.4	9039.6	9041.6	-5.1	7306.5	7308.0	-4.4	5942.7	5943.9	-5.0	4862.6	4863.5	-4.7	4001.9	4002.6	-4.6	3311.8	3312.3	-4.0
5102	11259.5	11259.1	0.8	9041.1	9040.9	0.5	7307.3	7307.3	0.0	5943.0	5943.1	-0.4	4862.4	4862.7	-1.6	4001.3	4001.7	-2.6	3311.0	3311.4	-3.2
5104	11260.5	11265.3	-9.6	9040.3	9043.7	-8.7	7305.4	7307.9	-7.3	5940.4	5942.2	-7.4	4859.5	4860.9	-7.3	3998.3	3999.3	-6.5	3307.9	3308.7	-6.5
6003	98550.3	98526.8	4.7	76538.3	76529.8	2.2	59903.9	59902.5	0.4	47232.5	47233.8	-0.6	37056.1	37507.5	-0.8	29985.4	29986.0	-0.5	24129.0	24128.4	0.6
6014	98484.9	98477.4	1.5	76477.4	76476.6	0.2	59852.8	59854.6	-0.6	47192.8	47195.0	-1.0	37477.1	37478.8	-1.0	29966.0	29966.7	-0.5	24117.6	24117.2	0.4
6017	98358.4	98357.1	0.3	76383.9	76359.9	-0.5	59798.6	59801.5	-0.9	47158.5	47161.0	-1.1	37456.4	37458.0	-0.9	29954.5	29955.0	-0.4	24112.2	24111.8	0.4
6046	98412.0	98388.8	4.6	76447.1	76435.4	3.1	59848.9	59843.3	1.8	47204.8	47202.0	1.3	37498.2	37496.5	1.0	29991.8	29990.2	1.2	24145.3	24143.5	1.7
6057	98527.4	98519.1	1.6	76526.2	76523.2	0.8	59903.9	59903.3	0.2	47243.9	47243.9	-0.1	37526.2	37526.4	-0.1	30012.4	30012.2	0.2	24160.8	24160.2	0.7
6059	98504.5	98488.8	3.1	76513.9	76506.8	1.9	59899.6	59896.3	1.0	47245.1	47243.0	1.0	37531.6	37529.6	1.2	30020.4	30017.9	1.9	24170.5	24167.3	3.1
6099	98504.8	98500.4	0.9	76498.9	76499.6	-0.2	59872.4	59874.8	-0.8	47208.9	47211.3	-1.1	37489.5	37491.0	-0.9	29974.8	29975.2	-0.3	24123.3	24122.6	0.7
6118	98513.1	98488.4	4.9	76521.8	76511.3	2.8	59901.1	59896.8	1.4	47238.6	47236.3	1.0	37517.5	37515.3	1.3	30000.0	29996.8	2.4	24145.3	24140.8	4.4

6. B. IWEX

During November 1973 a stable tripod mooring was deployed by the Buoy Project at 27° 43'N, 69° 51'W in 5455 m water depth. The mooring was in place for 44 days. On the IWEX (for Internal Wave Experiment) mooring were mounted 17 VACMs, 9 temperature/pressure recorders, and 4 model 850 current meters. The VACMs were modified to measure temperature difference between thermistors mounted in pods at the top and bottom of each instrument as well as absolute temperature. Because of the temperature difference measurements extensive calibration operations were performed. These calibration operations, combined with the stability of the mooring and the close spacing of a cluster of 7 VACMs at the top, offered an excellent chance to determine the achievable accuracy in the VACM measurement of absolute temperature *in situ*.

Figure 6 illustrates the configuration of the IWEX mooring. The depths of the levels and the horizontal separations of instruments on two different legs but at the same level are given in Table 5 as well as the temperature gradient at each level derived from a mean temperature profile (Millard, 1974; Tarbell, Briscoe and Chausse, 1975).

Calibrations

The thermistors used in the absolute temperature circuit of the IWEX VACMs were manufactured by Thermometrics, Inc. Mechanically and electrically they are quite similar to the YSI thermistors we had used previously. Instead of being mounted within the current meter, they were mounted externally in pods to decrease the time constant.

Before delivery the thermistors were stabilized by temperature cycling and then tested for maximum stability by repeated calibrations at regular intervals by the manufacturer. In addition, they were calibrated in our own facility (see Section 4 of this report) before and after the experiment and twice more in the two years since. We have not included these in the thermistors reported on in Section 5 because of this limited calibration history.

Because of the stringent requirements of the temperature difference measurements the thermistor pods were immersed, several at a time, in a constant temperature bath before and after the experiment for system calibration. The bath was run at 0, 15, 30° C while the thermistors remained connected to the current meters. These data were recorded on the IWEX data tape for each instrument.

The constant temperature bath was a Tronac Model 400, modified by the addition of one inch of urethane insulation on all sides. The temperature controller was a Tronac Model 40 used in conjunction with an external cooling unit. These provided excellent temperature control for the calibrations, maintaining control to within 2 m° C (averaged over 225 seconds) for periods of hours with temperature differences through the tank of less than .2 m° C. Absolute temperature of the tank was measured with a platinum resistance thermometer with calibrations traceable to the National Bureau of Standards.

The noise level and short-term stability of the instruments, and the stability of the calibration bath were within design specifications. As a test five instruments were run overnight in the bath. The absolute temperatures recorded by the current meters were constant within ±1 data count (±.2 m° C) averaged over 225 seconds.

Results

Biases and drift rates of the thermistors were computed from the bath tests and our standard thermistor calibrations. Bias is the error in measurement of absolute temperature by a current meter and thermistor at the time of the pre-mooring bath test. Drift rate is computed from the difference in error of measurement between the pre-mooring and post-mooring bath tests and the pre-mooring and post-mooring thermistor calibrations. Only two of the seventeen thermistors, those at the positions B2 and C5, showed significant drift and needed to be corrected but the magnitudes of these two drift rates, 9 and 11 m° C/month, were surprisingly large in view of the pretesting performed by the manufacturer.

Table 6 lists means of absolute temperature for all the levels where there was more than one current meter. They are listed as ten consecutive 4-day means and the overall 40-day mean. The B2 and C5 temperatures have been corrected for bias and drift. No corrections were required for the rest of the temperatures.

In Table 7 are the temperature differences at each level for the 4-day means, the 40-day mean, and the 40-day mean divided by the temperature gradient at that level from Table 5. If we assumed that the temperature sensors were all perfect then this last quantity would be the mean depth difference between sensors on one level.

Now look at Table 7 in detail keeping in mind our stated temperature accuracy of 10 m° C. Sensors A1 and C1 are only 6.1 meters apart and the temperatures agree within, at most, 2 m° C. At level 2, with a separation of 8.5 meters, A2 and C2 agree to no worse than 3 m° C. B2 is one of the two thermistors which had a rather large drift rate and is, therefore, not as reliable as the others. In spite of this, it agrees with A2 and C2 within 5 m° C except for one of the 4-day periods. A4 and B4 agree within 5 m° C. At levels 5, 6, 10 with substantially larger sensor separations the B leg temperatures are substantially higher than for legs A or C. To explain this requires that the sensors on the B leg be 1, 2, 3 meters higher for the 5, 6, 10 levels than the sensors on the other two legs. Although there were not enough working pressure sensors on the mooring to define the motions we can rationalize the direction if not the magnitude, of the leg motions.

Anchors at the base of legs A and C were lined up along a north-south line. The currents in the top 1500 m were predominantly from west to east during the whole 40 days. This would cause legs A and C to be depressed relative to leg B. The current veered somewhat about the easterly direction with time, however, so we cannot say much about the relative depths of sensors on legs A and C. It is apparent from Table 7 that the B-A and B-C temperature differences are substantially larger than the C-A at levels 5, 6, and 10.

The absolute temperature data from the IWEX mooring are consistent with our claimed temperature accuracy of 10 m° C. They are particularly supportive where the horizontal separations are small and we can expect the vertical separations to be less than about 50 cm.

Table 5

IWEX Mooring Data

Level	Depth (m)	Horizontal Separation of Instruments (m)	Temperature Gradient (m° C/m)
1	603.6	6.1	18.6
2	605.7	8.5	18.6
4	610.6	14.0	18.8
5	639.5	44.0	19.8
6	730.6	139	22.5
8	1014.4	441	12.2
10	1023.1	450	11.7
14	2050.4	1600	1.4

Table 6

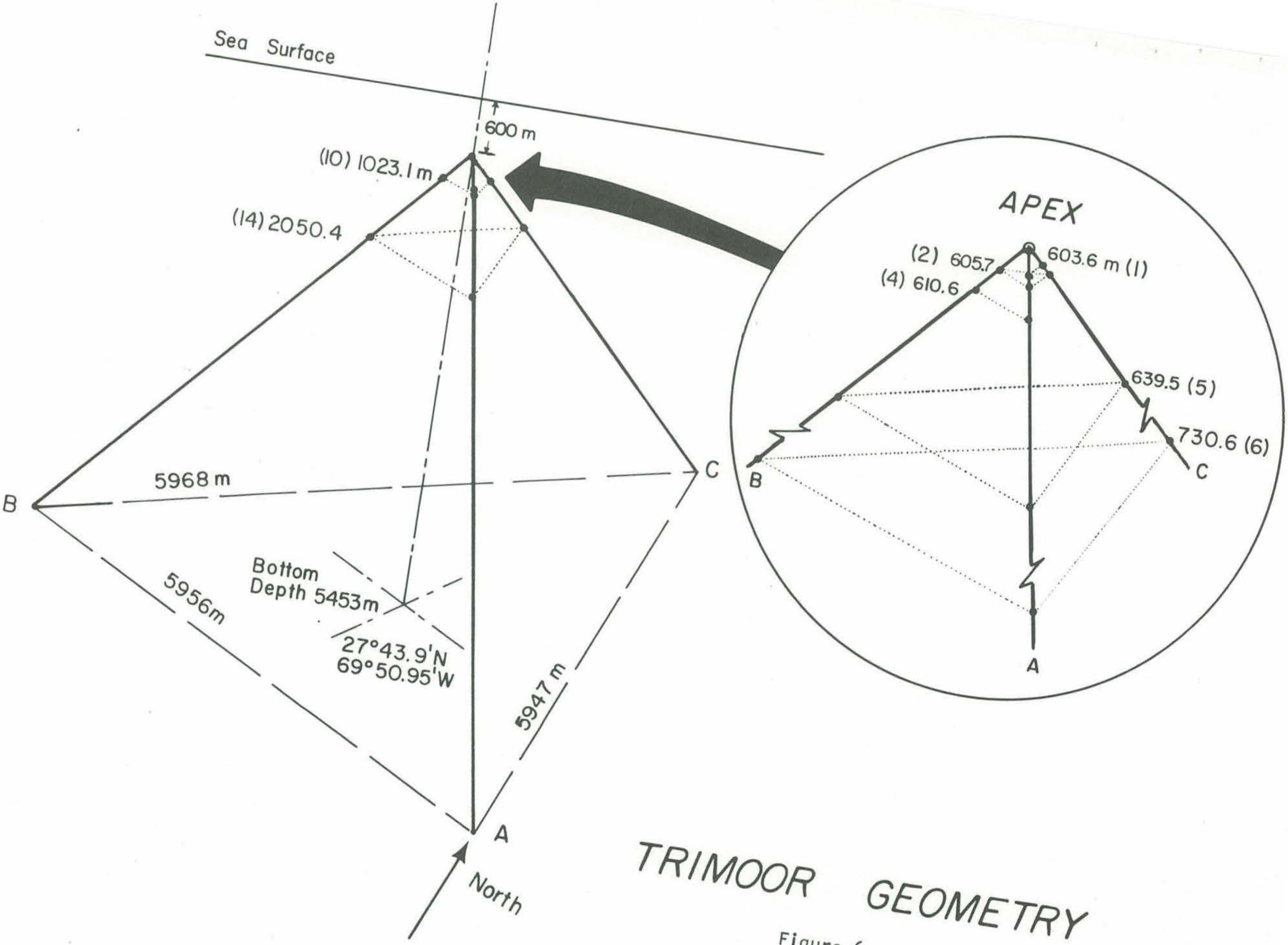
IWEX 4-Day Mean Temperatures, B2 and C5 Corrected for Thermistor Drift

	1	2	3	4	5	6	7	8	9	10	40-Day Mean
A1	14.029	13.964	13.968	14.015	14.116	14.158	14.180	14.186	14.181	14.173	14.097
C1	14.027	13.962	13.967	14.014	14.116	14.157	14.179	14.184	14.180	14.172	14.096
A2	13.995	13.927	13.930	13.975	14.079	14.120	14.144	14.152	14.144	14.141	14.061
B2	13.988	13.922	13.925	13.972	14.075	14.117	14.141	14.150	14.141	14.139	14.057
C2	13.995	13.926	13.930	13.974	14.078	14.119	14.142	14.149	14.141	14.138	14.059
A4	13.865	13.798	13.793	13.836	13.946	13.985	14.008	14.024	14.005	14.015	13.927
B4	13.866	13.800	13.794	13.839	13.949	13.990	14.011	14.027	14.009	14.017	13.930
A5	13.288	13.231	13.181	13.241	13.358	13.429	13.452	13.461	13.429	13.463	13.353
B5	13.301	13.249	13.198	13.262	13.380	13.453	13.473	13.484	13.448	13.482	13.373
C5	13.289	13.237	13.188	13.250	13.367	13.436	13.457	13.467	13.430	13.468	13.359
A6	11.254	11.155	11.142	11.134	11.264	11.389	11.383	11.413	11.431	11.442	11.301
B6	11.293	11.198	11.184	11.183	11.317	11.447	11.435	11.464	11.488	11.496	11.350
C6	11.260	11.162	11.150	11.147	11.276	11.387	11.371	11.402	11.410	11.434	11.300
A10	6.196	6.219	6.244	6.269	6.271	6.317	6.437	6.594	6.617	6.583	6.375
B10	6.219	6.247	6.278	6.303	6.315	6.365	6.476	6.635	6.669	6.627	6.413
C10	6.192	6.222	6.252	6.280	6.278	6.312	6.422	6.575	6.594	6.572	6.370
A14	3.538	3.563	3.605	3.605	3.580	3.581	3.620	3.635	3.629	3.619	3.597
B14	3.554	3.589	3.628	3.629	3.615	3.602	3.641	3.664	3.655	3.639	3.622
C14	3.547	3.597	3.622	3.621	3.598	3.592	3.626	3.641	3.626	3.619	3.609

Table 7

IWEX Temperature Differences

	1	2	3	4	5	6	7	8	9	10	Means	Equivalent Depth Differences (m)
C1-A1	2	2	1	1	0	1	1	2	1	1	1	.1
C2-A2	0	-1	0	-1	-1	-1	-2	-3	-3	-3	-2	.1
B2-A2	-7	-5	-5	-3	-4	-3	-3	-2	-3	-4	-4	.2
B2-C2	-7	-4	-5	-2	-3	-2	-1	-1	0	-1	-2	.1
B4-A4	1	2	1	3	3	5	3	3	4	2	3	-.2
C5-A5	1	6	7	9	9	7	5	6	1	5	6	-.3
B5-A5	13	18	17	21	22	24	21	23	19	19	20	-1.0
B5-C5	12	12	10	12	13	17	16	17	18	14	14	-.7
C6-A6	6	7	8	13	12	-2	-12	-11	-21	-8	-1	0
B6-A6	29	43	42	49	53	58	52	51	57	54	49	-2.2
B6-C6	33	36	34	36	41	60	64	62	78	62	50	-2.2
C10-A10	-4	+3	+8	11	7	-5	-15	-19	-23	-11	-5	.4
B10-A10	23	28	34	34	44	48	39	41	52	44	38	-3.2
B10-C10	27	25	26	23	37	53	54	60	75	55	43	-3.7
C14-A14	9	34	17	16	18	11	6	6	-3	0	12	8.6
B14-A14	16	26	23	24	35	21	21	29	26	20	25	17.9
B14-C14	7	-8	6	8	17	10	15	23	29	20	13	9.3



TRIMOOR GEOMETRY

Figure 6

6. C. Mooring 551 Intercomparison

In December 1974, a mooring was implanted at Site J, 36°N, 70°W, with four VACMs rigidly shackled together at a nominal 2000 m depth. Mooring 551 was in place for 128 days during which all four instruments worked satisfactorily. A fifth instrument, containing a pressure sensor, did not work. Because of this, the depths of the VACMs are known only to about ±20 m.

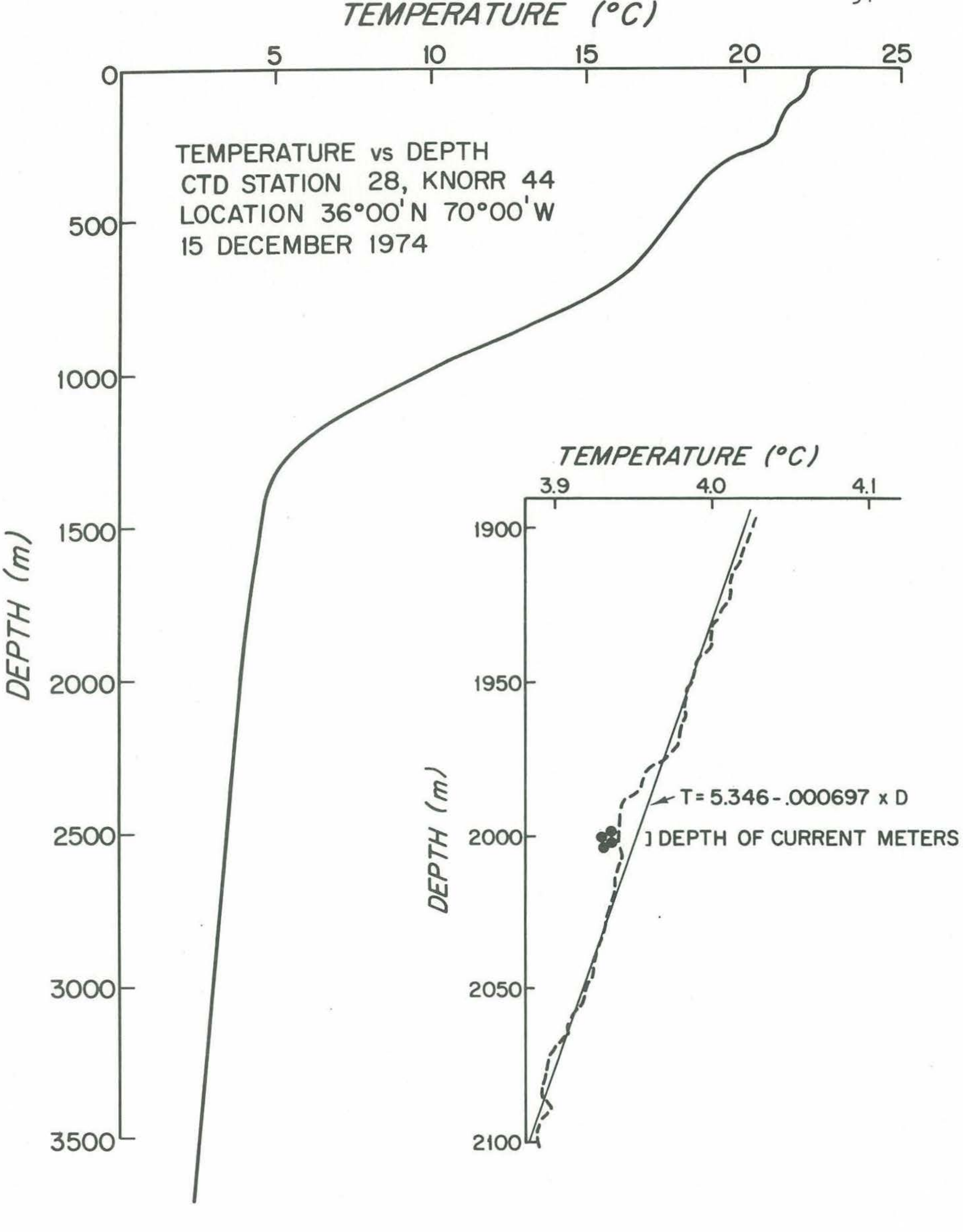
Since the mooring's purpose was a detailed comparison of the VACMs, the depth of the instrument grouping was chosen to be in a region of low gradients. Figure 7 shows temperature vs. depth from a CTD station made at the mooring location when it was set. The inset shows a more detailed plot for the depth range 1900-2100 m, a straight line least squares fitted to the CTD data, and four points representing the 128 day temperature means for the four VACMs. The straight line has a slope of -0.71 m° C/m, or the equivalent of a 4.3 m° C spread in temperature over the 6 m between the top and bottom thermistors.

Table 8 shows the 128 day temperature means from the four VACMs and their standard deviations. For each 7.5 minute recording interval a mean temperature was computed from the four individual temperatures and the difference between the mean and the individual temperatures computed to see how well the four instruments tracked. Row 4 is the 128 day time mean of these differences for each instrument and row 5 is the standard deviation of this quantity. The results show that the instruments track very well and that the agreement of the means is not fortuitous.

Table 8

Mooring 551 Temperatures Averaged over 128 Days

1.	Instrument	5512	5513	5514	5515
2.	Mean temperature	3.935° C	3.933° C	3.936° C	3.932° C
3.	Standard deviation	0.024	0.024	0.024	0.024
4.	Mean difference	0.001	-0.001	0.002	-0.002
5.	Standard deviation	0.002	0.001	0.001	0.002


TEMPERATURE (°C)
0
5
10
15
20
25
TEMPERATURE vs DEPTH
CTD STATION 28, KNORR 44
LOCATION 36°00'N 70°00'W
15 DECEMBER 1974
500
1000
1500
2000
2500
3000
3500
DEPTH (m)
TEMPERATURE (°C)
3.9
4.0
4.1
1900
1950
2000
2050
2100
DEPTH (m)
T = 5.346 - .000697 x D
] DEPTH OF CURRENT METERS

It would be appealing to attempt some kind of a direct comparison between absolute temperatures from VACMs and CTD but the uncertainty in current meter depth rules this out. The CTD data allow us to say that the time averaged temperature gradient in the vicinity of 2000 m is probably very close to -0.7 m° C/m. The absolute temperatures are consistent with the CTD temperatures to within the accuracy of the VACM depths.

6. D. Error Analysis

In the previous sections of this report we have described the components of the VACM temperature measuring system, some of the errors in those systems, and intercomparisons which have indicated some of the relative uncertainties in our temperature measurements. We have not been able to make an in situ comparison with a different, and preferably certifiably accurate, instrument, nor have we been able to test the absolute accuracy in the laboratory. In this section we will compute analytically the accuracies of both relative and absolute temperature measurements. To the extent that our computed accuracy of relative measurements agrees with the intercomparison results we may have some confidence in the computed absolute accuracy.

In Table 9 is a list of possible sources of error with an estimate of the contribution of each to the instrument bias in the measurements and the measurement variation.

Table 9

Error Sources in VACM Temperature Measurements

	Instrument Bias	Measurement Variation
Thermistor		
a. Calibration and drift rate		±4m°C
b. Linearity	+.3m°C	0
c. Self heating	+1m°C	0
V/F Converter		
a. Stability		1m°C
b. Linearity		1m°C
Rest of VACM		
a. Time base stability (900 second recording interval)		±.3m°C
b. Integrator		±.06m°C

The following describes the terms in the table in more detail and justifies the uncertainties given.

Thermistor

a. Calibration and drift rate - From the NBS intercomparison we feel sure that the absolute accuracy of each of our calibrations is about ±3 m° C. The scatter about the line fitting calibration vs. time data is ±1 m° C or less. The total uncertainty in expressing T as a function of R by the equation

$$T^{-1} = A + B(\ell nR) + C(\ell nR)^3$$

is then about ±4 m° C.

b. Linearity - Thermistors are nonlinear sensors. Computing a mean temperature from a mean thermistor resistance introduces an error which depends on the amplitude of fluctuations during the averaging interval. Typical temperature records, both in and below the thermocline show temperature standard deviations of about 200 m° C. For a sine wave fluctuation of this amplitude the error would be +.3 m° C. This is a systematic and not a random error so it contributes to the instrument bias.

c. Self heating - In the input circuit of the V/F converter, a precise 3.9 volts is impressed across the thermistor and a precision 37.3 KΩ fixed resistor is connected in series with the thermistor. In Table 10 are shown:

T - nominal temperature

R - mean resistance and standard deviation for the thermistors in Table 3 with drift rates less than 3.5 m° C/year.

P - power dissipated in thermistor with standard deviation due to deviation in R.

T - thermistor self-heating with assumed dissipation constant of 3 mw/°C and standard deviation due to deviation in R.

V_{th} - volts across thermistor resistance R in current meter circuit with standard deviation due to deviation in R.

V_{calib} - volts applied across thermistor in calibration equipment.

dT/dV - sensitivity of indicated temperature to an error in the voltage applied across the thermistor.

Table 10

Thermistor Self-Heating

T	R(ohms)	P(μw)	ΔT(m° C)	V_{th}(volts	V_{cal}(volts	$\frac{dT}{dV}$ $(\frac{m° C}{volt})$
0°C	95080±377	82.52±.14	27.51±.05	2.801±.003	2.80	20
5	74453±286	90.68±.12	30.23±.04	2.598±.003	2.60	23
10	58712±220	96.87±.08	32.29±.03	2.385±.003	2.39	27
15	46611±171	100.69±.04	33.56±.01	2.166±.004	2.17	31
20	37244±135	101.94±.0003	33.98±.0001	1.949±.004	1.95	35
25	29947±106	100.73±.04	33.58±.01	1.737±.003	1.74	39
30	24222±84	97.34±.07	32.45±.02	1.535±.003	1.54	42

Since the same voltage is applied to the thermistor during calibration as in the current meter, the bias due to self-heating is very nearly the same in the two situations. This net bias, therefore, does not appear in Table 9. There are three kinds of errors that can occur through the self-heating:

1. An error in the volts applied to the thermistor during calibration can cause an amount of self-heating differing from that in the current meter. An error of 0.1 volt would cause up to 5 m° C error, indicating that a modicum of care is required.

2. Because various thermistors have somewhat different resistances at the same temperature, the voltage across them, and thus the self-heating varies. For the range of thermistors in this study, however, the difference is at most .05 m° C, a negligible amount.

3. The assumed dissipation constant of 3 mw/°C is a nominal value. The important thing is to have the dissipation constant the same in the current meter and in the calibration setup. We have not been able to measure either dissipation constant but have tried to make the situations quite similar physically. We feel confident that the error due to difference in self-heating is less than ±1 m° C.

V/F Converter

a. Stability - We saw in Section 3 that the V/F converter is stable to 3 parts in 10^5, equivalent to about ±1 m° C.

b. Linearity - We saw, also in Section 3, that the period of the V/F converter output signal is a linear function of thermistor resistance to within the equivalent of ±1 m° C.

Rest of VACM

a. Time base stability. The stability of the crystal oscillator which provides the time base in the VACM is stable to 1 part in 10^5, equivalent to .009 sec for a recording interval of 900 sec. The uncertainty in temperature due to this uncertainty can be derived from the three equations:

$$T = [A + B(\ln R) + C(\ln R)^3]^{-1}$$

$$R = \frac{(\frac{1}{P} + K_2)\ R_S}{K_1 - K_2 - \frac{1}{P}}$$

$$P = \frac{t}{N}$$

where:

A, B, C - thermistor calibration constants

R - thermistor resistance at temperature T

R_S = fixed resistor, see section 2

K_1, K_2 = V/F converter constants, see section 2

t = current meter recording interval

N = counts accumulated during T by counter on output of the V/F converter

The uncertainty in temperature due to variations in the time base is given by:

$$\Delta T\Big|_N = \frac{\partial T}{\partial R}\frac{\partial R}{\partial P}\frac{\partial P}{\partial t}\Delta t$$

$$\frac{\partial T}{\partial R} = -\frac{T^2}{R}[B + 3C(\ln R)^2]$$

$$\frac{\partial R}{\partial P} = \frac{R_S(K_2 - K_1)}{[P(K_1 - K_2) - 1]^2}$$

$$\frac{\partial P}{\partial t} = \frac{1}{N}$$

Typical values of the variables at 10° C are:

$T = 283.15°\ C$	$R_1 = 24270\ \Omega$
$R = 58712\ \Omega$	$R_2 = 94980\ \Omega$
$B = .22519048 \times 10^{-3}$	$P_1 = 1.0036 \times 10^{-3}$ sec
$C = .114084 \times 10^{-6}$	$P_2 = 2.1548 \times 10^{-3}$ sec
$N = 575117$	$\Delta t = .009$ sec

Substituting these

$$\Delta T\big|_N = \pm .3\ m°\ C$$

b. Integrator - The integrator is just a counter and has an uncertainty of ±1 count. From Table 1 we see that this is equivalent to ±.06 m° C, a negligibly small uncertainty.

The total variance of temperature is the sum of the squares of the uncertainties. For the measurement variations,

$$Var_T \simeq 18(m°\ C)^2$$

The relative uncertainty we expect in the temperature measurements is then of the order of ±4.2 m° C which agrees well with the results of the IWEX intercomparison.

Adding the contributions of instrument biases to the variance,

$$Var_T \simeq 19(m°\ C)^2$$

the uncertainty we expect in the absolute temperature measurements is then about ±4.4 m° C.

We feel that this uncertainty estimate is a little optimistic but not completely out of line. Nelson Hogg (personal communication) after contouring, separately, temperatures recorded during MODE by current meters and CTDs, stated that the two sets appeared to agree within ±10 M° C. Our best guess as to the achievable accuracy of absolute temperatures with the VACM then, is perhaps better than ±10 m° C but no better than ±4.5 m° C.

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Appendix I

Some Useful Numbers

Some useful information is summarized in Table I-1.

Column 1 - The seven nominal temperatures at which we monitor thermistor and V/F converter characteristics.

Column 2 - Nominal resistances at these temperatures of the YSI 44032 thermistor.

Column 3 - Nominal dT/dR for YSI 44032 thermistors.

Column 4 - Nominal period of the V/F converter output signal for the Column 2 resistances. Our V/Fs are normally adjusted to agree with the nominal periods within ±.01 μs at 74,440Ω.

Column 5 - Some typical VACM recording intervals.

Column 6 - Numbers of counts which would be accumulated during the various recording intervals with thermistor resistances of Column 2.

Column 7 - Temperature resolution due to 1 count resolution in the total counts.

Column 8 - Uncertainty in temperature due to uncertainty in either P1 or P2 of ±1 μs.

Column 9 - Accuracy requirement for P1, P2 for a ±1 m° C accuracy in temperature.

Columns 10, 11, 12 - Accuracy requirements in A, B, C thermistor constants for ±1 m° C temperature accuracy. See Section 5 for definition of A, B, C.

TABLE I-1

Temp. (C)	Nominal Resist. (Ω)	dT/dR (mC/Ω)	Nominal Period (μS)	Record. Interval (S)	Nominal Counts	Temp. Resol. (mC/count)	Temp. Uncert. due to P1,P2 (mC/μS)	P1,P2 Require. for ±1 mC Accuracy (μS)	Tolerable Uncertainty for ±1 mC Accuracy		
									A $X10^{-8}$	B $X10^{-9}$	C $X10^{-12}$
0	94980	-.213	2154.8	900	417662	.07	-13.1	.076	1.3	1.2	8.9
				450	208831	.13					
				225	104416	.26					
				112.5	52208	.52					
5	74440	-.280	1820.4	900	494397	.06	-17.2	.058	1.3	1.2	9.2
				450	247198	.13					
				225	123599	.25					
				112.5	61800	.51					
10	58750	-.364	1564.9	900	575117	.06	-22.4	.045	1.3	1.1	9.4
				450	287558	.12					
				225	143778	.25					
				112.5	71890	.49					
15	46670	-.472	1368.2	900	657799	.06	-29.0	.034	1.2	1.1	9.7
				450	328899	.12					
				225	164450	.24					
				112.5	82225	.48					
20	37300	-.608	1215.7	900	740314	.06	-37.3	.027	1.2	1.1	10.0
				450	370157	.12					
				225	185079	.25					
				112.5	92539	.49					
25	30000	-.775	1096.9	900	820494	.06	-47.6	.021	1.1	1.1	10.3
				450	410247	.13					
				225	205124	.26					
				112.5	102562	.51					
30	24270	-.985	1003.6	900	896772	.07	-60.5	.017	1.1	1.1	10.6
				450	488386	.13					
				225	224193	.26					
				112.5	112096	.52					

Appendix II

CALIBB Program

Included in this appendix are a description of the CALIBB program, a listing of the program, and an example of input and output data from a calibration. CALIBB was written using Xerox FORTRAN IV and contains some statements which are not compatible with other versions of FORTRAN IV.

NAME: CALIBB

TYPE: Main program - processor

PURPOSE: To process thermistor calibration data

MACHINE: XDS Sigma 7

SOURCE LANGUAGE: Xerox FORTRAN IV

PROGRAM CATEGORY: Utility

DESCRIPTION:

CALIBB was written to fit thermistor calibration data to the equation

```
1/T = A + B*LN(R) + C*(LN(R))**3
```

where T is absolute temperature in °K and R is thermistor resistance.

CALIBB provides a choice of three inputs;

1. Direct values of temperature and corresponding thermistor resistance.
2. Output of a Guildline bridge connected to a platinum resistance thermometer is converted to temperature. Thermistor resistance has corrections applied for lead resistance and bridge dial resistance.
3. Output of a Mueller bridge connected to a platinum resistance thermometer is converted to temperature.

The result of all three types of input data is a set of temperatures and thermistor resistances for each thermistor. These are then fitted to the above equation by the method of least squares. The resulting A, B, C constants are used for computing temperature from thermistor resistance.

CALIBB was written particularly to process the calibration data produced by K. Schleicher and A. Bradshaw for Buoy Project thermistors used in current meters.

INPUT: By cards

For each batch
Card 1 is the same for all three types of input data.
1 card - Batch number, type of input (DIRECT, GUILD,MUELL), number of thermistors in batch, number of nominal temperatures per thermistor, date of calibration, source of calibration data

```
(T7,I3, T16,A4, T36,I2, T51,I2, 2X,A2, 1X,A3, 1X,A2, 1X,3A4)
```

Type 1, Direct

For each thermistor

1 card - Header card - thermistor number, batch number
(T13,I4, T25,I3)
1 or more cards - Data - 4 pairs of temperature,resistance
(4(2F))

Type 2, Guildline bridge

For each batch

1 or more cards - list of thermistor number in calibration batch in order of subsequent data appearance
(16I)

1 card - Platinum probe identifier, zero ratio of bridge
(T9,A4, T25,F)

For each nominal temperature

1 card - nominal temperature, data date, initial bridge ratio, volts across thermistor, number of book containing original data, page in book
(T9,F4.1, T14,3A4, T36,F, T52,F, T63I, T74,I)

1 or more cards - data pairs consisting of position in bath, bridge ratio, and uncorrected resistance
(T8,I2, T10,2F)

Type 3, Mueller bridge

For each batch

1 or more cards - list of thermistor numbers in calibration batch in order of subsequent data appearance
(16I)

For each nominal temperature

2 cards - nominal temperature, data date, zero error of bridge, volts across thermistor, book containing original data, page in book
(T9,F, T13,3A4, T34,F, T52,F, T63,I, T74,I)

1 card - NRML1MA,RVRS1MA,RVRS14MA,COEFF,RZERO (For definitions see program listing)
(T9,F, T26,F, T44,F, T59,F, T73,F)

For each thermistor

1 card - data for this nominal temperature; BRIJN1MA,NULLN1MA, BRIJR1MA,NULLR1MA,BRIJM14MA,NULLM14MA,RES
(T9,7F)

OUTPUT:

For GUILDLINE or MUELLER input

Printer: Listing of computed platinum resistance temperatures and corrected thermistor resistances by nominal temperature for data validation

Card punch: Temperatures and resistances for each thermistor for data archiving

For all three input types

Printer: Listing of A,B,C constants and statistics of fit for each thermistor

Card punch: Three duplicate cards for each thermistor containing thermistor number, batch number, calibration data, A,B,C constants, temperature RMS residual (measure of fit)

USEAGE:

For processing using the source deck

```
!LIMIT (TIME,2),(CORE,20)

!MESSAGE PUNCHES CARDS

!INTERP FULL

!FORTRAN LS,GO

!LOAD (GO), (UNSAT,(3))

    SOURCE DECK

!RUN

!DATA

    DATA CARDS
```

RESTRICTIONS: None

STORAGE REQUIREMENTS: Not applicable

SUBPROGRAMS REQUIRED: None

OPERATIONAL ENVIRONMENT: CP-V Monitor

TIMING:

Batch of 24 thermistors and 7 nominal temperatures requires about 3.9 charge units when run with the source deck, 2.2 charge units when run with an object deck

ERRORS AND DIAGNOSTICS:

1. NUMTHERM TOO LARGE
Number of thermistors on first data card greater than 25

2. NUMNOMTEMP TOO LARGE
Number of nominal temperatures on first data card greater than 10

PROGRAMMER: R. E. Payne

ORIGINATOR: Buoy Project

DATE: August 1976

REFERENCES: None

```
C***************************************************************************
C
C   PROGRAM CALIBB
C   BY R. PAYNE ET AL
C   8 SEPTEMBER 1976
C
C***************************************************************************
C
C CALIB FITS A SET OF THERMISTOR CALIBRATION DATA TO THE EQUATION
C    1/T=A+B*LN(R)+C*(LN(R)**3). CALIB PERFORMS THE FOLLOWING TASKS:
C      1. READS THE INPUT DATA
C      2. COMPUTES TEMPERATURES FROM THE PLATINUM RESISTANCE THERMOMETER (PRT)
C         BRIDGE READINGS AND PRINTS OUT THE RESULTING R/T VALUES FOR DATA
C         VALIDATION. PROVISION IS MADE FOR INPUT OF R,T DATA DIRECTLY FOR TASK 3
C      3. FITS THE R/T DATA TO THE ABOVE EQUATION AND OUTPUTS THE RESULTS OF
C         THE FIT FOR EACH INDIVIDUAL THERMISTOR.
C
C ORDINARILY, CALIBRATION MEASUREMENTS ARE MADE ON 24 THERMISTORS AT SEVEN
C TEMPERATURES, NOMINALLY 0-30 C AT 5 C INTERVALS.
C
C BOTH A MUELLER AND A GUILDLINE BRIDGE HAVE BEEN USED TO MEASURE THE PRT
C RESISTANCE ALTHOUGH ONLY THE GUILDLINE IS   ED AT PRESENT. STARTING WITH
C BATCH 52 CORRECTIONS ARE APPLIED WITHIN THE PROGRAM FOR LEAD RESISTANCE AND
C BRIDGE DECADE RESISTANCES.
C
C
C***************************************************************************
C OUTLINE OF CALIBB AND SUBROUTINES
C***************************************************************************
C
C #READ BATCH NUMBER (BATCHNUM), INPUT SOURCE TYPE (GMD), NUMBER OF THERMISTORS
C IN BATCH (NUMTHERM), NUMBER OF NOMINAL TEMPERATURES (NUMNOMTEMP,
C CALIBRATION DATE (CALIBDATE), PLACE OF DATA ORIGIN (CALIBPLACE).
C #TEST FOR EOD=END OF DATA
C #TEST FOR REASONABLE VALUES OF NUMTHERM,NUMNOMTEMP
C #TEST GMD FOR GUILDLINE, OR MUELLER BRIDGE, OR DIRECT R,T INPUT
C    #CALL GUILD,MUELL,OR DIRECT
C #FOR EACH THERMISTOR
C    #CALL ABCFIT
C #CALL PRINTOUT
C   PRINT OUTPUT OF LEAST SQUARES FIT FOR ONE THERMISTOR
C #CALL PUNCHOUT
C   PUNCH R,T DATA POINTS AND RESULTS OF LEAST SQUARES FIT FOR EACH THERMISTOR
C #END
C
C SUBROUTINES FOR INPUT AND CONVERSION OF BRIDGE DATA
C    GUILDLINE BRIDGE
C    #SUBROUTINE GUILD
C       #READ THERMISTOR BATH SEQUENCE NUMBERS (THERMID)
C       #READ PTPROBE = WHICH PLATINUM PROBE USED. BRAD=BRADSHAW, BUOY=BUOY LAB;
C          AND PROBE BRIDGE RATIO AT 0 C AND 1 MA (ZERORATIO)
C       #FOR EACH NOMINAL TEMPERATURE
C          #READ: NOMINAL TEMP (NOMTEMP),DATE,BRIDGE RATIO WHEN PROBE IS AT
C             MEASUREMENT TEMPERATURE(INITRATIO),VOLTS ACROSS THERMISTOR(VOLTS),
C             BOOK AND PAGE OF DATA IN SCHLEICHER'S NOTEBOOK.
C          #FOR EACH THERMISTOR
C             #READ: BATH SEQUENCE NUMBER(BATHID),DIFFERENCE BETWEEN INITRATIO
C              AND ACTUAL BRIDGE RATIO(DELTRATIO,UNCORRECTED RESISTANCE OF
C              THERMISTOR(URES).
```

```
C                  #TEST FOR BATCHNUM.GT.51
C                  #YES
C                     #CALL RESCORR
C                      CORRECT ALL THERMISTOR RESISTANCES FOR LEAD AND BRIDGE DIAL
C                      RESISTANCE
C                  #SET PLATINUM PROBE CONSTANTS
C                  #FOR EACH THERMISTOR
C                     COMPUTE PLATINUM PROBE TEMPERATURE
C                     #COMPUTE INDIVIDUAL BRIDGE RATIO
C                     COMPUTE FIRST APPROXIMATION TO PRT
C                     #CALL CALLENDAR
C                        COMPUTE ITERATIVELY A CORRECTION TO PRT TO YIELD FINAL
C                        CORRECTED TEMPERATURE
C               OUTPUT DATA FOR VALIDATION
C               #WRITE BATCHNUM,DATE,PTPROBE,VOLTS,ZERORATIO,INITRATIO,BOOK,PAGE,
C                  NOMTEMP
C               #FOR EACH THERMISTOR
C                  #WRITE BATHID,THERMID,RATIO,T68,URES,RES
C         #RETURN
C      MUELLER BRIDGE
C      #SUBROUTINE MUELL
C         #READ THERMISTOR BATH SEQUENCE NUMBERS (THERMID)
C         #FOR EACH NOMINAL TEMPERATURE
C            #READ: NOMINAL TEMP (NOMTEMP),DATE,BRIDGE ZERO ERROR (ZEROERR),
C             VOLTS ACROSS THERMISTOR (VOLTS), BOOK AND PAGE OF DATA IN
C             SCHLEICHER'S NOTEBOOK, INITIAL BRIDGE READING WITH NORMAL 1 MA
C             CURRENT THROUGH PRT AT MEASUREMENT TEMPERATURE (NRML1MA), AS NRML1MA
C             BUT WITH CURRENT REVERSED (RVRS1MA), SENSITIVITY OF INTERPOLATING
C             NULL BRIDGE RECORDER IN OHMS/CHART DIVISION (COEFF), PROBE
C             RESISTANCE AT 0 C AND 0 MA CURRENT (RZERO).
C            #FOR EACH THERMISTOR
C               #READ: CHANGE IN BRIDGE SETTINGS FROM NRML1MA IN STEPS OF .0001OHM
C                (BRIJN1MA), AMOUNT BRIDGE IS OFF NULL WHEN SET AT NRML1MA+BRIJ1MA
C                IN CHART DIVISIONS (NULLN1MA), CHANGE IN BRIDGE SETTINGS FROM
C                RVRS1MA IN STEPS OF .0001 OHM (BRIJR1MA), AMOUNT BRIDGE IS OFF
C                NULL WHEN SET AT RVRS1MA+BRIJR1MA IN CHART DIVISIONS (NULLR1MA),
C                CHANGE IN BRIDGE SETTINGS FROM RVRS14MA IN STEPS OF .0001 OHM
C                (BRIJM14MA), AMOUNT BRIDGE IS OFF NULL WHEN SET AT RVRS14MA+
C                BRIJR14MA IN CHART DIVISIONS (NULLM14MA), THERMISTOR RESISTANCE
C                (RES)
C            #FOR EACH THERMISTOR
C               COMPUTE PLATINUM PROBE TEMPERATURE (T68)
C               #COMPUTE PRT RESISTANCE
C               #COMPUTE FIRST APPROXIMATION TO PRT
C               #CALL CALLENDAR
C                  COMPUTE A CORRECTION TO FIRST PRT ITERATIVELY
C            OUTPUT DATA FOR VALIDATION
C            #WRITE BATCHNUM,DATE,PTPROBE,VOLTS,RZERO,ZEROERR,COEFF,BOOK,PAGE
C             NOMTEMP
C            #FOR EACH THERMISTOR
C               #WRITE BATH SEQUENCE NUMBER,THERMID,PRT RESISTANCE(PTRES),T68,RES
C         #RETURN
C
C      DIRECT R,T INPUT
C      #SUBROUTINE DIRECT
C         #FOR EACH THERMISTOR
C            #READ THERMID AND BATCHNUM
C            #FOR EACH NOMINAL TEMPERATURE
C               #READ: TEMPERATURE AND THERMISTOR RESISTANCE
C      #RETURN
```

```
C
C SECOND LEVEL SUBROUTINES
C
C SUBROUTINE CALLENDAR
C     CALLENDAR COMPUTES A CORRECTION TO THE COMPUTED PRT TEMPERATURE BY AN
C     ITERATIVE TECHNIQUE SPECIFIED IN THE PRT PROBE MANUAL.
C     #COMPUTE CORRECTION (CORR) BASED ON DELTA (PRT CONSTANT) AND TEMPERATURE.
C        IS LESS THAN .00001
C     #COMPUTE ANOTHER CORRECTION (DELTAT) BASED ON THUS FAR CORRECTED
C        TEMPERATURE AND SOME CONSTANTS.
C     #FINAL T68 HAS BATH CORRECTIONS INCORPORATED.
C     #RETURN
C
C SUBROUTINE RESCORR
C     RESCORR CORRECTS THE THERMISTOR RESISTANCES(URES) FOR THE RESISTANCE OF
C     THE BATH THERMISTOR LEADS AND THE BRIDGE DIAL RESISTANCES.
C     #TEST FOR GMD.EQ.4HERBR (ER BRIDGE)
C        YES-GO TO LEAD RESISTANCE CORRECTIONS
C        NO-PROCEED WITH GUILDLINE BRIDGE DIAL CORRECTIONS
C     #FOR EACH THERMISTOR
C         #TEST FOR URES.LT.100.
C             YES-SET CORRECTION EQUAL TO 0
C             NO-PROCEED WITH COMPUTING CORRECTION
C        #CALL GETDIGITS
C        #COMPUTE CORRECTION FOR EACH DIAL (LEAD 3 DIGITS ONLY)
C        #APPLY TOTAL CORRECTION TO URES, OBTAINING RES
C     #FOR EACH THERMISTOR
C        #APPLY LEAD CORRECTION TO RES
C     #RETURN
C
C SUBROUTINE GETDIGITS
C    GETDIGITS CONVERTS A 6 DIGIT 'NUMBER' INTO A 1 DIMENSIONAL ARRAY, 'STORE'.
C     #ZERO THE ARRAY 'STORE'
C     #CONVERT THE 6 DIGITS OF THE RESISTANCE INTO AN INTEGER
C     #PUT THE DIGITS OF THE INTEGER RESISTANCE INTO 'STORE'
C     #RETURN
C SUBROUTINE ABCFIT
C      ABCFIT PERFORMS A LEAST SQUARES FIT OF THE CALIBRATION DATA TO THE
C      FUNCTION    Y=A+B*X+C*X**3
C      WHERE Y=1/T68, X=LOG(RES)
C      ABCFIT IS RUN ONCE FOR EACH THERMISTOR IN THE BATCH
C     #FOR EACH NOMINAL TEMPERATURE
C        #COMPUTE MEANS OF X,Y,X**3
C     #FOR EACH NOMINAL TEMPERATURE
C        #SUBTRACT MEANS FROM EQUATION TO BE FITTED AND COMPUTE SUMMATIONS
C            NECESSARY FOR DETERMINING B,C. REMOVING THE MEANS REDUCES THE
C            ROUNDOFF ERROR.
C     #COMPUTE B,C,A CONSTANTS
C     #FOR EACH NOMINAL TEMPERATURE
C        #COMPUTE ESTIMATED VALUES OF Y AND T USING A,B,C AND X, AND RESIDUALS
C     #RETURN
C
C SUBROUTINE PRINTOUT
C     PRINT OUTPUT OF LEAST SQUARES FIT FOR ONE THERMISTOR
C     #PRINT THERMID, BATCHNUM
C     #PRINT TIME OF CALIB RUN(ICLK),CALIBDATE,CALIBPLACE
C     #PRINT A,B,C CONSTANTS
C     #PRINT Y,YHAT,RESIDY FOR EACH NOMINAL TEMPERATURE
C     #PRINT RES,T68,THAT,RESIDT FOR EACH NOMINAL TEMPERATURE
C     #RETURN
```

```
C
C SUBROUTINE PUNCHOUT
C   PUNCH R,T DATA POINTS AND RESULTS OF LEAST SQUARES FIT FOR EACH THERMISTOR
C   #FOR EACH BATCH
C       #PUNCH BATCHNUM,NUMTHERM,NUMNOMTEMP,CALIBDATE,CALIBPLACE
C       #COMPUTE NUMBER OF CARDS(NCARDS) REQUIRED TO HOLD R,T DATA FOR ONE
C           THERMISTOR AT 4 POINTS PER CARD
C       #FOR EACH THERMISTOR
C           #PUNCH THERMID,BATCHNUM,CALIBDATE
C           #FOR EACH R,T CARD
C               #COMPUTE THE SUBSCRIPT OF THE FIRST DATA PAIR ON THE CARD (PAIRI),
C                   AND THE LAST PAIR(PAIRF)
C               #IF PAIRF IS GREATER THAN NUMNOMTEMP THEN SET PAIRF
C                   EQUAL TO NUMNOMTEMP
C               #COMPUTE THE NUMBER OF R,T DATA PAIRS TO BE PUNCHED
C                   ON THIS CARD (NONCARD)
C               #PUNCH NONCARD,NONCARD SETS OF T68,RES, AND THERMID,BATCHNUM
C       #PUNCH 3 SETS OF:
C           #FOR EACH THERMISTOR
C               #PUNCH THERMID,BATCHNUM,CALIBDATE,A,B,C,NUMNOMTEMP,RMSRESIDT
C   #RETURN
C
C******************************************************************************
*******************************************************************************
C
C******************************************************************************
C
C PROGRAM CALIBB
C
C R. PAYNE  9 JULY 1976
C
C******************************************************************************
C
      REAL CALIBDATE(3), CALIBPLACE(3)
      INTEGER BATCHNUM,GMD,ICLK(4)
      CALL TODAY(ICLK)
  100 READ (105,1000,END=150) BATCHNUM, GMD, NUMTHERM, NUMNOMTEMP,
     $   CALIBDATE,CALIBPLACE
      IF (NUMTHERM.GT.25)   OUTPUT 'NUMTHERM TOO LARGE',
     $                      GO TO 900
      IF (NUMNOMTEMP.GT.10) OUTPUT ' NUMNOMTEMP TOO LARGE',
     $                      GO TO 900
      IF (GMD.EQ.4HGUIL) CALL GUILD
      IF (GMD.EQ.4HERBR) CALL GUILD
      IF (GMD.EQ.4HMUEL) CALL MUELL
      IF (GMD.EQ.4HDIRE) CALL DIRECT
      DO 120 NTH=1,NUMTHERM
         CALL ABCFIT
         CALL PRINTOUT
  120 CONTINUE
      IF (GMD.EQ.4HDIRE) GO TO 100
      CALL PUNCHOUT
      GO TO 100
  150 CONTINUE
  900 CONTINUE
C
 1000 FORMAT (T7,I3, T16,A4, T36,I2, T51,I2, 2X,A2, 1X,A3, 1X,A2,
     $   1X,3A4)
C
C******************************************************************************
```

```
C
      SUBROUTINE DIRECT
C
C*****************************************************************************
C
C SUBROUTINE DIRECT READS INPUT TO CALIB FROM CARDS. INPUT IS PROVIDED
C AS VALUES OF PRECISE TEMPERATURE AND RESISTANCE FOR EACH THERMISTOR.
C
C INPUT: CALIBB-NUMTHERM,NUMNOMTEMP
C        CARDS-THERMID,T68,RES
C OUTPUT: CALIBB-THERMID,T68,RES FROM 1 CALIBRATION BATCH
C
C                     **********
C
      INTEGER THERMID(25)
      DOUBLE PRECISION RES(10,25),T68(10,25)
      DO 200 NTH=1,NUMTHERM
         READ (105,2005) THERMID(NTH),BATCHNUM
         READ (105,2010)(T68(NNT,NTH),RES(NNT,NTH),NNT=1,NUMNOMTEMP)
  200 CONTINUE
      RETURN
C
 2005 FORMAT (T13,I4, T25,I3)
 2010 FORMAT (4(2F))
C
C*****************************************************************************
C
      SUBROUTINE GUILD
C
C*****************************************************************************
C
C GUILD READS IN ON CARDS PLATINUM THERMOMETER BRIDGE DATA AND THERMISTOR
C RESISTANCES, CORRECTS FOR LEAD AND BRIDGE RESISTANCE (VIA RESCORR), COMPUTES
C TEMPERATURES FROM PRT DATA (VIA CALLENDAR), AND OUTPUTS BOTH INPUT AND
C COMPUTED DATA FOR VALIDATION.
C
C INPUT: CALIBB-NUMTHERM,NUMNOMTEMP,BATCHNUM
C        CARDS-THERMID,PTPROBE,ZERORATIO,NOMTEMP,INITRATIO,VOLTS,BOOK,PAGE,
C              DELTRATIO,URES
C OUTPUT: CALIBB-THERMID,T68,RES(CORRECTED)
C         PRINT-BATCHNUM,DATE,PTPROBE,ZERORATIO,INITRATIO,VOLTS,BOOK,PAGE,
C               NOMTEMP,THERMID,RATIO,T68,RES,URES
C
C                    **********
C
      REAL NOMTEMP,DATE(3)
      INTEGER BOOK,PAGE,PTPROBE,BATHID(25)
      DOUBLE PRECISION URES(10,25),ALPHA,DELTA,INITRATIO,ZERORATIO,
     $   RATIO(25),DELTRATIO(25),PT
C
C     ***INPUT***
C
      READ (105,2101)(THERMID(NTH),NTH=1,NUMTHERM)
      READ (105,2102) PTPROBE, ZERORATIO
      DO 215 NNT=1,NUMNOMTEMP
         READ (105,2104) NOMTEMP,DATE,INITRATIO,VOLTS,BOOK,PAGE
         READ (105,2106)(BATHID(NTH),DELTRATIO(NTH),URES(NNT,NTH),
     $      NTH=1,NUMTHERM)
C
         IF (BATCHNUM.GT.51) CALL RESCORR
```

```
C
C     ***COMPUTE TEMPERATURES FROM PLATINUM PROBF INPUT
C
          IF (PTPROBE.EQ.4HBRAD) ALPHA=.00392577  ; DELTA=1.497
          IF (PTPROBE.EQ.4HBUOY) ALPHA=.003926364 ; DELTA=1.4966
          IF ((PTPROBE.NE.4HBRAD).AND.(PTPROBE.NE.4HBUOY)) OUTPUT
     $                                             'PTPROBE INCORRECT'
          DO 214 NTH=1,NUMTHERM
             RATIO(NTH)=INITRATIO+DELTRATIO(NTH)
             PT=((RATIO(NTH)/ZERORATIO)-1.D0)/ALPHA
             CALL CALLENDAR
  214     CONTINUE
C
C     ***OUTPUT***
C
          WRITE (108,2190) BATCHNUM,DATE,PTPROBE,VOLTS,
     $       ZERORATIO,INITRATIO,BOOK,PAGE,NOMTEMP
          WRITE (108,2192)
          WRITE(108,2194)(BATHID(NTH),THERMID(NTH),RATIO(NTH),
     $       T68(NNT,NTH),URES(NNT,NTH),RES(NNT,NTH),NTH=1,NUMTHERM)
  215 CONTINUE
      RETURN
C
 2101 FORMAT (16I)
 2102 FORMAT (T9,A4, T25,F)
 2104 FORMAT (T9,F4.1, T14,3A4, T36,F, T52,F, T64,I, T75,I)
 2106 FORMAT (T8,I2, T10,2F)
 2190 FORMAT (1H1,9X,'BATCHNUM=', I3/
     $    10X,'DATE DONE=', 3A4/
     $    10X,'PTPROBE=',2X, A4/
     $    10X,'VOLTS ACROSS THERM=', F6.3/
     $    10X,'ZERORATIO=', F10.6/
     $    10X,'INITRATIO=', F10.6/
     $10X,'BOOK NUMBER=', I5/10X,'PAGE=', I5//
     $    2X,'NOMINAL TEMPERATURE=', F6.2//)
 2192 FORMAT(' BATH  THERM',T17,'PRT',T28,'PRT',T35,'UNCORR',T48,'CORR'/
     $'  ID',T8,'NO',T16,'RESIST',T27,'TEMP',T34,'THERM RES  THERM RES')
 2194 FORMAT (1X, I3, I7, F11.6, F9.4, 2F11.2)
 2195 FORMAT (' THERMISTOR ', I4,'  BATCH ', I3, 2X,3A4)
 2196 FORMAT (4(F12.4,F8.2))
C
C*****************************************************************************
C
      SUBROUTINE MUELL
C
C*****************************************************************************
C
C SUBROUTINE MUELL READS IN ON CARDS PRT BRIDGE DATA AND THERMISTOR
C RESISTANCES, COMPUTES TEMPERATURES FROM PRT DATA (VIA CALLENDAR), AND
C OUTPUTS BOTH INPUT AND COMPUTED DATA FOR VALIDATION. ONL' THE BRADSHAW PROBE
C HAS BEEN USED WITH THE MUELLER BRIDGE. MUELL IS FOR HISTORICAL DATA ONLY.
C THE MUELLER BRIDGE IS NO LONGER USED.
C
C INPUT: CALIBB-NUMTHERM,NUMNOMTEMP
C          CARDS-THERMID,NOMTEMP,DATE,ZFROERR,VOLTS,BOOK,PAGE,NRML1MA,RVRS1MA,
C                RVRS14MA,COEFF,RZERO,BRIJN1MA,NULLN1MA,BRIJR1MA,NULLR1MA,
C                BRIJM14MA,NULLM14MA,RES
C OUTPUT: CALIBB-THERMID,T68,RES
C           PRINT-BATCHNUM,DATE,PTPROBE,VOLTS,RZERO,ZEROERR,COEFF,BOOK,PAGE,
C                 NOMTEMP,THERMID,PTRES,T68,RES
C
```

```
C
C                        **********
C
      REAL NRML1MA,NULLN1MA(25),NULLR1MA(25),NULLM14MA(25),
     $   BRIJN1MA(25),BRIJR1MA(25),BRIJM14MA(25)
      DOUBLE PRECISION TOTALN1MA(25),TOTALR1MA(25),MEANTOT,SHR,
     $   PTRES(25)
C
C     ***INPUT***
C
      READ (105,2402)(THERMID(NTH),NTH=1,NUMTHERM)
      PTPROBE=BRAD ; ALPHA=.00392577 ; DELTA=1.497
      DO 245 NNT=1,NUMNOMTEMP
         READ (105,2406) NOMTEMP,DATE,ZEROERR,VOLTS,BOOK,PAGE,
     $      NRML1MA,RVRS1MA,RVRS14MA,COEFF,RZERO
C
         READ (105,2408)(BRIJN1MA(NTH),NULLN1MA(NTH),BRIJR1MA(NTH),
     $      NULLR1MA(NTH),BRIJM14MA(NTH),NULLM14MA(NTH),RES(NNT,NTH),
     $      NTH=1,NUMTHERM)
C
C     ***COMPUTE TEMPERATURES FROM PRT INPUT
C
         DO 244 NTH=1,NUMTHERM
            TOTALN1MA(NTH)=NRML1MA+BRIJN1MA(NTH)+NULLN1MA(NTH)*COEFF
            TOTALR1MA(NTH)=RVRS1MA+BRIJR1MA(NTH)+NULLR1MA(NTH)*COEFF
            MEANTOT=(TOTALN1MA(NTH)+TOTALR1MA(NTH))/2.D0
C
            SHR=RVRS14MA-RVRS1MA+BRIJM14MA(NTH)-BRIJR1MA(NTH)
     $         +(NULLM14MA(NTH)/1.4D0-NULLR1MA(NTH))*COEFF
            PTRES(NTH)=MEANTOT-SHR-.0001D0-ZEROERR
            NUN=INT(PTRES(NTH))-20
C
            IF ((NUN.EQ.5).OR.(NUN.GE.7)) PTRES(NTH)=PTRES(NTH)-.00001
            PT=(PTRES(NTH)-RZERO)/(RZERO*ALPHA)
            CALL CALLENDAR
  244    CONTINUE
C
C     ***OUTPUT***
C
         WRITE (108,2490) BATCHNUM,DATE,PTPROBE,VOLTS,RZERO,
     $      ZEROERR,COEFF,BOOK,PAGE,NOMTEMP
         WRITE (108,2492)
         WRITE (108,2494)(NTH,THERMID(NTH),PTRES(NTH),T68(NNT,NTH),
     $      RES(NNT,NTH),NTH=1,NUMTHERM)
  245 CONTINUE
      RETURN
C
 2402 FORMAT (16I)
 2406 FORMAT (T9,F, T13,3A4, T34,F, T52,F, T63,I, T74,I/
     $ T9,F, T26,F, T44,F, T59,F, T73,F)
 2408 FORMAT ( T9,7F)
 2490 FORMAT (1H1,9X,'BATCHNUM=',I3/
     $   10X,'DATE DONE=',3A4/
     $   10X,'PTPROBE=',2X,A4/
     $10X,'VOLTS ACROSS THERM=',F6.3/
     $   10X,'RESISTANCE OF PROBE AT T=0 DEGREES=',F9.6/
     $   10X,'ZERO OF BRIDGE=',F9.6/
     $   10X,'COEFF.(OHMS/DIAL DIV AT 1MA)=',F9.6/
     $   10X,'BOOK NUMBER=',I5/10X,'PAGE NUMBER=',I5/
     $   '0',9X,'NOMINAL TEMPERATURE=',F6.2//)
```

```
 2492 FORMAT (' BATH  THERM    PT RES   PT TEMP  THERM RES')
 2494 FORMAT (1X, I3, I7, F11.6, F9.4, F11.2)
 2495 FORMAT (' THERMISTOR ', I4, '  BATCH ', I3, 2X,3A4)
 2496 FORMAT (4(F12.4,F8.2))
C
C***********************************************************************
C
      SUBROUTINE CALLENDAR
C
C***********************************************************************
C
C CALLENDAR COMPUTES A CORRECTION TO T BY AN ITERATIVE TECHNIQUE SPECIFIED
C IN THE PRT PROBE MANUAL.
C
C INPUT: GUILD OR MUELL-PT
C OUTPUT: GUILD OR MUELL-T68
C
C                     **********
C
      NCOUNT=1 ; CORR1=1 ; CORR=0
      TEMP=PT
      REPEAT 225, WHILE DABS(CORR1-CORR).GT.0.00001
         CORR1=CORR
         CORR=DELTA*.01D0*TEMP*(.01D0*TEMP-1.D0)
         TEMP=PT+CORR
         NCOUNT=NCOUNT+1
         IF(NCOUNT.GT.15) OUTPUT 'CALLENDAR EQUATION DOES NOT CONVERGE',
     $                         RETURN
  225 CONTINUE
      DELTAT=.045D0*.01D0*TEMP*(.01D0*TEMP-1.D0)*(TEMP/419.58D0-1.D0)*
     $   (TEMP/630.74D0-1.D0)
      T68(NNT,NTH)=TEMP+DELTAT
      RETURN
C INPUT
C***********************************************************************
C
      SUBROUTINE RESCORR
C
C***********************************************************************
C
C RESCORR CORRECTS THE THERMISTOR RESISTANCES FOR THE RESISTANCE OF THE BATH
C LEADS AND THE BRIDGE DIAL RESISTANCES.
C
C INPUT: GUILD OR MUELL - URES
C OUTPUT: GUILD OR MUELL - RES
C
C                     **********
C
      REAL LEADRES(25),BDC(0:10,1:3)
      INTEGER STORE(6),DIG,DECIMALS
      DATA LEADRES/12(.35),12(.40)/
      DATA BDC/0D0,1D-5,2D-5,2(0D0),2(-5D-5),2(-7D-5),2(-8D-5),
     $   2(0D0),-1D-5,2(0D0),1D-5,0D0,2D-5,3D-5,2D-5,1D-5,
     $   8(0D0),3(1D-5)/
C
C     ***ER BRIDGE IS USED WITH 5000 SERIES THERMISTORS. NO DIAL CORRECTIONS
C        ARE USED WITH THE ER BRIDGE BUT LEAD RESISTANCE CORRECTIONS THE
C        SAME AS FOR THE L AND N GUARDED WHEATSTONE BRIDGE.
C
      IF (GMD.EQ.4HERBR) GO TO 239
```

```
C
C       *** CORRECT FOR BRIDGE DIAL RESISTANCES
C
        DO 238 NTH=1,NUMTHERM
           DCORR=0
           IF (URES(NNT,NTH).LT.100.) DCORR=0.;
     $                                GO TO 236
           CALL GETDIGITS
           MULT=NUMDIGIT-2
           DO 236 DIG=1,3
              DCORR=DCORR+BDC(STORE(DIG),DIG)*10**MULT
  236      CONTINUE
           RES(NNT,NTH)=URES(NNT,NTH)+DCORR
  238   CONTINUE
C
C       ***APPLY LEAD RESISTANCE CORRECTIONS.
C
  239   CONTINUE
        DO 240 NTH=1,NUMTHERM
           IF (RES(NNT,NTH).LT.100.) GO TO 240
           IF (GMD.EQ.4HERBR) RES(NNT,NTH)=URES(NNT,NTH)
           RES(NNT,NTH)=RES(NNT,NTH)-LEADRES(NTH)
  240   CONTINUE
        RETURN
C
C*****************************************************************************************
C
        SUBROUTINE GETDIGITS
C
C*****************************************************************************************
C
C GETDIGITS CONVERTS A 6 DIGIT 'NUMBER' INTO A 1 DIMENSIONAL ARRAY, 'STORE'.
C THE VALUES OF 'STORE' ARE THE DIGITS OF RES STARTING WITH THE HIGHEST ORDER.
C FOR EXAMPLE, RES=417135 BECOMES:
C             STORE(1)=4          STORE(4)=1
C             STORE(2)=1          STORE(5)=3
C             STORE(3)=7          STORE(6)=5
C INPUT: URES(NNT,NTH)
C OUTPUT: NUMDIGIT,STORE
C
C                           **********
C
        INTEGER NUMDIGIT,NUM,DIGIT,TRUNCNUM
        INTEGER BLANK/'    '/
        REAL R,D
C
C       ***ZERO THE ARRAY 'STORE'
        DO 21 NDX=1,6
           STORE(NDX)=BLANK
   21   CONTINUE
        R=URES(NNT,NTH)
        IF (R.LT.100.) GO TO 26
C       ***MAKE THE 6 DIGITS OF THE RESISTANCE INTO AN INTEGER
        D=R-100000
        DECIMALS=0
        REPEAT 23, WHILE D.LT.0
           R=R*10
           D=R-100000
           DECIMALS=DECIMALS+1
   23   CONTINUE
```

```
C       *** PUT INTEGER INTO STORE
      NUM=R
      DIGIT=7
      REPEAT 25, WHILE DIGIT.GT.0
         DIGIT=DIGIT-1
         TRUNCNUM=NUM/10
         STORE(DIGIT)=NUM-(TRUNCNUM*10)
         NUM=TRUNCNUM
   25 CONTINUE
      NUMDIGIT=6
   26 CONTINUE
      RETURN
C
C****************************************************************************
C
      SUBROUTINE ABCFIT
C
C****************************************************************************
C
C ABCFIT PERFORMS A LEAST SQUARES FIT OF THE CALIBRATION DATA TO THE FUNCTION
C          Y=A+B*X+C*X**3
C          WHERE Y=1/T, X=LOG(R)
C
C INPUT: CALIBB-T68,RES,NUMNOMTEMP
C OUTPUT: CALIBB-A,B,C,YHAT,THAT,RESIDY,RESIDT,RMSRESIDT
C
C                     **********
C
      REAL RESIDY(10),RESIDT(10),RMSRESIDT(25)
      DOUBLE PRECISION Y(10),X(10),YMEAN,XMEAN,X3MEAN,SDXDX,SDXDX3,
     $   SDXDY,SDX3DX3,SDX3DY,DY,DX,DX3,A(25),B(25),C(25),YHAT(10),
     $   THAT(10)
C
C       ***COMPUTE NEW VARIABLES AND MEANS.
C
      YMEAN=XMEAN=X3MEAN=0.
      DO 302 NNT=1,NUMNOMTEMP
         Y(NNT)=1.D0/(T68(NNT,NTH)+273.15D0)
         X(NNT)=DLOG(RES(NNT,NTH))
         YMEAN=YMEAN+Y(NNT)/NUMNOMTEMP
         XMEAN=XMEAN+X(NNT)/NUMNOMTEMP
         X3MEAN=X3MEAN+(X(NNT)**3)/NUMNOMTEMP
  302 CONTINUE
C
C       ***SUBTRACT MEANS TO AVOID ROUND OFF ERROR IN CURVE FIT
C
C       ***COMPUTE SUMS FOR CALCULATING B AND C CONSTANTS.
C
      SDXDX=SDXDX3=SDXDY=SDX3DX3=SDX3DY=0.
      DO 304 NNT=1,NUMNOMTEMP
         DY=Y(NNT)-YMEAN
         DX=X(NNT)-XMEAN
         DX3=X(NNT)**3-X3MEAN
         SDXDX=SDXDX+DX*DX
         SDXDX3=SDXDX3+DX*DX3
         SDXDY=SDXDY+DX*DY
         SDX3DX3=SDX3DX3+DX3*DX3
         SDX3DY=SDX3DY+DX3*DY
  304 CONTINUE
C
```

```
C     ***COMPUTE A,B,C CONSTANTS
C
      B(NTH)=(SDXDY*SDX3DX3-SDXDX3*SDX3DY)/(SDXDX*SDX3DX3-SDXDX3**2)
      C(NTH)=(SDXDX*SDX3DY-SDXDY*SDXDX3)/(SDXDX*SDX3DX3-SDXDX3**2)
      A(NTH)=YMEAN-B(NTH)*XMEAN-C(NTH)*X3MEAN
C
C     ***COMPUTE ESTIMATED VALUES OF Y AND T USING A,B,C AND X
C
      RMSRESIDT(NTH)=0.
      DO 306 NNT=1,NUMNOMTEMP
         YHAT(NNT)=A(NTH)+B(NTH)*X(NNT)+C(NTH)*(X(NNT)**3)
         THAT(NNT)=1.D0/YHAT(NNT)-273.15D0
         RESIDY(NNT)=YHAT(NNT)-Y(NNT)
         RESIDT(NNT)=THAT(NNT)-T68(NNT,NTH)
         RMSRESIDT(NTH)=RMSRESIDT(NTH)+RESIDT(NNT)**2/NUMNOMTEMP
  306 CONTINUE
      RMSRESIDT(NTH)=SQRT(RMSRESIDT(NTH))*1000.
      RETURN
C
C******************************************************************************
C
      SUBROUTINE PRINTOUT
C
C******************************************************************************
C
C PRINT OUTPUT OF LEAST SQUARES FIT FOR ONE THERMISTOR
C
C INPUT: CALIBB-THERMID,BATCHNUM,ICLK,CALIBDATE,A,B,C,
C                Y,YHAT,RESIDY,RES,T68,THAT,RESIDT,RMSRESIDT
C OUTPUT: PRINT-SAME AS INPUT
C
C                          **********
C
         WRITE (108,4000) THERMID(NTH),BATCHNUM
         WRITE (108,4002) ICLK,CALIBDATE,CALIBPLACE
         WRITE (108,4004) A(NTH),B(NTH),C(NTH)
         WRITE (108,4006)
         WRITE (108,4008)
         WRITE (108,4010)(NNT,Y(NNT),YHAT(NNT),RESIDY(NNT),
     $      NNT=1,NUMNOMTEMP)
         WRITE (108,4012)
         WRITE (108,4014)(NNT,RES(NNT,NTH),T68(NNT,NTH),THAT(NNT),
     $      RESIDT(NNT),NNT=1,NUMNOMTEMP)
      WRITE (108,4016) RMSRESIDT(NTH)
      RETURN
C
 4000 FORMAT ('1THERMISTOR: ', I4,'  BATCH: ', I3)
 4002 FORMAT ('0 DATE OF COMPUTER RUN:  ',4A4/
     $   '0 CALIBRATION DATE:', 2X,A2, 1X,A3, 1X,A2//
     $   ' CALIBRATION SOURCE:', 3A4)
 4004 FORMAT ('0 CALIBRATION CONSTANTS'/
     $   5X,'A=', F15.13/
     $   '0',4X,'B=', F15.13/
     $   '0',4X,'C=', F15.13)
 4006 FORMAT (///25X,'TABLE OF RESIDUALS')
 4008 FORMAT ('0',T13,'OBSERVED',T28,'ESTIMATED',T45,'RESIDUAL'/
     $   T16,'Y', T32,'Y', T48,'Y')
 4010 FORMAT (1X, I5, F15.10, 2F16.10)
 4012 FORMAT (///T11,'OBSERVED    OBSERVED  ESTIMATED  RESIDUAL'/
     $   T14,'R', T26,'T', T37,'T', T47,'T')
```

```
 4014 FORMAT (1X, I5, F13.3, F11.4, F10.5, F11.6)
 4016 FORMAT ('0',T33,'RMS RESIDUAL',F7.3,'  MDEG')
 4022 FORMAT (I4, '/',I3, '/',A2, '-',A3, '-',A2, '/',E13.9, '/',E13.9,
     *   '/',E13.9, '/',I2, '/',F5.2)
C
C*********************************************************************************
C
      SUBROUTINE PUNCHOUT
C
C*********************************************************************************
C
C PUNCH CARDS WITH R,T CALIBRATION DATA FOR FILES AND A,B,C CONSTANTS FOR
C THERMISTOR INTERCOMPARISONS.
C
C INPUT: CALIBB(MUELL).BATCHNUM,GMD,NUMTHERM,NUMNOMTEMP,CALIBDATE,THERMID,
C                     T68,RES
C OUTPUT: PUNCH. SAME AS INPUT
C
C                     **********
C
      INTEGER NCARDS,PAIRI,PAIRF,NONCARD
C
      IF (GMD.EQ.4HERBR) GO TO 504
      WRITE (106,5010) BATCHNUM,NUMTHERM,NUMNOMTEMP,CALIBDATE,
     *   CALIBPLACE
      NCARDS=NUMNOMTEMP/4+1
      DO 502 NTH=1,NUMTHERM
         WRITE (106,5025) THERMID(NTH),BATCHNUM.CALIBDATE
         DO 501 NC=1,NCARDS
            PAIRI=4*NC-3
            PAIRF=4*NC
            IF (PAIRF.GT.NUMNOMTEMP) PAIRF=NUMNOMTEMP
            NONCARD=PAIRF-PAIRI+1
            WRITE (106,5028) NONCARD,(T68(JP,NTH),RES(JP,NTH),
     *         JP=PAIRI,PAIRF),THERMID(NTH),BATCHNUM
 501     CONTINUE
 502  CONTINUE
 504  DO 505 K=1,3
         WRITE (106,5035)(THERMID(NTH),BATCHNUM,CALIBDATE,A(NTH),
     *   B(NTH),C(NTH),NUMNOMTEMP,RMSRESIDT(NTH),NTH=1,NUMTHERM)
 505  CONTINUE
      RETURN
C
 5010 FORMAT ('BATCH=',I3, T12,'GMD=DIRECT', T27,'NUMTHERM=',I2,
     *   T40,'NUMNOMTEMP=',I2, 2X,A2, 1X,A3, 1X,A3, 3A4)
 5025 FORMAT (' THERMISTOR ',I4,'  BATCH ', I3, 9X,A2, 1X,A3, 1X,A2)
 5028 FORMAT (N(F7.4, 1X,F9.2, 1X), T73,I4, '-',I3)
 5035 FORMAT (I4, '/',I3, '/',A2, '-',A3, '-',A2, '/',E13.9, '/',E13.9,
     *   '/',E13.9, '/',I2, '/',F5.2)
C
      END
```

THERMISTOR CALIBRATION

RAW DATA

CALIBRATION BATCH NUMBER 67

DATA CALIBRATION BEGUN 22 JULY 1976

DATA TAKEN BY K. SCHLEICHER

	1 2 3 4 5	6 7 8 9 10	11 12 13 14 15	16 17 18 19 20	21 22 23 24 51 52 53 54	25 55	26 27 28 29 30 56 57 58 59 60	31 32 33 34 35 61 62 63 64 65	36 37 38 39 40 66 67 68 69 70	41 42 43 44 45 71 72 73 74 75	46 47 48 49 50 76 77 78 79 80
1	B A T C H	= 67	G M D =	G U I L D	L I N E		N U M T	H E R M =	24 N	U M N O M	T E M P =
					7	23	JUL	76	W H O I		
2	7	32	109	132	155		156	163	168	187	189
					190		238	239	240	242	244
3	319	320	323	324	326		328	345	357		

4 P T P R O B E = BUOY Z E R O R A T I O = 2.555259

```
    1  2  3  4  5  6  7  8 |9  10 11 12 13 14|15 16 17|18 19 20 21|22 23 24 25 26 27 28 29 30 31 32 33 34 35|36 37 38 39 40 41 42 43 44 45|46 47 48 49 50
                                                                  |51 52 53 54 55 56 57 58 59 60 61 62 63|64|65 66 67 68 69 70 71 72 73 74|75 76 77 78 79
 1  N  O  M  T  E  M  P  = |_0.               |22      |JUL        |76          I N I T R A T I O        =|2.555330                      |V  O  L  T  S
                                                               =   |2.80                    B O O K =     |761                P A G E =    |41
 2 _67_ - _1_/  1    . 0 0 0 0 06     95046.2_
 3 ___  - ___/  2    . 0 0 0 0 07     94927.0_
 4 ___  - ___/  3    . 0 0 0 0 07     95067.0_
 5 ___  - ___/  4    . 0 0 0 0 07     95799.1_
 6 ___  - ___/  5    . 0 0 0 0 07     94763.8_
 7 ___  - ___/  6    . 0 0 0 0 07     95351.1_
 8 ___  - ___/  7    . 0 0 0 0 07     94615.0_
 9 ___  - ___/  8    . 0 0 0 0 07     94968.1_
10 ___  - ___/  9    . 0 0 0 0 07     95264.8_
11 ___  - ___/ 1 0   . 0 0 0 0 07     95175.7_
12 ___  - ___/ 1 1   . 0 0 0 0 07     95041.5_
13 ___  - ___/ 1 2   . 0 0 0 0 07     95210.4_
14 ___  - ___/ 1 3   . 0 0 0 0 07     97882.1_
15 ___  - ___/ 1 4   . 0 0 0 0 08     95042.4_
16 ___  - ___/ 1 5   . 0 0 0 0 08     95995.0_
17 ___  - ___/ 1 6   . 0 0 0 0 08     95460.1_
18 ___  - ___/ 1 7   . 0 0 0 0 08     95115.0_
19 ___  - ___/ 1 8   . 0 0 0 0 08     95188.4_
20 ___  - ___/ 1 9   . 0 0 0 0 08     95017.3_
21 ___  - ___/ 2 0   . 0 0 0 0 08     95167.3_
22 ___  - ___/ 2 1   . 0 0 0 0 08     95038.8_
23 ___  - ___/ 2 2   . 0 0 0 0 08     95012.0_
24 ___  - ___/ 2 3   . 0 0 0 0 08     95196.5_
25 ___  - ___/ 2 4   . 0 0 0 0 08     95189.0_
```

```
     1  2  3  4  5  6  7  8 | 9 10 11 12 13 14|15 16 17|18 19 20 21|22 23 24 25 26 27 28 29 30 31 32 33 34 35|36 37 38 39 40 41 42 43 44 45|46 47 48 49 50
                                                                   |51 52 53 54 55 56 57 58 59 60 61 62 63|64 65 66 67 68 69 70 71 72 73 74|75 76 77 78 79
1    N  O  M  T  E  M  P  = | 5 .            | 2 2    | J U L     | 7 6             I  N  I  T  R  A  T  I  O |= 2 . 6 0 6 1 1 0             | V  O  L  T  S
                                                              =   | 2 . 6 0                       B  O  O  K  = | 7 6 1        P  A  G  E  = | 4 1
2     6 7  -  2 /     1     . 0 0 0 0 0 8      7 4 4 8 6 . 3
3          -    /     2     . 0 0 0 0 0 8      7 4 3 7 8 . 3
4          -    /     3     . 0 0 0 0 0 8      7 4 4 8 5 . 8
5          -    /     4     . 0 0 0 0 0 8      7 5 0 9 1 . 1
6          -    /     5     . 0 0 0 0 0 8      7 4 2 6 0 . 5
7          -    /     6     . 0 0 0 0 0 8      7 4 7 0 2 . 5
8          -    /     7     . 0 0 0 0 0 8      7 4 1 3 7 . 3
9          -    /     8     . 0 0 0 0 0 8      7 4 3 9 5 . 1
10         -    /     9     . 0 0 0 0 0 8      7 4 6 1 2 . 3
11         -    /   1 0     . 0 0 0 0 0 8      7 4 5 5 9 . 0
12         -    /   1 1     . 0 0 0 0 0 8      7 4 4 8 6 . 6
13         -    /   1 2     . 0 0 0 0 0 8      7 4 6 2 6 . 4
14         -    /   1 3     . 0 0 0 0 0 8      7 6 8 1 6 . 6
15         -    /   1 4     . 0 0 0 0 0 8      7 4 5 2 6 . 2
16         -    /   1 5     . 0 0 0 0 0 8      7 4 8 6 4 . 1
17         -    /   1 6     . 0 0 0 0 0 8      7 4 7 2 5 . 3
18         -    /   1 7     . 0 0 0 0 0 8      7 4 5 2 9 . 0
19         -    /   1 8     . 0 0 0 0 0 8      7 4 5 7 7 . 9
20         -    /   1 9     . 0 0 0 0 0 8      7 4 4 7 9 . 6
21         -    /   2 0     . 0 0 0 0 0 8      7 4 5 7 4 . 6
22         -    /   2 1     . 0 0 0 0 0 8      7 4 5 3 4 . 3
23         -    /   2 2     . 0 0 0 0 0 8      7 4 4 7 5 . 1
24         -    /   2 3     . 0 0 0 0 0 8      7 4 5 9 2 . 8
25         -    /   2 4     . 0 0 0 0 0 8      7 4 5 7 8 . 4
```

```
   1 2 3 4 5 6 7 8 |9 10 11 12 13 14|15 16 17|18 19 20 21|22 23 24 25 26 27 28 29 30 31 32 33 34 35|36 37 38 39 40 41 42 43 44 45 46 47 48 49 50
                                                         51 52 53 54 55 56 57 58 59 60 61 62 63|64 65 66 67 68 69 70 71 72 73 74|75 76 77 78 79
1    N O M T E M P = |1 0 .          |2 2     |J U L      |7 9          I N I T R A T I O = |2 . 6 5 6 9 8 0        |V O L T S
                                                       = |2 . 3 9           B O O K = |7 6 1       P A G E = |4 2
2    6 7 - 3 /   1   . 0 0 0 0 0 1      5 8 7 3 7 . 3
3        -   /   2   . 0 0 0 0 0 1      5 8 6 4 1 . 2
4        -   /   3   . 0 0 0 0 0 1      5 8 7 2 3 . 7
5        -   /   4   . 0 0 0 0 0 1      5 9 2 2 5 . 3
6        -   /   5   . 0 0 0 0 0 1      5 8 5 5 6 . 5
7        -   /   6   . 0 0 0 0 0 1      5 8 8 8 9 . 2
8        -   /   7   . 0 0 0 0 0 1      5 8 4 5 6 . 0
9        -   /   8   . 0 0 0 0 0 1      5 8 6 4 4 . 0
10       -   /   9   . 0 0 0 0 0 1      5 8 8 0 1 . 4
11       -   / 1 0   . 0 0 0 0 0 1      5 8 7 7 2 . 5
12       -   / 1 1   . 0 0 0 0 0 1      5 8 7 4 0 . 0
13       -   / 1 2   . 0 0 0 0 0 1      5 8 8 4 8 . 0
14       -   / 1 3   . 0 0 0 0 0 2      6 0 6 4 7 . 5
15       -   / 1 4   . 0 0 0 0 0 2      5 8 7 9 1 . 4
16       -   / 1 5   . 0 0 0 0 0 2      5 9 0 4 6 . 5
17       -   / 1 6   . 0 0 0 0 0 2      5 8 8 6 5 . 8
18       -   / 1 7   . 0 0 0 0 0 2      5 8 7 5 8 . 1
19       -   / 1 8   . 0 0 0 0 0 2      5 8 7 8 9 . 4
20       -   / 1 9   . 0 0 0 0 0 2      5 8 7 3 8 . 8
21       -   / 2 0   . 0 0 0 0 0 2      5 8 7 9 6 . 6
22       -   / 2 1   . 0 0 0 0 0 2      5 8 8 0 6 . 6
23       -   / 2 2   . 0 0 0 0 0 2      5 8 7 3 5 . 0
24       -   / 2 3   . 0 0 0 0 0 2      5 8 8 0 6 . 9
25       -   / 2 4   . 0 0 0 0 0 2      5 8 7 8 9 . 2
```

```
   1 2 3 4 5 6 7 8 |9  10 11 12 13 14|15 16 17|18 19 20 21|22 23 24 25 26 27 28 29 30 31 32 33 34 35|36 37 38 39 40 41 42 43 44 45 46 47 48 49 50
                                                           |51 52 53 54 55 56 57 58 59 60 61 62 63|64 65 66 67 68 69 70 71 72 73 74|75 76 77 78 79
1  N O M T E M P = |15.              |23      |JUL        |79            I N I T R A T I O =|2.707670                |V O L T S
                                                        = |2.17                   B O O K =|761            P A G E =|43
2  67 - 4 /  1   . 0 0 0 0 04    46649.1
3         /  2   . 0 0 0 0 04    46564.4
4         /  3   . 0 0 0 0 05    46627.8
5         /  4   . 0 0 0 0 04    47044.7
6         /  5   . 0 0 0 0 05    46503.4
7         /  6   . 0 0 0 0 05    46754.3
8         /  7   . 0 0 0 0 05    46422.3
9         /  8   . 0 0 0 0 05    46559.8
10        /  9   . 0 0 0 0 05    46672.8
11        / 1 0  . 0 0 0 0 05    46660.2
12        / 1 1  . 0 0 0 0 05    46653.0
13        / 1 2  . 0 0 0 0 05    46730.7
14        / 1 3  . 0 0 0 0 05    48212.7
15        / 1 4  . 0 0 0 0 05    46701.9
16        / 1 5  . 0 0 0 0 06    46896.4
17        / 1 6  . 0 0 0 0 06    46708.9
18        / 1 7  . 0 0 0 0 06    46652.4
19        / 1 8  . 0 0 0 0 06    46671.5
20        / 1 9  . 0 0 0 0 06    46651.6
21        / 2 0  . 0 0 0 0 06    46684.5
22        / 2 1  . 0 0 0 0 06    46721.3
23        / 2 2  . 0 0 0 0 06    46648.4
24        / 2 3  . 0 0 0 0 06    46689.3
25     -  / 2 4  . 0 0 0 0 06    46670.9
```

```
    1 2 3 4 5 6 7 8 |9 10 11 12 13 14|15 16 17|18 19 20 21|22 23 24 25 26 27 28 29 30 31 32 33 34 35|36 37 38 39 40 41 42 43 44 45 46 47 48 49 50
                                                          |51 52 53 54 55 56 57 58 59 60 61 62 63|64|65 66 67 68 69 70 71 72 73 74|75 76 77 78 79
1   N O M T E M P = |2 0 .           |2 3     |J U L      |7 6         I N I T R A T I O         |= |2 . 7 5 8 3 0 0             |V O L T S
                                                        = |1 . 9 5            B O O K =        |_ 7 6 1        P A G E =         |_ 4 3
2   _ 6 7 - _ 5 /   1  . 0 0 0 0 0 5     3 7 2 8 6 . 4 _
3   _ _ _ - _ _ /   2  . 0 0 0 0 0 5     3 7 2 1 2 . 4 _
4   _ _ _ - _ _ /   3  . 0 0 0 0 0 5     3 7 2 6 1 . 0 _
5   _ _ _ - _ _ /   4  . 0 0 0 0 0 5     3 7 6 0 8 . 5 _
6   _ _ _ - _ _ /   5  . 0 0 0 0 0 5     3 7 1 6 8 . 8 _
7   _ _ _ - _ _ /   6  . 0 0 0 0 0 5     3 7 3 5 8 . 0 _
8   _ _ _ - _ _ /   7  . 0 0 0 0 0 5     3 7 1 0 3 . 9 _
9   _ _ _ - _ _ /   8  . 0 0 0 0 0 5     3 7 2 0 4 . 0 _
10  _ _ _ - _ _ /   9  . 0 0 0 0 0 5     3 7 2 8 4 . 5 _
11  _ _ _ - _ _ / 1 0  . 0 0 0 0 0 5     3 7 2 8 2 . 6 _
12  _ _ _ - _ _ / 1 1  . 0 0 0 0 0 5     3 7 2 9 0 . 6 _
13  _ _ _ - _ _ / 1 2  . 0 0 0 0 0 5     3 7 3 4 2 . 2 _
14  _ _ _ - _ _ / 1 3  . 0 0 0 0 0 5     3 8 5 6 4 . 6 _
15  _ _ _ - _ _ / 1 4  . 0 0 0 0 0 5     3 7 3 3 0 . 1 _
16  _ _ _ - _ _ / 1 5  . 0 0 0 0 0 5     3 7 4 8 0 . 5 _
17  _ _ _ - _ _ / 1 6  . 0 0 0 0 0 5     3 7 3 0 4 . 6 _
18  _ _ _ - _ _ / 1 7  . 0 0 0 0 0 5     3 7 2 7 7 . 0 _
19  _ _ _ - _ _ / 1 8  . 0 0 0 0 0 5     3 7 2 8 7 . 1 _
20  _ _ _ - _ _ / 1 9  . 0 0 0 0 0 5     3 7 2 8 6 . 7 _
21  _ _ _ - _ _ / 2 0  . 0 0 0 0 0 5     3 7 3 0 3 . 3 _
22  _ _ _ - _ _ / 2 1  . 0 0 0 0 0 5     3 7 3 5 2 . 1 _
23  _ _ _ - _ _ / 2 2  . 0 0 0 0 0 5     3 7 2 8 4 . 0 _
24  _ _ _ - _ _ / 2 3  . 0 0 0 0 0 5     3 7 3 0 4 . 3 _
25  _ _ _ - _ _ / 2 4  . 0 0 0 0 0 6     3 7 2 8 6 . 4 _
```

```
   1 2 3 4 5 6 7 8 |9 10 11 12 13 14|15 16 17|18 19 20 21|22 23 24 25 26 27 28 29 30 31 32 33 34 35|36 37 38 39 40 41 42 43 44 45|46 47 48 49 50
                                                          51 52 53 54 55 56 57 58 59 60 61 62 63|64|65 66 67 68 69 70 71 72 73 74|75 76 77 78 79
 1 N O M T E M P = |2 5 .           |2 3     |J U L      |7 6      I N I T R A T I O  =|2 . 8 0 8 8 8 0        |V O L T S
                                                        = |1 . 7 4       B O O K =|_ 7 6 1      P A G E =|_ 4 4
 2  6 7 - _ 6 /   1   . 0 0 0 0 0 8     2 9 9 8 3 . 0
 3 _ _ _ - _ _ /   2   . 0 0 0 0 0 7     2 9 9 1 9 . 1
 4 _ _ _ - _ _ /   3   . 0 0 0 0 0 7     2 9 9 5 6 . 3
 5 _ _ _ - _ _ /   4   . 0 0 0 0 0 7     3 0 2 4 7 . 1
 6 _ _ _ - _ _ /   5   . 0 0 0 0 0 7     2 9 8 8 8 . 1
 7 _ _ _ - _ _ /   6   . 0 0 0 0 0 7     3 0 0 3 0 . 7
 8 _ _ _ - _ _ /   7   . 0 0 0 0 0 7     2 9 8 3 6 . 7
 9 _ _ _ - _ _ /   8   . 0 0 0 0 0 7     2 9 9 0 9 . 5
10 _ _ _ - _ _ /   9   . 0 0 0 0 0 7     2 9 9 6 5 . 7
11 _ _ _ - _ _ / 1 0   . 0 0 0 0 0 7     2 9 9 7 0 . 9
12 _ _ _ - _ _ / 1 1   . 0 0 0 0 0 6     2 9 9 8 7 . 8
13 _ _ _ - _ _ / 1 2   . 0 0 0 0 0 6     3 0 0 1 6 . 9
14 _ _ _ - _ _ / 1 3   . 0 0 0 0 0 6     3 1 0 2 7 . 6
15 _ _ _ - _ _ / 1 4   . 0 0 0 0 0 5     3 0 0 1 5 . 2
16 _ _ _ - _ _ / 1 5   . 0 0 0 0 0 5     3 0 1 3 3 . 0
17 _ _ _ - _ _ / 1 6   . 0 0 0 0 0 5     2 9 9 7 7 . 6
18 _ _ _ - _ _ / 1 7   . 0 0 0 0 0 5     2 9 9 6 4 . 9
19 _ _ _ - _ _ / 1 8   . 0 0 0 0 0 5     2 9 9 6 8 . 9
20 _ _ _ - _ _ / 1 9   . 0 0 0 0 0 5     2 9 9 8 0 . 5
21 _ _ _ - _ _ / 2 0   . 0 0 0 0 0 5     2 9 9 8 6 . 2
22 _ _ _ - _ _ / 2 1   . 0 0 0 0 0 5     3 0 0 3 8 . 2
23 _ _ _ - _ _ / 2 2   . 0 0 0 0 0 5     2 9 9 7 8 . 1
24 _ _ _ - _ _ / 2 3   . 0 0 0 0 0 5     2 9 9 8 4 . 6
25 _ _ _ - _ _ / 2 4   . 0 0 0 0 0 5     2 9 9 6 8 . 0
```

```
   1 2 3 4 5 6 7 8 |9  10 11 12 13 14|15 16 17|18 19 20 21|22 23 24 25 26 27 28 29 30 31 32 33 34 35|36 37 38 39 40 41 42 43 44 45 46 47 48 49 50
                                                          |51 52 53 54 55 56 57 58 59 60 61 62 63|64|65 66 67 68 69 70 71 72 73 74|75 76 77 78 79
1  N O M T E M P = |3 0 .            |2 3     |J U L      |7 6        I N I T R A T I O   =|2 . 8 5 9 3 8 0              |V O L T S
                                                       = 1 . 5 4               B O O K =|  7 6 1            P A G E =|  4 5
2   6 7 -   7 /  1  . 0 0 0 0 0 1    2 4 2 5 6 . 1
3       -     /  2  . 0 0 0 0 0 2    2 4 2 0 0 . 8
4       -     /  3  . 0 0 0 0 0 2    2 4 2 2 9 . 0
5       -     /  4  . 0 0 0 0 0 2    2 4 4 7 3 . 2
6       -     /  5  . 0 0 0 0 0 2    2 4 1 7 9 . 0
7       -     /  6  . 0 0 0 0 0 2    2 4 2 8 5 . 8
8       -     /  7  . 0 0 0 0 0 1    2 4 1 3 8 . 4
9       -     /  8  . 0 0 0 0 0 2    2 4 1 9 1 . 1
10      -     /  9  . 0 0 0 0 0 2    2 4 2 2 9 . 3
11      -     / 1 0 . 0 0 0 0 0 2    2 4 2 3 8 . 7
12      -     / 1 1 . 0 0 0 0 0 2    2 4 2 6 0 . 5
13      -     / 1 2 . 0 0 0 0 0 1    2 4 2 7 1 . 5
14      -     / 1 3 . 0 0 0 0 0 0    2 5 1 0 9 . 1
15      -     / 1 4 . 0 0 0 0 0 0    2 4 2 7 5 . 7
16      -     / 1 5 . 0 0 0 0 0 1    2 4 3 6 8 . 8
17      -     / 1 6 . 0 0 0 0 0 2    2 4 2 3 7 . 0
18      -     / 1 7 . 0 0 0 0 0 2    2 4 2 3 1 . 1
19      -     / 1 8 . 0 0 0 0 0 1    2 4 2 3 0 . 7
20      -     / 1 9 . 0 0 0 0 0 0    2 4 2 4 9 . 5
21      -     / 2 0 . 0 0 0 0 0 0    2 4 2 4 8 . 2
22      -     / 2 1 . 0 0 0 0 0 0    2 4 2 9 8 . 5
23      -     / 2 2 . 0 0 0 0 0 1    2 4 2 4 7 . 2
24      -     / 2 3 . 0 0 0 0 0 1    2 4 2 4 4 . 8
25      -     / 2 4 . 0 0 0 0 0 1    2 4 2 2 9 . 9
```

```
        BATCHNUM= 67
        DATE DONE= 22 JUL 76
        PTPROBE=  BUOY
        VOLTS ACROSS THERM= 2.800
        ZERORATIO=  2.555259
        INITRATIO=  2.555330
        BOOK NUMBER=  761
        PAGE=   41

NOMINAL TEMPERATURE=    .00

BATH  THERM     PRT          PRT      UNCORR        CORR
 ID   NO       RESIST        TEMP    THERM RES    THERM RES
  1      7    2.555336      .0076    95046.20     95045.15
  2     32    2.555337      .0077    94927.00     94925.95
  3    109    2.555337      .0077    95067.00     95065.95
  4    132    2.555337      .0077    95799.10     95798.05
  5    155    2.555337      .0077    94763.80     94762.65
  6    156    2.555337      .0077    95351.10     95350.05
  7    163    2.555337      .0077    94615.00     94613.85
  8    168    2.555337      .0077    94968.10     94967.05
  9    187    2.555337      .0077    95264.80     95263.75
 10    189    2.555337      .0077    95175.70     95174.65
 11    190    2.555337      .0077    95041.50     95040.45
 12    238    2.555337      .0077    95210.40     95209.35
 13    239    2.555337      .0077    97882.10     97881.20
 14    240    2.555338      .0078    95042.40     95041.30
 15    242    2.555338      .0078    95495.00     95493.90
 16    244    2.555338      .0078    95460.10     95459.00
 17    319    2.555338      .0078    95115.00     95113.90
 18    320    2.555338      .0078    95188.40     95187.30
 19    323    2.555338      .0078    95017.30     95016.20
 20    324    2.555338      .0078    95167.30     95166.20
 21    326    2.555338      .0078    95038.80     95037.70
 22    328    2.555338      .0078    95012.00     95010.90
 23    345    2.555338      .0078    95196.50     95195.40
 24    357    2.555338      .0078    95189.00     95187.90
```

Input data verification page for 0° C nominal temperature

```
THERMISTOR:     7  BATCH:  67

 DATE OF COMPUTER RUN:  14:05 SEP 24,'76

 CALIBRATION DATE:  23 JUL 76

 CALIBRATION SOURCE: WHOI

 CALIBRATION CONSTANTS
    A= .0009087846954

    B= .0002250005862

    C= .0000001149649


                          TABLE OF RESIDUALS

         OBSERVED            ESTIMATED            RESIDUAL
            Y                    Y                    Y
 1     .0036608908         .0036608901         -.0000000007
 2     .0035952332         .0035952344          .0000000012
 3     .0035316941         .0035316951          .0000000010
 4     .0034704710         .0034704679         -.0000000031
 5     .0034113163         .0034113182          .0000000019
 6     .0033541115         .0033541112         -.0000000003
 7     .0032988069         .0032988070          .0000000000


        OBSERVED      OBSERVED    ESTIMATED    RESIDUAL
           R             T            T            T
 1     95045.150        .0076       .00761      .000051
 2     74485.250       4.9961      4.99598     -.000090
 3     58736.750      10.0002     10.00015     -.000082
 4     46648.750      14.9953     14.99559      .000258
 5     37286.250      19.9920     19.99181     -.000163
 6     29983.150      24.9915     24.99157      .000028
 7     24255.950      29.9899     29.98990     -.000002

                                RMS RESIDUAL     .126    MDEG
```

Output page for thermistor No. 7

Appendix III

CALCOLIN Program

The CALCOLIN program is used to evaluate the calibration data and compare the results of several calibrations on a single thermistor. Its use over the last three years has allowed us to determine drift rates of thermistors, has helped us to detect errors in calibration data, and to evaluate the consistency of our calibrations. CALCOLIN is written in Xerox FORTRAN IV.

Following the listing of CALCOLIN is an example of the output of the program. There are two sets of numbers for each thermistor.

In the first set of numbers, the first four columns are, respectively, thermistor number, calibration batch number, r.m.s. calibration residual and calibration date. The numbers in the following seven columns are derived in the following way. The numbers at the tops of the columns, at the top of the page, are temperatures (+0, +5, etc.) in °C. The numbers directly below these are nominal resistances for this thermistor type at those temperatures from one of the input cards. The numbers for the individual thermistors and calibrations in Table A for each thermistor are the temperature differences which result from: (1) calculating a temperature using the nominal resistance at the head of the column and the A, B, C constants for that thermistor and calibration; (2) subtracting the temperature at the top of the column; (3) multiplying by 1000 to get the temperature difference in m° C. The absolute value of one of these temperature differences has little meaning except to tell one whether an individual thermistor is within manufacturer's specifications or not. Comparing all the temperature differences at a given temperature for one thermistor can reveal several things. If the numbers stay quite constant over a period of several years as in thermistor 122, we can say that the thermistor is stable and the random variations in the temperature difference give us a good idea of the repeatability of a given temperature in the calibration bath. If the numbers change with time as in thermistor 131 then we know the thermistor is drifting. If the temperature difference increases with time this indicates that the thermistor resistance at the specified temperature is increasing and vice versa.

The second table of numbers, for each thermistor, is an estimate of drift rate of the thermistor together with data which allow us to evaluate that drift rate. Each row in this second table is the result of computations on the numbers in the corresponding column of the first table.

The columns represent:

T - The nominal temperature in °C as in the previous table

N - The number of calibrations performed on this thermistor

TIME - The elapsed time in days between the first and latest calibrations of this thermistor

YBAR - Mean of the temperature differences in the previous table for nominal temperature T over all the calibrations

SEMV - The standard error of YBAR

YINTER -b in the equation

$$y = at + b$$

where y = temperature difference from Table A
t = time in days from the first calibration to the calibration from which y was obtained and a and b are the result of the least squares fit of temperature difference vs. time

SLOPE - a in the above equation; the drift rate in m° C/day

DRIFT - The drift rate in m° C/year; SLOPE * 365

SELF - Standard error of the least squares fit

VSL - Variance due to the slope of the line

VAL - Variance about the line

CORR - Correlation between temperature difference and time

SELF/SEMV - An indication of whether the least squares fit with time variation is better than a simple mean

CAL/VSL - An indication of how important the variance about the line is compared to the variance due to the slope of the line

\- Following the seven lines at nominal calibration temperatures is a final line with five numbers. These are, respectively, the overall means of YBAR, SEMV and DRIFT, the square root of the mean of VAL, and the overall mean of CORR

The final table is a listing of all the input cards.

Of the two examples shown, thermistor number 126 is stable with a standard deviation about the mean of ±1.2 m° C. Thermistor number 76 is drifting although the drift rate has decreased considerably in recent calibrations.

```
C CALCOLIN
C CALCULATE DELTA TEMPS AT GIVEN RESISTANCES AND LEAST SQUARES
C     FIT OF DELTA TEMPS TO TIME
C**PROGRAMMER*R.PAYNE**16 SEPTEMBER 1976**
      DIMENSION NTHERM(1000),NB(1000),DATE(3,1000),NPTS(1000),
     1RESID(1000),IND(11),MD(1000),MB(1000),DTEMP(25,7),DTEMP1(25),
     2D(25),NDAY(100),ICLK(4),DAYDIFF(25)
      DOUBLE PRECISION RES(7),NRES(7),NRESK(7),T(7),
     1  A(1000),B(1000),C(1000),TEMP
      DATA T/273.15,278.15,283.15,288.15,293.15,298.15,303.15/
C  NDAY THROUGH BATCH 69, DAY 1 IS 1 JAN. 1973
      DATA NDAY/33,46,57,72,66,0,0,0,0,0,254,260,264,267,270,277,282,
     1  0,0,0,331,352,373,379,387,0,402,407,416,456,0,477,0,515,0,528,
     2  557,564,0,673,702,733,738,708,750,754,795,808,816,822,0,918,
     3  927,946,970,988,1026,0,1109,1124,0,1171,0,1208,1221,0,1299,1331,
     4  1349/
C**********FORMAT STATEMENTS**********
1010  FORMAT (T10,I1)
1012  FORMAT (A4)
1015  FORMAT (I4,1X,I3,1X,3A3,1X,3(F13.9,1X),I2,1X,F5.2,9X,2A1)
1020  FORMAT (7(F10.2))
1110  FORMAT ('1',5X,'THERMISTOR CALIBRATION COMPARISON',4X,4A4)
1112  FORMAT ('  SLOPE AND DRIFT ARE MINUS THE RATE AT WHICH TEMPERATURE
     $ WOULD APPEAR'/'  TO CHANGE IF THE THERMISTOR WERE MOUNTED IN A CO
     $NSTANT TEMPERATURE BATH')
1115  FORMAT (51X,'RESISTANCE/TEMPERATURE')
1120  FORMAT (40X,'+0',6X,'+5',5X,'+10',5X,'+15',5X,'+20',5X,'+25',
     1  5X,'+30')
1125  FORMAT (4X,'THER DAYS BTCH  RSDL     DATE     ',7F8.1)
1145  FORMAT ('1')
1205  FORMAT ('0')
1210  FORMAT (1X,2A1,3I5,F6.2,1X,3A3,7F8.1,5X,2A1)
1215  FORMAT (13X,'T    N TIME     YBAR    SEMV     YINTER         SLOPE     DRI
     1FT   SELF    VSL      VAL     CORR   SELF/    VAL/')
1216  FORMAT (13X,'C        DAYS     MDEG    MDEG      MDEG         MD/DA     MD/
     1YR   MDEG   MD2      MD2               SEMV     VSL')
1220  FORMAT (23X,F9.3,F7.3,20X,F9.3,14X,F7.2,F6.3)
1314  FORMAT ('1',4X,4A4)
1315  FORMAT ('        TH  BA   DATE            A               B              C
     1            PTS RES')
1320  FORMAT (1X,2A1,1X,2I4,1X,3A3,3E15.9,I3,F5.2,2X,2A1)
C**********PROGRAM**********
      M=IEND=0
      L=J=1
      CALL TODAY(ICLK)
C********** INPUT **********
C** IDB=0 USES ONLY GOOD CALIBRATIONS
C** IDB=1 USES ALL CALIBRATIONS
      READ (105,1010) IDB
C** RES ARE RESISTANCES TO BE SUBSTITUTED TO GET TEMPERATURES
      READ (105,1020) (RES(I),I=1,7)
C**WRITE PAGE HEADING
      WRITE (108,1110) ICLK
      WRITE (108,1112)
      WRITE (108,1115)
      WRITE (108,1120)
      WRITE (108,1125)(RES(I),I=1,7)
      WRITE (108,1205)
  100 CONTINUE
```

```
C** READ CARD FROM CALIB PROGRAM
C*** D IN COLUMN 79 MEANS THERMISTOR HAS BEEN LOST OR DESTROYED
C*** B IN COLUMN 80 MEANS BAD CALIBRATION
C* L INCREMENTS 1 FOR EACH NEW A,B,C CARD
      READ (105,1015,END=405) NTHERM(L),NB(L),(DATE(I,L),I=1,3),
     1A(L),B(L),C(L),NPTS(L),RESID(L),MD(L),MB(L)
      IF (L.EQ.1) NTHERM(0)=NTHERM(1); NDAY1=NDAY(NB(L))
      IF (IDB.EQ.1) GO TO 200
      IF (MD(L).EQ.1HD.OR.MB(L).EQ.1HB) GO TO 100
C**********CALCULATIONS**********
  200 CONTINUE
      IF (NTHERM(L).NE.NTHERM(L-1)) GO TO 410
  210 CONTINUE
C**   CALCULATE TEMPS FOR GIVEN RES
        DO 400 I=1,7
        TEMP=1./(A(L)+B(L)*DLOG(RES(I))+C(L)*DLOG(RES(I))**3)
        DTEMP(J,I)=(TEMP-T(I))*1000
C**   DAYDIFF IS NO. OF DAYS FROM FIRST CALIB. TO CALIB.
C***     UNDER CONSIDERATION
  400   CONTINUE
      DAYDIFF(J)=NDAY(NB(L))-NDAY1
      WRITE (108,1210) MD(L),MB(L),NTHERM(L),DAYDIFF(J),NB(L),
     1RESID(L),(DATE(I,L),I=1,3),(DTEMP(J,M),M=1,7),MD(L),MB(L)
      J=J+1
      L=L+1
      GO TO 100
C* J INCREMENTS 1 FOR EACH NEW A,B,C CARD BUT RESETS WHEN
C***  THERMISTOR NUMBER CHANGES
  405 IEND=1
  410 CONTINUE
      WRITE (108,1215)
      WRITE (108,1216)
      J1=J-1
C**********LINEAR FIT OF TEMP DIFFS**********
      YBARM=DRIFTM=YBARVARM=ALFM=CORM=0
        DO 620 M=1,7
           DO 610 K=1,J1
           DTEMP1(K)=DTEMP(K,M)
  610      CONTINUE
        TE=T(M)-273.150
        CALL LINFIT (DAYDIFF,DTEMP1,J1,TE,YBARVAR,VALF,COR)
        YBARM=YBARM+YBAR/7.
        DRIFTM=DRIFTM+DRIFT/7.
        YBARVARM=YBARVARM+YBARVAR/(7.*J1)
        ALFM=ALFM+VALF/7.
        CORM=CORM+COR/7.
  620   CONTINUE
      YBARSD=SQRT(YBARVARM)
      ALSD=SQRT(ALFM)
      WRITE (108,1220) YBARM,YBARSD,DRIFTM,ALSD,CORM
      WRITE (108,1205)
      IF (IEND.EQ.1) GO TO 1000
      J=1
      NDAY1=NDAY(NB(L))
      GO TO 210
 1000 CONTINUE
      L=L-1
C** OUTPUT, IMAGE OF INPUT CARDS
      WRITE (108,1314) ICLK
      WRITE (108,1315)
```

```
      WRITE (108,1320)(MD(I),MB(I),NTHERM(I),NB(I),
     1  (DATE(K,I),K=1,3),A(I),B(I),C(I),
     2  NPTS(I),RESID(I),MD(I),MB(I),I=1,L)
C
C*************************************************************************
C
      SUBROUTINE LINFIT (X,Y,N,TEM,SDY2,VAL,CORR)
C
C*************************************************************************
C
      DIMENSION X(25),Y(25),TIME(25)
C     COMPUTE MEANS
      XBAR=YBAR=0
        DO 100 I=1,N
        XBAR=XBAR+X(I)/N
        YBAR=YBAR+Y(I)/N
  100   CONTINUE
C     COMPUTE SLOPE,YINTERCEPT,CORRELATION (R),VARIANCE DUE TO SLOPE OF
C     LINE(VSL), TOTAL VARIANCE OF LINEAR FIT(VLF)
      SDXDY=SDX2=SDY2=0
        DO 200 I=1,N
        SDXDY=SDXDY+(X(I)-XBAR)*(Y(I)-YBAR)
        SDX2=SDX2+(X(I)-XBAR)**2
        SDY2=SDY2+(Y(I)-YBAR)**2
  200   CONTINUE
      SLOPE=SDXDY/SDX2
      DRIFT=SLOPE*365
      YINTER=YBAR-SLOPE*XBAR
      CORR=SDXDY/((SDX2*SDY2)**0.5)
      VSL=SDXDY**2/SDX2
C CAMPUTE VARIANCE ABOUT LINE (VAL),STANDARD ERROR OF LINEAR FIT (SELF)
C     AND STANDARD ERROR OF MEAN VALUE (SEMV)
C     IF VSL IS MUCH GREATER THAN VAL THEN SLOPING LINE IS BETTER
C     FIT TO DATA THAN MEAN VALUE
      VAL=0.
        DO 300 I=1,N
        VAL=VAL+(Y(I)-YINTER-SLOPE*X(I))**2
  300   CONTINUE
      SELF=SQRT(VAL/N)
      SEMV=SQRT(SDY2/N)
      TOTIME=X(N)-X(1)
      RSLM=0.0
      IF (SDY2.GT..001) RSLM=SELF/SEMV
      RVLM=0.0
      IF (VSL.GT.0.001) RVLM=VAL/VSL
C**********OUTPUT**********
      WRITE (108,3001) TEM,N,TOTIME,YBAR,SEMV,YINTER,
     1SLOPE,DRIFT,SELF,VSL,VAL,CORR,RSLM,RVLM
 3001 FORMAT (11X,F4.0,I3,I5,F9.3,F7.3,F10.3,F10.5,F9.3,
     1  F7.3,2F7.2,F7.4,2F8.3)
      RETURN
      END
```

```
   THERMISTØR CALIBRATIØN CØMPARISØN     11:12 SEP 17,'76
SLØPE AND DRIFT ARE MINUS THE RATE AT WHICH TEMPERATURE WØULD APPEAR
TØ CHANGE IF THE THERMISTØR WERE MØUNTED IN A CØNSTANT TEMPERATURE BATH
                                              RESISTANCE/TEMPERATURE
                                 +0       +5      +10      +15      +20      +25      +30
 THER DAYS BTCH  RSDL     DATE     95011.9 74405.4 58677.0 46536.1 37226.5 29932.3 24211.7


  76    0    2   .38 15*FEB*73    66.2     65.6     65.2     64.8     64.2     64.0     63.5
  76  285   21   .31 27*NØV*73    55.4     54.8     54.3     53.5     52.4     51.5     50.1
  76  687   42   .13  3*JAN*75    48.8     48.4     48.2     47.8     47.2     46.8     46.1
  76  704   45   .17 20*JAN*75    45.9     46.1     46.5     46.4     45.9     45.5     44.6
  76  708   46   .23 24*JAN*75    46.4     46.6     46.8     46.6     46.0     45.5     44.4
  76  749   47   .24  6*MAR*75    46.2     46.1     46.2     45.9     45.5     45.1     44.3
  76  980   57   .09 23*ØCT*75    46.0     45.8     45.8     45.5     45.1     44.8     44.2
  76 1285   68   .08 23*AUG*76    45.7     46.1     46.5     46.6     46.4     46.3     45.8
          T     N TIME     YBAR    SEMV     YINTER     SLØPE    DRIFT   SELF    VSL     VAL     CØRR     SELF/    VAL/
          C       DAYS     MDEG    MDEG      MDEG      MD/DA    MD/YR   MDEG    MD2     MD2              SEMV     VSL
         0.     8 1285   50.068   6.827    60.960    -.01614   -5.892  3.379 281.52   91.33  -.8689     .495     .324
         5.     8 1285   49.932   6.547    60.300    -.01537   -5.609  3.313 255.09   87.83  -.8625     .506     .344
        10.     8 1285   49.935   6.336    59.857    -.01471   -5.367  3.308 233.64   87.55  -.8529     .522     .375
        15.     8 1285   49.623   6.192    59.178    -.01416   -5.169  3.356 216.65   90.11  -.8404     .542     .416
        20.     8 1285   49.104   6.115    58.369    -.01373   -5.012  3.454 203.72   95.43  -.8252     .565     .468
        25.     8 1285   48.691   6.106    57.744    -.01342   -4.897  3.601 194.51  103.72  -.8076     .590     .533
        30.     8 1285   47.896   6.167    56.815    -.01322   -4.825  3.799 188.78  115.47  -.7877     .616     .612
                         49.321   6.332                        -5.253                  9.79  -.835


 126    0   22   .38 18*DEC*73    -1.7     -1.7      -.2      2.2      5.7     10.5     16.3
 126  163   34   .21 30*MAY*74    -4.3     -3.7     -1.7      1.1      5.0     10.1     16.0
 126  176   36   .27 12*JUN*74    -4.4     -3.2      -.7      2.6      6.8     12.3     18.5
 126  205   37   .22 11*JUL*74     -.2       .3      2.1      4.9      8.7     13.8     19.8
 126  321   40   .19  4*NØV*74    -2.7     -2.3      -.4      2.4      6.3     11.6     17.7
 126  350   41   .17  3*DEC*74    -2.6     -2.4      -.6      2.1      6.1     11.5     17.9
 126  464   49   .23 27*MAR*75    -1.6     -1.2       .6      3.4      7.4     12.7     19.0
 126  757   59   .10 15*JAN*76    -5.0     -4.3     -2.0      1.3      5.7     11.6     18.4
          T     N TIME     YBAR    SEMV     YINTER     SLØPE    DRIFT   SELF    VSL     VAL     CØRR     SELF/    VAL/
          C       DAYS     MDEG    MDEG      MDEG      MD/DA    MD/YR   MDEG    MD2     MD2              SEMV     VSL
         0.     8  757   -2.830   1.551    -2.035    -.00261    -.953  1.445   2.53   16.70  -.3630     .932    6.590
         5.     8  757   -2.309   1.351    -1.616    -.00227    -.830  1.259   1.92   12.67  -.3629     .932    6.593
        10.     8  757    -.379   1.209      .149    -.00173    -.633  1.150   1.12   10.57  -.3092     .951    9.461
        15.     8  757    2.504   1.119     2.806    -.00099    -.362  1.099    .36    9.66  -.1908     .982   26.472
        20.     8  757    6.448   1.083     6.461    -.00005    -.016  1.083    .00    9.38  -.0090    1.000     .000
        25.     8  757   11.761   1.106    11.425     .00110     .403  1.081    .45    9.34   .2149     .977   20.550
        30.     8  757   17.952   1.203    17.205     .00245     .895  1.081   2.24    9.35   .4394     .898    4.178
                          4.735   1.241                         -.214                  3.33  -.083
```

```
     11:12 SEP 17,'76
      TH   BA   DATE            A                B                C          PTS  RES
      76    2 15*FEB*73  .907276662E-03  .225276166E-03  .113410045E-06   7   .38
      76   21 27*NOV*73  .908975703E-03  .225058981E-03  .114031042E-06   7   .31
      76   42  3*JAN*75  .908024765E-03  .225184518E-03  .113765542E-06   7   .13
      76   45 20*JAN*75  .909638957E-03  .224953966E-03  .114474836E-06   7   .17
      76   46 24*JAN*75  .909740989E-03  .224942586E-03  .114489273E-06   7   .23
      76   47  6*MAR*75  .908756534E-03  .225080322E-03  .114095987E-06   7   .24
      76   57 23*OCT*75  .908270114E-03  .225147885E-03  .113906734E-06   7   .09
      76   68 23*AUG*76  .909072729E-03  .225026889E-03  .114297329E-06   7   .08
     126   22 18*DEC*73  .896564289E-03  .226727017E-03  .110085143E-06   7   .38
     126   34 30*MAY*74  .897339085E-03  .226609665E-03  .110487051E-06   7   .21
     126   36 12*JUN*74  .897704056E-03  .226546207E-03  .110728311E-06   7   .27
     126   37 11*JUL*74  .896910969E-03  .226668113E-03  .110289750E-06   7   .22
     126   40  4*NOV*74  .896478946E-03  .226728121E-03  .110142294E-06   7   .19
     126   41  3*DEC*74  .895666766E-03  .226841587E-03  .109816519E-06   7   .17
     126   49 27*MAR*75  .896160833E-03  .226770858E-03  .110018335E-06   7   .23
     126   59 15*JAN*76  .895809412E-03  .226809092E-03  .109991134E-06   7   .10
*STOP* 0
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by Richard E. Payne, Alvin L. Bradshaw, Jerome P. Dean and Karl E. Schleicher. 78 pages. October 1976. Prepared for the Office of Naval Research under Contract N00014-76-C-0197; NR 083-400.

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