AUTOMATION OF THE CLASSICAL STEADY-STATE METHOD FOR MEASURING THERMAL CONDUCTIVITY, AT LOW TEMPERATURES, USING A MICROPROCESSOR

by

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ABSTRACT

The development of a program and interface to enable a DAI† micro-processor to measure thermal conductivity in the temperature range of 4.2 to 100^{0}K is described. The measurements are to be made on cylindrical crystaline specimens and the method is an adaptation of Searle's bar experiment.

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§ 1 INTRODUCTION

The low temperature laboratory in the Physics Department required a means whereby the thermal conductivity of various crystaline specimens could be conveniently measured, as a function of temperature. Plots of thermal conductivity against temperature were needed, not as accurate academic records, but as rough tools for studying the effects of impurities on phonon scattering processes.

The cryostat and low temperature apparatus to be used was that described in (1). A cylindrical shaped specimen is used in the cryostat and the experiment is a simple adaptation of Searle's bar method. There are two 1K-ohm heaters (one at each end of the specimen) and two germanium resistance thermometers (one calibrated, one uncalibrated) in the cryostat. To measure the current and voltage on the thermometers and heaters, a digital nanovoltmeter (Keithley Model 180) is employed.

Part of the problem was to interface the DAI microprocessor with the thermometers, heaters and DVM; such that it could control the experiment without human supervision. Also a program had to be written for the microprocessor to perform the required functions.

In designing any complicated system, one has to build a prototype and it evolves as the experimenter finds and corrects deficiencies in its performance. The philosophy employed in writing the program was to make it as simple and flexible as possible.

The work here is intended to be a useful building block, which can be readily adapted and developed upon.

§ 2 INITIAL CONSIDERATIONS

The logical sequence used in tackling the project is depicted in Fig 1. To 'define the problem' it is important to make clear the basic principles of the experiment and to outline the sequence of operations.

2.1 Thermal Conductivity

The method is based on Searle's bar experiment (ie, the classical steady-state longitudinal heat flow method). Consider a bar of cross-sectional area, A, shown in Fig 2. There is a temperature gradient along the bar when heat is sourced at one end and sunk at the other. If heat is supplied at a rate $\dot{Q}$, then the thermal conductivity, K, is defined by

$$\dot{Q} = -AK.\frac{dT}{dx} \qquad (2.1)$$

the negative sign indicating that heat flows down the gradient.

The temperature gradient, (dT/dx), is obtained by measuring the temperature difference, ΔT, between two points on the specimen a known distance, Δx, apart. Assuming that there are no heat losses from the specimen or heater,

$$K = \frac{\dot{Q}}{A}.\frac{\Delta x}{\Delta T} \qquad (2.2)$$

2.2 Heat Losses

The expression (2.2) is only valid if there is no temperature gradient at right angles to the direction of heat flow. Such a temperature gradient can be caused by heat losses, as shown in Fig 3. If heat losses are minimised so that the lines of heat flow are longitudinal to a good approximation, then eqn (2.2) is applicable.

The cryogenic apparatus to be used is that described in (1). The specimen and heaters are mounted in a vacuum chamber which can be evacuated to a pressure less than 10^{-4} torr. This effectively eliminates heat losses due to convection and conduction through the surrounding gas.

Heat loss due to conduction through electrical leads is minimised by using long fine copper wires, which are thermally anchored at $4.2^{0}K$ (which is the boiling point of liquid Helium). This is the lowest temperature used and is our 'thermal earth', (c.f. electrical analogy). Long thin wires are used because they will conduct away minimal heat, due to their high thermal resistance. As the wires are thermally 'earthed' they will remain consistently at $4.2^{0}K$, because any stray heat will be sunk by the liquid helium.

Heat loss by radiation has been shown to be negligible, at low temperature (2). Brown (1971) used a computer model and showed that, under the worst experimental conditions, the effect of radiation losses introduced an error of about $10^{-3}\%$ in K.

2.3 Further Heat Problems

Using an electrical analogy we saw in the previous section that heat losses were due to thermal resistances in parallel with the specimen. These heat losses were minimised by maximising the thermal resistance of the offending elements.

However, thermal contacts between the specimen and heaters are series thermal resistances. These tend to impede heat flow and their effect is reduced by minimising their thermal resistance. This is done by bonding the specimen to the heaters using Wood's metal, which has a thermal resistance of around three orders of magnitude less than the crystaline specimen under test (typically ruby).

There are two ways in which heat can actually leak into the specimen:

i) Radiation can get into the experimental chamber through the vacuum pumping tube. This is reduced by placing radiation shields inside the chamber.

ii) Joule heating in the resistance thermometers. If an excessively high measuring current is used, I^2R heating will cause an erroneous reading. If the current is too low, the thermometers loose their sensitivity. Optimum measuring currents are given in (3) and are listed below.

Resistance of Thermometer	Current
1 to 12 ohms	1 mA
10 to 120 ohms	100 μA
100 to 1200 ohms	10 μA
1000 to 12000 ohms	1 μA
Above 10,000 ohms	0.1 μA

2.4 The Integration Effect

'True' thermal conductivity is given by (2.2) as $\Delta x \to 0$. In practice it is totally impossible to measure temperature gradient at a point. Instead we measure the temperature gradient over a distance, Δx; but as K varies with temperature, its measured value is an average over the range of temperatures, existing in the specimen within the length Δx.

We would like Δx to be as small as possible so that the measured 'integrated' thermal conductivity is as close as possible to the 'true' thermal conductivity. If Δx is too small, then our system may not be sensitive enough to measure the corresponding ΔT.

It has been shown by Brown in (2), that

$$\frac{\Delta K}{K} = \frac{n(n - 1)}{24} \cdot \left(\frac{\Delta T}{T_0}\right)^2 \tag{2.3}$$

where

$$\Delta T = T_1 - T_2$$

$$T_o = (T_1 + T_2)/2$$

and $$\frac{\Delta K}{K} = \frac{\text{measured } K - \text{true } K}{\text{true } K}$$

$$= \text{uncertainty in measured } K$$

If we assume that $K \propto T^3$ then $n = 3$ and (2.3) becomes

$$\frac{\Delta K}{K} = \frac{1}{4}\left(\frac{\Delta T}{T_o}\right)^2 \tag{2.4}$$

If we insist that ΔT should be at least 1^oK at $T_o = 4.2^oK$, then the uncertainty in the measured K is roughly 1%. If we can afford a maximum uncertainty of 1% then from (2.4) our governing relation becomes

$$\Delta T \lesssim \frac{T_o}{5} \tag{2.5}$$

This expression will be of great use in our computer program, because if we want to measure K at T_o, with an uncertainty no greater than 1%, then we adjust ΔT so that it is no greater than a fifth of T_o.

There is a problem in that, in practice, to obtain a particular T_o, ΔT might have to be greater than $T_o/5$. This problem is overcome by having an auxillary heater (A.H.) that varies the heatsink temperature (see Fig 2). The effect of raising the heatsink temperature is to raise the average temperature of the sample, whilst keeping the slope of the temperature gradient unchanged. So the A.H. can be used to set the desired T_0 and the M.H. be used to set the optimal ΔT.

This ability to vary T_0 and ΔT independently is of great value, as we shall see later.

2.5 The usage of the Thermometers

We see from Fig 2 that the germanium resistance thermometers are used to measure the temperatures at two positions on the sample, separated by a distance Δx. T_1 is measured by finding the resistance of the thermometer and obtaining the corresponding temperature from a table of calibration data (see Appendix I).

T_2 cannot be measured in this way as an uncalibrated thermometer is used, in this case. Instead, we have to note the voltage drop across the thermometer; then the M.H. is switched off. The A.H. output is increased until the voltage across the uncalibrated thermometer is the same as before. As there are little or no heat losses the sample will be uniformly heated to the temperature T_2. Thus the calibrated thermometer can now be used to read T_2.

In this way the same calibrated thermometer is used to measure T_1 and T_2. Using two calibrated thermometers would be more expensive and would introduce a consistent unknown error, equal to the offset in their calibrations. However, as our method uses the same thermometer to take all the temperature readings, any errors will be random and can be averaged out by taking repeated readings.

§ 3 EXPERIMENTAL OPERATIONS

Given that the computer is in some way interfaced to the heaters and thermometers, we discuss in this section the sequence of operations, in the experiment, necessary to formulate the main part of the program. Details of the program subroutines will be dealt with in §4.

Note that the main segment of the program is directly concerned with operations for finding thermal conductivity, whilst the subroutines are more concerned with controlling the interfaces.

3.1 The General Scheme

A flow chart with the important features of the main segment of the program is given in Fig 4. The same symbols (see Table 1) are used as those in the actual program (See Appendix II).

The system is initialised by switching the heaters off and switching to the lowest thermometer current (for minimum Joule heating). Also all the variables are given their initial values.

Let us consider the flow chart in Fig 4, and examine the operations when we start to take the Nth measurement. The temperature difference ΔT (ie, TD in program notation) has to be measured in the way described in §2.5. T1 and V2 are measured, then the M.H. is turned off. The voltage, VA, on the A.H. has to be raised until the new voltage across the uncalibrated thermometer, Vu, equals the old value, V2.

This is a subtle problem as we do not know how much to raise VA by. However, we know that if VA is increased the temperature goes up and the resistance of the uncalibrated germanium thermometer goes down; thus Vu goes down. Although we do not know the relation between VA and Vu, we can use the principle of feedback,

$$VA = VA * \left(\frac{Vu}{V2}\right) \tag{3.1}$$

So, if Vu > V2 then VA is increased making Vu smaller and if Vu < V2 then VA is decreased making Vu larger. By iterating the process we eventually will end up with Vu = V2. In practice we terminate the process when Vu is approximately V2, within an error limit, ERR. When Vu ≃ V2, T2 is found by reading the calibrated thermometer, as described in §2.5.

Main heater voltage and current (VM and CM) are measured so that its resistance, RM, and rate of heat output, HM, can be calculated. Instead of calculating thermal conductivity, CON, a variable Z is introduced, which is simply HM/TD. Note that CON = Z * FF; the form factor, FF, is just a constant and it is convenient to work in terms of Z.

This calculated value of Z will be subject to a certain amount of error and is improved upon by using it to recalculate various variables and repeating the above process. This iterative process is stopped when Z is within an error, ERR, of its previous value. The whole process is then repeated for a new average temperature, TA, which is stepped up by an increment DT.

3.2 Improving Z by Successive Iterations

Once we have a value of Z, it is improved upon by using it to calculate the best conditions under which to measure Z again. This process is repeated until Z has the desired accuracy.

In this section we discuss how Z is used to set up the best conditions governed by the integration effect relation (2.5), as described in §2.4, the temperature at which we wish to measure a particular Z ~~in~~ is TA. To obtain the optimum conditions laid down by §2.4, we must set up a temperature difference, TD = TA/5.

To obtain this particular TD, the M.H. must give out heat at a rate

$$HM = X * TD \tag{3.3}$$

where X is the latest value of Z.

The voltage needed across M.H., to give an output HM is

$$VM = HM/RM \tag{3.4}$$

If we apply VM across the M.H., the sample will heat up, and T1 and T2 will be such that (T1 - T2) will equal the desired TD. However, (T1 + T2)/2 will not necessarily equal the desired average temperature TA. The desired TA is obtained by appro~~xima~~priately adjusting the A.H. output.

To 'tune' the A.H. to give the desired TA, we can use the same feed-back idea as that used in §3.1. This time, VA is adjusted by the relation

$$VA = VA * \left\{\frac{(T1 + T2)/2}{TA}\right\} \tag{3.5}$$

This relation is impossible to implement in practice as the A.H. is needed in the measurement of T2; whilst the A.H. is being used for the purpose of 'tuning' TA to its desired value - the A.H. cannot do two things at once!

Now, the value of TD = T1 - T2 is fixed by the M.H. and (T1 + T2)/2 is variable and is varied by the A.H., therefore eqn (3.5) can be written as

$$VA = VA * \left\{\frac{T1 - \frac{1}{2}TD}{TA}\right\} \tag{3.6}$$

This solves ~~out~~ our problem as we have fixed the T2 variable in (3.5) and we need only measure T1 in practice.

Once TA is 'tuned' the program loops back and repeats the process described in §3.1. In this way accurate values of Ƶ are found for the desired temperature values.

If Ƶ is produced by an iterative process dependent on the previous value of Ƶ, where does the first value of Ƶ come from? The answer to this is found at the beginning of the flow chart in Fig 4. The experimenter initiates the process by entering a guess M.H. voltage, VMS, and a guess A.H. voltage, VAS.

From these guessed conditions an intial crude Ƶ value is obtained for N = 0. The program increments the guess temperature, TA(0), by DT, and iterates for N = 1. Eventually an accurate Ƶ value for N = 1 will be produced; the temperature, TA(1) is incremented by DT and the process repeats for N = 2 and so on upto N = N1.

The experimenter will learn by trial and error the best guess values for a particular situation. This guessing method makes the program simpler, but if it proves inconvenient, it can be improved upon at a later date.

§ 4 INTERFACES AND SUBROUTINES

The main reason why the DAI microprocessor system was chosen for this project is that it can be readily multiplexed to the outside world, by means of a purpose made bus supplied by the manufacturers. This so called DCE bus is linked to the microprocessor and has 16 locations. Each location can accommodate an interface card which is addressed by a preselectable hexadecimal number (0,1,2 ... F). Each interface card has three separately addressable 8-bit ports and has room for the experimenter to build purpose designed buffer circuitry. The DCE bus and so called 'real world' interface cards are described in (4).

4.1 Controlling the Heaters

The interface used to supply the M.H. and A.H. voltages is a 'real world' card with two 12-bit D/A converters on it (see Fig 5). The card is referred to as an RWC - A02 in (4). The selected address for this card is '2'.

This card is able to operate in different modes, supplying various ranges of current and voltage. The voltage modes have 11-bit digital resolution with the most significant bit (MSB) used for the polarity sign. We only need one polarity and the zero to 10 mA current mode is chosen, giving us full 12-bit resolution. The current is applied across a 1.5 K-ohm resistor giving a zero to 15 volt swing.

In deciding on this form of operation, we have placed two problems on our hands,

i) The 1K-ohm heaters are of the same order of magnitude as the 1.5 K-ohm resistors and will load the supply.

ii) The current source is a floating supply and we have no guarantee that it will zero exactly.

The solution we came up with is shown in Fig 5. Two, unity gain, J-FET input, double stage, op-amp buffers are used. The beauty of this solution is that the J-FET op-amps take very little current and effectively isolate the heaters from the rest of the circuitry. This eliminates the loading problem described in (i). The first amplifier stage has floating inputs and the second stage is referenced to earth, thus alleviating problem (ii). The earthed ±16V power supply is shown in Fig 6.

Heater current is read by using the DVM across a standard 1-ohm resistor. There will be virtually no loading due to the high input impedance of the DVM. The maximum voltage the DVM can read is 2 volts; therefore it cannot read heater voltage directly. A possible solution is to sense the heater voltage with a J-FET op-amp and then divide by ten, using a resistor potential divider.

Looking at Fig. 5 we see that port 2 is divided into two halves and each half is ganged with another port to produce two 12-bit channels. The question of what numbers to send the ports to obtain the desired voltage arises. The subroutine that performs this function is in appendix II and is made elegantly short by using binary bitwise logic, as expounded in (5).

The RWC-A02 uses inverted natural binary, in the zero to 10 mA mode. That is, digital zero will give maximum analogue output and $(2^{12} - 1)$ will give zero analogue output.

Line 1020 in the program inverts the voltages. Line 1030 masks off the 4 LSBs and shifts the bits 4 places down - thus supplying ports 1 and 2 with the correct numbers. In line 1040 the 4 MSBs of the M.H. voltage are made all ones and the 4 MSBs of the A.H. voltage are replaced by the values of the 4 LSBs (the 4 LSBs then being made all ones). The two results are ANDed together giving the number that is sent to port 2.

4.2 Relay Multiplexing

DIL reed relays (as in Fig. 7) were deemed to be the most convenient and flexible way of multiplexing the DVM, for reading the heaters and thermometers, and for switching the thermometer current ranges.

The relays are normally open, and are closed by applying a 5 volt level. A 'real world' interface card, RWC-F, is used to switch the relays. On the card each port is buffered by a permanently enabled octal line driver (74S241).

The relays are mounted on a separate board, connected by ribbon cable to the RWC-F (the pin numbers and wire colours are given in Table 3). On the relay board, there are yet another stage of octal buffers (74LS244) buffering the signals from the RWC-F. The reason for two stages of buffers is one of flexibility (the RWC-F can be used for other experiments). Also the relay board is run off an external earthed 5 volt power supply (Fig. 8), which is best isolated from the DCE circuitry.

The purpose of the particular relay that is controlled by bit 1, port 2 (see Fig. 7) is to short out the DVM when it is not measuring anything. This is done to save time, because when the DVM terminals are left floating, the display floats up and takes a while to float down when a reading is tak~~ing~~en - shorting the terminals keeps the display at zero.

The double-pole-changeover relay is used so that the DVM can take a reading, then its reverse and average the two. This process is important when reading the thermometers, in particular, as error due to EMFs (created by inhomogeneities in the wires and by contacts) will be alleviated.

The subroutine that switches the relays is very simple. All relays are given a number and when the main program wants a quantity measured, it sends the number to the subroutine. The subroutine switches the appropriate relays and takes the reading. It waits for a time, ITS, and takes the reading again. If the second reading agrees with the first, within the error, ERR, it sends the result to the main program.

The stabilisation time, ITS, needs to be made longer, the higher the temperature. In line 590 of the main program ITS is set to be equal to some factor, TF, times the temperature. TF is recommended to be about 1. This very simple relation is a rough estimate from experience and can be refined later.

The subroutine that finds the optimum current for the thermometers, simply makes use of the table in §2.3. According to the resistance of the thermometer, the subroutine selects a number NRR. This number is sent to card 3, port 2 and switches the appropriate relay.

Looking at the third subroutine in appendix II, we see that there is no danger of oscillation between two ranges caused by borderline resistance values. A 'hysteresis' principle is used and borderline values are biased towards the lower current ranges.

4.3 Reading the DVM

The digital nanovoltmeter (Keithley model 180[(6)]) has a special digital output so that it can be read by a microprocessor. To read the DVM display, however, 26 bits of information have to be sent to the computer. It would be very costly to send all these bits of information in parallel and would take too long done serially. Therefore a compromise is made by having 4 parallel each reading 6 or 7 bits serially. There are 7 strobe lines, one to enable each row of serial data.

The DVM conveniently has open collector data outputs. We have put 1K8 resistors, pulled up to +5V, on these outputs so that they operate at the same logic level as the RWC-F interface (see Fig 9). Each port of the RWC-F is buffered by an octal line driver TTL chip (74S241). The buffers are configured so that port 0 can output the strobe pulses and so that port 1 can input the data from the DVM. (Port 2 is unused.)

The 4 parallel data lines are bits 0 to 3 of port 1. This data gives information on the digits appearing on the DVM display, the decimal point (DP), the range (function), the polarity, the highest digit '1 or 0' (overrange) and overload. The DVM display is composed of four digits, an overrange '1', a floating decimal point and μV or mV designations. To summarise,

i) data # 1 gives units in binary
   data # 2 gives tens in binary
   data # 3 gives hundreds in binary
   data # 4 gives thousands in binary
   (+5V ≡ logic '1')

ii) Overrange gives the 1×10^4 digit.

iii) DP1, DP2, DP3 and DP4 give the decimal point position (see Fig 9).

iv) Function 1 is '1' and function 2 is '0' for mV and vice versa for the μV range.

(function 3 is unused).

v) Polarity is logic '1' for +.

vi) Overload is '1' when reading is in excess of 1.9999.

Bit 4 of port 1 is '0' if the range changes. Bit 7 of port 1, which is connected to the flag, is '1' when the most recent reading is available at the data lines. Port 0 strobes the DVM with an active '0' (ie. '0' enables the data and '1' inhibits).

When hold #2 is '0' the DVM stops sampling new information and the display is frozen - the data must be read in this state. A flow chart of the sequence of operations needed to read the DVM is given in Fig 10. The operation is very simple and there are two things to bear in mind:

i) If the flag or range changes then abhort the reading and start again.

ii) Wait for stability after every dynamic conversion. (Waiting times are found by trial and error.)

The DVM has a 50-way Amphenol socket in the back. Connections are made to the interface by connecting an Amphenol plug to a strip connector, using ribbon cable. A list of connections is given in table 4. A policy of keeping unused lines unwired was maintained, so as to minimise stray capacative coupling.

§ 5 FUTURE DEVELOPMENT AND CONCLUDING REMARKS

We established the validity and feasibility of the longitudinal heat flow method, for measuring thermal conductivity in §2. In §3 we tackled important ideas, such as feedback and iterative processes, necessary for achieving our aims. Using the principles expounded in these sections, a program was written and is shown in Appendix II. The subroutines were tested and performed well. The arrangement and use of the interface electronics was described in §4. This hardware has been constructed and was deemed to work satisfactorily. The first stage of this project is complete and we now discuss the areas that need attention and refinement.

The system, in principle, can be used to measure thermal conductivity at any temperature of interest. The external limiting factors are,

i) The calibrated range of the thermometer (~1.4 - 125K, see Appendix I)

ii) The design specification of the cryostat (1) used, 4.2 - 30K.

The internal limiting factors that need investigation are,

i) The assumption that $K \propto T^3$, when saying that we would only get a maximum of 1% uncertainty in K (§2.4)

ii) The waiting time between readings which was assumed to be directly proportional to temperature (§4.2)

The feedback method that we used to raise the temperature of the sample to a predetermined value (§3.1) must be looked at critically. The possibility of instability and oscillations must be assured against. Also, looking into ways of making the process converge faster may be fruitful.

In retrospect, it is debatable whether the method of using one calibrated thermometer is better than using two. Is the method of using an uncalibrated thermometer (§2.5) more trouble than it is worth? This question can be answered by investigating to see if the use of two calibrated thermometers introduces a consistent error (due to the ~~effect~~ offset in their calibration) greater or smaller than other inherent consistent errors produced by the system (eg, voltage offsets in the hardware). If the error is greater then our present method is worthwhile.

When the program detects Joule heating, in the thermometers, it does not abhort the faulty readings and start again. Instead it carries on iterating with the faulty readings. As the process is iterative, the correct values will be produced eventually. It should be investigated to decide whether it is more efficient to abhort or to carry on iterating.

There is the problem that the DVM used can only read a maximum voltage of 2V. This means that the heater voltages (which go up to 10V) cannot be read directly. A separate DVM is unnecessary, because our iterative method of finding thermal conductivity does not require exact values of heater voltage. Instead it is recommended (§4.3) to simply use

~~on~~ an op-amp followed by a divide-by-ten potential divider. It must be remembered to multiply these voltage readings by ten in the program!

§ 6 ACKNOWLEDGEMENTS

I thank Dr Brown for lucidly setting the scene to this project. Thanks to my friends and colleagues who have shown interest and have given much encouragement.

I am grateful to Julie Smith for skillfully and efficiently typing this report.

§ 7 REFERENCES

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2 Investigation of Phonon Scattering and Cross-Relaxation by Paramagnetic Ions using Thermal Conductivity Techniques, by M A Brown, Nottingham (PhD Thesis), 1971.

3 Installation and Application Notes for Cryogenic Sensors, by Lake Shore Cryotronics Inc, Ohio, 1977.

4 DCE Microcomputer Systems Designer's Handbook, by Data Applications International, Belgium, 1979.

5 DAI Personal Reference Computer Manual, by Data Applications International, Belgium, 1979.

6 Instruction Manual: Model 180 Digital Nanovoltmeter, by Keithley Instruments Inc, Ohio, 1977.

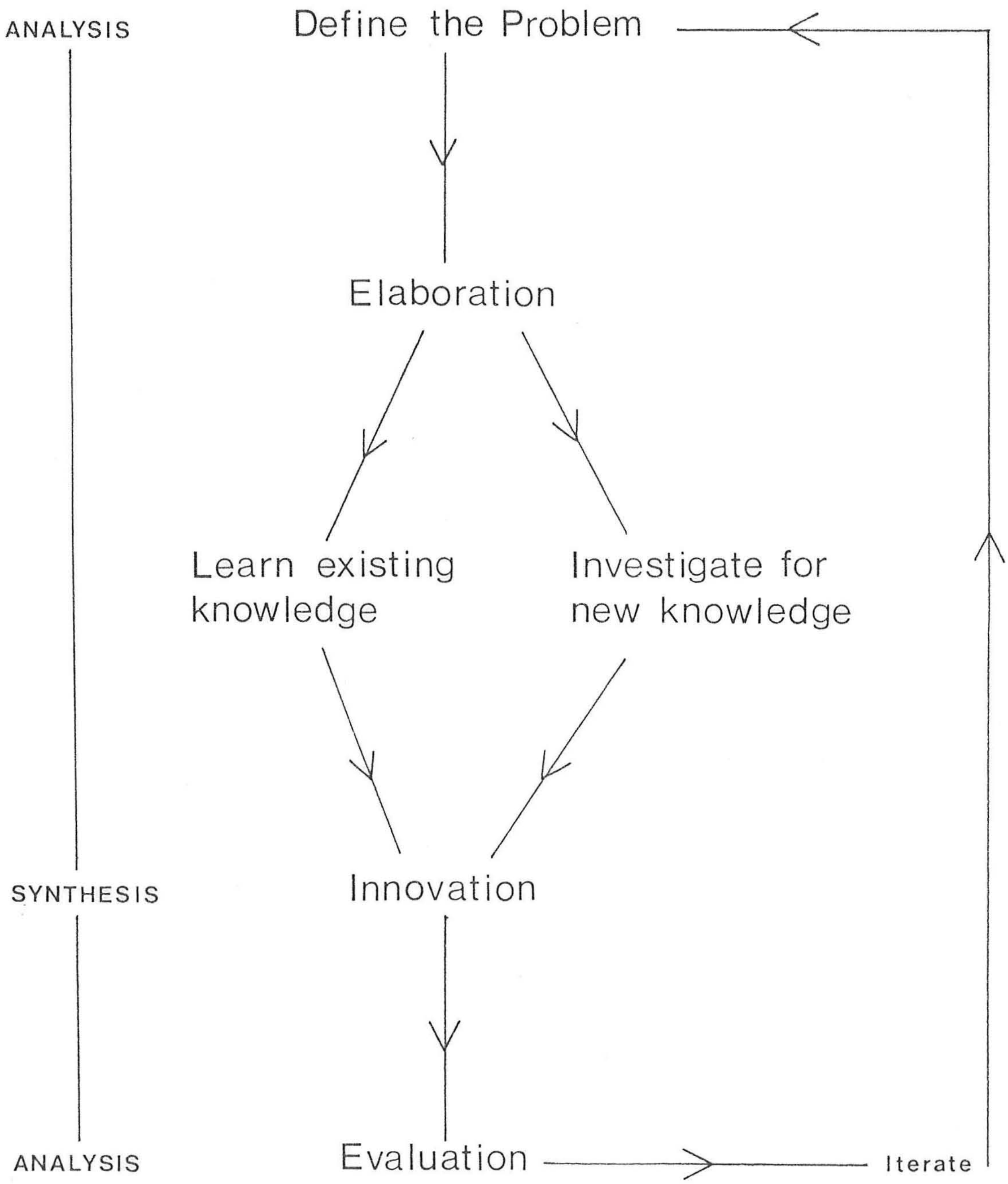

Fig.1 Sequence for tackling problem

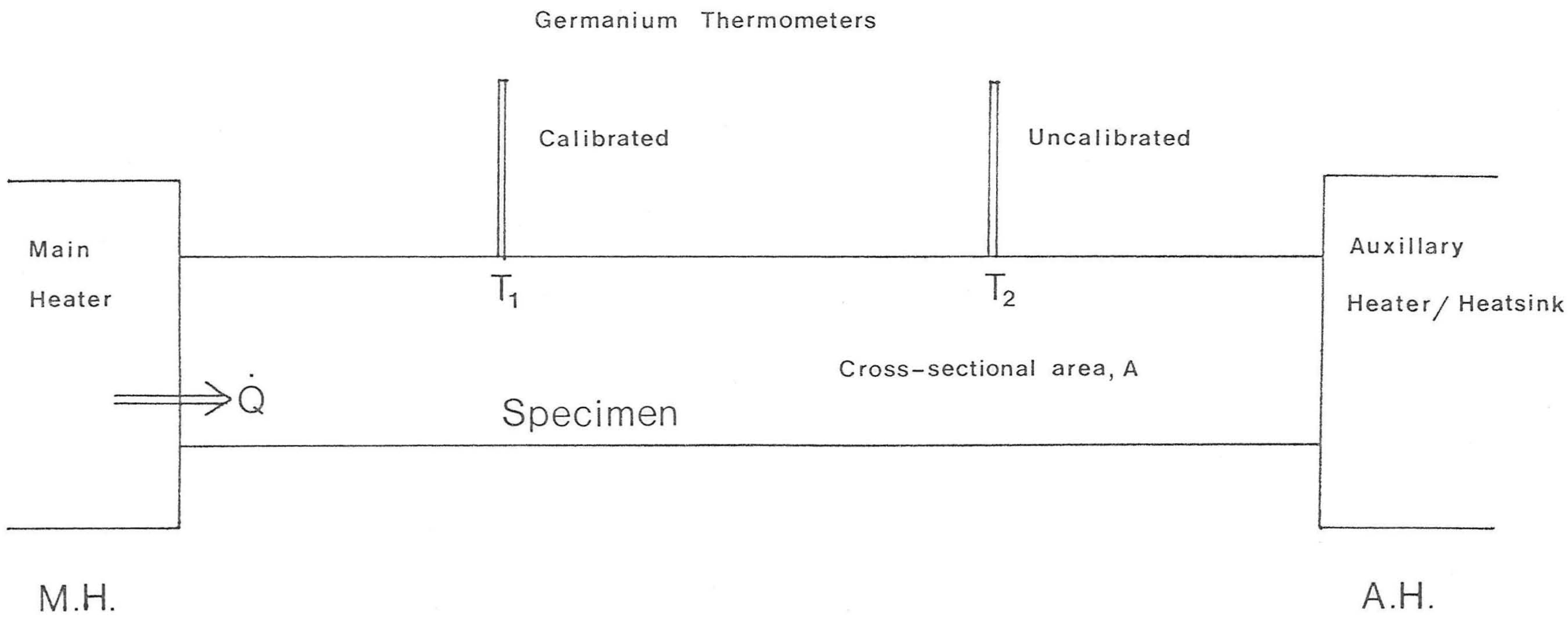

Fig.2 Schematic of thermometer & heater arrangement

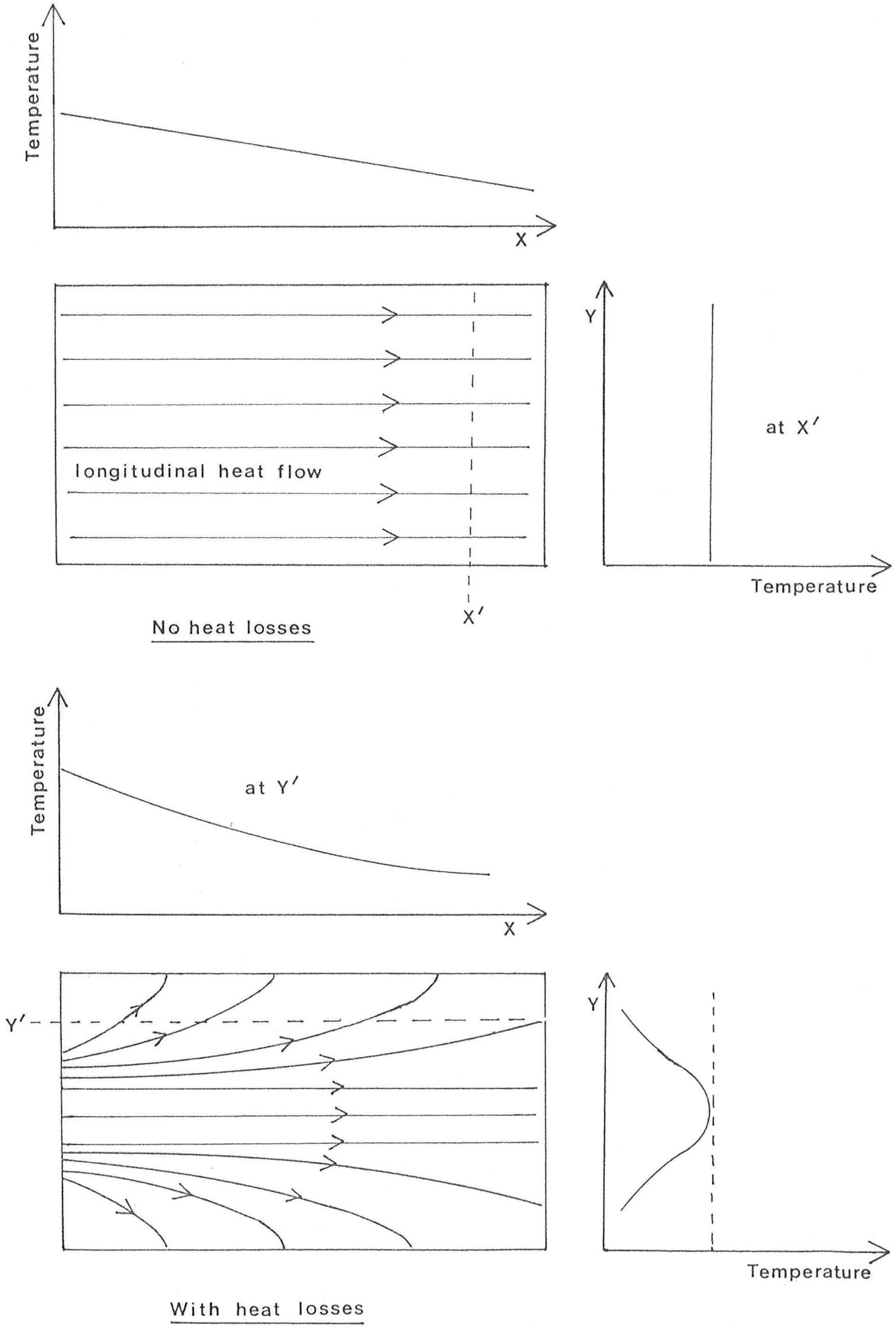

Fig.3 Effect of heat losses on lines of heat flow & temperature gradient

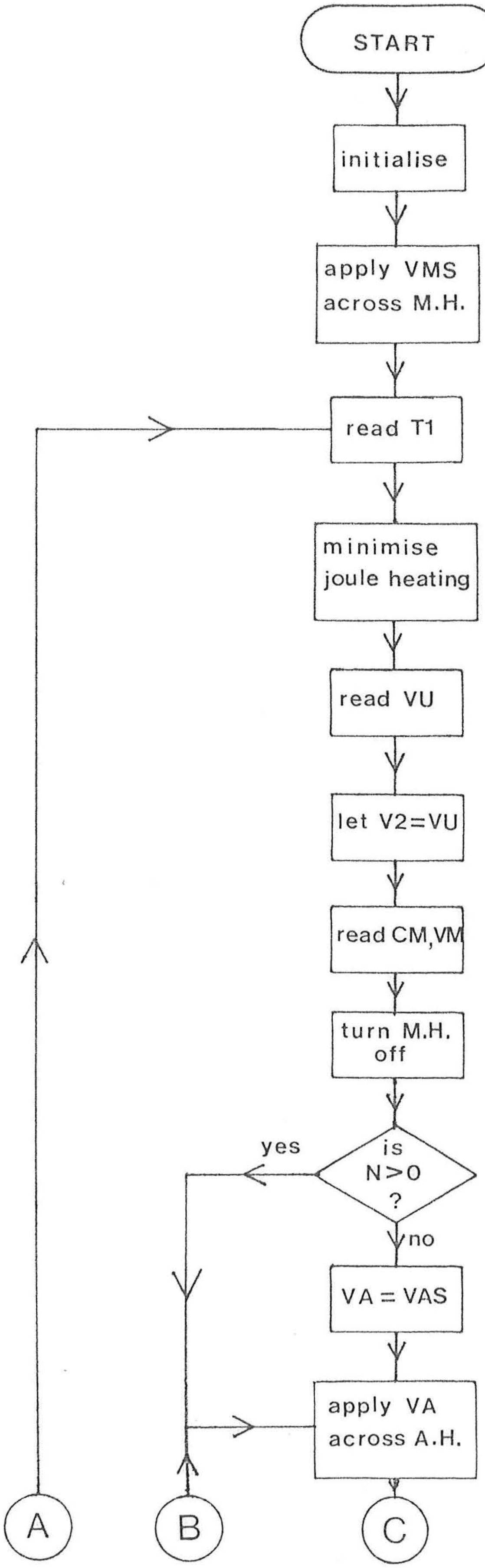

Fig.4 Flow chart of main program

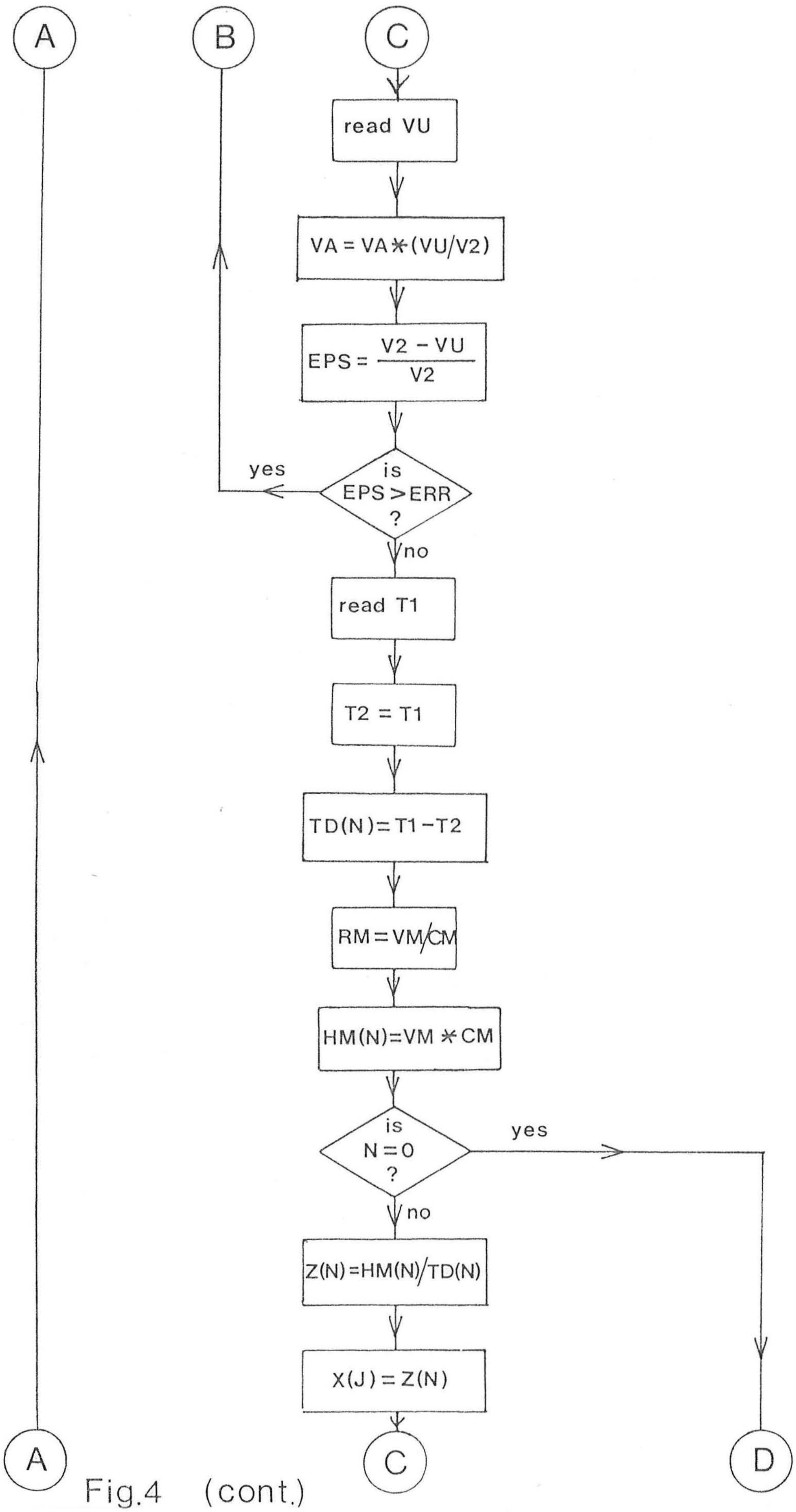
A
B
C
read VU
VA = VA*(VU/V2)
EPS = (V2 - VU)/V2
yes
is EPS > ERR ?
no
read T1
T2 = T1
TD(N)=T1-T2
RM=VM/CM
HM(N)=VM*CM
is N=0 ?
yes
no
Z(N)=HM(N)/TD(N)
X(J)=Z(N)
A
C
D

Fig.4 (cont.)

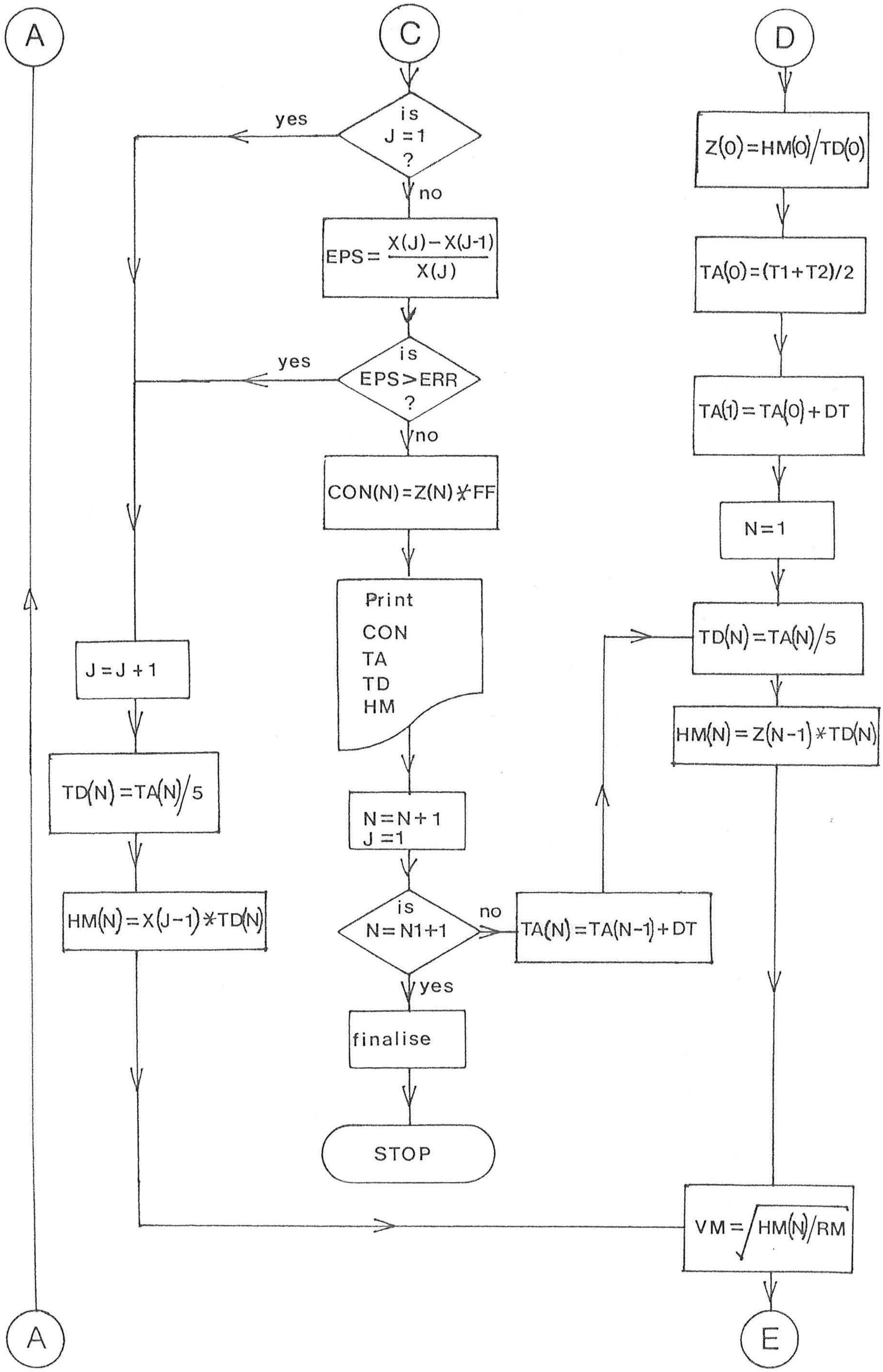
A
C
D
yes
is
J = 1
?
no
EPS = X(J) − X(J-1) / X(J)
yes
is
EPS > ERR
?
no
CON(N) = Z(N) * FF
Print
CON
TA
TD
HM
N = N + 1
J = 1
is
N = N1+1
no
yes
TA(N) = TA(N−1) + DT
finalise
STOP
J = J + 1
TD(N) = TA(N)/5
HM(N) = X(J−1) * TD(N)
Z(0) = HM(0)/TD(0)
TA(0) = (T1 + T2)/2
TA(1) = TA(0) + DT
N = 1
TD(N) = TA(N)/5
HM(N) = Z(N−1) * TD(N)
VM = √(HM(N)/RM)
A
E

Fig. 4 (cont.)

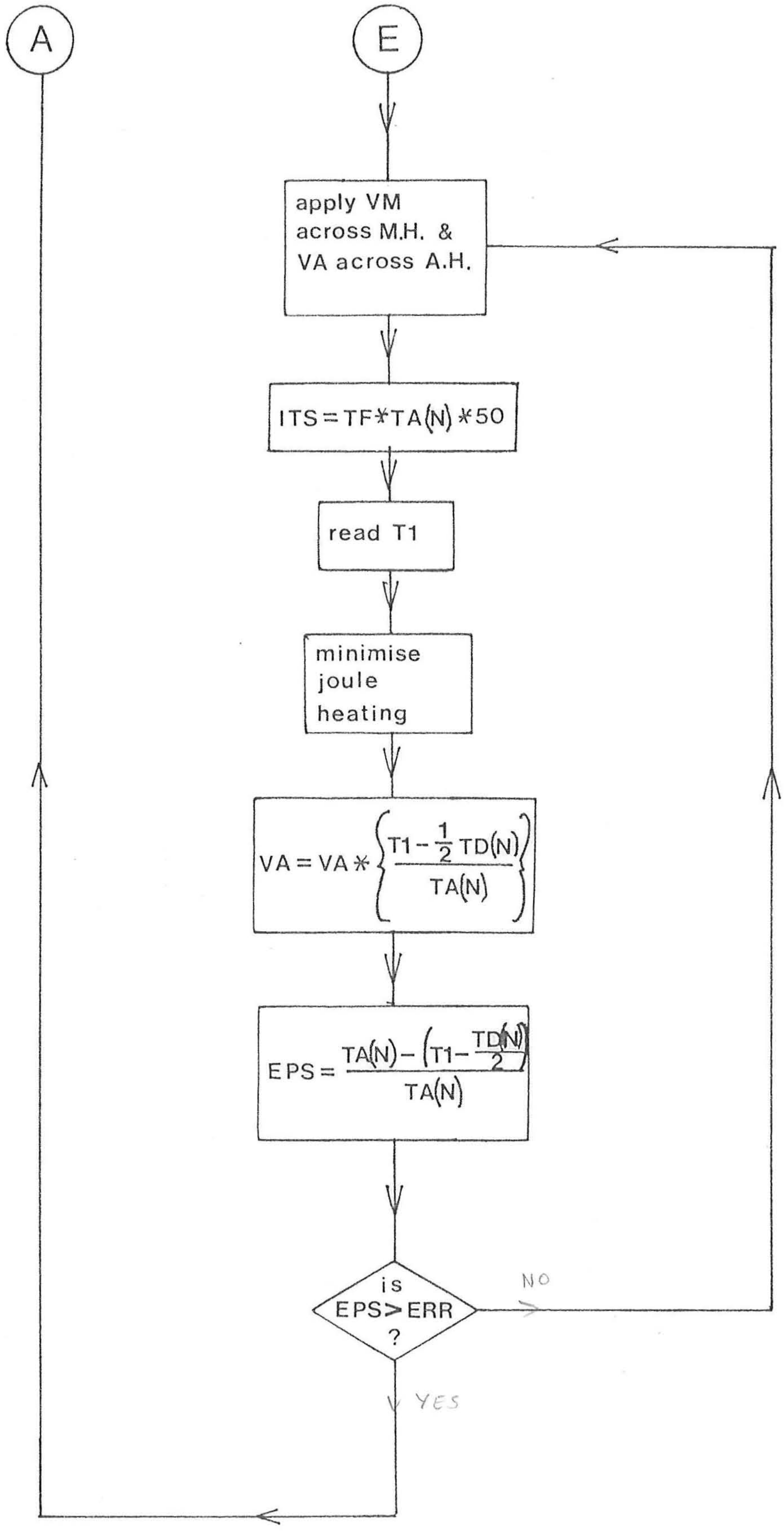
A
E
apply VM across M.H. & VA across A.H.
ITS=TF*TA(N)*50
read T1
minimise joule heating
VA = VA * {(T1 - 1/2 TD(N)) / TA(N)}
EPS = (TA(N) - (T1 - TD(N)/2)) / TA(N)
is EPS>ERR ?
NO
YES

Fig.4 (cont.)

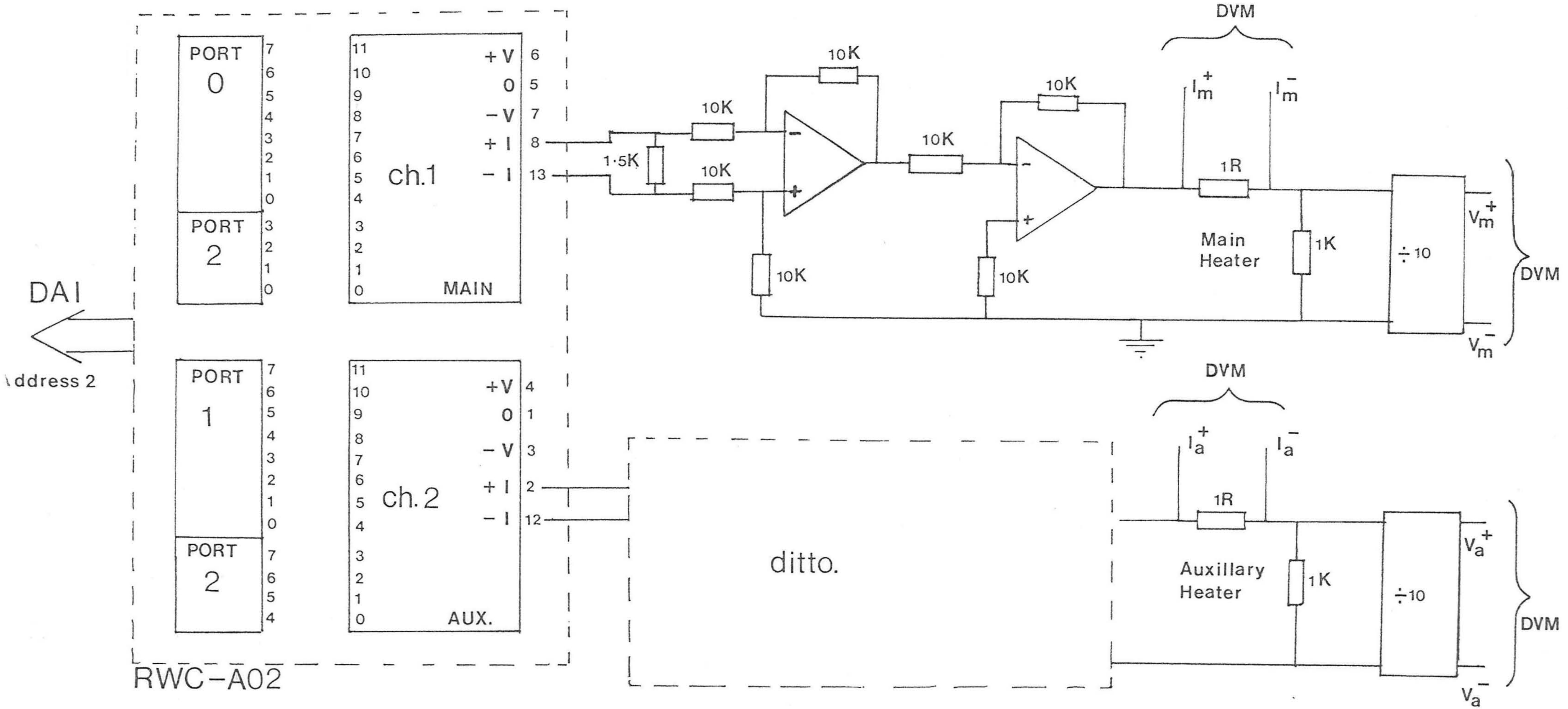

Fig. 5 Heater Interface

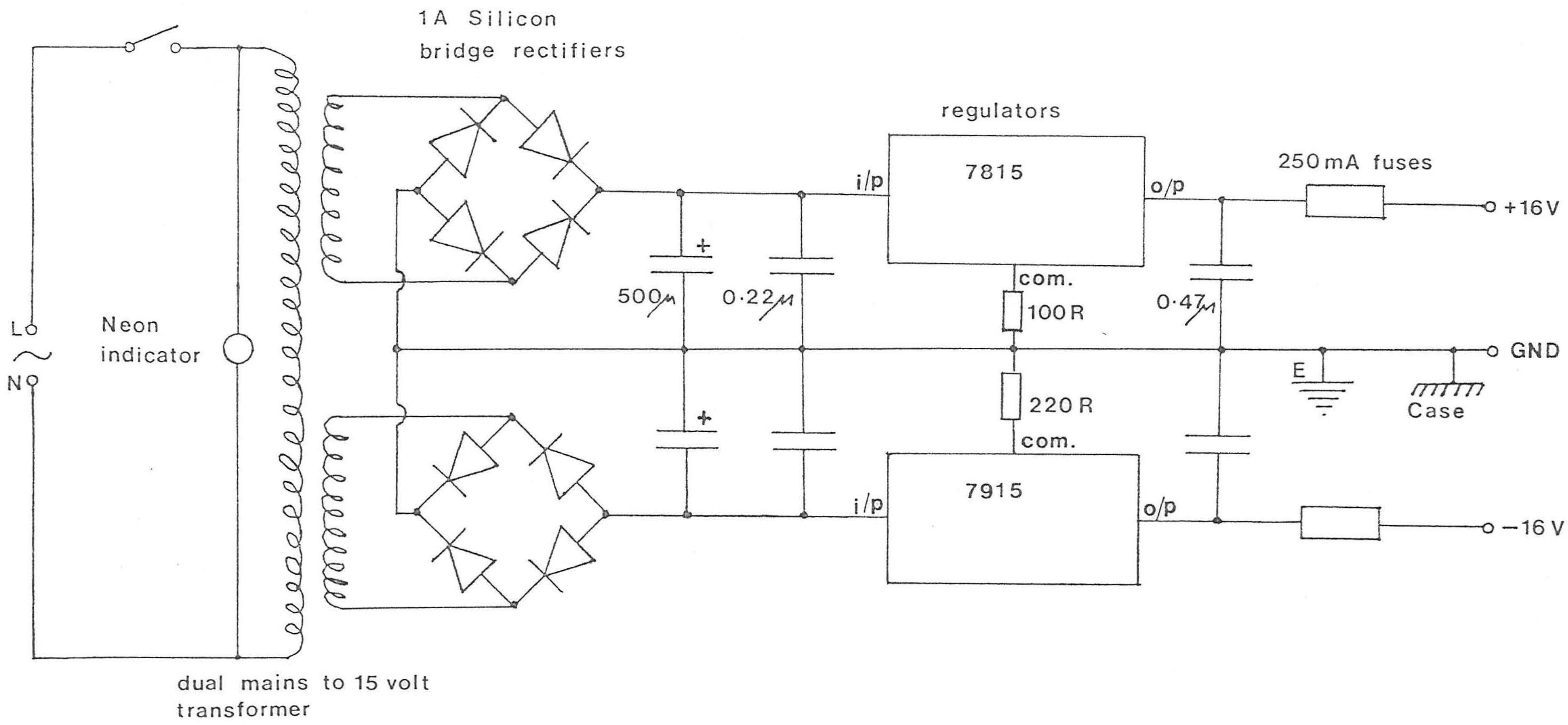

Fig.6 ±16V Supply

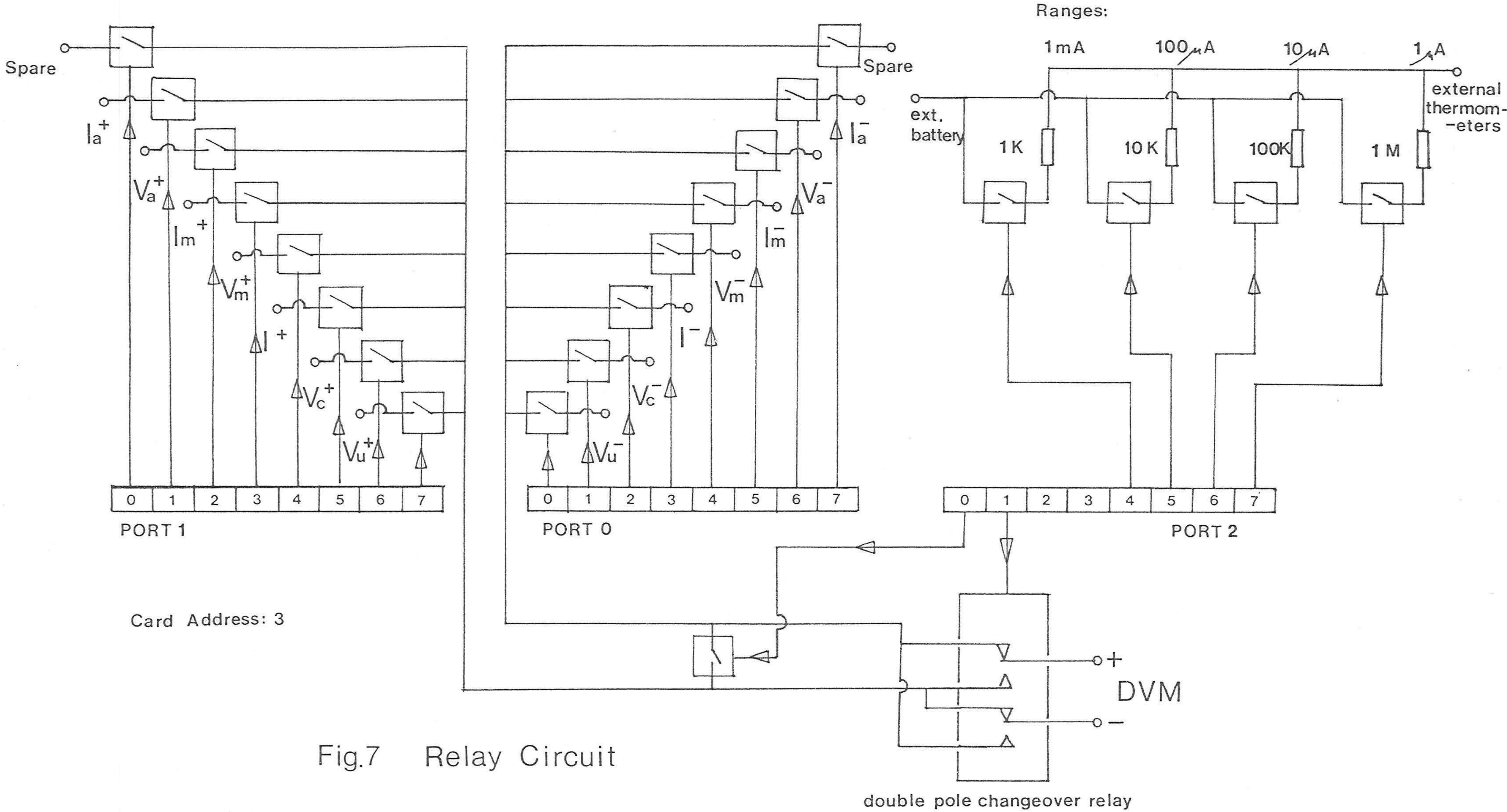

Fig.7 Relay Circuit

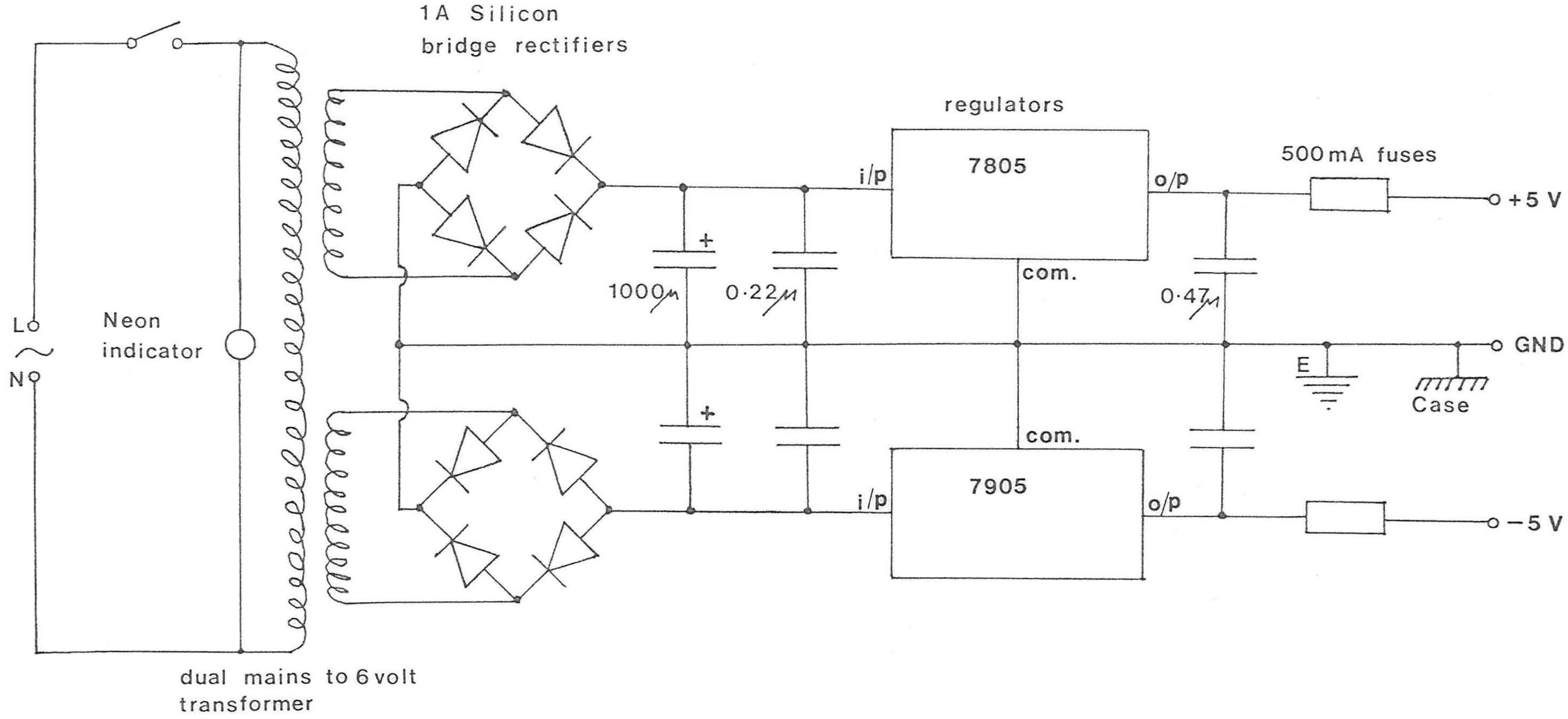

Fig. 8 5V Supply

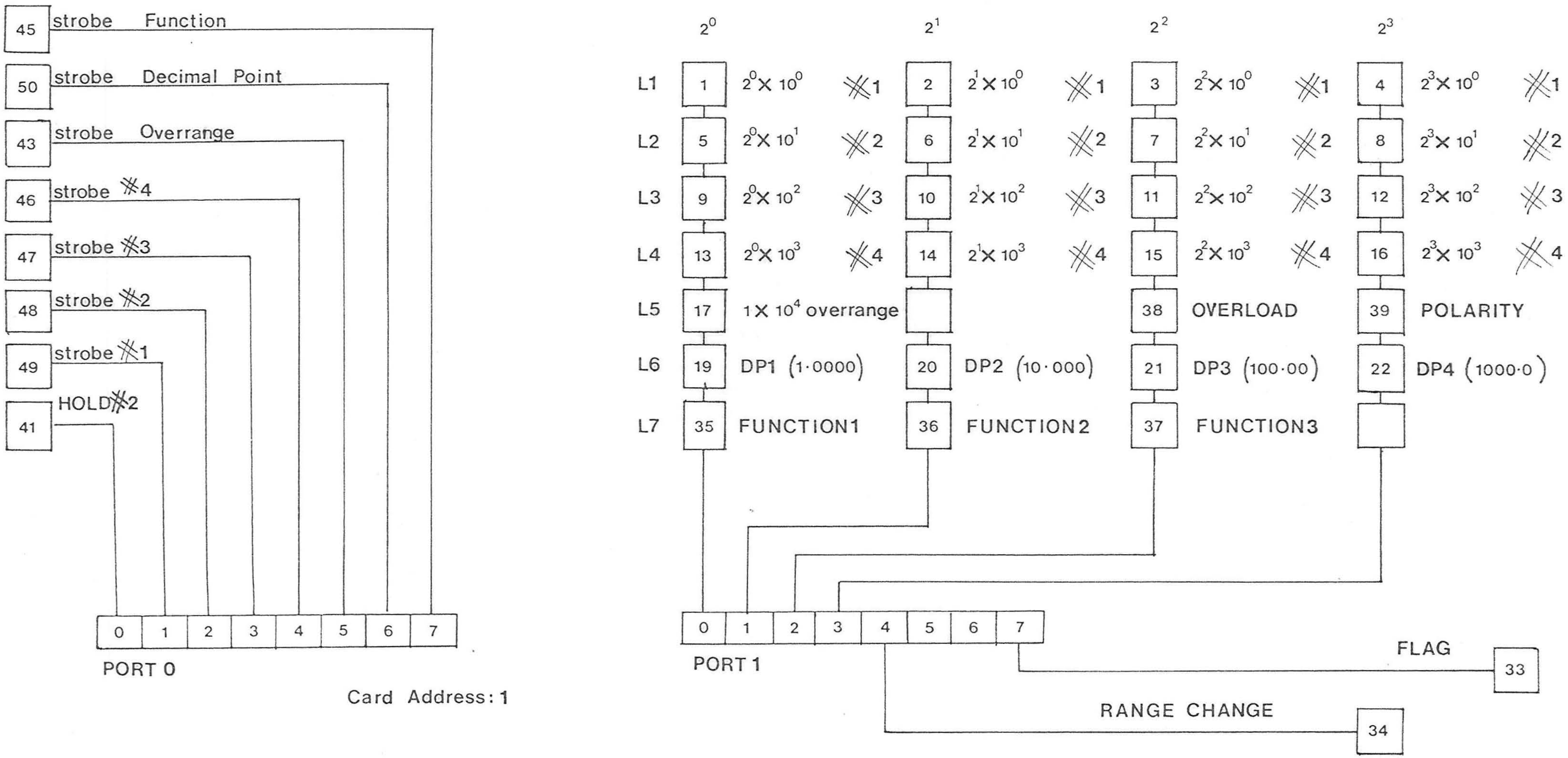

Fig.9 DVM Interface

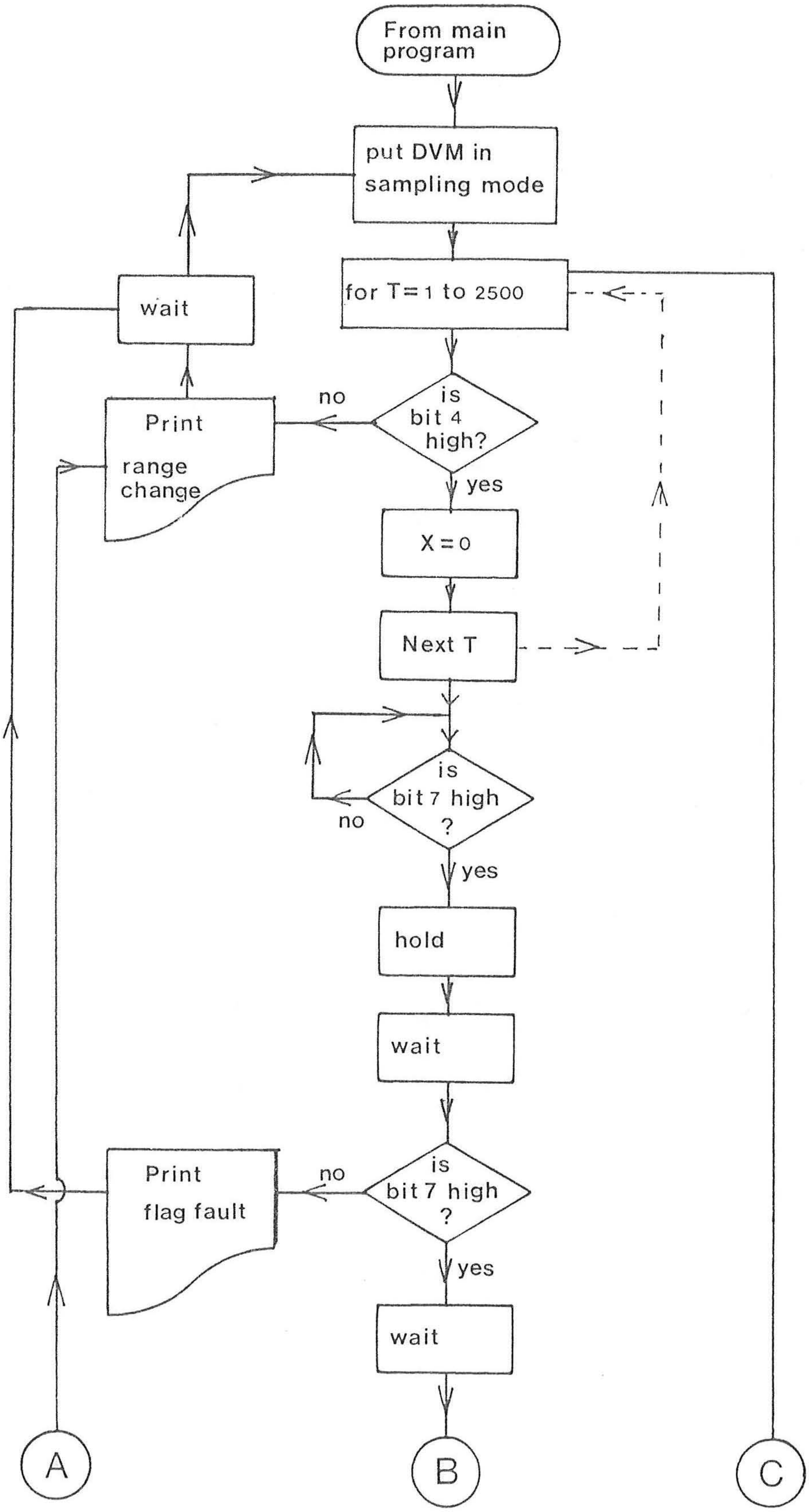

Fig.10 Flow chart of DVM subroutine

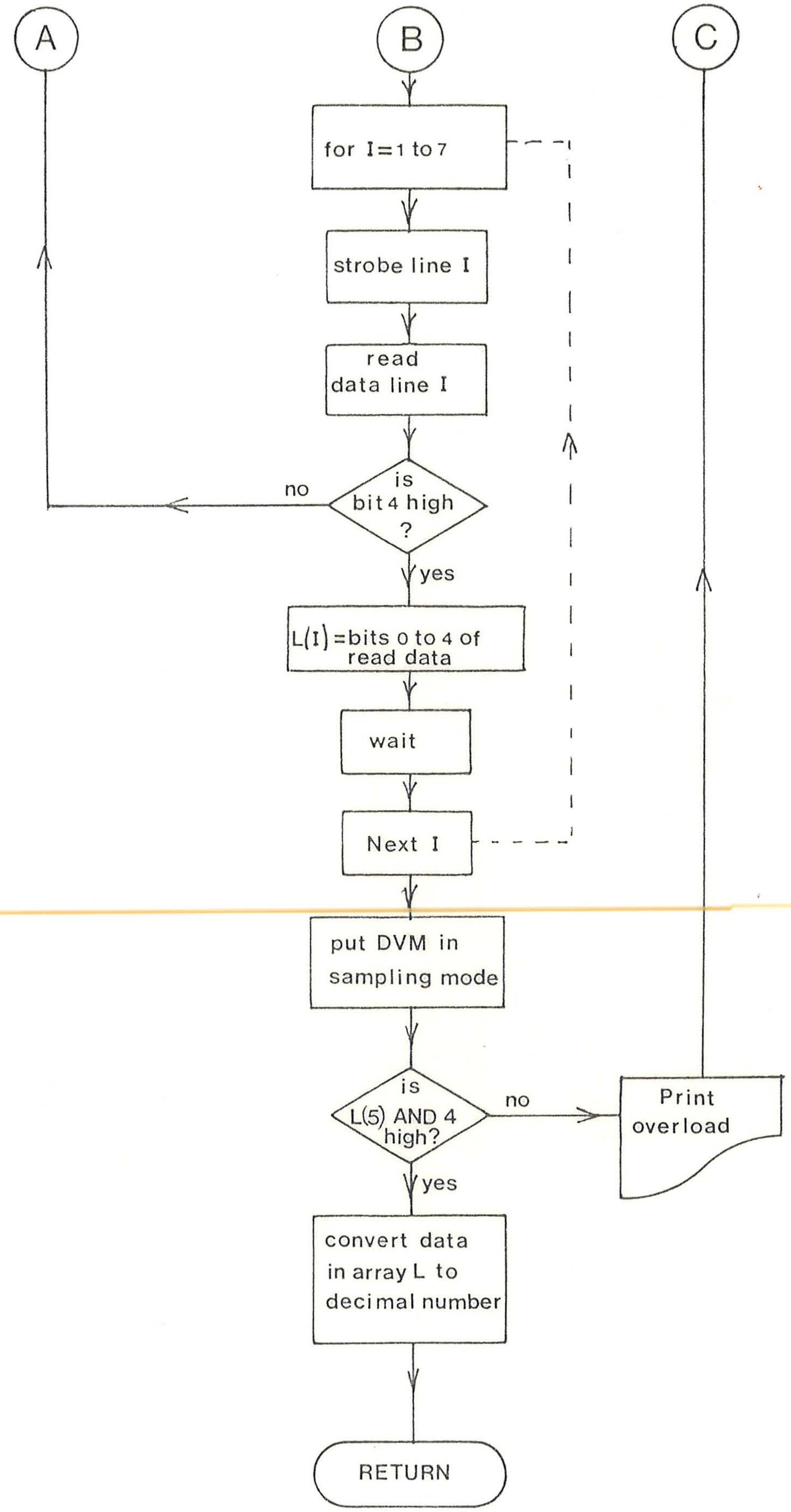
A
B
C
for I=1 to 7
strobe line I
read data line I
is bit 4 high ?
no
yes
L(I) =bits 0 to 4 of read data
wait
Next I
put DVM in sampling mode
is L(5) AND 4 high?
no
Print overload
yes
convert data in array L to decimal number
RETURN

Fig.10 (cont.)

VMS	Starting (guess) main heater voltage (volts)
VAS	Starting (guess) aux heater voltage (volts)
DT	Temperature increment (Kelvin)
N1	Number of data points
FF	Form factor, $\frac{\Delta x}{A}$ (metres^{-1})
ITS	Stabilisation time (seconds)
ERR	Allowable error
VM	Main heater voltage (volts)
VA	Auxillary heater voltage (volts)
N	Number of thermal conductivity readings (N = 0 for first crude guess)
J	No. of iterations for a particular N (J = 1 to start with)
VC	Voltage across calibrated thermom. (volts)
Vu,V2	Voltage across uncalibrated thermom. (volts) (Vu is varied to match V2)
CC	Current through thermometers (Amps)
R	Resistance of calibrated thermometer (ohms)
T1	Upper temperature (Kelvin) (read by cal. thermom.)
T2	Lower temperature (Kelvin)
TD	This is (T1 - T2)
TA	This is (T1 + T2)/2
CON	Thermal conductivity ($Wm^{-1}K^{-1}$)
Z	This is CON/FF
EPS	A discriminant for checking error
RM	Main heater resistance (ohms)
HM	Rate of heat supplied by M.H. (Joules/sec)

TABLE 1 - List of symbols used in flow chart. (Same as those in program.)

The RWC-A02 is connected to external circuitry by means of a D-type connector and multicore coloured cable.

Pin No		Signal	Wire Colour
1	Ch.2	0 volts (analogue)	Blue
2	Ch.2	Current +	Green
3	Ch.2	Voltage -	Red
4	Ch.2	Voltage +	Purple
5	Ch.1	0 volts (analogue)	Grey
6	Ch.1	Voltage +	Orange
7	Ch.1	Voltage -	Yellow/Red
8	Ch.1	Current +	White/Red
9		+5 Volts	Brown
10		+12 Volts	Orange/Brown
11		0 volts (logical)	Pink
12	Ch.2	Current -	Black
13	Ch.1	Current -	Yellow/Green
14		-15 Volts	Turquoise
15		+15 Volts	Yellow

TABLE 2 - Connections to RWC-A02

PORT/BIT	STRIP SOCKET PIN NUMBER	WIRE COLOUR	RELAY
0/0	25	Red	Vu-
0/1	24	Brown	VC-
0/2	23	Black	I-
0/3	22	White	VM-
0/4	21	Grey	IM-
0/5	20	Violet	VA-
0/6	19	Blue	IA-
0/7	18	Green	Spare
1/0	9	Grey	Spare
1/1	8	Violet	IA+
1/2	7	Blue	VA+
1/3	6	Green	IM+
1/4	5	Yellow	VM+
1/5	4	Orange	I+
1/6	3	Red	VC+
1/7	2	Brown	Vu+
2/0	10	White	D.P.C.
2/1	11	Black	DVM short
2/2	-	-	-
2/3	-	-	-
2/4	14	Brown	1mA select
2/5	15	Red	100μA select
2/6	16	Orange	10 μA select
2/7	17	Yellow	1 μA select
-	28	Orange	(Ground)

TABLE 3 - Interface Card to Relay Board Connections

DVM		Ribbon Cable	Strobe/Read Card	
Amphenol Pin No.	Function	Colour	Strip Con Pin No.	Port/Bit
-	-	-	1 (+5V)	-
1	$2^0 \times 10^0$ Data#1	Black	2	1/0
2	$2^1 \times 10^0$ Data#1	White	3	1/1
3	$2^2 \times 10^0$ Data#1	Grey	4	1/2
4	$2^3 \times 10^0$ Data#1	Violet	5	1/3
5	$2^0 \times 10^1$ Data#2	Blue	2	1/0
6	$2^1 \times 10^1$ Data#2	Green	3	1/1
7	$2^2 \times 10^1$ Data#2	Yellow	4	1/2
8	$2^3 \times 10^1$ Data#2	Orange	5	1/3
9	$2^0 \times 10^2$ Data#3	Red	2	1/0
10	$2^1 \times 10^2$ Data#3	Brown	3	1/1
11	$2^2 \times 10^2$ Data#3	Black	4	1/2
12	$2^3 \times 10^2$ Data#3	White	5	1/3
13	$2^0 \times 10^3$ Data#4	Grey	2	1/0
14	$2^1 \times 10^3$ Data#4	Violet	3	1/1
15	$2^2 \times 10^3$ Data#4	Blue	4	1/2
16	$2^3 \times 10^3$ Data#4	Green	5	1/3
17	1×10^4 overrange	Yellow	2	1/0
18	NC	Not connected	-	-
19	DP1 (1.000)	Orange	2	1/0
20	DP2 (10.00)	Red	3	1/1
21	DP3 (100.0)	Brown	4	1/2
22	DP4 (1000.0)	Black	5	1/3
23	HOLD	Not connected	-	-
24	FLAG RESET	Not connected	-	-
25	NC	Not connected	-	-

TABLE 4 - DVM to Strobe/Read Card Connections

DVM		Ribbon Cable	Strobe/Read Card	
Amphenol Pin No.	Function	Colour	Strip Con. Pin No.	Port/Bit
26	NC	Not connected	-	-
27	Output L_O	White	28 (GND)	-
28	NC	Not connected	-	-
29	CLOCK	Not connected	-	-
30	Count Interval	Not connected	-	-
31	NC	Not connected	-	-
32	$\overline{\text{FLAG}}$	Not connected	-	-
33	FLAG	Grey	9	1/7
34	Range Change	Violet	6	1/4
35	Function 1	Blue	2	1/0
36	Function 2	Green	3	1/1
37	Function 3	Yellow	4	1/2
38	Overload	Orange	4	1/2
39	Polarity	Red	5	1/3
40	Trigger	Not connected	-	-
41	HOLD#2	Brown	18	2/0
42	NC	Not connected	-	-
43	Strobe overrange	Black	23	2/5
44	Strobe Flag	White	28 (GND)	-
45	Strobe Function	Grey	25	2/7
46	Strobe Data#4	Violet	22	2/4
47	Strobe Data#3	Blue	21	2/3
48	Strobe Data#2	Green	20	2/2
49	Strobe Data#1	Yellow	19	2/1
50	Strobe Dec.Pt.	Orange	24	2/6

TABLE 4 (continued)

APPENDIX I

C. C.

CRYOGENIC CALIBRATIONS LTD

Your Ref. Our Ref. PITCHCOTT, Nr. AYLESBURY, BUCKINGHAMSHIRE, HP22 4HT, ENGLAND

TEL: 029-664 259 (WHITCHURCH 259)

CALIBRATION NUMBER CCG 520

Thermometer Specification: CryoCal Inc., Type CR1000
No. 6149

Temperature (Kelvin)	Resistance (ohms)
1.498	9,215
1.603	7,835
1.798	6,099
2.021	4,756
2.200	4,005
2.417	3,335
2.605	2,898
2.820	2,508
3.011	2,232.8
3.208	2,000.8
3.417	1,796.3
3.602	1,643.0
3.796	1,505.7
3.998	1,380.8
4.205	1,269.7
4.447	1,157.5
4.629	1,083.5
5.010	949.7
5.423	830.4
5.783	743.7
6.205	657.3
6.607	587.8
7.049	522.75
7.476	469.34
7.995	414.44
8.503	369.42
9.010	331.57
9.504	300.14
10.003	272.89
10.500	249.58
11.036	227.92
12.068	194.31
13.015	170.50
13.980	151.18
15.081	133.62

C. C. CRYOGENIC CALIBRATIONS LTD

Your Ref. Our Ref. PITCHCOTT, Nr. AYLESBURY, BUCKINGHAMSHIRE, HP22 4HT, ENGLAND

TEL: 029-664 259 (WHITCHURCH 259)

CALIBRATION NUMBER CCG 520

Temperature (Kelvin)	Resistance (ohms)
16.001	121.640
17.117	109.634
17.991	101.657
18.976	93.886
20.035	86.671
22.537	73.056
24.955	63.077
27.549	54.718
30.185	47.979
33.039	42.127
35.177	38.497
37.669	34.909
40.284	31.7340
45.618	26.6898
50.249	23.4141
54.877	20.8576
60.240	18.5469
65.019	16.9202
70.252	15.4845
75.582	14.3053
80.475	13.4166
85.894	12.6018
90.620	12.0076
95.696	11.4676
100.714	11.0158
125.781	9.5873

The temperatures were obtained from germanium, rhodium-iron and platinum thermometers whose own calibrations are accurate to $\pm$ .005K of the IPTS (68) down to 20K. Below 20K, the scale has been obtained from a National Physical Laboratory gas thermometer related to the boiling point of hydrogen using the IPTS (68) value of 20.28K. The scale is probably 2.5×10^{-4} x T K in excess of thermodynamic temperature. To obtain the T_{58} Helium Vapour Pressure Scale subtract .0019 x T K from the given temperature.

The above calibration should be accurate to $\pm$ .008K or $\pm$ .0005 ohms. With suitable interpolation procedures there are sufficient points to obtain an accuracy including interpolation of $\pm$ .01K up to 40K and $\pm$ .015K up to 100K.

Checked.....[signature].....

APPENDIX II

```
1       REM **************************************************
2       REM
3       REM :  CONTROL PROGRAM FOR THERMAL CONDUCTIVITY MEASUREMENTS
4       REM :               (4.2 to 100 Kelvin)
5       REM :     Derek Abbott, final year project 1981/82,
6       REM :    Dept. of Physics, Loughborough University.
7       REM
8       REM ***************************************************
9       REM
10      OUT #13,130:OUT #23,128:OUT #33,128:REM :SET COMMAND REGISTERS
20      OUT #10,255:REM :PUT DVM IN SAMPLING MODE
30      OUT #20,255:OUT #21,255:OUT #22,255:REM :SET HEATERS TO ZERO
40      OUT #31,0:OUT #30,0:REM :LEAVE MAIN RELAYS OPEN
50      OUT #32,130:REM :SHORT DVM & SELECT LOWEST THERMOM. CURRENT RANGE
60      CLEAR 32767
70      PRINT "I/P  MHV,AHV,TEMP.INCREM.,NO. OF PTS.,FORM FAC.,TIME,TIM.FAC."
80      INPUT VMS,VAS,DT,N1%,FF,ITS%,TF
90      DIM IS%(7.0),TD(254.0),HM(254.0),Z(254.0),TA(254.0),X(254.0)
100     DIM Y(254.0),Q(2.0),L%(7.0),F(2.0,70.0),XX(2.0,5.0),CON(254.0)
110     N%=0:VM=VMS:VA=0.0:J%=1:NRR%=-1:L%=1
120     NR%=130:ITS%=ITS%*50:ERR=5E-3:NIL%=0:UNO%=1:TWO%=2
130     REM :SET UP STROBE ARRAY
140     FOR I%=1 TO 7
150     L%=2*L%:IS%(I%)=254-L%
160     NEXT I%
165     GOSUB 4500:REM :READ CALIBRATION DATA
170     VA=0.0
180     GOSUB 1000:REM :SET HEATER VOLTAGES
185     IF NRR%=NR% GOTO 250
190     IR%=6:GOSUB 1500:REM :READ VOLTAGE ON CAL,THERMOM.
200     VC=M
210     IR%=5:GOSUB 1500:REM :READ CURRENT ON THERMOM.
220     CC=M:R=VC/CC
230     GOSUB 2000:REM :CHECK FOR JOULE HEATING
240     NR%=NRR%:GOTO 185
250     GOSUB 4000:REM :LEGENDRE FIT
260     T1=T
270     IR%=7:GOSUB 1500:REM :READ VOLTAGE ON UNCAL. THERMOM.
280     VU=M:V2=VU
290     IR%=4:GOSUB 1500:REM :READ MH VOLTAGE
300     VM=M
310     IR%=3:GOSUB 1500:REM :READ MH CURRENT
320     CM=M:IVM%=0:GOSUB 1000:REM :PUT MH OFF
330     IF N%>NIL% GOTO 350
335     VA=VAS
350     GOSUB 1000:REM :SET AH VOLTAGE
360     IR%=7:GOSUB 1500:REM :READ UNCAL.THERMOM. VOLTAGE
370     VU=M:VA=VA*(VU/V2):EPS=(V2-VU)/V2
380     IF EPS>ERR GOTO 350
390     IR%=6:GOSUB 1500:REM :READ CAL. THERMOM. VOLTAGE
```

```
400   VC=M
410   IR%=5:GOSUB 1500:REM :READ THERMOM. CURRENT
420   CC=M:R=VC/CC:GOSUB 4000:REM :LEGENDRE FIT
430   T2=T:TD(N%)=T1-T2:RM=VM/CM:HM(N%)=VM*CM
440   IF N%<>NIL% GOTO 470
450   Z(NIL%)=HM(NIL%)/TD(NIL%):TA(NIL%)=(T1+T2)/2.0
460   TA(UNO%)=TA(NIL%)+DT:N%=1:GOTO 555
470   Z(N%)=HM(N%)/TD(N%):X(J%)=Z(N%)
480   IF J%=UNO% GOTO 730
490   EPS=(X(J%)-X(J%-UNO%))/X(J%)
500   IF EPS>ERR GOTO 730
510   CON(N%)=Z(N%)*FF
520   PRINT "CONDUCTIVITY","TEMP.","TEMP.DIFF.";"MH POWER"
530   PRINT CON(N%),TA(N%),TD(N%),HM(N%)
540   N%=N%+1:J%=1:IF N%=N1%+1 GOTO 745
550   TA(N%)=TA(N%-UNO%)+DT
555   TD(N%)=TA(N%)/5.0:HM(N%)=Z(N%-UNO%)*TD(N%)
560   VM=SQR(HM(N%)/RM)
570   NRR%=-1
580   GOSUB 1000:REM :SET HEATER VOLTAGES
590   ITS%=TF*TA(N%)*50.0:REM :UPDATE STABALISATION TIME
600   IR%=6:GOSUB 1500:REM :READ CAL.THERMOM. VOLTAGE
610   IF NRR%=NR% GOTO 670
620   VC=M
630   IR%=5:GOSUB 1500:REM :READ THERMOM. CURRENT
640   CC=M:R=VC/CC
650   GOSUB 2000:REM :CHECK FOR JOULE HEATING
660   NR%=NRR%:GOTO 610
670   GOSUB 4000:REM :LEGENDRE FIT
680   T1=T
690   VA=VA*((T1-TD(N%)/2.0)/TA(N%))
700   EPS=(TA(N%)-(T1-TD(N%)/2.0))/TA(N%)
710   IF EPS>ERR GOTO 580
720   NRR%=-1:GOTO 185
730   J%=J%+1:TD(N%)=TA(N%)/5.0
740   HM(N%)=X(J%-UNO%)*TD(N%):GOTO 560
745   REM :SET PORTS TO ORIGINAL STATE
746   OUT #10,255:OUT #20,255:OUT #21,255:OUT #22,255
747   OUT #31,0:OUT #30,0:OUT #32,130
750   STOP
997   REM
998   REM *********************************************
999   REM
1000  REM : SUBROUTINE TO SET HEATER VOLTAGES
1001  REM
1002  REM *********************************************
1003  REM
1005  BIT%=4095:VMMAX=15.0:VAMAX=15.0
1010  IVM%=(BIT%/VMMAX)*VM:IVA%=(BIT%/VAMAX)*VA
1020  IM%=(IVM% IXOR BIT%):IA%=(IVA% IXOR BIT%)
1030  I0%=(IM% IAND 4080) SHR 4:I1%=(IA% IAND 4080) SHR 4
1040  I2%=((IM% IAND 15)+240) IAND (((IA% IAND 15) SHL 4)+15)
1220  OUT #20,I0%:OUT #21,I1%:OUT #22,I2%
1230  RETURN
```

```
1497  REM
1498  REM *************************************************
1499  REM
1500  REM : SUBROUTINE TO SWITCH RELAYS AND TAKE
1501  REM : READINGS, CHECKING FOR STABILITY
1502  REM
1503  REM *************************************************
1504  REM
1510  IX%=0:JJ%=1:IRC%=7-IR%
1520  NR%=NR%-2:OUT #32,NR%:REM :OPEN RELAY THAT SHORTS DVM
1530  OUT #30,IR%:OUT #31,IRC%:REM :CLOSE RELAY PAIR TO MAKE MEASUREMENT
1535  WAIT TIME ITS%
1540  IX%=IX%+1
1550  GOSUB 3000:REM :READ DVM
1560  Y(IX%)=D
1570  WAIT TIME ITS%
1580  IF IX%=1 GOTO 1540
1590  EPS=(Y(IX%)-Y(IX%-UNO%))/Y(IX%)
1600  IF EPS>ERR GOTO 1540
1610  Q(JJ%)=Y(IX%)
1620  IF JJ%=TWO% GOTO 1660
1630  JJ%=2:IX%=0:NR%=NR%+1
1640  OUT #32,NR%:REM :SWITCH CHANGEOVER RELAY
1650  GOTO 1540
1660  M=(ABS(Q(UNO%))+ABS(Q(TWO%)))/2.0:REM :TAKE AVERAGE OF TWO READINGS
1670  NR%=NR%+1:REM :THIS IS TO RETURN NR% TO ITS SENT VALUE
1680  OUT #30,0:OUT #31,0:OUT #32,NR%
1690  RETURN
1997  REM
1998  REM *************************************************
1999  REM
2000  REM : SUBROUTINE TO MINIMISE JOULE HEATING IN THERMOMETERS
2001  REM
2002  REM *************************************************
2003  REM
2010  IF R<1200.0 GOTO 2030
2020  NRR%=130:GOTO 2110
2030  IF R>1000.0 GOTO 2020
2040  IF R<120.0 GOTO 2060
2050  NRR%=66:GOTO 2110
2060  IF R>100.0 GOTO 2050
2070  IF R<12.0 GOTO 2090
2080  NRR%=34:GOTO 2110
2090  IF R>10.0 GOTO 2080
2100  NRR%=18
2110  OUT #32,NRR%
2120  RETURN
```

```
2997  REM
2998  REM ***************************************************
2999  REM
3000  REM : SUBROUTINE TO READ DVM
3001  REM
3002  REM *****************************************************
3003  REM
3010  OUT #10,255
3020  FOR IT%=1 TO 2500
3030  IN%=INP(#11)
3040  IF ((IN% IAND 16)=16) THEN 3080
3050  PRINT "RANGE CHANGE"
3060  WAIT TIME 225
3070  GOTO 3010
3080  X=0.0
3090  NEXT IT%
3100  IN%=INP(#11)
3110  IF ((IN% IAND 128)=128) THEN 3130
3120  GOTO 3100
3130  OUT #10,254
3140  WAIT TIME 75
3150  IN%=INP(#11)
3160  IF ((IN% IAND 128)=128) THEN 3190
3170  PRINT "FLAG FAULT"
3180  GOTO 3060
3190  WAIT TIME 150
3200  FOR I%=1 TO 7
3210  IS%=IS%(I%):OUT #10,IS%:REM :DVM IS STROBED
3215  WAIT TIME 30:IN%=INP(#11):REM :DATA LINES ARE READ
3220  IF ((IN% IAND 16)=16) THEN 3240
3230  GOTO 3050
3240  L%(I%)=(IN% IAND 15):REM :STROBED DATA STORED
3250  WAIT TIME 12
3260  NEXT I%
3270  OUT #10,255
3280  IF ((L%(5.0) IAND 4.0)=0.0) THEN 3300
3290  PRINT "OVERLOAD":GOTO 3200
3300  L%=L%(1.0)+10.0*L%(2.0)+100.0*L%(3.0)+1000.0*L%(4.0):D=L%
3310  IF ((L%(5.0) IAND 1.0)=0.0) THEN 3330
3320  D=D+10000.0
3330  IF ((L%(5.0) IAND 8.0)=8.0) THEN 3350
3340  D=-D
3350  IF ((L%(6.0) IAND 1.0)=0.0) THEN 3370
3360  D=D*1E-4
3370  IF ((L%(6.0) IAND 2.0)=0.0) THEN 3390
3380  D=D*1E-3
3390  IF ((L%(6.0) IAND 4.0)=0.0) THEN 3410
3400  D=D*1E-2
3410  IF ((L%(6.0) IAND 8.0)=0.0) THEN 3425
3420  D=D*0.1
3425  ARG1%=(L%(7.0) IAND 1.0):ARG2%=(L%(7.0) IAND 2.0)
3430  IF ((ARG1%=1.0) AND (ARG2%=0.0)) THEN 3470
3440  IF ((ARG1%=0.0) AND (ARG2%=2.0)) THEN 3490
3450  PRINT "SCALE ERROR"
3460  GOTO 3020
3470  D=D*1E-3
3480  GOTO 3500
3490  D=D*1E-6
3500  RETURN
```

```
3997  REM
3998  REM ************************************************
3999  REM
4000  REM : SUBROUTINE TO FIND TEMP. USING LEGENDRE POLYNOMIAL FIT
4001  REM : ON RESISTANCE THERMOMETER CALIBRATION DATA
4002  REM
4003  REM ************************************************
4004  REM
4010  NN2%=0:IF R<F(UNO%,3.0*UNO%) THEN NN2%=1
4020  IF R>F(UNO%,NN1%-TWO%) THEN NN2%=NN1%-4
4030  IF NN2%<>NIL% GOTO 4060
4040  FOR I%=1 TO NN1%:IF F(UNO%,I%)<R THEN NN2%=I%-2
4050  NEXT I%
4060  FOR I%=1 TO 5:NN3%=NN2%+I%-1:XX(UNO%,I%)=F(UNO%,NN3%)
4070  XX(TWO%,I%)=F(TWO%,NN3%):NEXT I%
4080  L1=0.0:FOR I%=1 TO 5:L2=XX(TWO%,I%):FOR K%=0 TO 5
4090  IF K%=1 THEN GOTO 4110
4100  L3=(R-XX(UNO%,K%))/(XX(UNO%,I%)-XX(UNO%,K%)):L2=L2*L3
4110  NEXT K%
4120  L1=L1+L2:NEXT I%:T=L1:RETURN
4497  REM
4498  REM ************************************************
4499  REM
4500  REM : SUBROUTINE TO READ CALIBRATION DATA
4501  REM
4503  REM ************************************************
4504  REM
4510  NN1%=0
4520  NN1%=NN1%+1:READ F(1.0,NN1%),F(2.0,NN1%)
4530  IF F(1.0,NN1%)<>NIL% GOTO 4520
4540  NN1%=NN1%-1
4560  RETURN
```

```
4997  REM
4998  REM ***********************************************
4999  REM
5000  REM : CALIBRATION DATA
5001  REM
5002  REM **********************************************
5003  REM
5150  DATA 9.5873,125.781,11.0158,100.714
5151  DATA 11.4676,95.696,12.0076,90.62
5152  DATA 12.6018,85.894,13.4166,80.475
5153  DATA 14.3053,75.582,15.4845,70.252
5154  DATA 16.9202,65.019,18.5469,60.24
5155  DATA 20.8576,54.877,23.4141,50.249
5156  DATA 26.6898,45.618,31.734,40.284
5157  DATA 34.909,37.669,38.497,34.177
5200  DATA 42.127,33.039,47.979,30.185
5210  DATA 54.718,27.549,63.077,24.955
5220  DATA 73.056,22.537,86.671,20.035
5230  DATA 93.886,18.976,101.657,17.991
5240  DATA 109. 634,17.117,121.64,16.001
5250  DATA 133.62,15.081,151.18,13 .98
5260  DATA 170.5,13.015,194.31,12.068
5270  DATA 227.92,11.036,249.58,10.5
5280  DATA 272.89,10.003,300.14,9.504
5290  DATA 331.57,9.01,369.42,8.503
5300  DATA 414.44,7.995,469.34,7.476
5310  DATA 522.75,7.049,587.8,6.607
5320  DATA 657.3,6.205,743.7,5.783
5330  DATA 830.4,5.423,949.7,5.01
5340  DATA 1083.5,4.629,1157.5,4.447
5350  DATA 1269.7,4.205,1380.8,3.998
5360  DATA 1505.7,3.796,1643,3.602
5370  DATA 1796.3,3.417,2000.8,3.208
5380  DATA 2232.8,3.011,2508,2.820
5390  DATA 2898,2.605,3335,2.417
5400  DATA 4005,2.2,4756,2.021,6099,1.798
5410  DATA 7885,1.603,9215,1.498,0,0
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Phys. Lett. Vol 21 pp 241-243

Cryostat $4° \to 300°K$ ✓ goodie
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Cadmium Sulfide
Phys Rev Vol. 179 pp 722-730
* Debye Integral &
assuming phonon scattering
by dislocations & impurities

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