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TECHNICAL MEMORANDUM NO. 7 OF 1972.

A LINEAR THERMISTOR THERMOMETER FOR THE TEMPERATURE RANGE, 10°C - 70°C.

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FOREWORD.

The author is a fourth-year engineering student at the University of Pretoria. As one of the tasks for the 1971/72 vacation, the student was required to make a study of an interesting engineering project, and submit a report thereon to the Faculty of Engineering at the University on completion of his vacation work.

The project reported herein was initiated by Dr. G.A.W. van Doornum, Chief of Engineering at the Institute, under whose guidance it was carried out.

The author wishes to convey his thanks to the Director of the Institute, Dr. A.J. Petrick, and to Dr. G.A.W. van Doornum, for permission to submit this technical memorandum in fulfilment of the above-mentioned requirements.

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INTRODUCTION:

A thermistor type sensing element is often preferred to more conventional temperature sensitive devices, such as thermocouples and mercury thermometers, when considerations such as accessability, robustness and temperature range are taken into account.

In many cases, the sensor cannot be removed upon completion of the experiment so that low cost is also an important consideration.

The Institute has found it necessary to utilize the less expensive N.T.C. (negative temperature coefficient) type non-linear thermistors in determining the vertical temperature profiles in coal dumps. The temperatures at various positions are required to assess the danger of spontaneous combustion.

A linear temperature scale is advisable to avoid inadvertent errors on the part of the operator. Linearity over the required temperature range, i.e. $10^{\circ}C - 70^{\circ}C$, was approached by incorporating the thermistor in a bridge network.

CIRCUIT:

The circuit employed in the prototype is shown in figure 1. The thermistor forms one leg of the bridge, whose output potential is fed to the input of a high performance operational amplifier, the output of which is registered on the meter, M. The operational amplifier was employed at an amplification of 10.

/Resistors ....

Resistors, R3 and R4, of the bridge are chosen so that the output of the bridge is linear* over the required temperature range.

Potentiometer, RV1, is set to the "cold" resistance value of the thermistor. In the prototype the "cold" resistance is the resistance corresponding to a temperature of 10°C, so that the bridge output is zero at this temperature.

Potentiometer, RV3, forms the offset null divider and is used for zeroing the operational amplifier output when the input is zero, i.e. at 10°C.

RT is a series of matched** thermistors incorporating selector facilities. The temperatures at the positions of the various thermistors can then rapidly be obtained.

Resistor R9, potentiometer RV2 and the meter M, in series, form a "voltmeter" on the output side of the operational amplifier. RV2 is adjusted so that the full scale deflection of the meter coincides with a temperature of 70°C. At this temperature the bridge output is in the order of 0,55 volt so that the "voltmeter" has a full scale deflection of 5,5 volt.

Switches S2 and S3 are used to select and test the batteries, B1 to B4 (9,0 volt each) and B5 (1,5 volt), respectively.

Switch S1 is the supply switch to the operational amplifier and the bridge.

/A printed ....

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* See "Calculation of R4" under same cover.

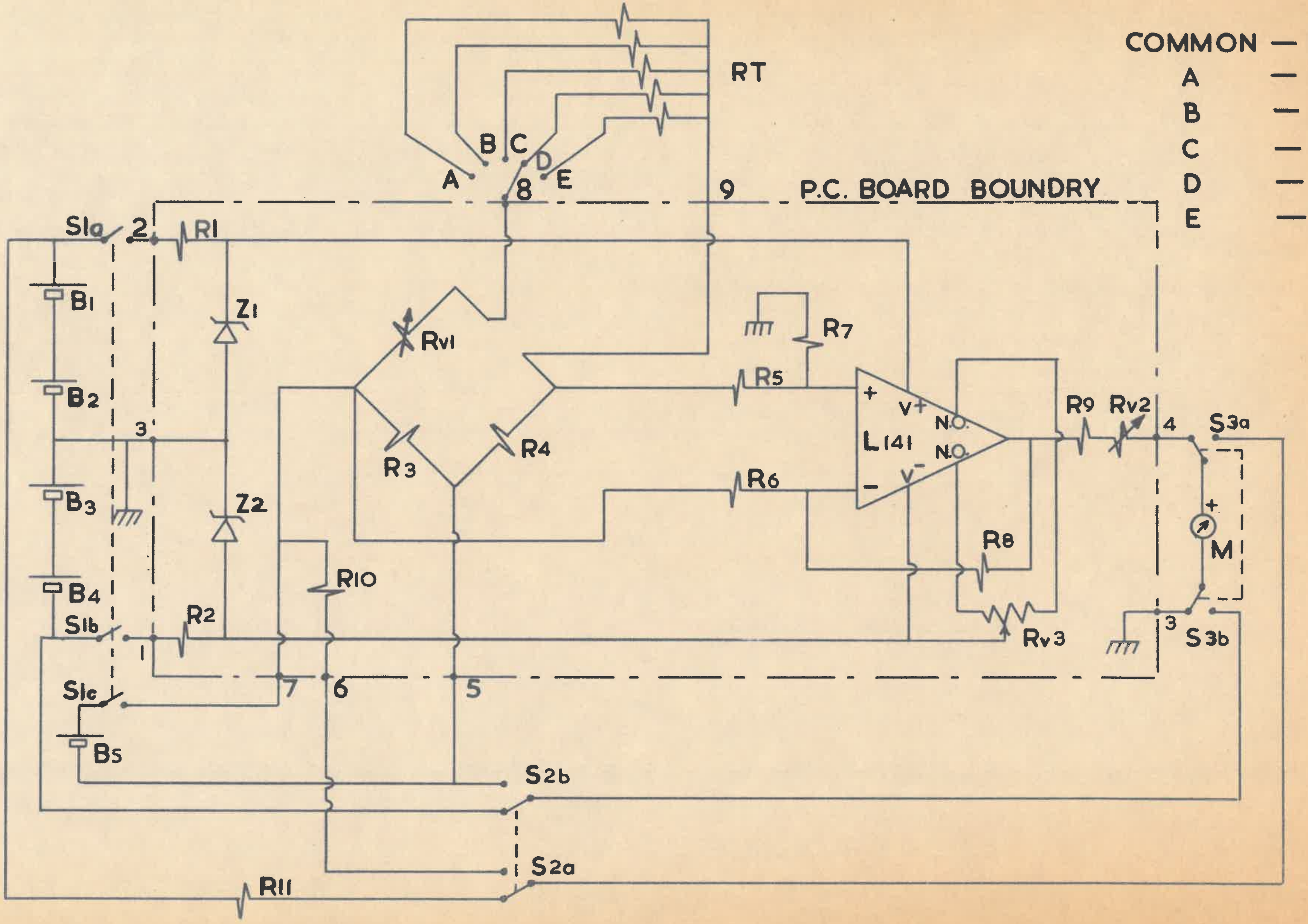
** See "Notes on matching thermistors" under same cover.

A printed circuit layout, incorporating the components within the dotted line in figure 1, is given in figure 2.

A typical temperature calibration curve is given in figure 3. This is a plot of the actual temperature, T, against the meter current in mA. The deviation from linearity was found to be within 2% of full scale for the temperature interval, 10°C - 70°C. This deviation is found to be within much closer limits if the swing on either side of 40°C is made smaller.

/figure 1 ....

FIG. I



COMMON — BROWN
A — YELLOW
B — BLUE
C — WHITE
D — PINK
E — GREY

CIRCUIT DIAGRAM

PARTS LIST: (used in prototype)

Resistors: (½ W., 5% cracked carbon)
R1, R2 - 100
R3, R4 - 330
R5, R6 - 1,2K.
R7, R8 - 12K.
R9 - 1,2K.
R10 - 2K.
R11 - 47K.

Potentiometers: (Bourne type 3009 P)
RV1 - 0-1K.
RV2 - 0-10K.
RV3 - 0-10K.

Batteries: (dry cell)
B1, B2, B3, B4 - 9V. (006 P)
B5 - 1,5V. (LP 950)

Zener Diodes: (General Electric)
Z1, Z2 - Z4XL18B.

Operational Amplifier: (S.G.S. Fairchild)
L141.

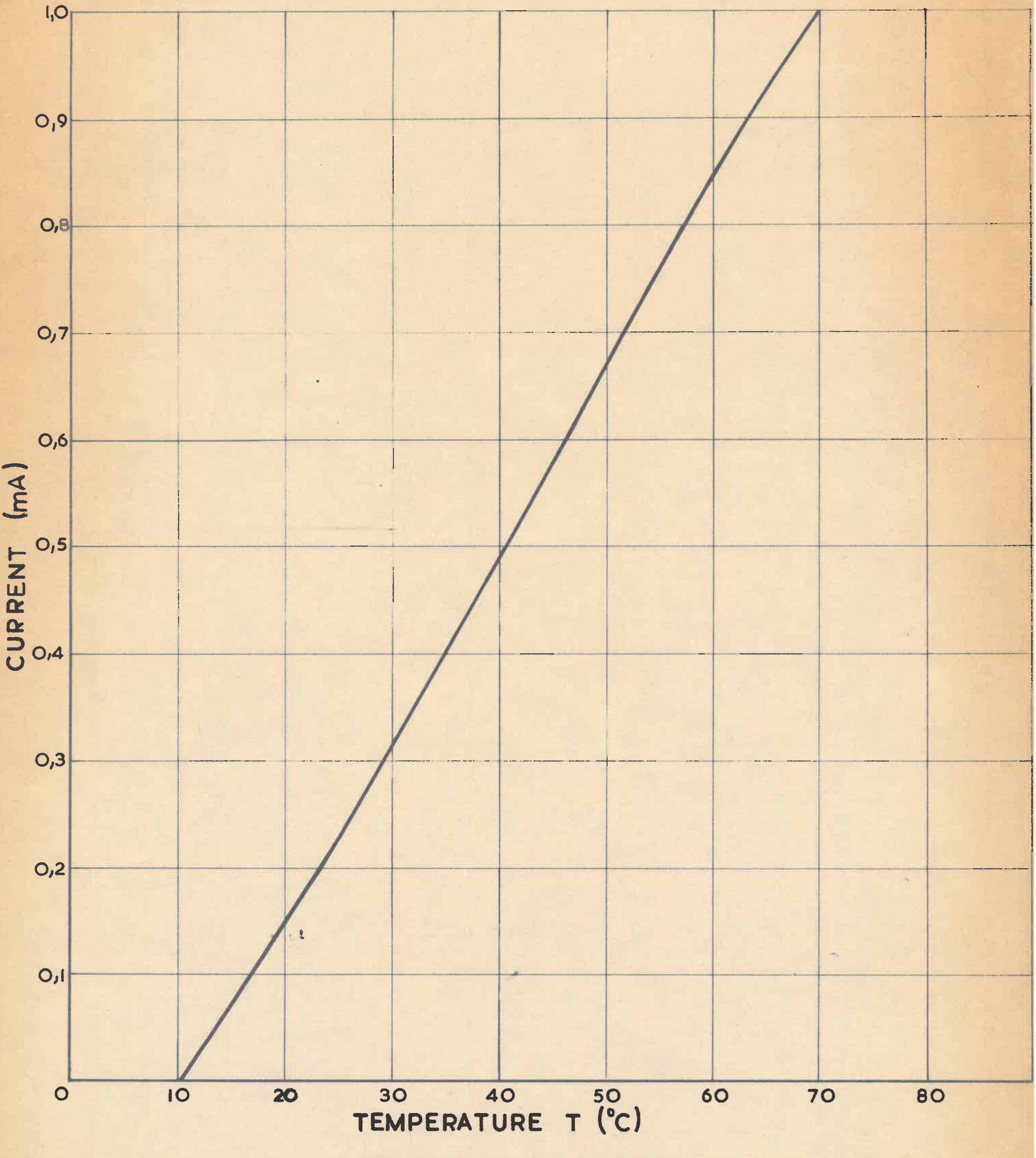
Meter: (scale calibrated - 10°C - 70°C)
M-0-1mA ammeter.

Switches:
S1 - 3 pole on-off press button
S2 - DPDT
S3 - DPDT biased

Thermistor: (Siemens)
RT - 1K.

/figure 2 ....

FIG. 2



CALIBRATION CURVE

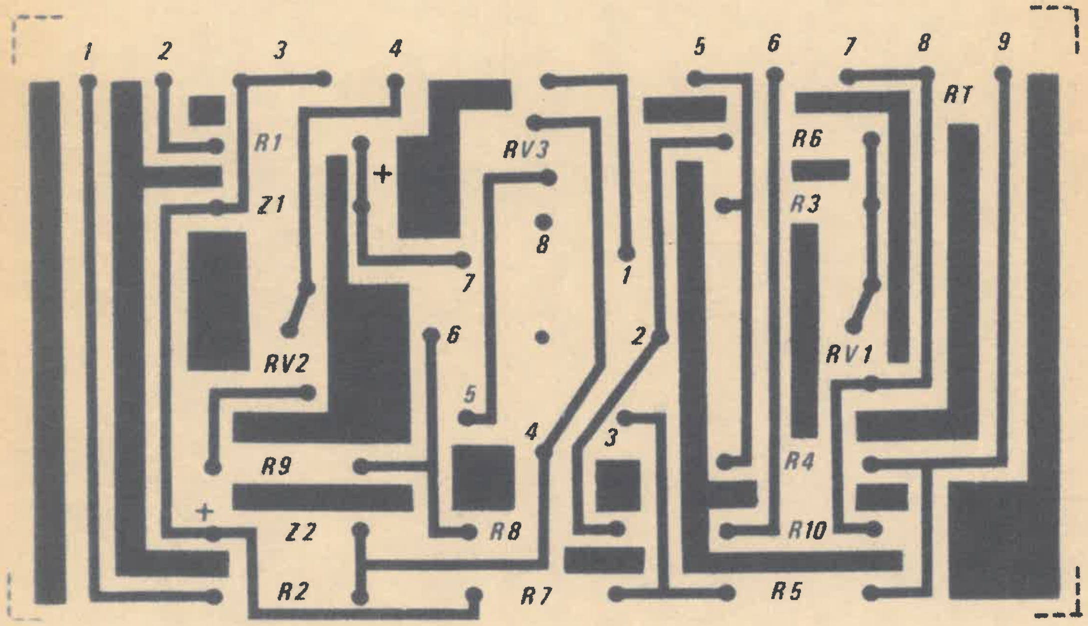


FIG 3: PRINTED CIRCUIT LAYOUT

CALCULATION OF R4:

The temperature dependent resistance, RT, of an N.T.C. thermistor can be approximated by equation 1, the validity of which is borne out by the experimentally determined graph of figure 4:

$$RT = R \exp. (B/T) \qquad \underline{\hspace{3cm}} \quad 1.$$

The current through the same thermistor in series with a resistor, R4, with an applied voltage, E, is, according to Ohm's law:

$$I = \frac{E}{RT + R4} \qquad \underline{\hspace{3cm}} \quad 2.$$

The Taylor expansion of I, being a function of T is:

$$I = Io + hI'o + \frac{h^2 \; I''o}{2!} + \text{-----------} + \frac{h^n I^n_o}{n!} \qquad \underline{\hspace{3cm}} \quad 3.$$

where $h = T - To$

and $I'o$, $I''o$, ----------, I^n_o the first to the nth derivatives of I, at the working temperature, To.

Linearisation is approached if the third and higher derivatives are neglected and the second derivative, I''_o, set equal to zero in equation 3.

The second derivative of I at the working temperature, To, is:

$$I''_o = - \frac{E \times B \times RTo \; (RTo + R4)}{(RTo + R4)^4 \; T_o^3} \left[(RTo + R4)(B/To + 2) - 2B/To \times RTo \right]$$

which when set equal to zero and simplified yields the condition:

/R4 ....

$$R4 = \frac{(B - 2To)}{(B + 2To)} RTo \quad \underline{\hspace{5cm}} \quad 4.$$

with RTo = R exp. (B/To), from equation 1, being the resistance of the thermistor at the working temperature.

Equation 4 gives the value of R4 for optimum linearisation. B is, however, unknown and is determined experimentally using the following results:

At $34^{o}C$ (307K), RT = 577,8 ohm,
at $40^{o}C$ (313K), RT = 469,9 ohm, and
at $46^{o}C$ (319K), RT = 386,6 ohm.

From this, three values of B can be obtained, viz.:

i) 3315
ii) 3238
iii) 3283
giving an average of 3279.

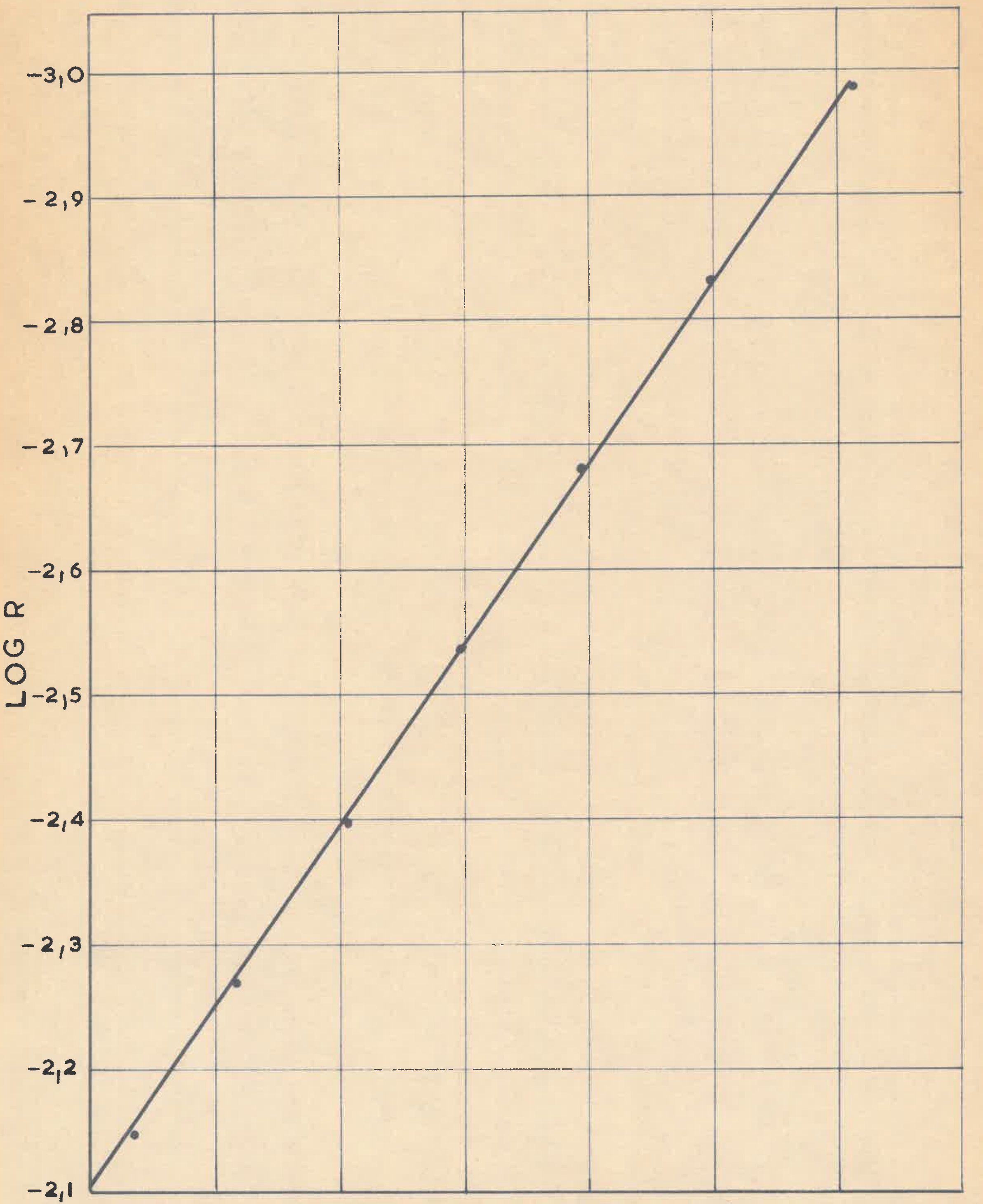
Substituting this value of B into equation 4 at the selected working temperature of $40^{o}C$, yields:

R4 = 320 ohm.

The nearest standard value of 330 ohm was chosen.

/figure 4 ....

FIG. 4



NOTES ON MATCHING THERMISTORS:

Matching could be defined as the agreement of two thermistors with regard to their R and B values in equation 1, within specified limits, over the required temperature range.

As can be imagined, it would be a very tedious task to single out even two thermistors of a batch, that would agree, according to the definition, within reasonable limits.

An easier way of matching two thermistors so that they agree at two temperatures is by adding series and parallel resistors. The technique can be illustrated by means of the following examples.

1. Assume we have the following data for two thermistors:

At $20^{\circ}C$ RT1 = 1000 ohm and RT2 = 950 ohm, and
at $70^{\circ}C$ RT1 = 200 ohm and RT2 = 190 ohm.

The resistance swing of RT1 is 800 ohm while that of RT2 is 760 ohm.
RT1 will acquire a parallel resistor RP and RT2 a series resistor RS.
At the two selected temperatures the total resistances must be equal:

$$\text{Thus:} \quad 190 + RS = \frac{200 \times RP}{200 + RP} \qquad \underline{\hspace{3cm}} \quad 5.$$

$$\text{and} \quad 950 + RS = \frac{1000 \times RP}{1000 + RP} \qquad \underline{\hspace{3cm}} \quad 6.$$

/Solving ....

Solving for RS and RP from 5 and 6 yields:

RP = 23K ohm and RS = 8 ohm.

At 20°C the total resistances are both 958 ohm, and at 70°C they are 198 ohm.

2. Assume the same RT1 is used while RT2 has a resistance of 1100 ohm at 20°C and 330 ohm at 70°C.
The swing of RT1 remains 800 ohm and that of RT2 is 770 ohm.
RT1 has the higher swing pointing to it being shunted by a resistor, RP. It can be seen, however, that the total value of RT1 will be lower than that of RT2 at 20°C.
This points to the addition of a series resistor, RS, to RT1.
Equality at both temperatures implies:

$$\frac{1000 \text{ x } RP}{1000 + RP} + RS = 1100 \qquad \_\_\_\_\_\_\_\_\_\_ \quad 7.$$

$$\frac{200 \text{ x } RP}{200 + RP} + RS = 330 \qquad \_\_\_\_\_\_\_\_\_\_ \quad 8.$$

Solving we get:

RP = 31K ohm and RS = 132 ohm.

If an attempt was made to shunt the higher resistor, RT2, initially, a negative value of RP would have resulted, clearly unattainable with passive components.

The following schedule emerges from these examples:

(a) Measure the resistances of the thermistors at two temperatures T1 and T2.

/(b) The ....

(b) The swing must be determined. The thermistor having the higher swing must be shunted with a resistor, RP.

(c) The thermistor having the lower resistance at the lower temperature must be supplied with a series resistor, RS.

(d) By equating the total resistances individually at T1 and T2, the values of RP and RS can be solved for.

As stated before, resistance agreement is reached at two temperatures, only, while the tolerance of the exponents B, determines the accuracy of matching anywhere between these temperatures.

This method also becomes more accurate as the temperatures, T1 and T2, approach the "cold" end of the thermistor characteristic. At this end the thermistor resistance is relatively high so that an error in the series resistance becomes less important.

From the foregoing discussion it is obvious that points (a) and (d) are only valid for N.T.C. thermistors.

In the prototype thermistor thermometer close matching was not of prime importance, so that matching was achieved by measuring the thermistor resistance at one temperature, viz.: 40°C, and choosing those which agree within 0,5 ohm.

(SIGNED) M.P. OBERHOLZER
ASSISTANT TECHNICIAN

PRETORIA.
2nd February, 1972.
/KW