Transducer Kit - Temperature Measurement

TK2942-2

Feedback

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TRANSDUCERS KIT
TK2942

Part 2 – Temperature Measurement

Feedback

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THE HEALTH AND SAFETY AT WORK ACT 1974

We are required under the Health and Safety at Work Act 1974, to make available to users of this equipment certain information regarding its safe use.

The equipment, when used in normal or prescribed applications within the parameters set for its mechanical and electrical performance, should not cause any danger or hazard to health or safety if normal engineering practices are observed and they are used in accordance with the instructions supplied.

If, in specific cases, circumstances exist in which a potential hazard may be brought about by careless or improper use, these will be pointed out and the necessary precautions emphasized.

While we provide the fullest possible user information relating to the proper use of this equipment, if there is any doubt whatsoever about any aspect, the user should contact the Product Safety Officer at Feedback Instruments Limited, Crowborough.

This equipment should not be used by inexperienced users unless they are under supervision.

We are required by European Directives to indicate on our equipment panels certain areas and warnings that require attention by the user. These have been indicated in the specified way by yellow labels with black printing, the meaning of any labels that may be fixed to the instrument are shown below:

CAUTION - RISK OF DANGER	CAUTION - RISK OF ELECTRIC SHOCK	CAUTION - ELECTROSTATIC SENSITIVE DEVICE

Refer to accompanying documents

PRODUCT IMPROVEMENTS

We maintain a policy of continuous product improvement by incorporating the latest developments and components into our equipment, even up to the time of dispatch.

All major changes are incorporated into up-dated editions of our manuals and this manual was believed to be correct at the time of printing. However, some product changes which do not affect the instructional capability of the equipment, may not be included until it is necessary to incorporate other significant changes.

COMPONENT REPLACEMENT

Where components are of a 'Safety Critical' nature, i.e. all components involved with the supply or carrying of voltages at supply potential or higher, these must be replaced with components of equal international safety approval in order to maintain full equipment safety.

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Any component may be ordered direct from Feedback or its agents by quoting the following information:

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2. Component value
3. Component reference
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Components can often be replaced by alternatives available locally, however we cannot therefore guarantee continued performance either to published specification or compliance with international standards.

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Should this equipment be used outside the classroom, laboratory study area or similar such place for which it is designed and sold then Feedback Instruments Ltd hereby states that conformity with the protection requirements of the European Community Electromagnetic Compatibility Directive (89/336/EEC) may be invalidated and could lead to prosecution.

This equipment, when operated in accordance with the supplied documentation, does not cause electromagnetic disturbance outside its immediate electromagnetic environment.

CONTENTS

NOTES

ASSIGNMENTS

The following assignments can be carried out using the TK2941M Measurements Package and the TK2941H Heat Transducers Kit:

18 The Heat Bar – Familiarisation

19 The Thermocouple

20 The Thermistor

21 Resistance Thermometry

22 ON-OFF Temperature Control

23 Continuous Temperature Control

THE HEAT BAR – FAMILIARISATION — ASSIGNMENT 18

CONTENT

The heat bar is described and its method of use is investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	–	Heat Bar
1	–	Thermometer
1	–	Calibration Tank

PRELIMINARY PROCEDURE

Check that the supply voltage selector on the Heat Bar Control Box is set to the correct value for your supply line.

To change the setting, if necessary, remove the two screws holding the locking plate, slide the switch to the correct position and replace the plate, aligning the slot to show the voltage setting.

Connect a suitable mains plug to the line connector cable, observing the following colour coding:

Line	Brown
Neutral	Blue
Earth	Green/Yellow

PRACTICALS

18.1 Heat-up Time

18.2 Heat Distribution

THE HEAT BAR – FAMILIARISATION — ASSIGNMENT 18

OBJECTIVES

When you have completed this assignment you will:

- Know how to use the heat bar.
- Have produced a calibration curve showing the temperature distribution along the bar.
- Recognise the terms thermal time constant and thermal conduction lag.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand how heat may be distributed by conduction, convection and radiation.
- Understand the term 'time constant' as applied to reactive components eg capacitive-resistive circuits.

INTRODUCTION

Temperature Scales

Temperature is as everyone knows a measure of hotness. Together with a measure of 'thermal mass' of a body it gives an indication of the total thermodynamic energy that body contains.

There are many scales for the comparison of temperature, the most important ones, with their corresponding values for melting ice and boiling water (which are common reference temperatures) being given in the table below.

Scale	Melting Ice	Boiling Water
Celsius (Also called Centigrade)	0°C	100°C
Fahrenheit	32°F	212°F
Kelvin (Absolute scale)	273°K	373°K

You will see that the Celsius and Kelvin scales have equal sized degrees but that the Kelvin starts at the 'absolute zero' temperature of 0°K (which is -273°C). The Fahrenheit scale has smaller degrees since there are 180 of them to 100 of the °C or °K. In this manual we shall refer only to degrees Celsius.

Temperature Measurement

Temperature is measured by observing one or other of its physical effects upon various materials. Some of the most commonly used effects are listed below with examples of their use and other comments.

The table is by no means comprehensive; there are other methods based on chemical changes, changes of physical form (melting and boiling) and on colour change, to name but a few.

In the following assignments we shall study most of the effects in the table, excluding only optical pyrometry which needs very high temperature sources.

Although the subject will arise again in various places in the assignments, it is worth noting here that the practical application of different temperature measuring methods is very dependent upon the type of access that is possible in individual circumstances, viz:

Immersion in a homogeneous gas or liquid
Surface contact with a solid
No contact (implying measurement only by radiation)

The Heat Bar – Familiarisation — Assignment 18

Effect	Example	Comment
Expansion of solid or liquid	Mercury thermometer Bimetal thermostat	Immersion measurements
Thermoelectric effect (Seebeck)	Thermocouple	Good for surface measurement – fast acting
Variation of resistance (temp. coefficient of resistance)	Platinum resistance thermometer (+) Thermistor (–)	Temperature coefficient may be positive or negative
Thermomagnetic effect (Curie)	Thermostats and safety devices	On-off control
Radiation of electro-magnetic energy	Optical pyrometers for furnaces, etc.	High temperature measurement

The heat bar is a means by which a range of temperatures can be established. It is illustrated in fig 5.18.1.

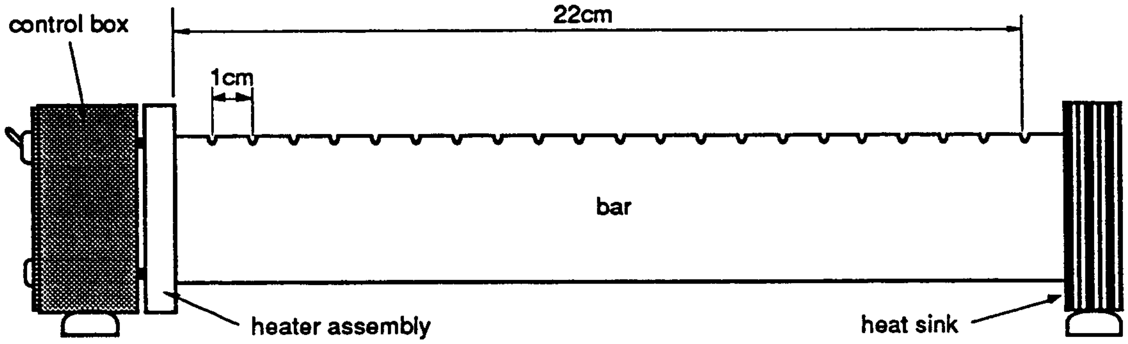


Fig 5.18.1 The heat bar assembly

The heat bar contains three heating elements, two of which are used in series or parallel to suit 220V or 110V line voltages respectively. The third 'aux heater' element is a low-power one separately terminated in two taper sockets on the control box panel, and it will be used in later assignments, driven from a power amplifier, to superimpose a small temperature increase for temperature control studies.

The bar itself conveys heat by conduction from the heater to the heat sink. It is marked off by notches at 1cm intervals for ease of positioning the various transducers along it.

The heat sink conveys heat away from the bar by convection to the surrounding air. Thus the cool end of the bar is only a little above the room temperature.

Question 18.1 ***What temperature pattern do you expect to be eventually established in the bar when the heater is switched on?***

The object of the heat bar is to provide a fairly wide range of temperatures simultaneously; by heating one end and keeping the other near room temperature we expect to set up temperatures which steadily decrease along the length of the bar.

Question 18.2 ***Will this pattern be established immediately upon switching on?***

Of course it will not. A kettle does not boil as soon as it is switched on. The speed with which the bar heats up will depend upon the rate at which energy is being injected (the power of the heater) as well as the 'thermal inertia' of the bar and other metal parts.

In the Practicals you are about to do you will discover how long the bar takes to reach a state of 'thermal equilibrium' (steady temperature) and also what maximum and minimum temperatures it produces.

PRACTICAL 18.1

Heat-up Time

Remove the mercury-in-glass thermometer from its plastic case and with it measure and record the room temperature.

Now look at the calibration tank; this has a white plastic cap with two holes in it. The smaller hole will not be used at present and the larger one is to accept the thermometer.

Remove the cap and fill the tank with water up to approximately 16mm (about 5/8in) from the top. If you look at the back of the thermometer you will see that it is marked '30mm Immersion'. This is the depth of immersion for which it was calibrated and should be adhered to for the most accurate measurement. If the water level is as suggested and the thermometer is inserted into the cap until the top surface is at the 1°C mark you should have about the correct immersion depth without having:

More water than needed

The thermometer touching the bottom.

Question 18.3 ***Why are both these conditions desirable?***

If the thermometer is loose in its hole you can stop it slipping down by fitting a narrow rubber sleeve or band around the stem above the cap. Fig 5.18.2 shows how the tank should be.

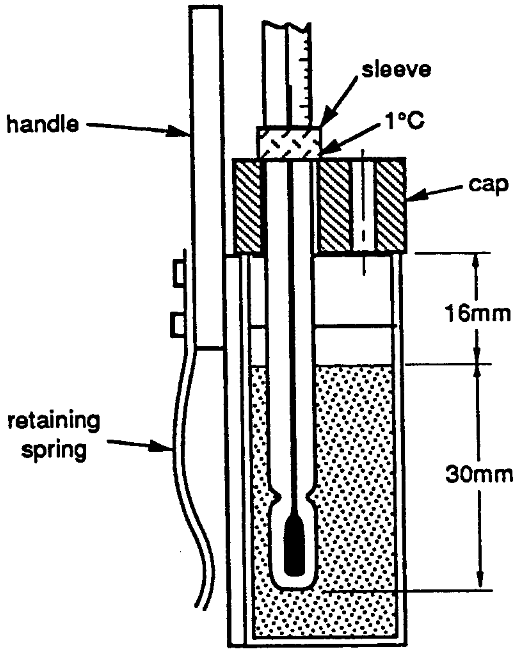


Fig 5.18.2 Calibration tank

Mount the tank on the heat bar centrally over notch Nº 14.

After a few minutes note the temperature indicated and then switch on the heat bar supply. Now take readings of temperature every 2 minutes for the first 20 minutes and then every 5 minutes until no further increase is observed. Take care during this test to avoid exposing the heat bar to draughts.

WARNING

When the bar is fully heated the hot end should not be touched. The temperature is not dangerously high but it can hurt.

Record your results in a table of temperature against time, also noting down the ambient temperature you measured earlier.

PRACTICAL 18.2

Heat Distribution

Move the heat tank to notch Nº 20 and wait until the temperature settles to a new steady value. Record the approximate time it takes to do so and the temperature.

Repeat this for notches 18,16, 12 10, 8,6, 4 and 2 and record all your results in a table. Whilst you are taking these reading you will have time to carry out Exercise 18.1.

Note Stop if the temperature at any point reaches 100°C as the water will then be boiling. Higher reading could be obtained in oil but the time constant would be larger.

Exercise 18.1 ***Plot the result of your reading from Practical 18.1 on a graph as in fig 5.18.3.***

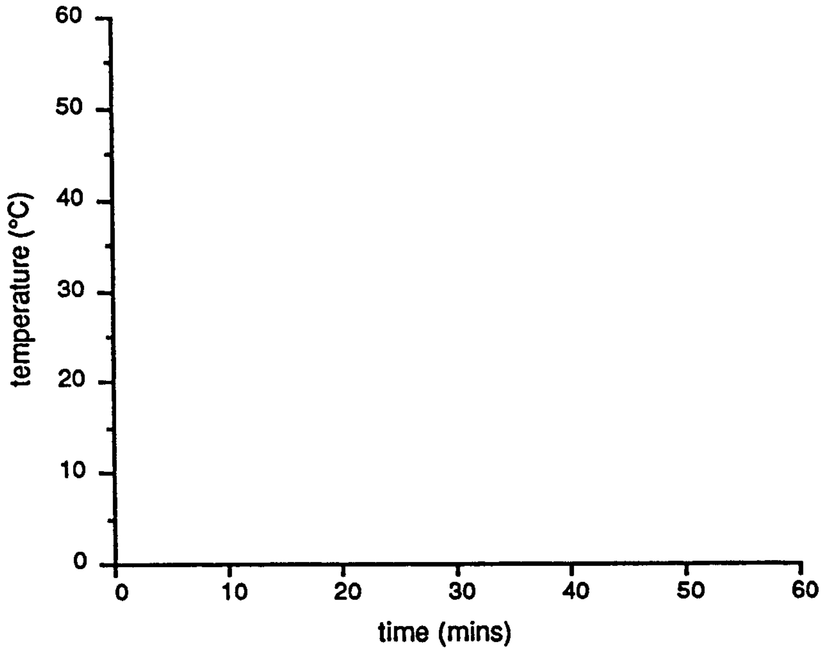


Fig 5.18.3

From your graph answer the following questions.

Question 18.4 ***How long did it take for the temperature to rise to within 1°C of its final steady value?***

Question 18.5 ***How long did it take for the temperature to rise to a value***

$$\theta = \theta_o + 0.64\,(\theta_f - \theta_o)$$

where θ_o ***= starting temperature***
θ_f ***= final temperature***

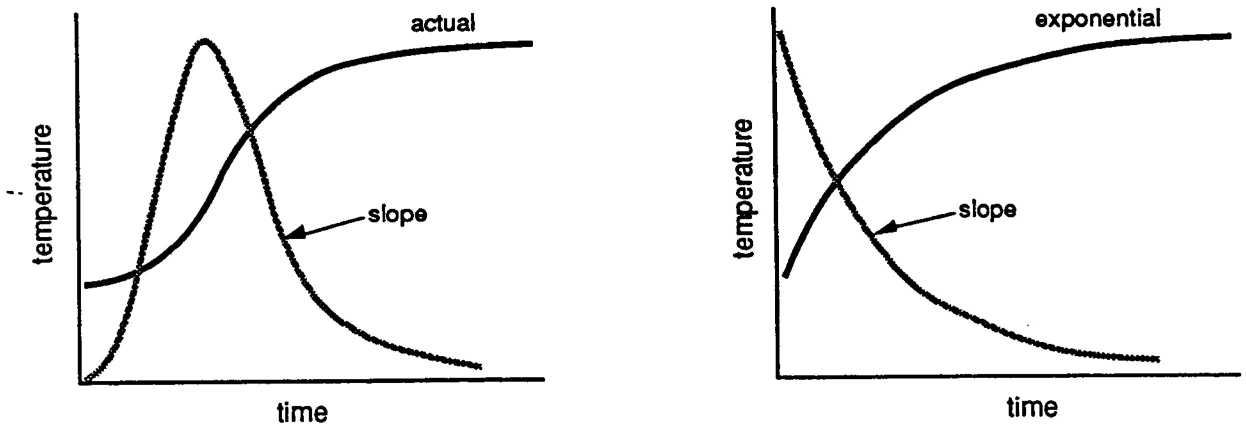
The figure obtained in Question 18.5 is of some interest because the heating process of a body to which a heat source is suddenly applied is somewhat similar to that of charging a capacitor through a resistor from a step of applied voltage. The shape of the curve is approximately exponential and you probably recall that the 'time constant' of such a process is the time taken to reach a value which is 0.64 of the final *rise*, that is of the difference between final and initial values.

Thus the figure you have obtained is the 'thermal time constant' of the heat bar and calibration tank combined.

However, this is only an approximate indication because when you heat up the bar from cold three things have to happen:

- The elements and their immediate surroundings must reach their working temperature.
- The heat must travel along the bar.
- The calibration tank and its contents must be heated.

These three effects cannot be readily distinguished on your graph but you should be able to notice one tell-tale feature in which it differs from a true exponential curve. Fig 5.18.4(a) shows a typical heating curve compared with the true exponential curve, shown in fig 5.18.4(b).



(a) *(b)*

Fig 5.18.4

The true exponential curve has a slope which continuously decreases with no upturns, whereas the slope of the actual curve starts off low, increases and then starts to decrease steadily.

This shape is characteristic of a time lag such as that caused by heat travelling along the bar.

Study your graph to see if it displays this characteristic.

Exercise 18.2 ***From the results of Practical 18.2 plot a curve as in fig 5.18.5 showing the temperature distribution along the bar.***

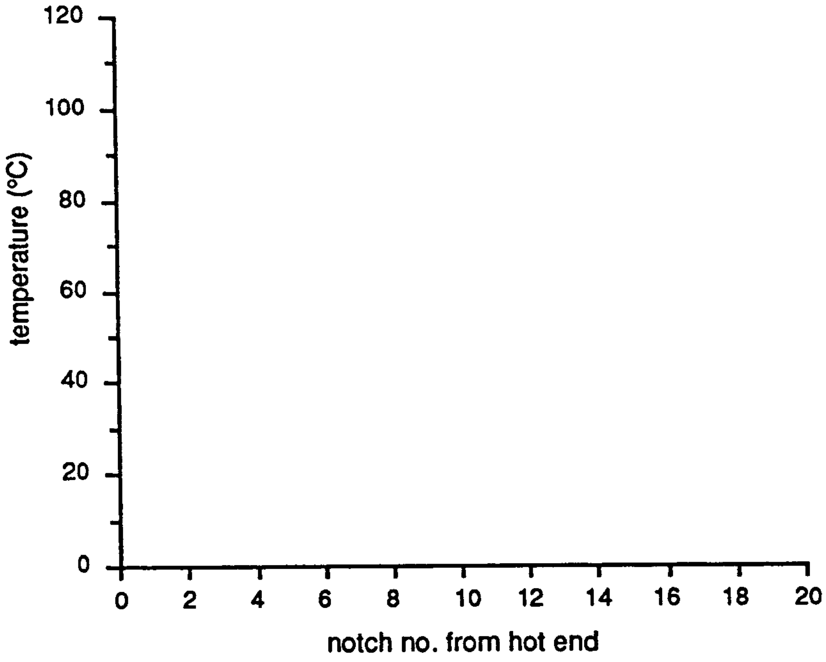


Fig 5.18.5

Also calculate the average value of time taken for each reading to reach within 1°C of its final value and compare this figure with the time taken to cool when moved from notch 14 to notch 20 and also with the time you obtained for Question 18.4 for the initial heating.

Question 18.6 ***What is significant about these different times in relation to one another?***

You should find that for each temperature increase in fig 5.18.5 the time is about the same and less than the time taken to cool from notch 14 to notch 2. It should also be very much less than the time taken for the initial heating.

Question 18.7 ***What explanations do you have for these results/***

The reason for the large difference is of course that when the bar was heated initially the whole mass of heater, bar, heat sink and tank had to be heated whereas in Practical 18.2 only the tank changed in temperature so the thermal time constant was much smaller. This explains the design of the heat rig since it is required, for calibration purposes, to be able to set up different temperatures rapidly.

The smaller difference between heating and cooling is accounted for as follows:

> From notch 14 to notch 20 the temperature drop is about 18°C.
>
> From, say, notch 18 to notch 16 the rise is about 6°C.

Both these changes take place on a roughly exponential curve of common time-constant so in the same time that the temperature falls by 17°C (ie within 1°C) it will rise by $\frac{17}{18} \times 6°C = 5.8°C$ (ie within 0.2°C). Thus it will take slightly less time to rise to within 1°C than it does to fall but both changes actually occur with the same time constant.

The important conclusion from this is that it does not take much longer to heat the tank from, say 40°C to 90°C than it does to heat it from, say, from 40°C to 60°C within the same accuracy.

If the bar were fully insulated except at the ends, preventing any lateral escape of heat, then in steady condition the flow of heat would be uniform at all points in the bar. Consequently the temperature would vary linearly with distance along it.

In fact heat does escape, so that the flow at the heater end is greater than the flow at the far end by the amount of the lateral leakage. This makes the temperature gradient change along the bar. Appendix G shows mathematically that the temperature varies exponentially along the bar.

Note Your graph of temperature versus notch number (fig 5.18.5) will be of use to you in later assignments as it tells you where a certain temperature is to be found. Keep it carefully.

PRACTICAL ASPECTS

We saw from the discussion above that the heat bar allows us to establish a range of temperatures which can be used to raise a small amount of water and a thermometer to any desired temperature quite rapidly.

If the temperature measuring device could do without water and have a lower thermal inertia it could be raised to one of these temperatures even more quickly. In later assignments, after calibration experiments are finished, we shall do just that.

A fast response is also needed in a heat source if it is to be used in dynamic control demonstrations since otherwise these would take very long to perform. On the other hand for accurate calibration purposes a longer thermal time constant is to be preferred to minimise the effects of local disturbances.

The design of the heat rig is thus a compromise between conflicting requirements. The heat bar itself is designed to be reasonably fast to respond by keeping the mass of the heater and bar to a minimum. For calibration of transducers against a mercury thermometer however, the addition of the heat tank and its small amount of water contents helps to provide local temperature stability without causing long delays when a temperature change is required.

In the commercial calibration of thermometers of various kinds considerable efforts must be made to provide uniform and stable temperatures.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 18

Question 18.1 The temperature pattern in the bar will eventually be one showing a steady decrease from the heater end to the heat sink end.

Question 18.2 Due to thermal inertia the pattern will take some time to establish.

Question 18.3 More water than necessary would increase the thermal inertia of the tank assembly and hence the time taken to reach a new temperature when a change occurs.

If the thermometer touches the tank wall it is possible to get a local hot spot which could cause errors in measurement.

Exercise 18.1 Plotting the results of Practical 18.1, Table 1, should give a curve similar to that of fig E5.18.3.

time (mins)	temperature (°C)	time (mins)	temperature (°C)
0	22	20	51.5
2	22	25	54.5
4	23.5	30	55.5
6	28.5	35	56.5
8	33	40	57
10	36.5	45	57
12	40.5	50	57.5
14	43	55	58
16	47	60	58.5
18	49.5		

Table 1

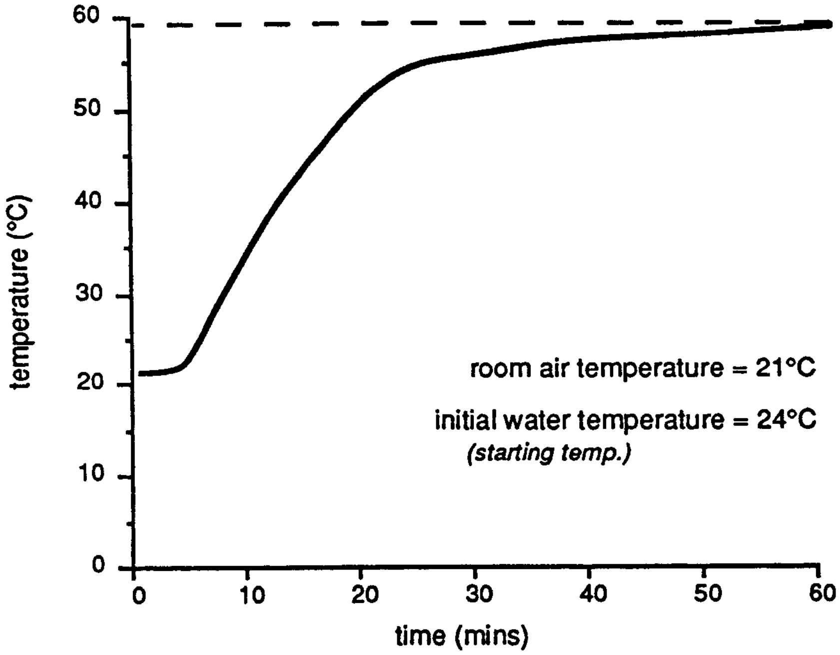


Fig E5.18.3

Question 18.4 Typically it will take about 45 minutes to reach to within 1°C at notch 14.

Question 18.5 With the time-constant as defined in this question approximately 16 minutes.

Exercise 18.2 The results of Practical 18.2, Table 2, should give a curve similar to that of fig E5.18.5.

Notch Nº	temperature (°C)	time (mins)
20	44	17 (cooling)
18	48	16
16	53	14
14	58	12
12	62	11
10	72	13
8	79	12
6	83	11
4	96	10
2	>100	

Table 2

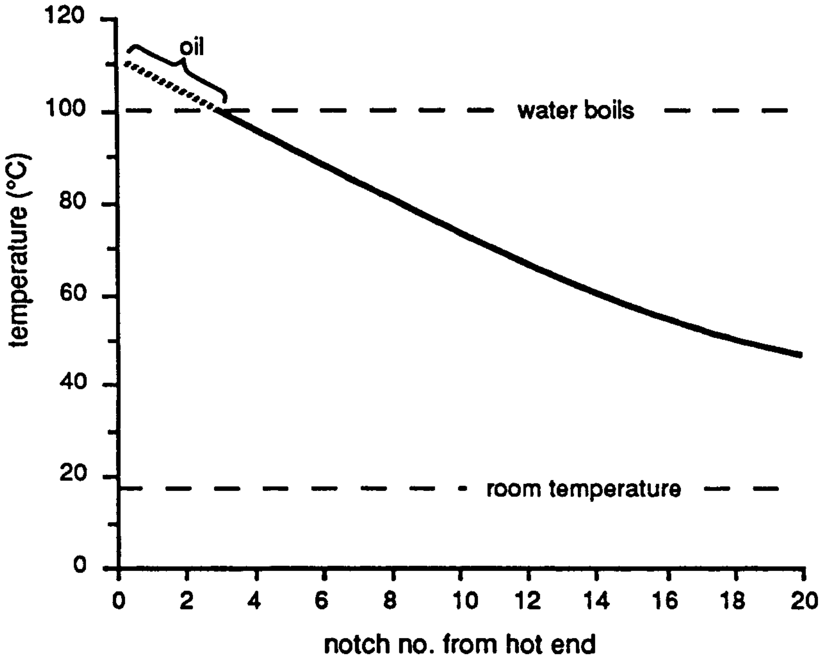


Fig E5.18.5

The average value of time taken to reach within 1°C of final temperature for each move is typically 12.5 minutes.

Question 18.6

The range of heating times for each step in Practical 18.2 is typically from 10 to 16 minutes, with an average change time of 12.5 minutes. So if 15 minutes is allowed for each change in a calibration test in later assignments the reading will be well within 1°C on average.

The time to cool from notch 14 to notch 20 is typically 18 minutes which, as explained in the text, is slightly larger than average due to the greater step in temperature. As the time taken to heat the bar initially was 45 minutes it is clear that the average change time of 12.5 minutes is much less.

Question 18.7

The answer is given in the text but briefly the differences in time are due to the fact that on each move of the tank only the tank temperature changes appreciably whereas initial heating must heat the whole heat bar and tank.

THE THERMOCOUPLE — ASSIGNMENT 19

CONTENT

The behaviour of a two-metal junction, when subject to a temperature difference, is investigated. The Peltier and Thomson effects are discussed and the uses of a thermocouple are introduced.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	–	Heat Bar
1	–	Thermometer
1	–	Calibration Tank
1	–	Transducer - thermocouple and flying compensating leads. Black sleeve.
1	–	Power Supply ±15V dc *(eg Feedback PS446)*
1	–	DC Voltmeter 15V *
1	–	Small container of ice cubes

* Alternatively a multimeter may be used.

PRACTICALS

19.1 Thermocouple EMF

19.2 Controlled Cold Junction

THE THERMOCOUPLE — ASSIGNMENT 19

OBJECTIVES

When you have completed this assignment you will:

- Recognise the terms Thomson effect and Peltier effect
- Understand the principle of operation of a thermocouple
- Understand the need for compensating leads to be used with thermocouples.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Be familiar with the use of the heat bar and preferably have completed Assignment 18, The Heat Bar - Familiarisation.

INTRODUCTION

Basic Principle

If two wires of dissimilar metals are connected in a loop as in fig 5.19.1 and the two junctions A and B are held at a temperature of θ_A and θ_B respectively, a current will circulate around the loop.

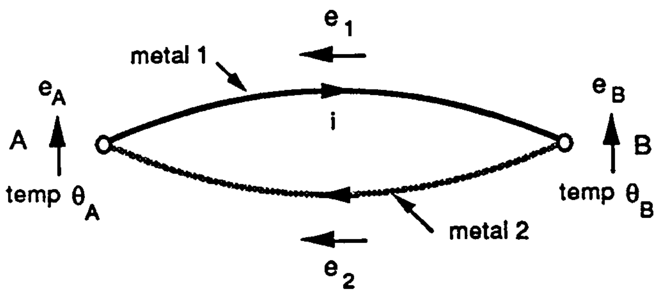


Fig 5.19.1

The current is due to small emf's generated by two quite separate effects, which sum algebraically.

Peltier effect

An emf is generated at each of the two junctions, shown as e_A and e_B in fig 5.19.1. These emf's are dependent upon the 'absolute temperatures' of the junctions. If A is hotter than B then there will be a resultant emf, e_p, of

$$e_A - e_B = P(\theta_A - \theta_B)$$

where P is the Peltier Coefficient.

Strictly speaking e_p is only approximately proportional to the temperature difference but the departure from linearity is very small for normal temperature measurements.

Thomson effect

Each wire of the loop generates a small emf, e_1 and e_2 in fig 5.19.1, simply as a result of the difference in temperature between its ends. The emf is different for different metals.

If T_1 is the Thomson Coefficient for metal 1

and T_2 is the Thomson Coefficient for metal 2

then $e_1 = T_1 (\theta_A - \theta_B)$

$$e_2 = T_2 (\theta_A - \theta_B)$$

so the resultant emf is:

$$e_2 - e_1 = (T_2 - T_1)(\theta_A - \theta_B)$$

Putting the two effects together we get a resultant emf round the loop:

$$(e_A - e_B)+(e_2 - e_1) = E = (P + T_2 - T_1)\ (\theta_A - \theta_B)$$

In practice the values of T_1 and T_2 are much smaller than that of P but for a given pair of metals they can all be lumped together into a single constant, let us call it K.

Thus:

$$E = K(\theta_A - \theta_B)$$

Referring back to fig 5.19.1, if the total loop resistance is R then by Kirchoff's law for circuit loops $i = \frac{E}{R}$

So that $i = \frac{K(\theta_A - \theta_B)}{R}$

Now we can see that if one of the junctions, say B is held at a known temperature and called the *cold* or *reference* junction, then by measuring the current i we can determine the unknown temperature of the other or *hot* junction, always provided we know the values of K and R.

Intermediate Metals

In order to measure the current a meter of some kind must be inserted in the loop as in fig 5.19.2. This meter is likely to have various metals used in its internal construction - how will these additional junctions affect the emf's generated?

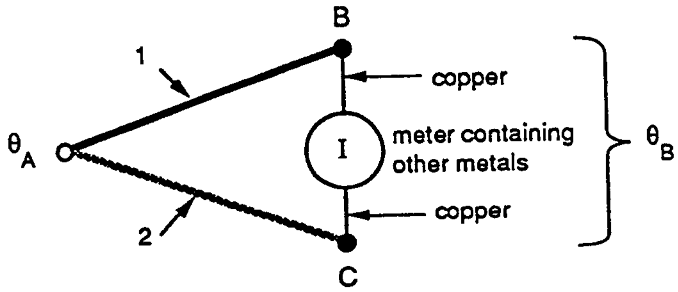


Fig 5.19.2

The Law of Intermediate Metals states that any number of junctions may be introduced into a circuit provided they are all at the same temperature.

In fig 5.19.2 therefore, the nett emf is not altered by inserting the meter provided that points B and C and all other junctions within the meter are at the same (cold junction) temperature.

Compensating Leads

Although the arrangement of fig 5.19.2 would give correct readings it necessitates bringing the thermocouple metals right up to the instrument, which ideally should be far enough from the hot junction to be unaffected by it in temperature.

Sometimes this is inconvenient because the couple metals are physically or electrically unsuitable for long leads, e.g they may be brittle or have high or very temperature-sensitive resistance; sometimes the couple metals will be too expensive, e.g platinum or rhodium to be used for long leads.

In these cases special compensating leads are used which are made of metals designed to cancel out errors caused by junctions occurring at intermediate temperatures. Fig 5.19.3 illustrates this.

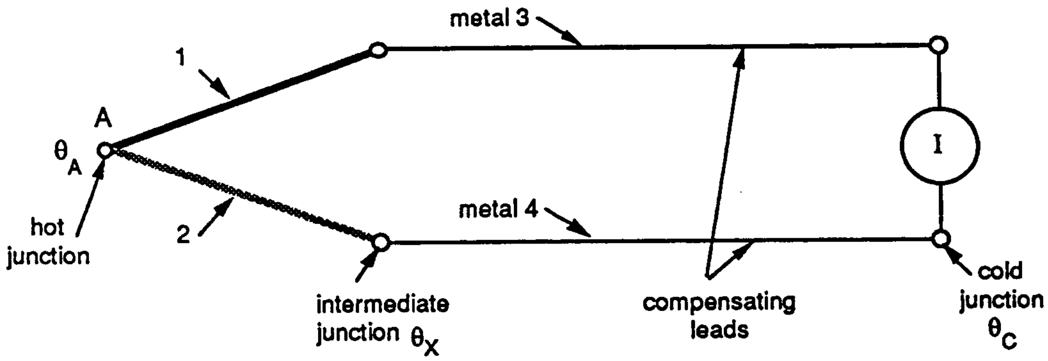


Fig 5.19.3

If the emf generated at junction 1-3 for temperature θ_X is equal and opposite to that generated at junction 2-4 then inserting the compensating leads has no effect on the nett emf and the effective cold junction is still at the meter.

PRACTICAL 19.1

Thermocouple EMF

Switch on the Heat Bar and allow it to heat up to a steady temperature. This will take approximately 45 minutes.

Examine the thermocouple transducer. You cannot see the actual hot junction because it is enclosed in a protective sheath but it is formed of Copper and Constantan.

The flexible lead is attached to the ends of the couple wires inside the black rubber sleeve.

Fig 5.19.4 shows the assembly.

Fig 5.19.4

The white and brown insulation of the inner leads are British Standard Colour Codes (BS4937/1993) and show that these leads are respectively:

+Ve:	BROWN:	COPPER
–Ve:	WHITE:	CONSTANTAN (COPPER-NICKEL)

In other words this connecting lead is not a true compensating lead but simply an *extension lead* of the same metals as the couple but in a more convenient physical form.

Question 19.1 ***Which metals are the blue and white leads connected to under the sleeve? Fig 5.19.2 gives you the clue to this question.***

Question 19.2 ***The junctions between the thermocouple wires and the extension lead wires are soldered with tin/lead solder and will be heated to some extent when the couple is heated. will this introduce errors?***

Measuring the Thermocouple emf

We saw above that the current in a thermocouple loop is given by:

$$i = \frac{K(\theta_x - \theta_c)}{R}$$

where θ_x = unknown temperature

θ_c = cold junction temperature

R = total circuit resistance

K = thermocouple constant

If the measuring instrument has a very high input resistance and is voltage-sensitive then the resistance of the couple and its extension leads will be negligible and the emf measured by the meter will be the 'open-circuit emf' of the couple. Fig 5.19.5 illustrates this; the cold junction is still at the meter terminals, which must both be at the same temperature as before.

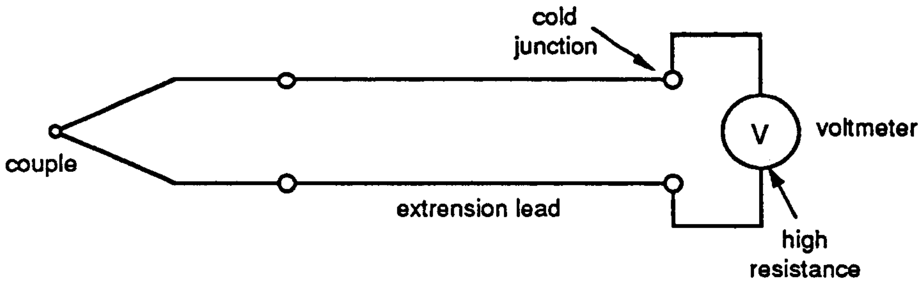


Fig 5.19.5

In this assignment we shall use the Instrumentation Module TK2941A to amplify the couple emf to a sufficient value to drive a meter.

The circuit resistance of the thermocouple assembly is about 3Ω (check this for yourself with an ohmmeter) and the input resistance of the amplifier, which varies according to the gain setting, is at least 40kΩ so that virtually the whole of the emf appears at the amplifier input terminals.

Connect the probe to the amplifier as shown in fig 5.19.6 and also connect at 0-15V meter between the amplifier output and 0V. Switch on the power supply and place the probe near to the amplifier input so that all points are at the same temperature.

To avoid possible 'pick-up' of signal, due to the proximity of the thermocouple lead to the TK2941A oscillator, the positive input to the operational amplifier is decoupled to 0V with a 100μF capacitor.

Use the thermometer to read the room temperature near the amplifier. This will be the cold junction temperature and should ideally be constant during the experiment. If you suspect that this temperature might vary and you have two thermometers available, use the second one to note the room temperature before every reading.

Now switch the gain on the Operational Amplifier to 1000, disconnect the probe, note the meter reading in your own copy of the table in fig 5.19.7, and place it and a thermometer (sleeved to give correct immersion depth – see Assignment 18) in the water tank and clip this on the heat bar at Notch 20.

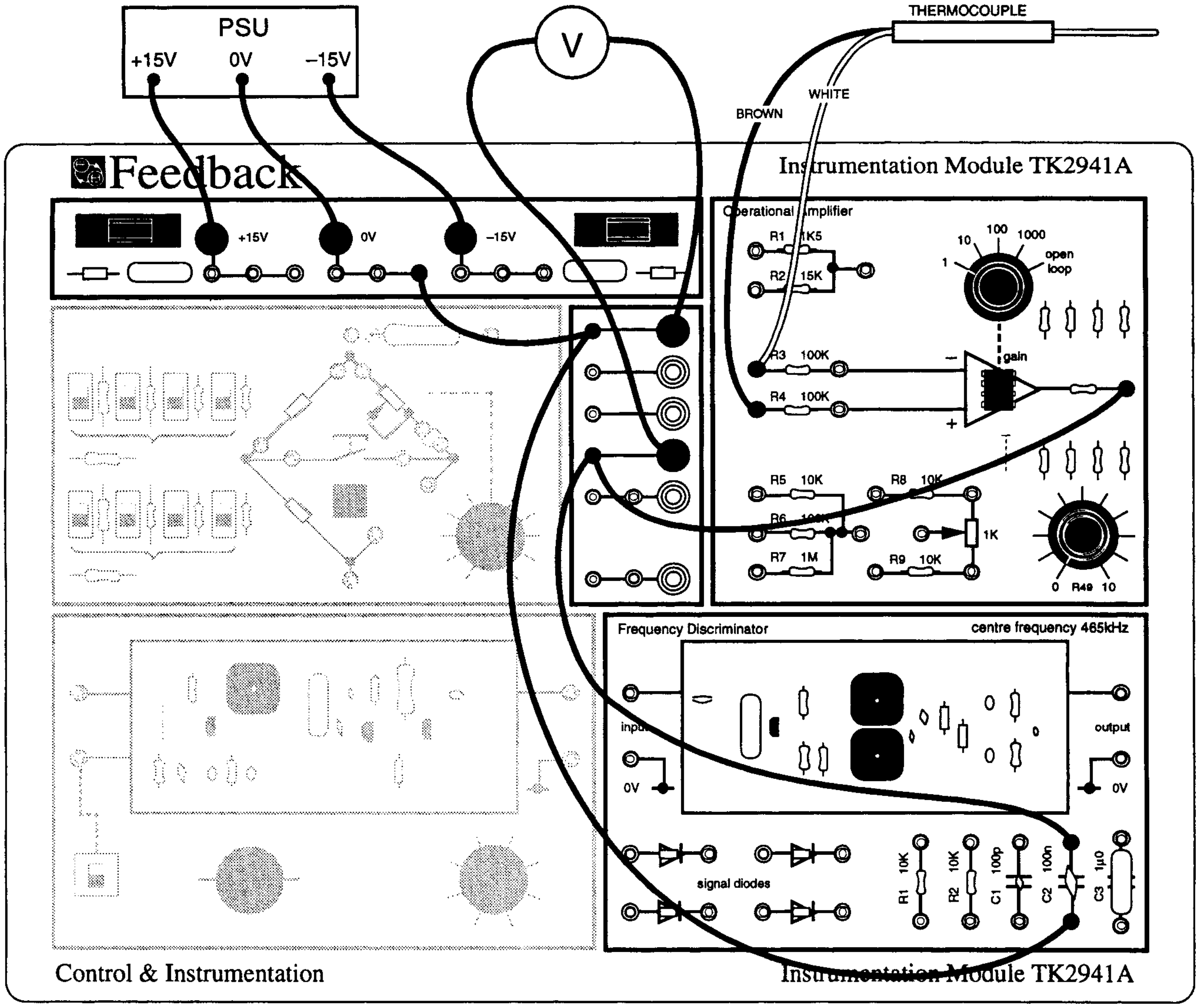

PSU
+15V
0V
−15V
V
THERMOCOUPLE
WHITE
BROWN
Feedback
Instrumentation Module TK2941A
+15V
0V
−15V
Operational Amplifier
R1 1K5
R2 15K
R3 100K
R4 100K
R5 10K
R6 100K
R7 1M
R8 10K
R9 10K
1K
gain
open loop
0 R49 10
Frequency Discriminator
centre frequency 465kHz
input
output
0V
signal diodes
R1 10K
R2 10K
C1 100p
C2 100n
C3 1µ0
Control & Instrumentation
Instrumentation Module TK2941A

Fig 5.19.6

When the temperature is steady (about 15 mins) note the thermometer reading and the meter reading. Repeat for Notches 18, 16, etc up to the point where 100° is reached. Enter your results in your own copy of the table shown in fig-5.19.7.

Notch Nº	Tank Temp. (°C)	Room Temp. (°C)	Temp. Difference (°C)	Meter (V)	Thermocouple emf (mV)

Fig 5.19.7

Exercise 19.1 — ***Calculate the temperature difference and the couple emf, which will be the meter reading divided by 1000 expressed in mV.***

Plot the emf against temperature difference.

Question 19.3 — ***Is the graph a straight line within the accuracy of your observation and plotting?***

Question 19.4 — ***If so, what is the slope in microvolt/°C? What source of error could contribute to uncertainty about this figure?***

PRACTICAL 19.2

Controlled Cold Junction

In the last Practical it was necessary to take note of the room temperature if this was likely to vary. If the cold junction were controlled at a suitable temperature this would be unnecessary. Also, if this temperature were 0°C the thermocouple output could be scaled to be direct reading in °C.

This can be achieved by immersing the cold junction in melting ice as in fig 5.19.8 but the meter is still at room temperature and to ensure that no spurious emf is generated due to the difference between the meter and ice temperatures, the lead from meter to ice must be of the same metal as that from couple to meter, as shown.

As before, it does not matter what other junctions occur within the dotted line provided they are all at the same temperature. Ideally the lead from the cold junction to the amplifier should be untinned copper but in practice we can use one of the leads supplied with the equipment.

Set up the circuit of fig 5.19.8 forming the cold junction by plugging a lead and the *white* extension lead together and immersing the connection in melting ice in a beaker.

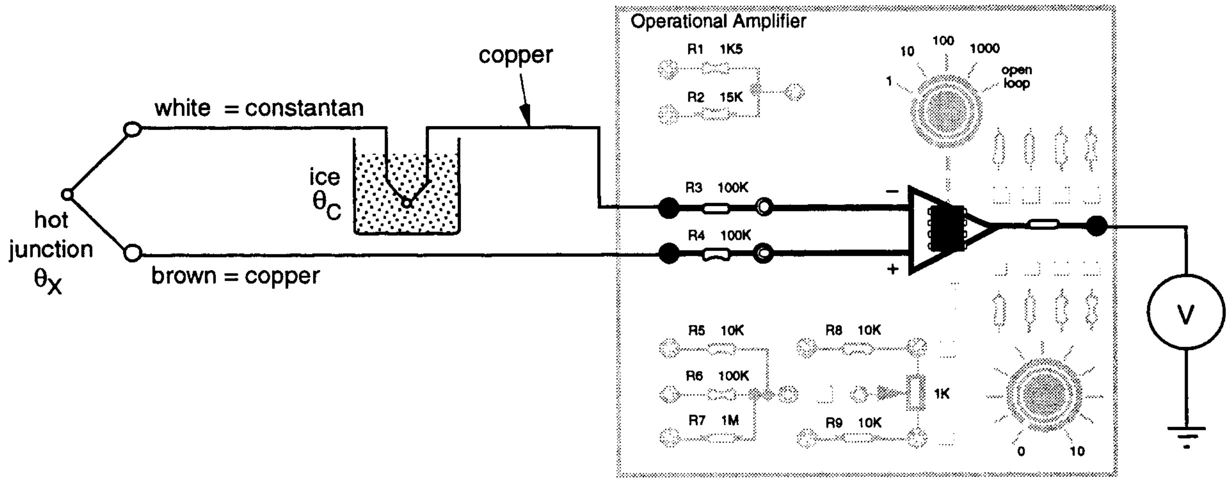


Fig 5.19.8

Set the water tank at Notches 20, 16, 12, 8 and 4 and note the temperatures and the meter reading at each notch in your own copy of fig 5.19.9.

Notch Nº	Tank Temp. (°C)	Cold Junction Temp. (°C)	Temp. Difference (°C)	Meter (V)	Thermocouple emf (mV)

Fig 5.19.9

Exercise 19.2

Plot your results of temperature against emf and once again compare the slope with a reference value. If you have available a table of actual emf's for different temperatures referred to °C, compare these with your individual readings.

PRACTICAL ASPECTS

Many different types of couple exist, the principle differences being due to the various temperature ranges they must work over.

A thermocouple must give a near linear emf-temperature relation, without melting or deterioration of either material, over the desired range and possible in the presence of corrosive liquids or atmospheres, although it is usual to enclose the couple in a protective tube in such cases. Some common couples and their ranges are given below.

Type	°C range
Copper-Constantan	–190 to 400
Iron-constantan	–190 to 850
Platinum-Rhodium/Platinum	1000 to 1600
Nickel/Chromium-Nickel/Aluminium	–200 to 1100

The leads of the couple itself and, naturally, the insulating material used must resist the highest temperature of operation for an indefinite period.

Fig 5.19.10 shows a typical assembly for industrial use, with the couple inside a protective pocket and its leads kept apart by ceramic insulators.

You will have noticed that the emf per °C of the thermocouple is quite small. In order to increase the sensitivity it is possible to connect a number of couples in series but each couple must have its cold junction remote as shown in fig 5.19.10.

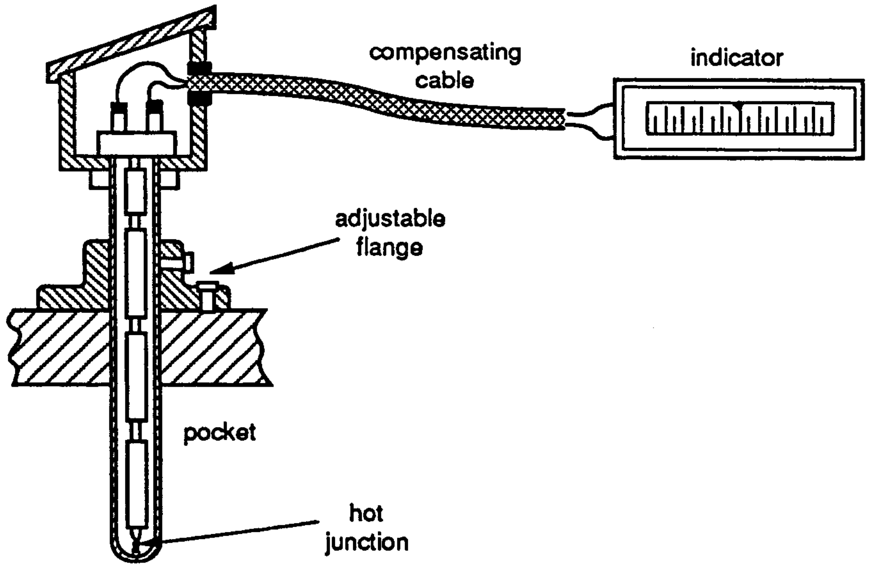


Fig 5.19.10

A development of this principle is sometimes used in the measurement of temperature by radiated energy and is called the 'thermopile'. It comprises many junctions in series but the cold junctions are not remote as they were in fig 5.19.11.

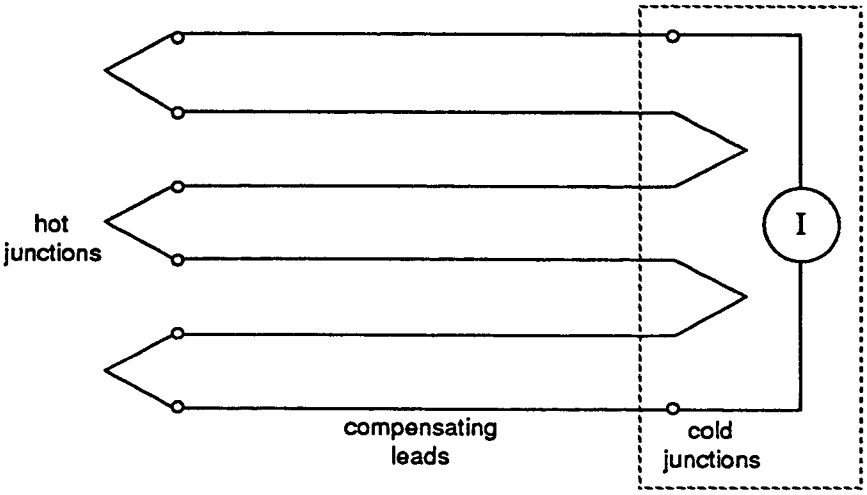


Fig 5.19.11

However, steps are taken to reduce the flow of heat from the hot to the cold junctions and to dissipate as much as possible from the cold junction.

The whole assembly can be calibrated for different degrees or radiation directed (often by a focussing system) upon the hot junctions.

The applications of thermocouples are very numerous and various as the fundamental cost, particularly of the base metal couples, is very low and the small size of a junction makes it very convenient for measurement in restricted spaces and on surfaces.

Also its low thermal mass mean that its attachment to a hot body has very little effect upon the temperature to be measured, that is it imposes very little load upon the heat source.

The only serious disadvantages are the need for a high sensitivity voltmeter or ammeter and the need to maintain the cold junction at a known and, preferably, constant temperature. However recent developments in digital instrumentation have made suitable voltmeters readily available and automatic means of compensation for cold junction variations are also feasible using, for example, negative temperature coefficient resistors (thermistors — see Assignment 20).

Question 19.1

Since fig 5.19.2 shows that normally the two metals must extend right up to the meter and since the connecting lead is only an extension lead in this case it follows that the brown lead (copper) connects to copper in the couple and white connects to constantan.

Question 19.2

Since both junctions are close together they will be at the same temperature and no errors should result by the Law of Intermediate Metals.

Plotting the results of Practical 19.1, fig E5.19.7 should give a curve similar to that of fig 5.19.12.

Notch Nº	Tank Temp. (°C)	Room Temp. (°C)	Temp. Difference (°C)	Meter (V)	Thermocouple emf (mV)
Probe disconnected	—	23	—	0.015	—
20	40.5	22.5	18	0.709	0.709
18	45.5	22.5	23	0.891	0.891
16	51.5	22.5	29	1.190	1.190
14	57.5	22.5	35	1.432	1.432
12	64.5	22.5	42	1.818	1.818
10	73.5	23	50.5	2.147	2.147
8	81.5	23	58.5	2.518	2.518
6	88.5	23	65.5	2.821	2.821
4	94	23.5	70.5	2.971	2.971

Fig E5.19.7

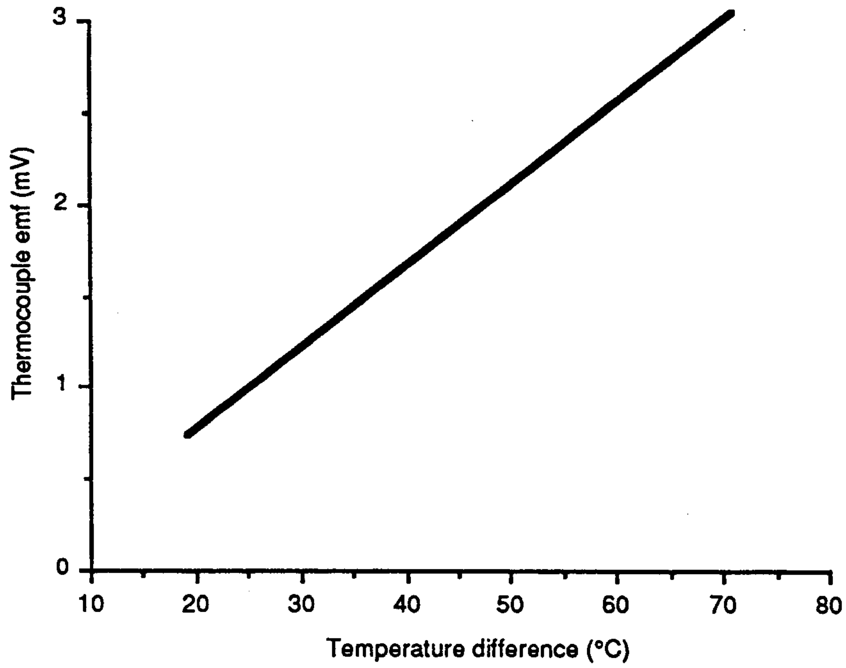


Fig 5.19.12

Question 19.3

Although the emf of a thermocouple is not exactly proportional to temperature the non-linearity is very small over the range available on the heat bar and to all intents a straight line will be observed.

Question 19.4

A typical measured slope would be 0.044mV/°C to 70°C. A reference value for this range is 42µV/°C. The discrepancy is easily accounted for by amplifier gain, metal scale and observational errors.

Plotting the results of Practical 19.2, fig E5.19.9, should give a curve similar to that of fig 5.19.13.

Notch Nº	Tank Temp. (°C)	Cold Junction Temp. (°C)	Temp. Difference (°C)	Meter (V)	Thermocouple emf (mV)
20	37	0	37	1.375	1.375
16	50	0	50	1.831	1.831
12	60.5	0.5	61.5	2.329	2.329
8	77.5	1	76.5	2.997	2.997
4	100	2	98	3.926	3.926

Fig E5.19.9

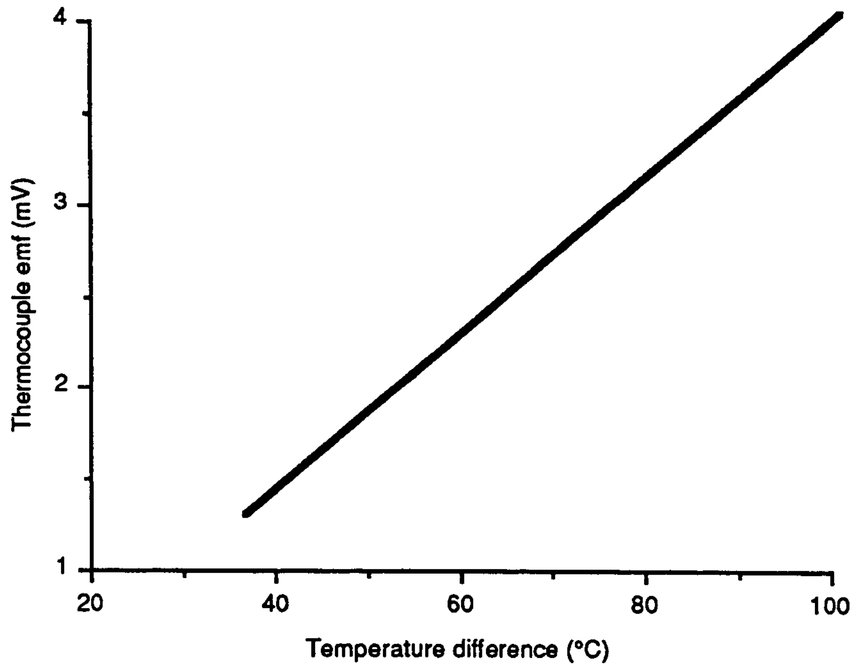

4
3
2
1
Thermocouple emf (mV)
20
40
60
80
100
Temperature difference (°C)

Fig 5.19.13

THE THERMISTOR — ASSIGNMENT 20

CONTENT

The characteristic behaviour of a thermistor is investigated and its negative temperature coefficient is determined.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	–	Heat Bar
1	–	Thermometer
1	–	Calibration Tank
1	–	Transducer - thermistor with flying leads. White sleeve
1	–	Transducer mount
1	–	Small container of ice cubes
1	–	Log 3 cycle x Linear graph paper
1	–	Decade Resistance Box 1Ω to 100KΩ
1	–	Power Supply ±15V d.c *(eg Feedback PS446)*
1	–	* DC Voltmeter 15V
1	–	* DC Milliammeter

* Alternatively a multimeter may be used

PRELIMINARY PROCEDURE

Switch on the Heat Bar and allow it to heat up to a steady temperature. This will take about 45 minutes.

PRACTICALS

20.1 Self-Heating

20.2 Calibration – Zero Power Measurement

OBJECTIVES

When you have completed this assignment you will:

- Know that a thermistor has a negative temperature coefficient of resistance.
- Have noted the practical implications of the self-heating effect.
- Have produced a calibration curve for the thermistor.
- Recognise the term dissipation constant.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Be familiar with the use of the heat bar and preferably have completed Assignment 18, The Heat Bar - Familiarisation.
- Understand the operation of a Wheatstone Bridge circuit.

INTRODUCTION

All electrical conductors possess resistance and in every case the resistance is to some degree dependent upon temperature. In most cases resistance increases with temperature rise and the change is usually an undesirable effect to be made as small as possible.

It is possible, however, to take advantage of this effect to enable temperature changes to be detected by it. In Assignment 21 we shall see one application of this idea in the Platinum Resistance Thermometer, which has a positive temperature coefficient (resistance increases with temperature increase).

In this Assignment, though, we shall study a device called the THERMISTOR (from THERMal and resISTOR) which has a very large, and nearly always negative, temperature coefficient. The applications of such a device extend far beyond simple temperature measurements and are very numerous indeed, as we shall see later.

Thermistors are made from various metal oxide materials fired at a high temperature and appear in many different physical forms. The one we shall use, although not visible inside its protective probe, is a glass encapsulated bead of material supported on its connecting wires as shown in fig 5.20.1.

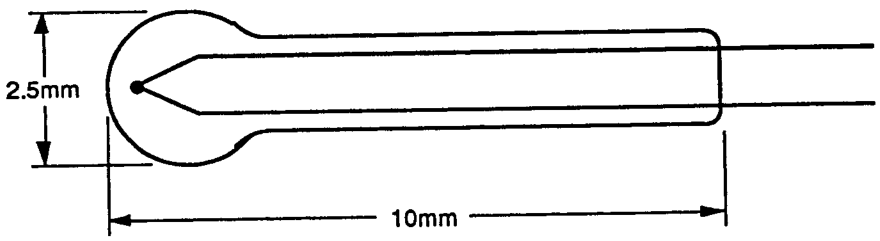


Fig 5.20.1

The resistance of a thermistor, once manufactured and fired, is dependent *solely* upon its temperature.

The shape of the curve relating resistance to temperature is governed by an equation of the type

$$R = A_e{}^{b/T}$$

where R = resistance in ohms

T = absolute temperature

e = base of natural logarithms

A, b are constants

For the thermistor in this Kit the value of R at 20°C is about 2000Ω and it varies with temperature as sketched in fig 5.20.2. Shortly you will plot such a curve experimentally but before you can there is another important consideration which you must understand.

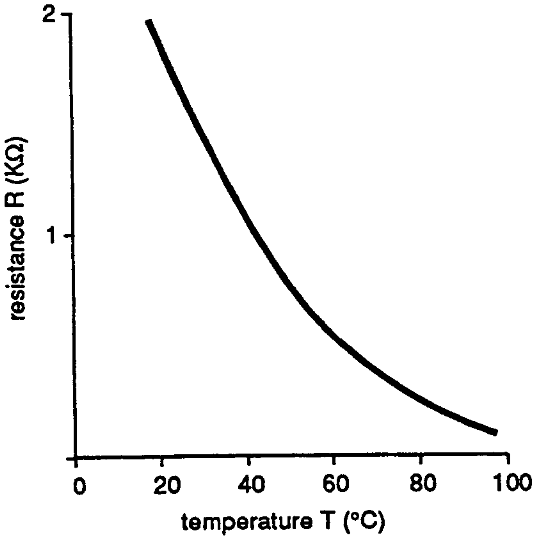


Fig 5.20.2

PRACTICAL 20.1

Self-Heating

You will recall from earlier work you have done that you cannot measure resistance without passing current through it.

Question 20.1

What happens when current flows in a resistance?

Put your answer to this question together with the fact that the thermistor resistance depends only upon its temperature and that it makes no difference how the thermistor comes to be heated.

We must measure the thermistor resistance if we are to know its temperature.

Question 20.2

What precaution do you therefore think is necessary when using a thermistor to measure the temperature of its surroundings?

The answer is quite easy to see — we must ensure that whatever measuring circuit we use does not appreciably heat up the thermistor, thus giving an artifically high temperature not representative of its surroundings.

This effect is called 'self-heating'. In some applications it is deliberately used but in most it must be kept small.

'But how small?' is the question we have to answer before we can calibrate the device against a mercury thermometer. In order to answer this question we must first carry out an experiment to determine how the resistance changes when power is dissipated in it by a current.

Connect the thermistor, a high impedance voltmeter and a milliammeter into the circuit shown in fig 5.20.3.

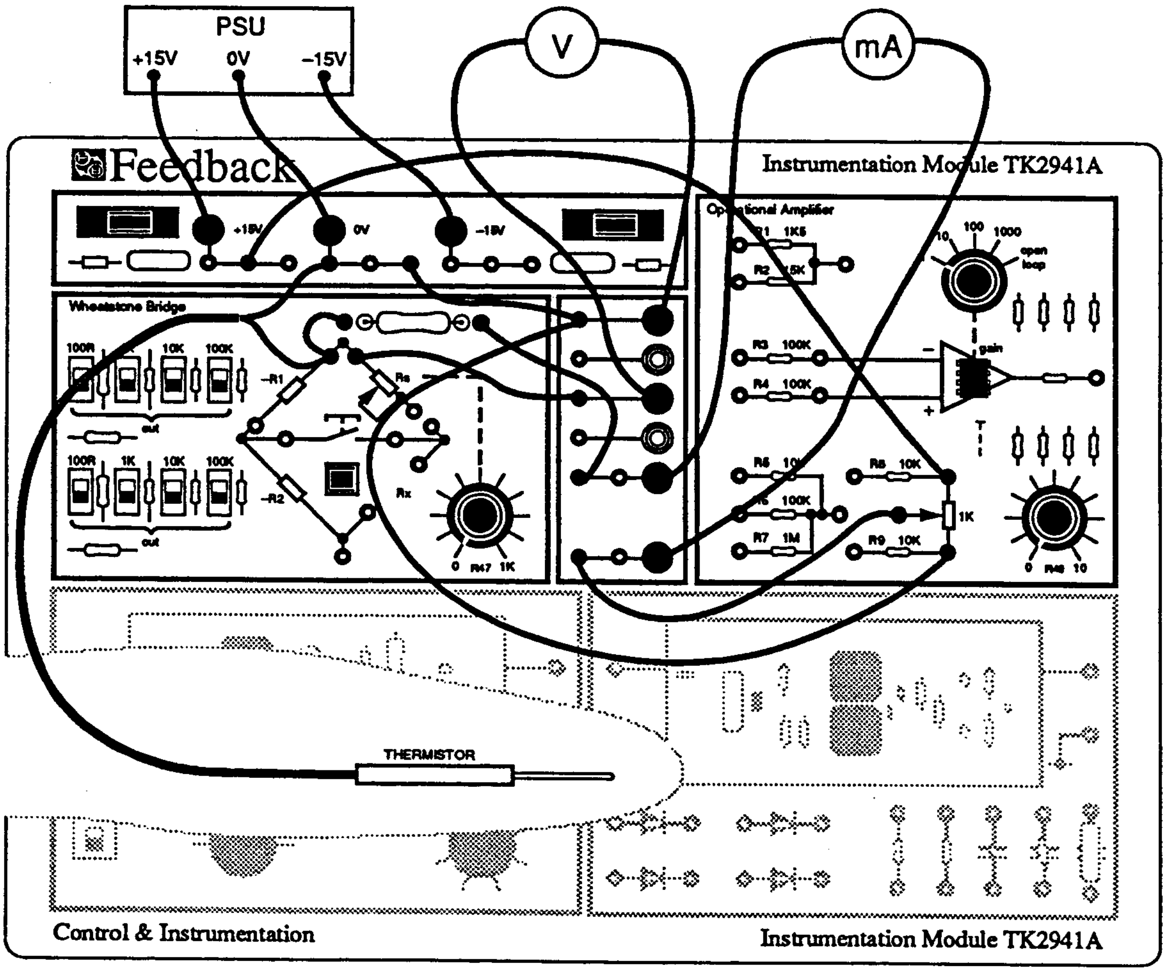


Fig 5.20.3

See that the potentiometer control on the Operational Amplifier is set to zero and switch on the supply.

Note The current taken by the voltmeter, although small, may need to be taken into account to obtain accurate results, as follows:

If I = measured current

V = measured voltage

I_{FS} = voltmeter full-scale current

V_{FS} = voltmeter full-scale voltage

The thermistor current $I' = I - \frac{V}{V_{FS}} \times I_{FS}$

and the thermistor resistance $R = \frac{V}{I'}$

The power dissipated in the thermistor is $V \times I'$.

For this experiment it is preferable that the ambient temperature is fairly constant over the period of the readings. Use a mercury thermometer to read room temperature before and after. Support the probe in free but still air and do not touch it with your fingers.

Now increase the variable d.c supply, using the potentiometer, so as to set the current to approximately 1, 2, 4, 10, 15 and 20mA. After each change wait at least 1 minute before recording both voltage and current. You will have to be careful at the higher currents because having changed the voltage the current will go on increasing for a while as the thermistor heats up and reduces in resistance.

Note Do not allow the current to exceed 20mA.

Question 20.3 ***Can you see why the 220Ω resistor is used in series with he probe?***

Complete your own copy of the table shown in fig 5.20.4 for each of your readings. Calculate R and P from V and I, using I' if necessary, as explained above.

I (mA)	V (V)	I' (mA)	R = V/I' (kΩ)	P = V x I' (mV)

		Air	Water
Room temperature:	Start:		
	Finish:		

Fig 5.20.4

Repeat the procedure but this time insert the probe into water at room temperature in the calibration tank.

Exercise 20.1

Plot a graph of R/P for both sets of readings on log/linear graph paper as in fig 5.20.5.

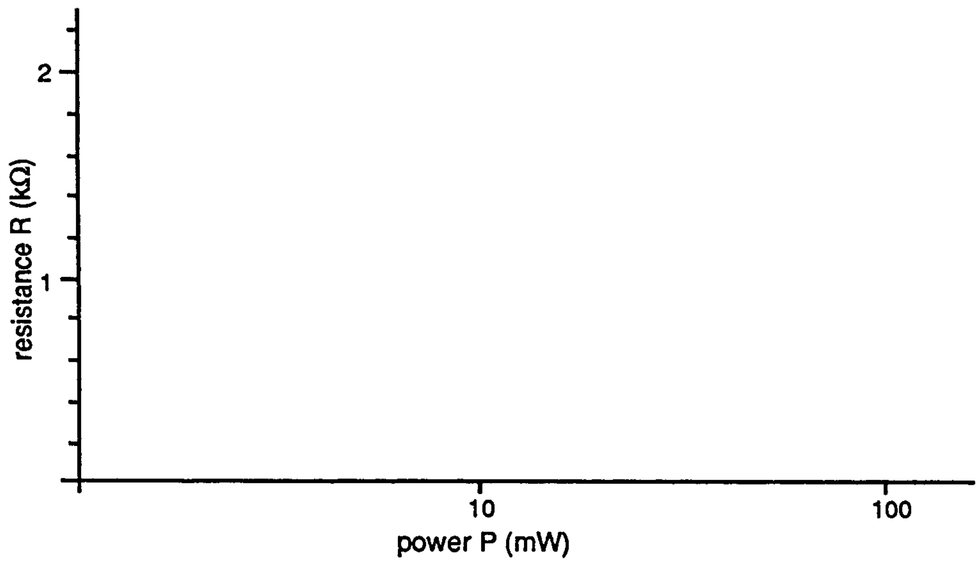


Fig 5.20.5

Question 20.4

Can you account for the differences between the curves obtained for air and for water?

Question 20.5

Study your curves of R/P. How many mW of power can safely be dissipated in the thermistor without lowering its resistance by more than 1% of its starting value for a) air b) water?

PRACTICAL 20.2

Calibration – Zero Power Measurement

To calibrate the thermistor we shall wish to place it in the calibration tank with a mercury thermometer and heat the water to various temperatures, measuring the thermistor resistance at each point by means of a Wheatstone Bridge. We know that the bridge design must not cause more than a certain power to be dissipated in the thermistor at any temperature.

Suppose we used an equal ratio bridge excited by about 1V d.c as in fig 5.20.6.

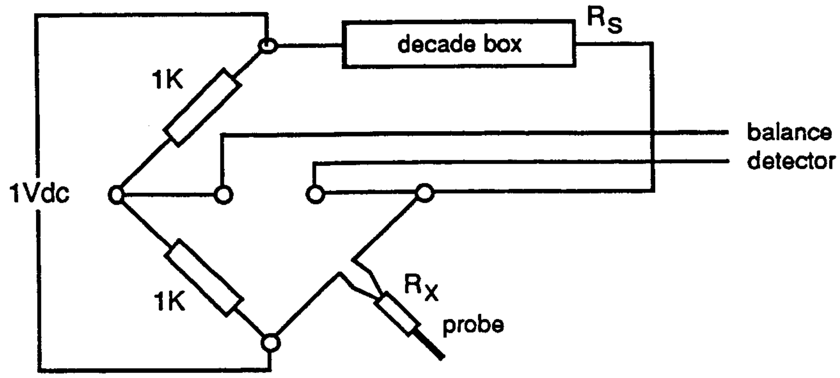


Fig 5.20.6

At balance the voltage across R_x will always be half the supply, that is 0.5V. If R_x should fall to say 100Ω when heated externally the power dissipated would be $0.5^2/100 = 2.5$mW.

Question 20.6 ***Is this more or less than your upper limit allowed in answer to Question 20.5?***

If it is more we must alter the circuit by reducing the voltage across R_x. This can be done either by reducing the supply voltage or by using a different ratio. For the same reduction in dissipation the latter method gives slightly better bridge sensitivity so we will adopt it here. To obtain adequate sensitivity it will still be necessary to follow the bridge by an amplifier of gain 1000. The resulting circuit is shown in fig 5.20.7.

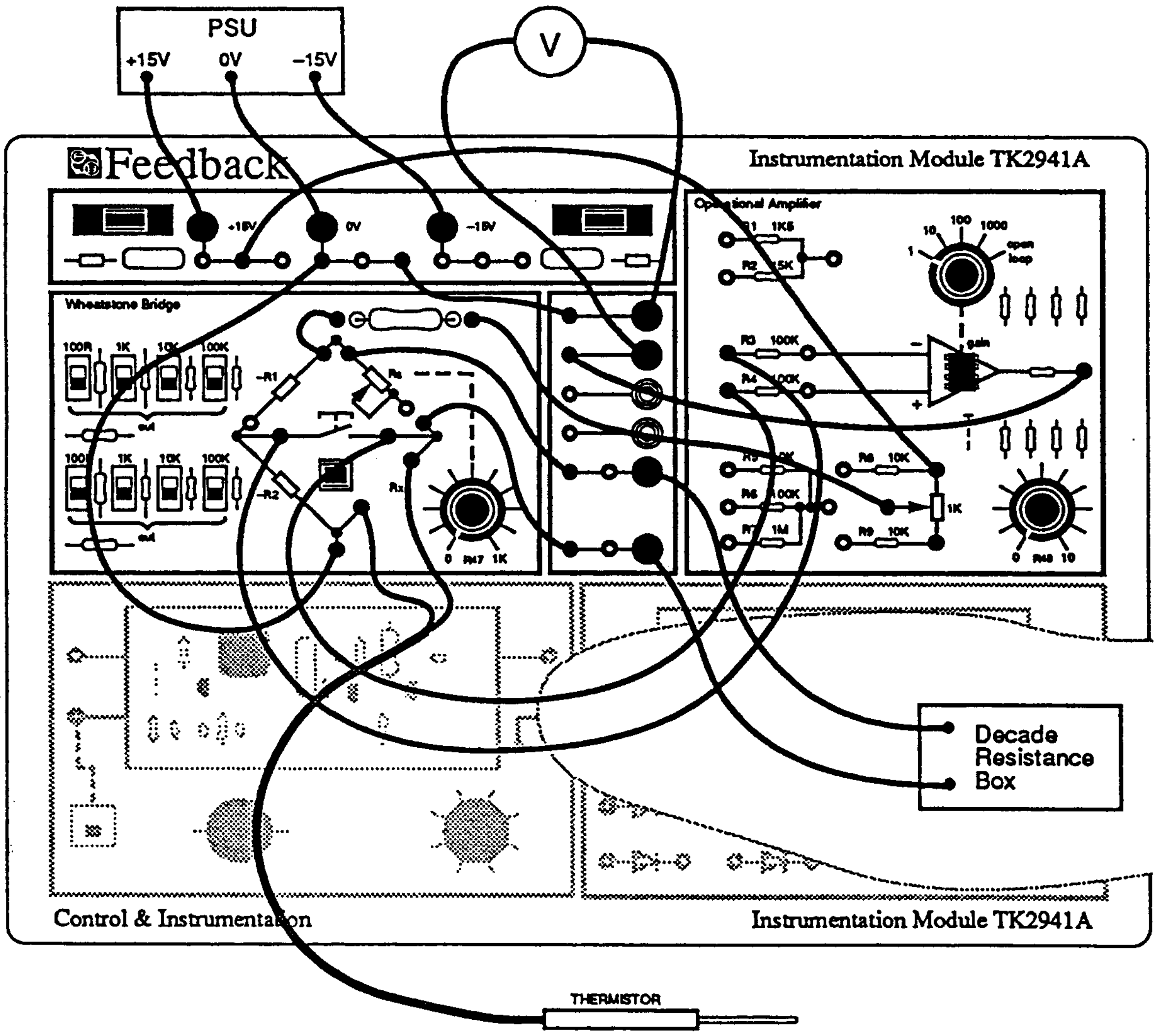


Fig 5.20.7

Question 20.7

What maximum power is now dissipated in the thermistor at balance?

Set up the circuit given in fig 5.20.7.

On the Wheatstone Bridge set switches SW3 and SW6 'in' and all other switches 'out'.

Switch on the power supply and set the potentiometer control on the Operational Amplifier to give 1V dc across the bridge circuit.

We are now in a position to make measurements of the thermistor resistance at different temperatures with negligible self-heating. This is often called 'zero-power measurement'.

Insert the probe and a mercury thermometer together into the calibration tank filled with water as described in Assignment 18. When the thermometer is steady at room temperature balance the bridge and note temperature and resistance.

Also insert into melting ice for a reading at 0°C.

Clip the tank to the heat bar at Notch 20, wait about 5 to 10 min for the temperature to stabilise and rebalance the bridge to read the thermistor resistance. Note the result and the thermometer reading in your own copy of the table in fig 5.20.7. Repeat at notches 18, 16, etc until a temperature of about 100°C is reached.

Notch Nº	Temperature θ (°C)	Resistance R (Ω)

Fig 5.20.7

Exercise 20.2 ***Plot a graph with temperature, θ, horizontally and resistance, R, vertically from your results.***

Question 20.8 ***Is the curve linear?***

Remove the calibration tank from the heat bar and insert the probe instead into the transducer mount, placing this at some arbitrary position on the bar. After a few minutes measure R and from your curve determine the temperature at that point on the bar. Repeat for several other positions. You could also try measuring your own body temperature, using the probe in place of a clinical thermometer.

Dissipation Constant

When a thermistor is to be used in a temperature measurement or control system there will usually be two conflicting requirements.

Greatest possible sensitivity from the detector circuit requiring as large an energising current as possible.

Limited error, implying a limit to the self-heating effect.

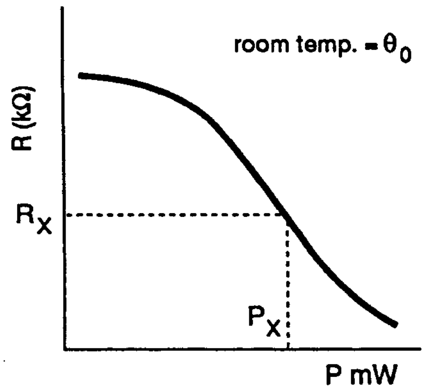
The 'dissipation constant' is a parameter which helps to resolve this conflict by specifying how much power can be dissipated by the energising current without causing more than the permitted amount of self-heating.

It is defined as:

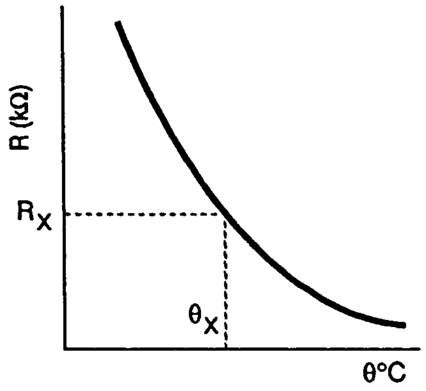
> Dissipation Constant = mW of power dissipation which will cause a temperature rise of 1°C.

Obviously the value of the constant will depend upon the thermal conduction characteristics of the medium in which the thermistor is situated because if this is high, more power will be needed to raise the temperature by 1°C than if it is low. That is why you obtained different curves in Practical 20.1, Question 20.4.

Those curves showed how resistance varied with power dissipation whilst the curve you have just obtained in Practical 20.2 showed how resistance varied with temperature. We can thus combine the information from these two graphs to show how the thermistor temperature is affected by its power dissipation. Fig 5.20.8 shows typical graphs.



(a) - Practical 20.1



(b) - Practical 20.2

Fig 5.20.8

By taking a number of values of R_x at arbitrary intervals you can find corresponding values of P_x and θ_x.

θ_x is the actual temperature of the thermistor when the ambient temperature is θ_o and it is dissipating a power P_x. Thus P_x causes an increase in temperature above ambient of $(\theta_x - \theta_o)$°C.

Exercise 20.3

Find P_x, θ_x and $(\theta_x - \theta_o)$ for about eight values of R_x, noting P_x in each case for each of the two graphs (in air and in water) from Practical 20.1. Now plot P_x (air) and P_x (water) against $(\theta_x - \theta_o)$ as shown in fig 5.20.9 using linear graph paper.

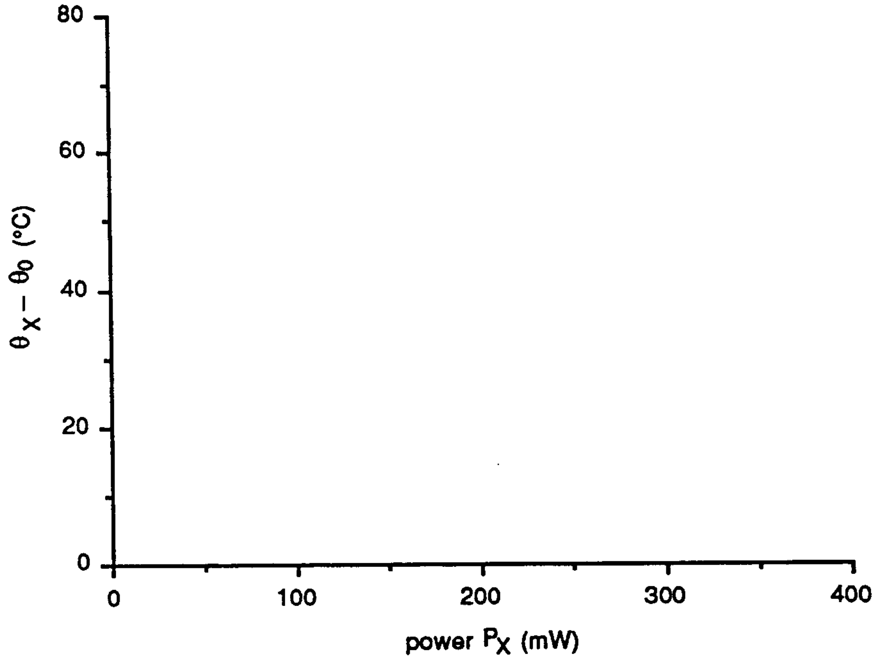


Fig 5.20.9

You should find that your curves are very nearly straight lines passing through the origin, allowing for reasonable experimental errors.

Exercise 20.4

From your graphs of fig 5.20.9 work out the slopes in terms of mW per °C for air and water immersion. These slopes are the dissipation constants for the two conditions.

PRACTICAL ASPECTS

Tolerance and Interchangeability

Considered simply as a means of detecting temperature changes the thermistor is an inexpensive, reliable and sensitive transducer. Until recently however, it was not very suitable for making measurements of absolute temperature to accuracies of better than about ±5°C, This arose from the difficulty of ensuring that manufactured devices conform over the whole of their range to a standard calibration curve.

For example suppose that in a typical case the resistance of a thermistor at 25°C is always within ±10% of nominal and within ±15% at 100°C. Applied to a graph of R versus θ as in fig 5.20.10 this gives a greater absolute temperature tolerance at 100°C than at 25°C, although as a percentage it is smaller due to the lower slope of the curve at 100°C.

Most practical applications require an accuracy of about ±1°C and to achieve this with the sort of tolerances of fig 5.20.10 would demand special steps to correct for the error at the temperatures of operation. Nowadays better control over the manufacture has made available devices which are interchangeable within ±1°C, 0.5°C or even 0.2°C over a wide range of operating temperatures.

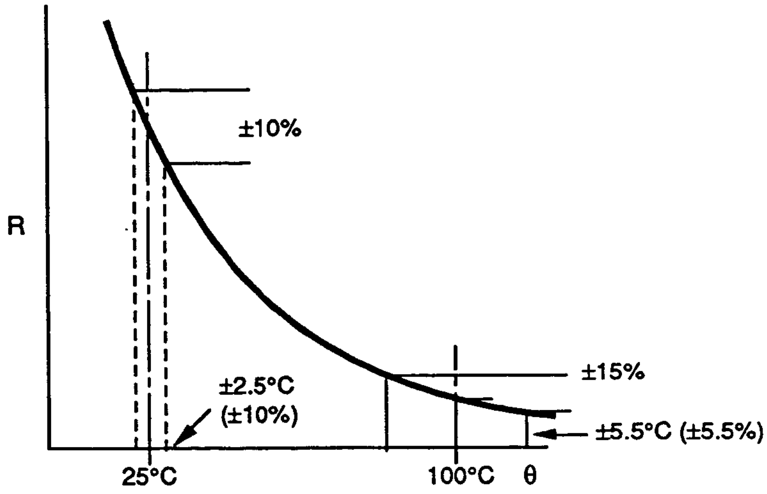


Fig 5.20.10

Linearisation

In some applications it is desirable that the variation in measured resistance should be linearly related to temperature. A very simple way of achieving this is to connect a resistor of suitable value in parallel with the thermistor. The resultant resistance is then

$$R = \frac{R_c R_T}{R_c + R_T}$$

Where R_T = thermistor resistance

R_c = compensating resistance

R_c is chosen so that the slope of the R/θ curve is the same at each end of the operating range and gives a near approximation to linearity.

For the thermistor used in this Assignment a value around 400Ω is optimum. As an additional exercise you could try computing values of R for various values of R_T and plotting them against θ. Although linearity is achieved it is at the cost of sensitivity since the slope of R/θ is reduced at all points to the lowest value in the operating range, as indicated in fig 5.20.11.

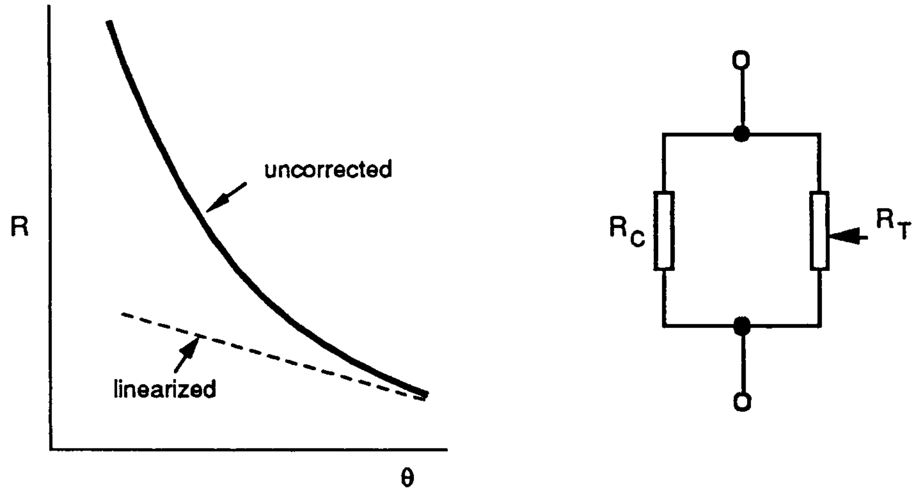


Fig 5.20.11

Enclosures and Speed of Response

The speed with which a thermistor responds to rapid temperature changes depends not only upon the size and thermal mass of the thermistor bead itself but also upon the type of enclosure it is contained in. Robust enclosures are sometimes necessary to give mechanical protection, for example if the medium being measured were corrosive, but otherwise the fastest response is obtained when no enclosure is used.

Fast response and high dissipation constant are conflicting parameters since the former requires low mass whilst the latter requires high mass.

Design Procedure

Designing a suitable detector circuit and selecting the right thermistor is usually a compromise between sensitivity and accuracy.

Suppose it is desired to measure a liquid temperature to an accuracy of ±2°C using a thermistor of maximum absolute tolerance of ±1°C over the range of 40°C to 80°C. The dissipation constant of the thermistor in the liquid is 5mW/°C. The resistance of the thermistor at mid-range is, say 1kΩ so to obtain optimum sensitivity we might use a bridge whose arms are 1000Ω as in fig 5.20.12.

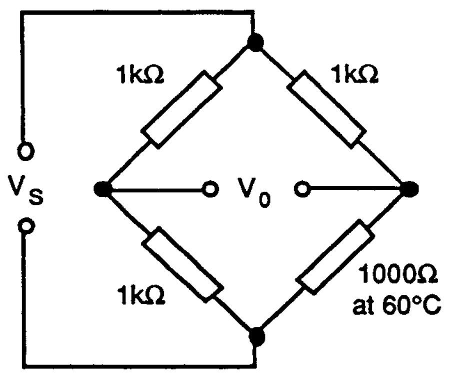


Fig 5.20.12

The maximum power dissipated in the thermistor will occur when R_T, its resistance, is 1000Ω and will be:

$$P = \frac{V_s^2}{4}\ \text{mW}$$

In order that it should not cause a self-heating error of more than 1°C this power must be less than 5mW so that V_s may not be greater than about 4.5V. If the slope of the R/θ curve at 60°C is, say, 30Ω/°C then the output V_o per °C change for V_s = 4.5V can be calculated to be about 30mV/°C.

At the high end of the range the sensitivity would be somewhat less and if insufficient for the application would necessitate a more sensitive thermistor.

Applications

Quite apart from their use as detectors for the measurement and control of temperature, in which role they find wide application, there are numerous other uses to which they can be put. Just a few of these are briefly described here.

RMS current detector

When excited by an alternating current the thermistor resistance is controlled by the heating effect of the current and, provided the frequency is high compared with the thermistor time constant, this will be a measure of rms value. This effect is often used in oscillator circuits to give good control over the oscillation amplitude.

Liquid level detector When energised by a suitable current the self-heating effect in air causes the resistance to drop sufficiently to light the lamp but when the liquid rises to immerse the detector the cooling effect raises the resistance and the lamp extinguishes. You could experiment with this idea yourself, using components available in the TK2942 kit.

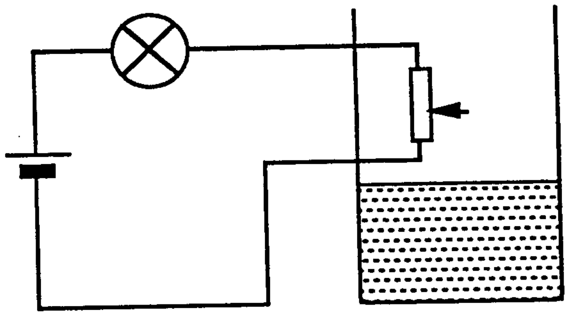


Fig 5.20.13

Flowmeters Self-heated thermistors will cool more in a rapidly moving stream of gas or liquid than in a slowly moving one and so give an indication of flow rate.

Thermal Conductivity A self-heated thermistor immersed in a stationary medium cools more or less according as its conductivity is higher or lower.

Question 20.1 When current flows in resistance heat is generated.

Question 20.2 It is necessary to avoid over-energising a thermistor when using it to measure external temperature.

Question 20.3 The 220Ω series resistor limits the current that can flow. Without it, as the thermistor heats up it takes more and more current due to reduction of resistance. Eventually thermal runaway occurs and the thermistor is destroyed.

Exercise 20.1 Typical graphs of thermistor resistance against power dissipation are shown in fig E5.20.4 for both air and water immersion.

I (mA)	V (V)	I' (mA)	$R = V/I'$ (kΩ)	P = V x I (mV)
AIR 0	0.5mV	0	∞	0
1	2.070	1	2.07	2.07
2	3.759	2	1.88	7.52
4	6.13	4	1.53	24.52
10	8.13	10	0.81	81.0
15	8.29	15	0.55	124.35
20	9.45	20	0.48	189.0
WATER 1	2.007	1	2.01	2.01
2	3.86	2	1.93	7.72
4	6.71	4	1.68	26.84
10	10.07	10	1.01	100.7
15	10.47	15	0.70	157.05
20	10.31	20	0.52	206.2

		Air	Water
Room temperature:	Start:	21°C	22°C
	Finish:	21°C	22°C

Fig E5.20.4

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 20

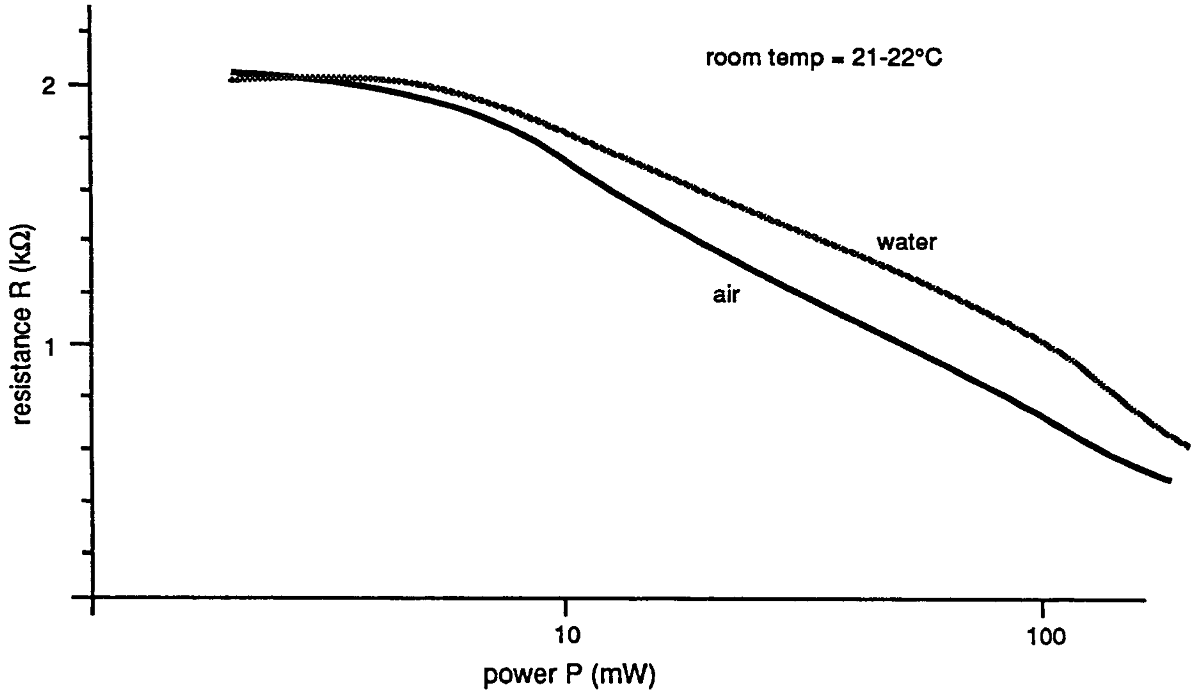


Fig E5.20.5

Question 20.4

The difference between the curves is due to the better conductivity of water, more power being needed to raise the temperature by the same amount.

Question 20.5

The power needed to reduce R by 1% of its initial value is typically and approximately

a) 1.5mW for air

b) 2.1mW for water

Question 20.6

The power dissipated in the thermistor in the circuit of fig 5.20.6 is greater than will cause a 1% fall in resistance as found in Question 20.5.

Question 20.7

The maximum power dissipated in the thermistor in the circuit of fig 5.20.7 occurs at minimum resistance of, say, 100Ω and is found as shown in fig 5.20.14.

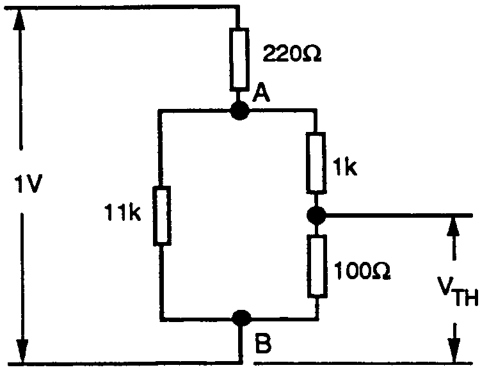


Fig E5.20.14

$$R_{AB} = \frac{11 \times 1.1}{12.1} = 1K\Omega$$

$$V_{TH} = 1 \times \frac{1}{1.22} \times \frac{0.1}{1.1} = 0.0745V$$

$$P = \frac{0.0745^2}{0.1} = 0.055mW$$

Exercise 20.2 A typical graph of θ against R is shown in fig 5.20.15

Notch Nº	Temperature θ (°C)	Resistance R (Ω)
off heat bar	0	4680
20	23	1930
18	42	1001
16	48.5	814
14	51	753
12	58	610
10	61	560
8	67.5	461
6	76	362
4	85	276
2	94.5	183

Fig E5.20.7

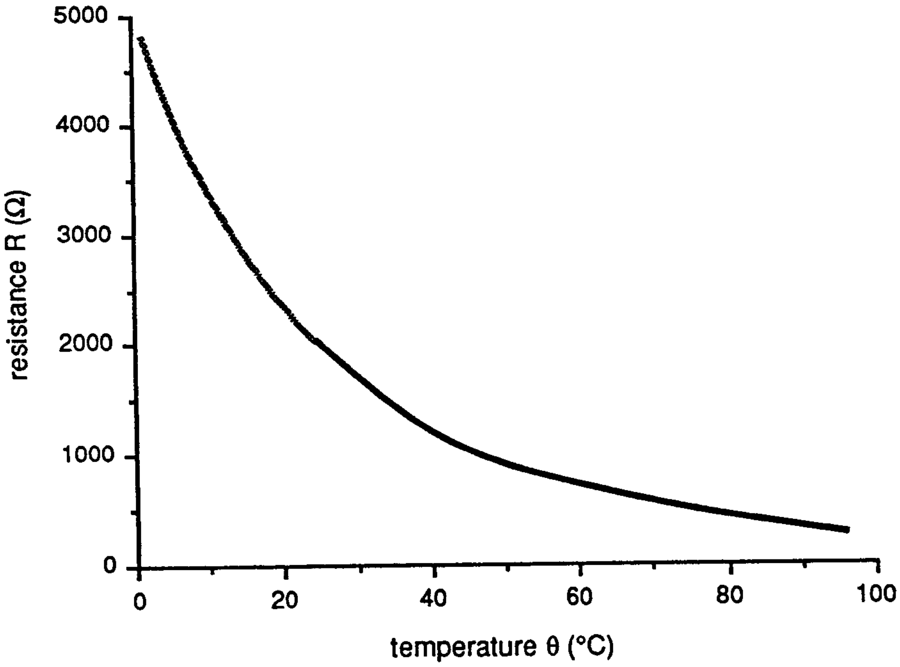


Fig 5.20.15

Question 20.8 The curve of R/θ is clearly not linear.

Resistance R_x (Ω)	Power P_x (mW)		Thermistor Temperature θ_x (°C)	Room Temperature θ_o (°C)	$\theta x - \theta o$ (°C)
	air	water			
250	175	350	86	20.5	65.5
500	125	220	64	20.5	43.5
750	94	142	51	20.5	30.5
1000	66	100	42.5	20.5	22.0
1250	43	64	36	20.5	15.5
1500	25	38	31	20.5	10.5
1750	15	20	26	20.5	5.5
2000	4	4.6	22	20.5	1.5

Fig 5.20.16

Exercise 20.3

Typical graphs obtained in this exercise for P again (θ_x-θ) are given in fig E5.20.9

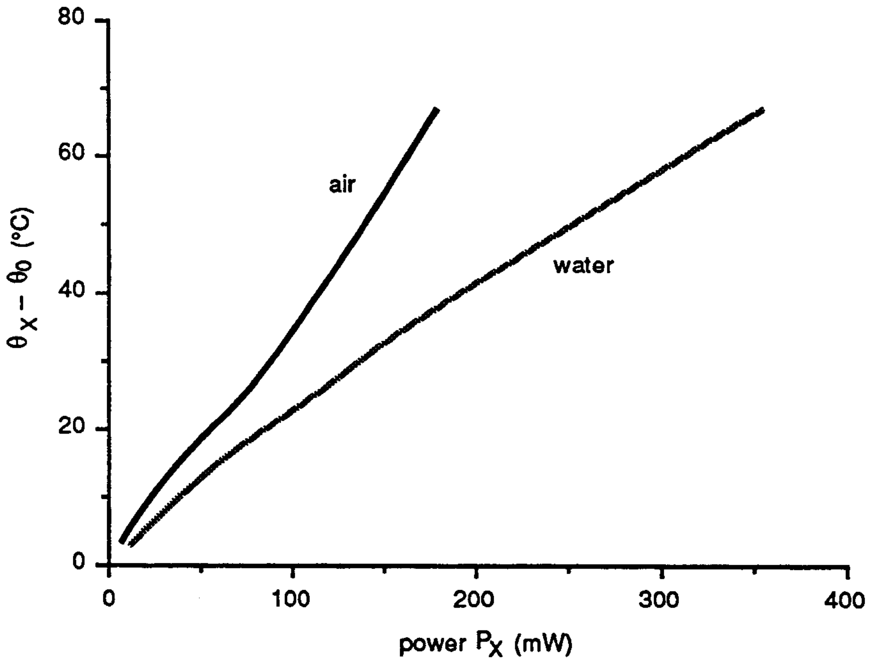


Fig E5.20.9

Exercise 20.4

	Air	**Water**
Dissipation Constant :	2.8mW/°C	5.5mW/°C

RESISTANCE THERMOMETRY — ASSIGNMENT 21

CONTENT

The behaviour of a transducer with a positive temperature coefficient is investigated. A platinum resistance transducer is used as a temperature measuring device.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	–	Heat Bar
1	–	Thermometer
1	–	Calibration Tank
1	–	Transducer — platinum resistance with flying leads. Yellow sleeve.
1	–	Transducer Mount
1	–	Decade Resistance Box 1Ω to 100kΩ
1	–	Power Supply ±15V d.c *(eg Feedback PS446)*
1	–	* DC Voltmeter 15V

* Alternatively a multimeter may be used.

PRELIMINARY PROCEDURE

Switch on the Heat Bar and allow it to heat up to a steady temperature. This will take about 45 minutes.

PRACTICALS

21.1 Dissipation Constant

21.2 Using the Platinum Resistance Thermometer

21.3 A Direct-reading Thermometer

RESISTANCE THERMOMETRY

ASSIGNMENT 21

OBJECTIVES

When you have completed this assignment you will:

- Have measured the dissipation constant for the platinum resistance transducer.
- Have constructed a direct-reading thermometer based on a platinum resistance transducer.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Be familiar with the use of the heat bar and preferably have completed Assignment 18, The Heat Bar — Familiarisation.
- Understand the operation of a Wheatstone Bridge circuit.
- Understand the term dissipation constant and recognise the self-heating effect in a thermal transducer.

INTRODUCTION

Many conductive materials possess positive temperature coefficients of resistance, that is their resistivity increases with temperature rise.

The percentage change of resistance for 1°C rise is usually much smaller than it is for negative coefficient devices like the thermistor studied in Assignment 20. Typically a pure metal could have a positive coefficient of about 0.4%/1°C whereas the minimum coefficient for a typical thermistor at 100°C could be about –2.5%°C. Thus a thermometer based on a pure metal will be much less sensitive.

Why then bother to use the method?

The answer is that for certain materials especially, the relationship between resistivity and temperature is very accurately predictable and can be relied upon to stay constant from one sample to another and over very long periods of time. Thus resistance thermometers, as they are called can be used as convenient sub-standards or even standards of temperature.

The metal platinum is especially useful as it is resistant to corrosion and general deterioration and has a resistance-temperature relationship which is nearly linear over a small range of temperature and accurately parabolic over the range of positive temperatures from 0°C to 630°C.

Over this range the following equation holds true.

$$R_\theta = R_o (1 + A\theta + B\theta^2)$$

where R_o = resistance at 0°C
R_θ = resistance at θ°C

A, B are typical constants of:

$A \approx 0.00398$
$B \approx 0.588 \times 10^{-6}$

For temperatures below 0°C a third term dependent upon θ^3 appears.

Putting $\theta = 100$°C in the above equation gives:

$$R_{100} = R_o (1 + 0.398 - 0.588 \times 10^{-2})$$

Thus even at this temperature the θ^2 term contributes about 0.006 compared with 0.4 for the θ term. Since 0.004

corresponds to 1°C, 0.006 represents 1.5°C, an appreciable amount which cannot be neglected in accurate measurement.

Self-Heating

It is important to ensure that the energising current used in the measurement of R_θ does not cause heat dissipation sufficient to artificially raise the platinum temperature.

If you carried out Assignment 20 you will recall that the dissipation constant is the power dissipation needed to cause an increase in temperature of 1°C and that the constant depends upon the conductivity of the surrounding medium.

Suppose that it takes PmW to cause a 1°C rise, then if the accuracy of measurement hoped for is, say ±0.2°C the power dissipated by the measuring current in the platinum element must be less than 0.2PmW.

We will start by making a measurement of the dissipation constant.

PRACTICAL 21.1

Dissipation Constant Connect up the circuit shown in fig 5.21.1 and use the potentiometer control on the Operational Amplifier to give 2V dc across the bridge. Support the probe in still air at room temperature and carefully balance the bridge, using an amplifier gain of 100.

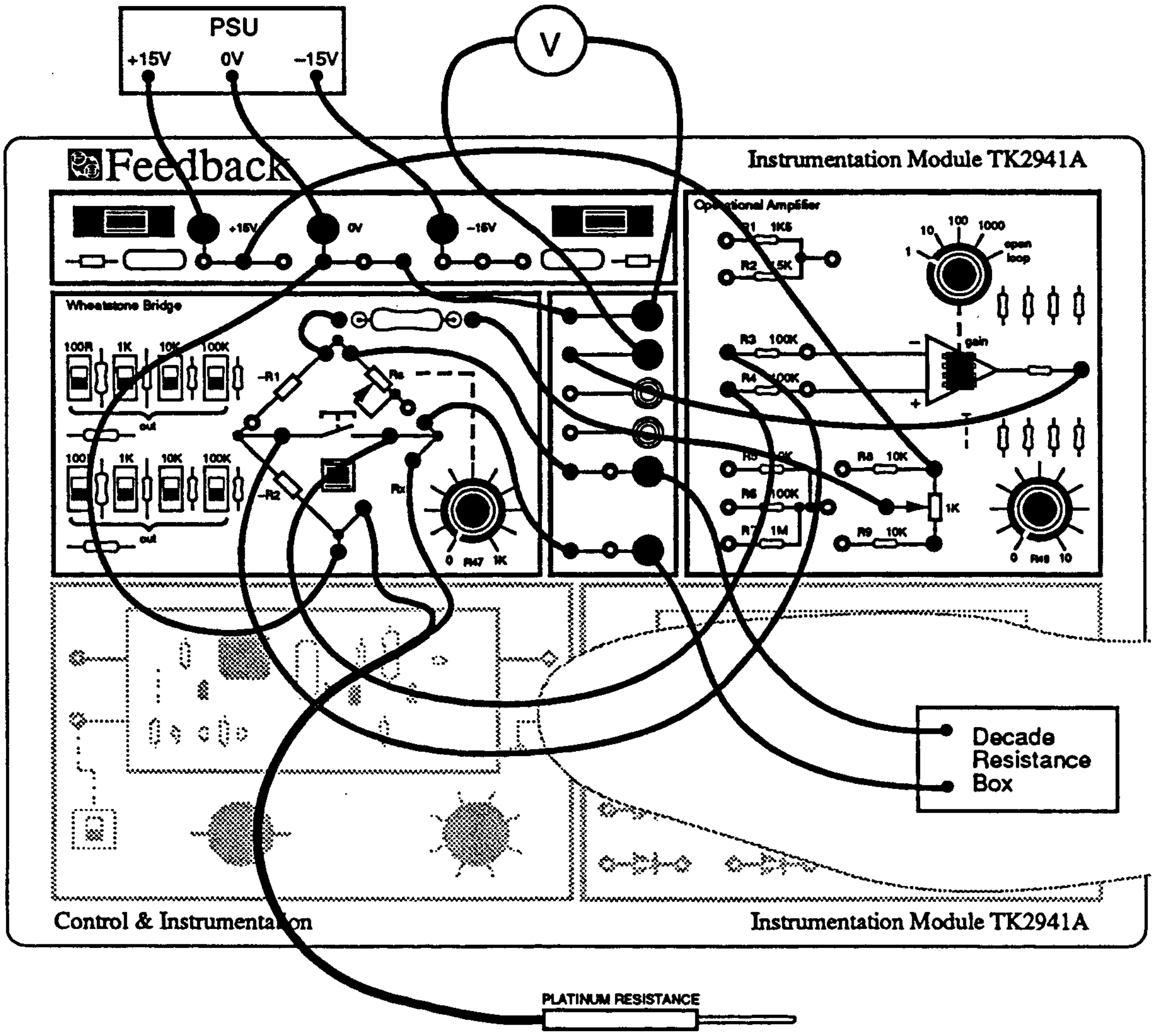


Fig 5.21.1

On the Wheatstone Bridge set switches SW1 and SW5 'in' and all other switches 'out'.

If your decade resistance box has no steps lower than 1 ohm estimate the tenths of an ohm required to give balance by noting the meter reading caused by 1Ω change and comparing it with the estimated reading needed to give balance.

Now increase the bridge supply to 10V dc. An increase of R_x should be observed and the bridge should be rebalanced as soon as steady conditions are reached (about 10-15 seconds).

Exercise 21.1

Calculate the voltage across the platinum resistance, R_x, for each setting of the supply voltage and hence, find the power in mW dissipated for each case.

Call these powers P_2 and P_{10}.

Also calculate the percentage change in R_x.

ie $$\frac{R_{10} - R_2}{R_2} \times 100 = Y\% \text{ (say)}$$

Now if we assume that a 0.4% change in R_x means a 1°C change in temperature we can say that a power increase of $(P_{10} - P_2)$ causes Y% resistance change and this corresponds

to $\frac{Y}{0.4}$ °C temperature rise.

Therefore the dissipation constant is:

$$\frac{(P_{10} - P_2)\ 0.4}{Y} \text{ mW/°C}$$

Calculate this value from your results. When you have a figure use it to decide what is the maximum energising voltage you can apply to the bridge of fig 5.21.1 without causing a self-heating error of greater than 0.2°C.

Now set the bridge voltage to the value you have found.

PRACTICAL 21.2

Using the Platinum Resistance Thermometer

The object of a thermometer is, of course, to read temperature. In the case of the platinum thermometer we wish to measure its resistance and then be able to say — 'that corresponds to X°C'.

Question 21.1

Could you do that easily from the equation above? If not, what procedure could you follow?

Your answer should be that it is not easy to use the equation directly since it expresses R in terms of θ rather than θ in terms of R. One possible solution is to solve the equation as a quadratic in θ to give θ as a function of R_1, R_o, A and B and although this can be done the calculations involved are tedious if accurate results are required.

Alternatively we could plot a careful graph of R_θ for different values of θ and use this to look up θ for measured values of R_θ. Again this is possible but, due to graphical errors, does not take full advantage of the inherent accuracy of the platinum resistance thermometer.

In practice the method used is as follows:

Write down one equation for a temperature of 100°C and one for θ°C.

$$R_{100} - R_o (1 + 100A + 10^4B)$$

Thus $$R_{100} - R_o = R_o (100A + 10^4B)$$

Similarly $$R_\theta - R_o = R_o (\theta A + \theta^2 B)$$

Dividing equations and multiplying by 100.

$$100 \frac{R_\theta - R_o}{R_{100} - R_o} = \frac{\theta A + \theta^2 B}{A + 100B}$$

The lefhand side of this equation is called the 'platinum temperature' and denoted by θ_p.

ie $$\theta_p = 100 \frac{R_\theta - R_o}{R_{100} - R_o}$$

Then expanding:

$$\theta - \theta_p = \theta - \frac{\theta A + \theta^2 B}{A + 100B}$$

$$= \frac{\theta(A + 100B) - \theta A + \theta^2 B}{A + 100B}$$

$$= \frac{\theta A + \theta 100B - \theta A + \theta^2 B}{A + 100B}$$

$$= \frac{\theta(100B - B\theta)}{A + 100B}$$

To simplify the calculations an equation called a 'difference equation', using a constant D, where $D = \frac{-10^4 B}{A + 100B}$ may be employed.

Substituting $D = \frac{-10^4 B}{A + 100B}$ in the righthand side of the equation:

$$\theta - \theta_p = \frac{\theta(100B - B\theta)}{A + 100B}$$

gives $$\theta - \theta_p = \frac{D\theta}{100}\left(\frac{\theta}{100} - 1\right)$$

From the values given for A and B in the Introduction to this assignment, $D \approx 1.5$.

The difference equation is used by successive approximation to give an accurate computation of θ, given θ_p. The first approximation is usually obtained from a table, a part of which is reproduced here.

θ_p	0	20	40	60	80	100	120	140
θ	0	19.76	39.64	59.64	79.76	100	120.4	140.9

The first approximation is substituted in the equation for D to give a second, which is again substituted and so on until no further change occurs.

Example

Suppose $R_o = 100\Omega$

Then $R_{100} = R_o (1 + 100A + 10^4B)$

$= 100 (1 + 0.398 - 0.00588)$

$= 139.2\Omega$

If R_θ is, say 105.5 ohm, what is θ?

θ_p is first calculated as:

$$\theta_p = 100 \frac{R_\theta - R_o}{R_{100} - R_o}$$

$$= 100 \frac{(105.5 - 100)}{139.2 - 100}$$

$$= 14.03°C$$

From the table we can get an approximation value of θ by linear interpolation to be:

$$\frac{19.76 \times 14.03}{20} = 13.86°C$$

Put this into the equation:

$$\theta - \theta_p = \frac{1.5\theta}{100}\left(\frac{\theta - 1}{100}\right)$$

$$= \frac{1.5 \times 13.86}{100}(0.1386 - 1)$$

$$= -0.179$$

Therefore $\theta = \theta_p - 0.179$

$$= 14.03 - 0.179$$

$$= 13.851°C$$

This is very close to the first approximation but we can try one more calculation

$$\theta - \theta_p = \frac{1.5 \times 13.86}{100}(0.13851 - 1)$$

$$= -0.17898$$

$$\theta = \theta_p - 0.17898$$

$$= 13.851°C$$

This is obviously as far as it is worth going because we already have two decimal places whereas the self-heating effect alone could cause errors up to 0.2°C.

Because the platinum thermometer is intrinsically accurate it seems pointless to calibrate it against a mercury thermometer of lesser accuracy. Therefore in this practical we shall simply confirm the relationship between R_{100} and R_o and then use the thermometer to make accurate measurements of some arbitrary temperatures.

With the bridge set as in fig 5.21.1 and supplied by the voltage that you calculated would give a self-heat error less than 0.2°C, place the probe in stirred melting ice and balance the bridge carefully to find R_o.

Note You may need to increase the amplifier gain to 1000 to obtain adequate senstitivity. Interpolate on the meter to obtain R_o to the nearest 0.1Ω.

Now mount the water tank at the hot end of the heat bar and wait till the water boils. Insert the probe into the boiling water and rebalance the bridge to find R_{100}.

Exercise 21.2

Calculate accurately to 3 or 4 decimal places the ratio

$$\frac{R_{100}}{R_o}$$

Question 21.2

Does the ratio agree with that given above in the discussion?

Now mount the probe in the Transducer mount and place at some arbitrary point along the heat bar, rebalancing when steady to give R_o.

Exercise 21.3

Carry out the successive approximation method explained earlier to find the temperature at that point of the bar.

Repeat the experiment placing the probe at the extreme hot end of the bar — this way you can measure the highest temperature accurately (this is above the boiling point of water).

Measure your body temperature, using the probe as you would a clinical thermometer.

PRACTICAL 21.3

A Direct-reading Thermometer

Because the platinum thermometer is almost linear in response a good direct-reading thermometer can be constructed quite easily.

If a substantially constant current is passed through the element the resistance changes can be converted linearly to voltage changes, amplified and displayed on a meter. Fig 5.21.2 shows a suitable circuit.

The measuring element, as you should already have found in previous Practicals, changes typically from 100Ω at 0°C to 138.5Ω at 100°C.

If 0-100°C is to correspond to 0-10V with a gain of 1000, the input variation must be 10mV between 0 and 100°C. Thus the current required is:

$$I = \frac{10}{38.5}\,\text{mA} = 0.26\text{mA}$$

The high series resistor (15kΩ) will keep the current almost constant and V must be about (15 + 0.1) x 0.26 = 3.93V.

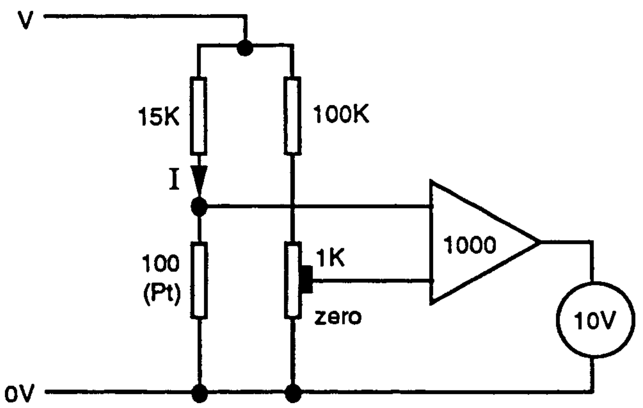


Fig 5.21.2

If the same voltage is used to supply the balancing potentiometer, any small changes in V will have little effect. The potentiometer offsets the standing potential caused by I flowing in 100Ω at 0°C.

Construct this circuit as shown in fig 5.21.3.

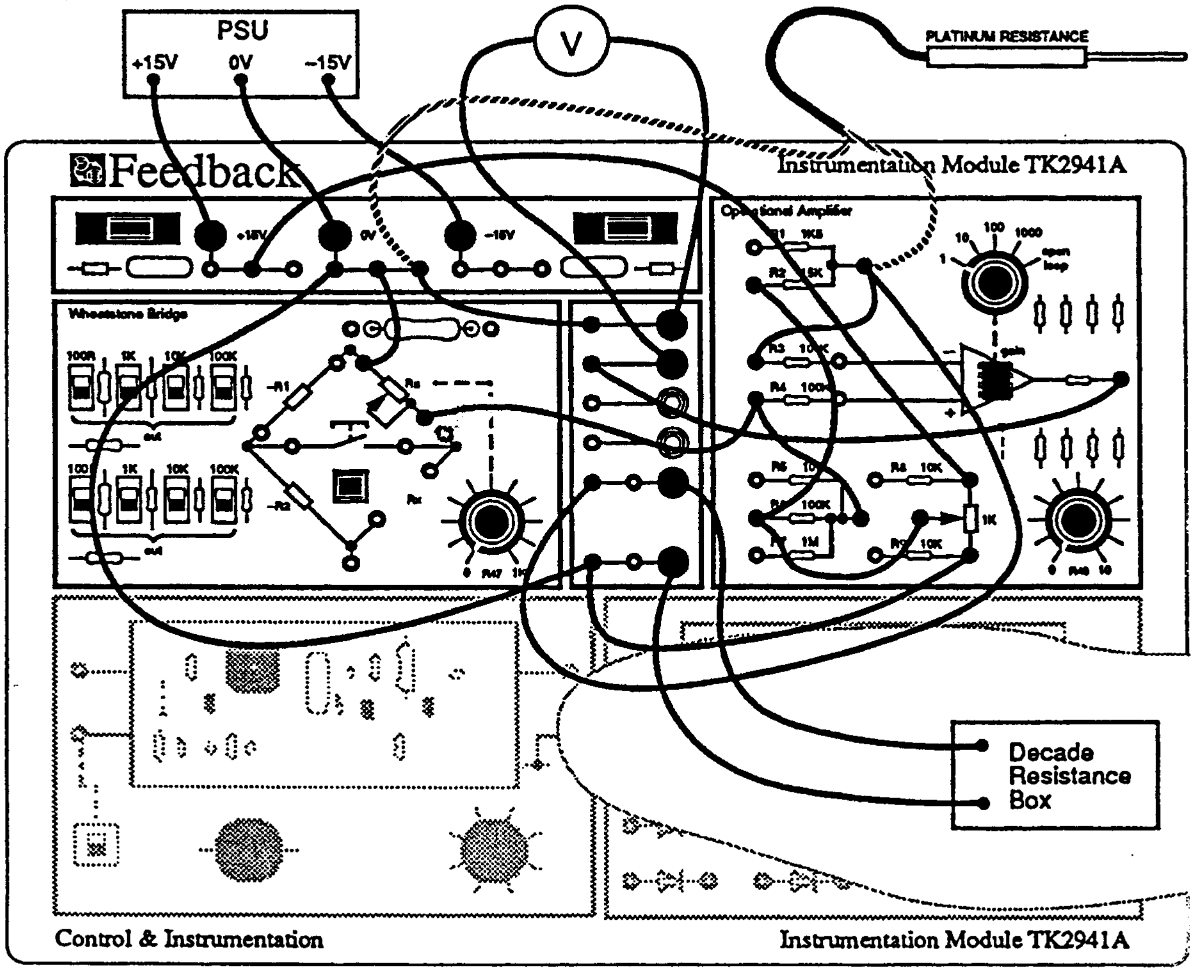


Fig 5.21.3

To set up the circuit proceed as follows:

Set the variable d.c voltage to about 4V.

Set the gain control on the Operational Amplifier to 1000.

Substitute a decade resistance box temporarily for the probe and set it at 100Ω.

Adjust the potentiometer R47 to give zero output on the meter.

Set the decade box to 138Ω.

Adjust the variable d.c volts, using the potentiometer control on the Operational Amplifier, so that the meter reads −10V.

Repeat this procedure until both settings are correct.

Replace decade box by the probe.

You should now be able to read any temperature between 0 and 100°C directly to an accuracy of about ±0.5°C.

PRACTICAL ASPECTS

As the platinum thermometer is an intrinsically accurate transducer it follows that to obtain the best results from it demands that careful attention is paid to the elimination of all possible sources of error.

These include:

- The resistance of the probe leads up to the platinum element and possible variation of this resistance with temperature.
- Thermocouple emf's caused by dissimilar metal junctions at unequal temperatures in the probe circuit.
- Errors in determining R_{100} and R_0; eg, due to changes of boiling point with water impurities or with atmospheric pressure.

It was not possible to take account of all these possibilities in the assignment practicals so if you found that your body temperature worked out to be 100°F or more, don't assume you are running a temperature!

For really accurate measurement the purest platinum is usec and the construction is carefully designed to overcome such error sources. Fig 5.21.4 shows a typical construction suitable for precise laboratory measurements.

P1 and P2 are the terminations of a spiral of fine platinum wound on an insulating mica frame whilst C1 and C2 are the ends of a compensating lead connected to a short length of the same fine wire. This compensating lead is placed in the opposite arm of the bridge to the main winding so that changes in lead resistance and any thermoelectric potentials are cancelled out.

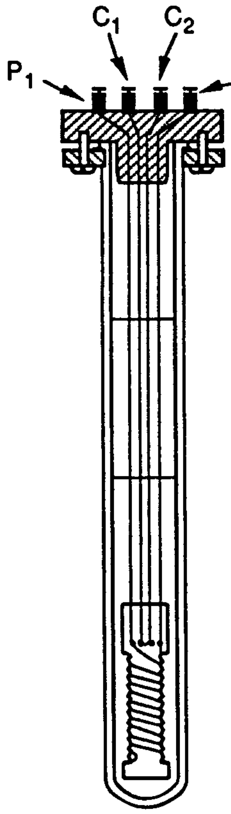


Fig 5.21.4

The probe used in the assignment is an example of the type of industrial element used in modern applications. The element is enclosed in a stainless steel tube and is very rugged and resistant to shock and vibration. Fig 5.21.5 shows the extent of the actual temperature-sensitive length of the probe.

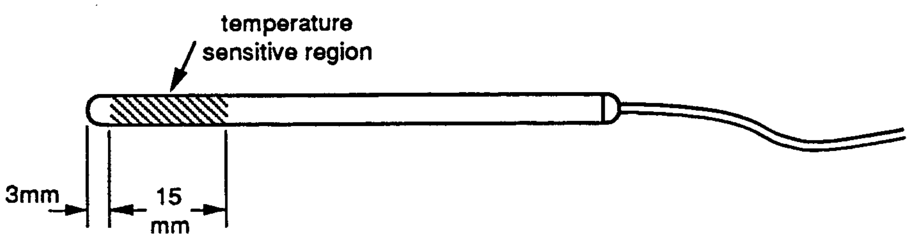


Fig 5.21.5

This probe can be used at temperatures up to 300°C.

Application

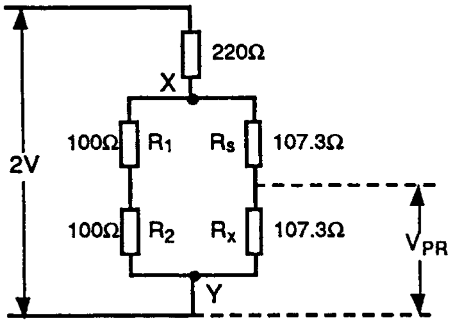
Platinum thermometers have the considerable advantages of near-linearity of response over the usual ranges of interest, good repeatability of indication and stability. They are, however, relatively insensitive and also expensive so they are used only where precision is of the greatest importance as, for example, in certain chemical processes where temperature of reagents must be controlled to accuracies of better than ±1°C.

Exercise 21.1

Typical results for the self-heating calculation are as follows:

2-volt energisation $R_2 = 107.3\Omega$

Power dissipated



$$R_{xy} = \frac{200 \times 214.6}{414.6} = 103.5\Omega$$

$$V_{PR} = 2 \times \frac{103.5}{323.5} \times \frac{1}{2} = 0.32\text{V}$$

$$P_2 = \frac{V^2}{R} = \frac{0.32^2}{107.3} = 0.95\text{mW}$$

Similarly:

10-volt energisation $R_{10} = 108.7\Omega$
$P_{10} = 4.75\text{mW}$

Therefore:

$$Y = \frac{108.7 - 107.3}{107.3} \times 100 = 1.305\%$$

Hence dissipation constant:

$$\frac{(P_{10} - P_2)\,0.4}{Y} = \frac{(4.75 - 0.95)\,0.4}{1.305} = 1.16\text{mW/°C}$$

To cause no more than 0.2°C rise the power must thus be less than

$$\frac{1.16\text{mW}}{5} = 0.232\text{mW}$$

A bridge voltage of 2V caused 0.95mW dissipation so the maximum voltage usable is

$$2 \times \frac{0.232}{0.95} \cong 1V$$

Question 21.1

Answered in the text.

Exercise 21.2

Typically R_{100} should be 138.5Ω

R_o should be 100Ω giving a ratio 1.385.

Question 21.2

The ratio 1.385 is rather less than that previously mentioned but is correct for the particular element used.

Exercise 21.3

This is just a repetition of the procedure already detailed. Within the temperature range used the first approximation obtained by a linear interpolation between the figures given in the table is usually sufficiently accurate.

NOTES

ON-OFF TEMPERATURE CONTROL — ASSIGNMENT 22

CONTENT

A thermostatic type of temperature control system will be constructed and its operation investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941M	Measurements Package
1	–	Heat Bar
1	–	Transducer - platinum resistance with flying leads. Yellow sleeve.
1	–	Thermal reed relay
1	–	Bimetal thermostat
1	–	Transducer Mount
1	–	Power Supply ±15V dc *(eg Feedback PS446)*
2	–	* DC Voltmeter 15V

* Alternatively multimeters may be used.

PRACTICALS

22.1 Thermal Reed Switch

22.2 The Bimetal Switch

OBJECTIVES

When you have completed this assignment you will:

- Understand the operation of a basic on-off closed loop control system.
- Recognise the terms 'duty ratio', 'hysteresis', 'resolution' and 'cycle-time'.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Be familiar with the use of the heat bar and preferably have completed Assignment 18, The Heat Bar – Familiarisation.
- Understand the principles of resistance thermometry and preferably have completed Assignment 21, Resistance Thermometry.

INTRODUCTION

In this Assignment we are going to construct a simple temperature control system but first we must take a brief look at the various ways in which control may be exercised.

Suppose a vessel of liquid is to be heated to 60°C and that the heating element to be used is an electrical one capable of heating the full vessel to 120°C and has a power of, say, 2000 watts.

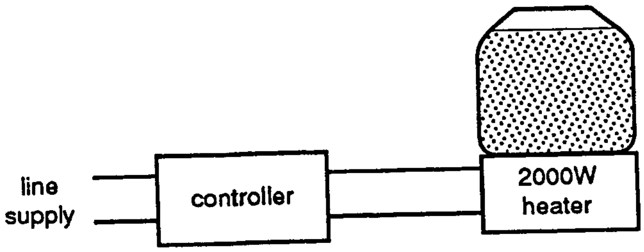


Fig 5.22.1

Obviously, if the heater were simply switched on and left on the vessel would heat to 120°C.

How can the power input be controlled so as to reduce the heating effect to give 60° instead, bearing in mind the rather large power to be controlled? Briefly, the possible methods, in order of complexity, are as follows.

Manual open-loop on-off

Since the power required to reach 60°C will be about half the available power we could switch the heater on manually for some period of time and then off again for the same period. Then the average heating power would be half the maximum available.

This is of course both tedious and inaccurate and subject to the effects of ambient temperature and changes in the quality of liquid in the vessel.

Automatic open-loop on-off

We could replace the manual switch by one automatically switched on and off at equal time intervals. Also, by altering the relative lengths of the on and off periods, other temperatures could be obtained.

This principle is often found on the controls of domestic electric cookers, where the heater is made to pass through a small heating coil around a bimetal strip. When the strip heats up it bends and opens a contact, as shown in fig 5.22.2. By moving the fixed contact nearer to or further from the bimetal contact

the ratio $\frac{\text{ON Time}}{\text{OFF Time}}$ = Duty Ratio can be changed.

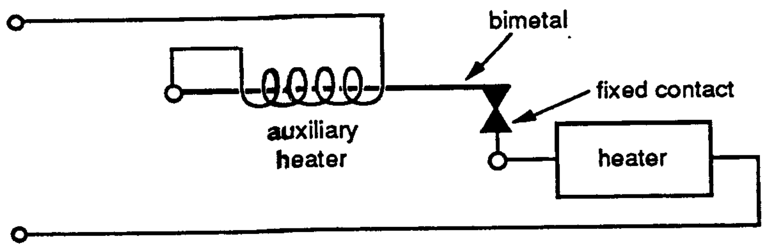


Fig 5.22.2

Question 22.1 ***Does the duty ratio increase or decrease when the fixed contact is brought nearer to the bimetal?***

This method suffers from the same inaccuracies and disturbances as the previous one but it is a cheap, practical solution in some applications.

Open-loop Continuous If, instead of switching the heater fully on and off we could just reduce the heater power to some fraction of its full value, the same effect would be achieved.

This can be achieved nowadays by thyristor control circuits, which permit current to flow for only a fraction of each cycle of the a.c line supply, thus reducing the average power. Prior to the introduction of thyristors, however, power could only be reduced by the use of variable transformers to lower the voltage or by placing resistors in series, which dissipated much wasted energy, or by the use of transductors, which are a form of variable inductor, placed in series to reduce the current without large energy dissipation.

Fig 5.22.3 illustrates the various ways mentioned.

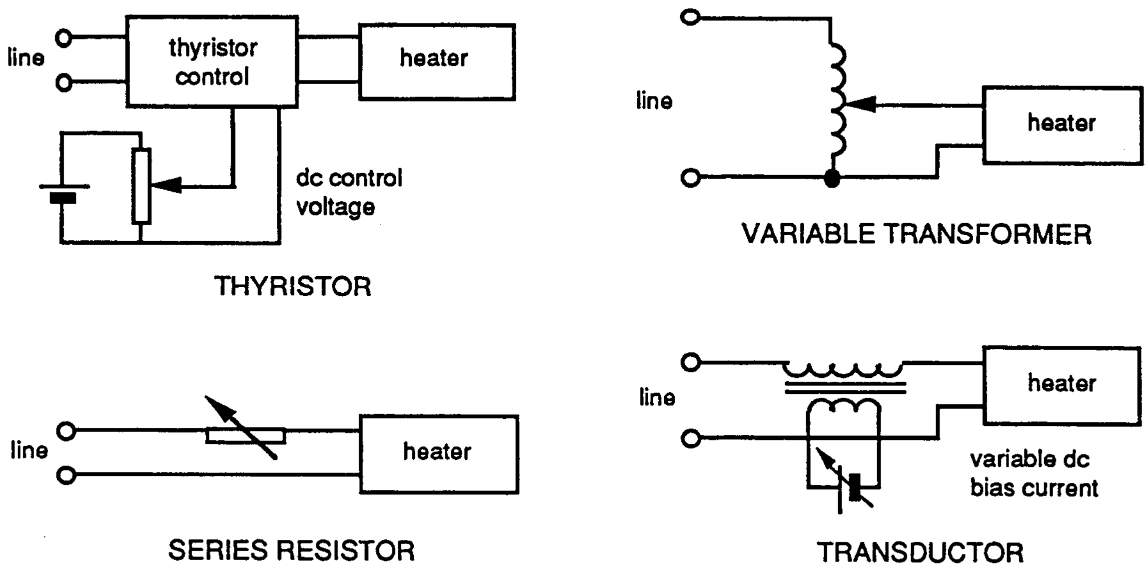


Fig 5.22.3

Closed-loop on-off

None of the previous methods employed any device to measure the actual temperature being produced. If a temperature-sensitive switch is placed in or near the heated vessel then that switch can be arranged to remove the power completely when the desired temperature is reached. Then, as the temperature falls again, at some point the switch recloses to re-apply power. Thus the heater is continuously cycled on and off to maintain the temperature near the desired value, although to avoid too-frequent switch operation a differential of several degrees is usually provided. This is often called 'hysteresis' or 'overlap'. Fig 5.22.4 illustrates the method; note that different amounts of water and different ambient conditions do not alter the set temperatures in this case.

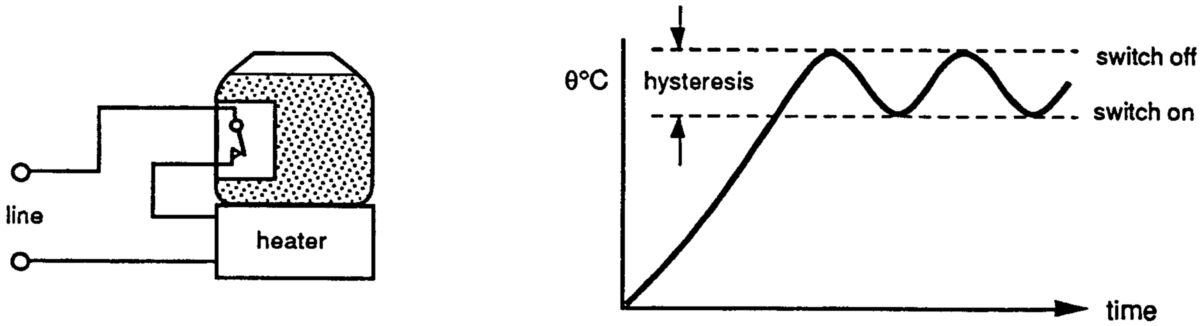


Fig 5.22.4

Thermostatic switches are usually adjustable for various temperatures. The two types used in this assignment are of fixed setting and one of them would not be capable of variation in any case.

Closed-loop continuous

Finally temperatures can be controlled by using a sensor and using its output to vary continuously the degree of heater power. Once again, for high powers a thyristor or other control circuit must be used. This method, correctly designed, can give very close control.

To return to this assignment we shall now use two different devices to achieve closed-loop on-off control as outlined above.

PRACTICAL 22.1

Thermal Reed Switch

A thermal reed switch comprises a pair of normally open contacts enclosed in a glass envelope which in turn is encircled by sintered permanent magnets and rings of temperature-sensitive magnetic material (Thermorite). In the type used the contacts are normally apart as in fig 5.22.5(a).

When the magnetic material reaches is Curie point temperature it quite suddenly loses its ferro-magnetic properties so that the reluctance increases and the flux takes the easier path through the contact blades, causing them to come together under the influence of the induced opposite magnetic poles, as shown in fig 5.22.5(b).

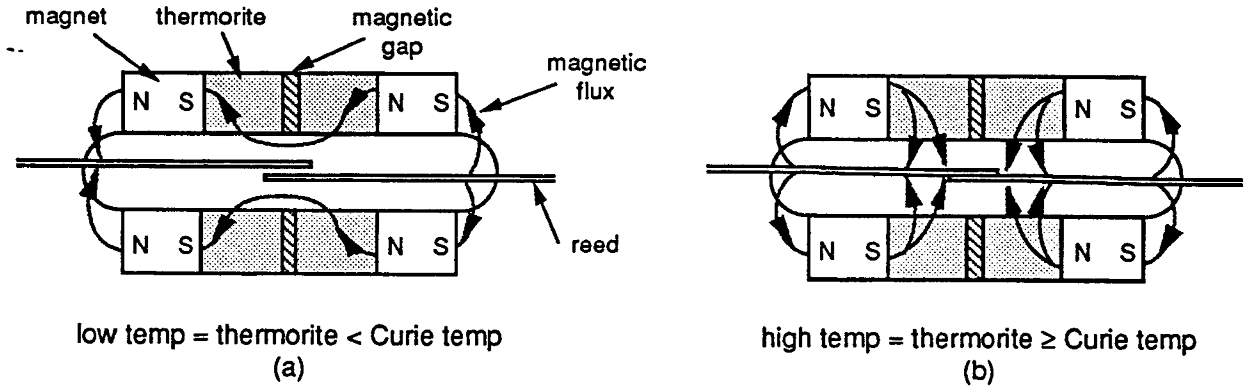


Fig 5.22.5

The temperature at which the switch operates can be varied by altering the composition of the magnetic material so as to alter its Curie point. The loss of magnetic properties is a reversible process so that when cooled again the field is removed and the contacts reopen.

To make use of the switch to control the heating of the bar we could use it to switch the line supply on and off. However the voltage and current ratings of the contacts are insufficient to make it advisable to do this directly, added to which would be the danger involved in bringing line voltage to terminals on a probe mounted on the heat bar.

Alternatively, we could use the reed switch in a low voltage circuit to operate a heavy duty relay which in turn would control the line supply, as in fig 5.22.6.

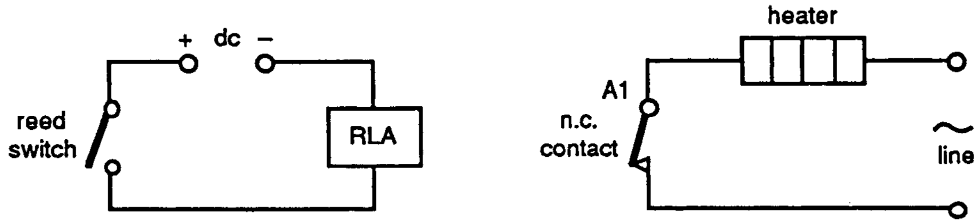


Fig 5.22.6

Even this complication is avoided in this practical by making use of the auxiliary heater on the heat bar, which is of low enough power to be driven directly from the Power Amplifier TK2941B, whilst being sufficiently powerful to raise the bar to the operating temperature at up to about notch 4. Fig 5.22.7 is the circuit to be used.

To monitor the temperature variation of the heat bar a circuit using the platinum resistance probe in a direct reading thermometer will be required. Set up the circuit shown in fig 5.22.8.

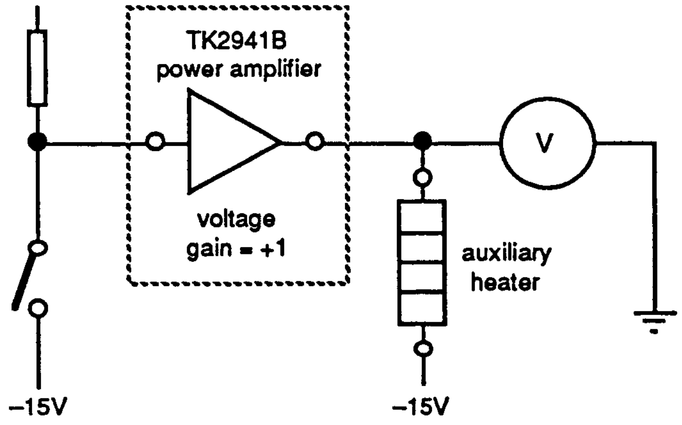


Fig 5.22.7

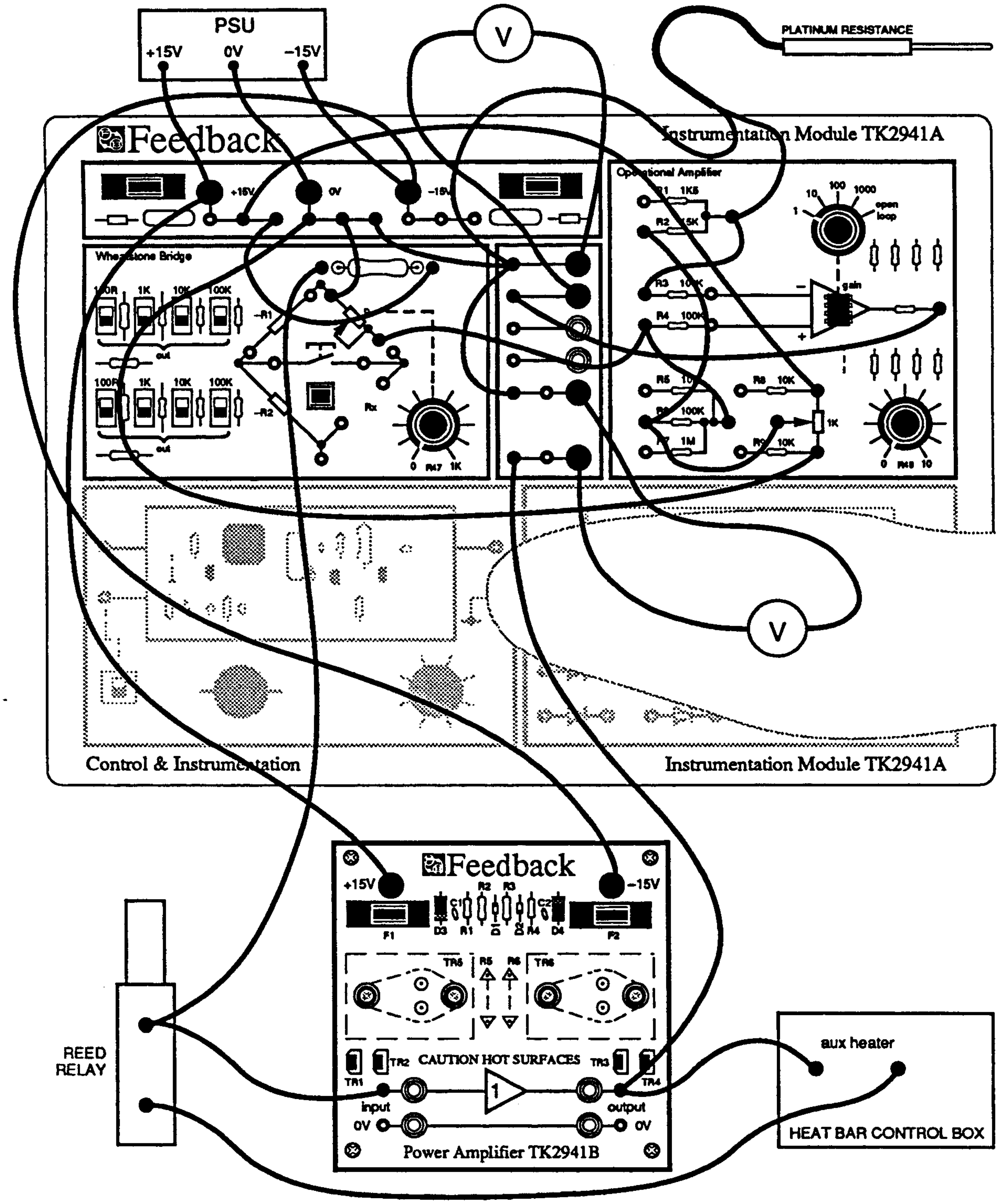

PSU
+15V
0V
-15V
V
PLATINUM RESISTANCE
Feedback
Instrumentation Module TK2941A
Operational Amplifier
Wheatstone Bridge
Control & Instrumentation
Instrumentation Module TK2941A
V
REED
RELAY
Feedback
+15V
-15V
CAUTION HOT SURFACES
input
output
0V
0V
Power Amplifier TK2941B
aux heater
HEAT BAR CONTROL BOX

Fig 5.22.8

Part of this circuit is similar to the one used in Assignment 21, Practical 21.3. Use the procedure described there to set up the direct-reading thermometer to read any temperature between 0 and 100°C.

Note Do not alter the settings of R47 or the potentiometer control on the Operational Amplifier once you have set up the thermometer.

Question 22.2

How does the heater section of the circuit of fig 5.22.8 function?

Mount the reed switch on the heat bar at Notch 1. Also mount the platinum probe in the transducer mount immediately adjacent to the reed switch.

Switch on the power and take a reading of the probe temperature. The meter monitoring the operation of the auxiliary heater circuit should indicate about +12V showing that the heater is ON. Note this on your result sheet.

Now take a reading of temperature every minute for about 40 minutes, also noting the times at which the heater switches OFF (–15V) and ON (+12V).

Exercise 22.1

Plot your results in your own copy of fig 5.22.9 showing the heater switching as vertical lines between ON and OFF.

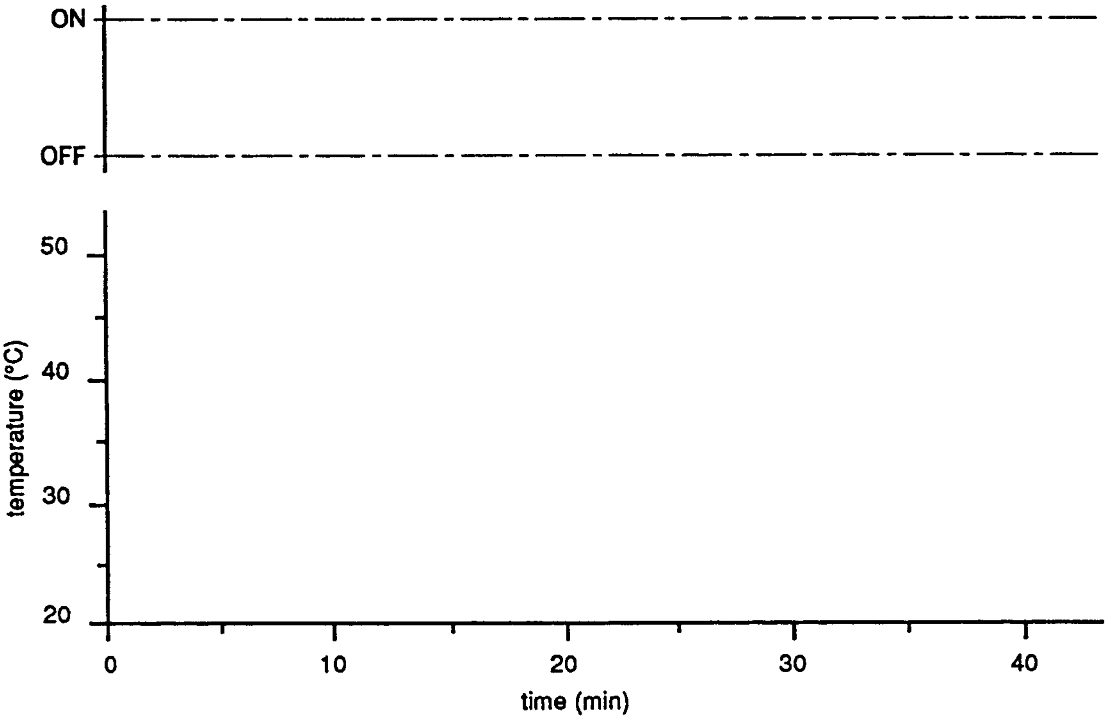


Fig 5.22.9

Once up to temperature the heater cycles on and off repeatedly. Study your curve and answer the following questions.

Question 22.3 *What is the total cycle time (ON to ON or OFF to OFF)?*

Question 22.4 *Is the duty ratio unity?*

Question 22.5 *What is the temperature differential (difference between the maximum and minimum temperatures in one cycle)?*

Question 22.6 *What is the average temperature?*

Question 22.7 *Does the indicated temperature continue to rise or fall slightly after the heater has switched OFF and ON respectively?*

If so, can you offer an explanation?

Question 22.8 *The reed switch supplied has a nominal operating temperature of 45°C and a differential of 3°C. Compare these figures with your answers to Questions 22.5 and 22.6. If there are differences can you explain them?*

As a further experiment move the reed switch and platinum probe, still in the same relative positions, so that the reed switch is at Notch 4. Observe the behaviour, noting the ON and OFF periods and the limit temperatures.

Question 22.9 *Is the duty ratio greater or less than previously observed?*

Question 22.10 *Is the mean temperature similar to that previously observed?*

PRACTICAL 22.2

The Bimetal Switch

The bimetal thermostat is probably the commonest type of ON/OFF temperature control in existence. Examine the one provided. You can see that it has a normally closed contact which snaps open sharply if you *gently* pull the end of the bimetal element away from the mounting plate. This type of action, combined with robust contacts, would allow this switch to be used directly to control a line supply, although we shall use it as in the previous Practical to control only the auxiliary heater.

Bimetal material comprises two layers of metals having dissimilar coefficients of expansion bonded together. When heated the strip takes up a curved shape with the high expansion layer on the outside as in fig 5.22.10.

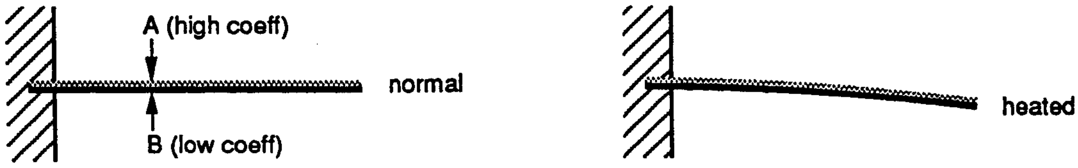


Fig 5.22.10

The configuration of this switch is not the only one. Often a fast break action is provided by mounting a small permanent magnet in such a position as to hold the contacts closed. When the bimetal strip is hot enough to generate a separating force just equal to the magnetic pull the contacts begin to separate. The movement results in a rapid reduction of the magnetic pull so the motion continues at an increasing rate, thus giving the fast action desired. See fig 5.22.11.

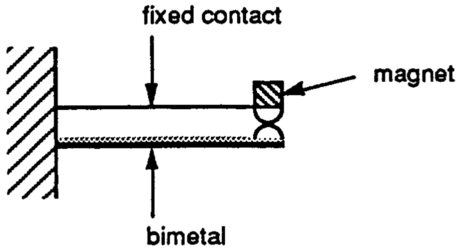


Fig 5.22.11

The practical procedure will be exactly as for the reed switch but substituting the bimetal swtich. Because the latter has a normally closed contact a slightly different circuit will be needed. In fact there are two alternatives shown in fig 5.22.12.

Although the circuit of fig 5.22.12(a) is satisfactory the type of contact makes (b) perfectly feasible and this is clearly much simpler.

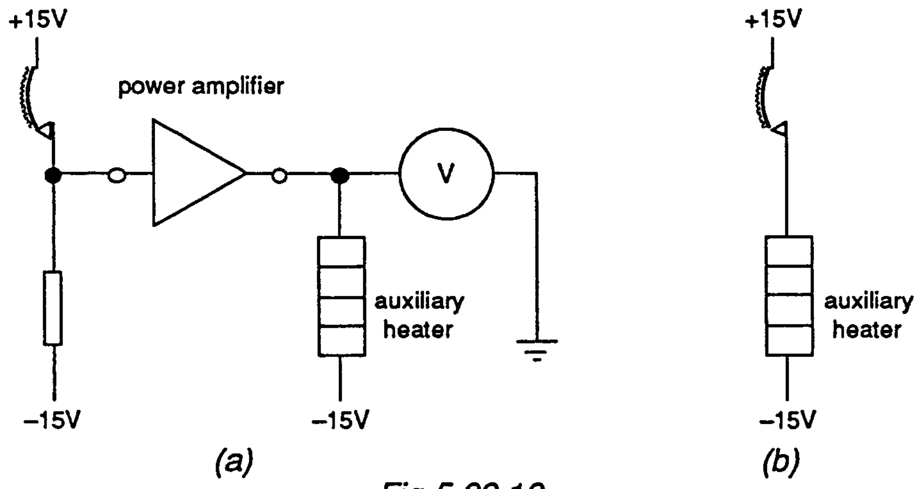


Fig 5.22.12

Switch off the power supply and alter the circuit to that shown in fig 5.22.13.

Switch on the power supply.

With the bimetal and platinum probe at the hot end of the bar take readings as before. Then move the bimetal to Notch 4 and observe the behaviour as before.

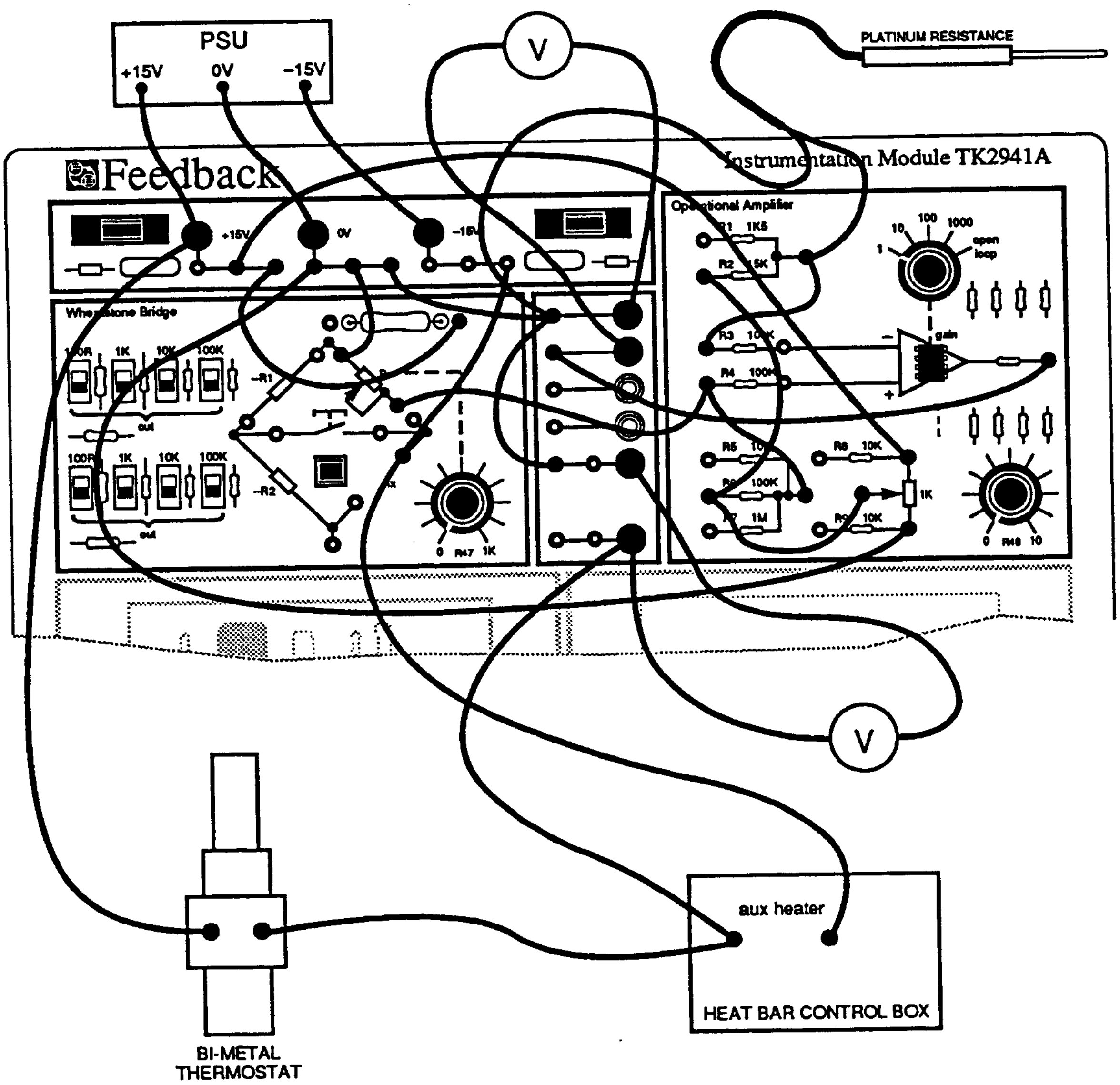


Fig 5.22.13

Exercise 22.2

Plot your readings as in Exercise 22.1.

The bimetal switch has a nominal operating temperature of 45°C and a differential of 5°C.

Compare these figures with your observations and also compare the latter with your results from Practical 22.1.

PRACTICAL ASPECTS

The principal features of thermostatic switches for practical application are as follows:

- Stability of operate temperature
- Adjustability of operate temperature
- Power carrying and breaking capacities
- Contact life
- Resistance to thermal and mechanical shock
- Protection from ambient conditions (e.g moisture, corrosion, etc)
- Ease of transfer of heat to the detecting element affecting the thermal lag.

Of the two types studied in this assignment the reed switch obviously cannot be adjusted for different temperatures but the bimetal switch, although not adjustable in this case, can be made so by applying a variable degree of pressure to the closed contacts. As the pressure is increased the temperature needed to separate them increases also.

Generally speaking the smaller the detector the faster will be its response to temperature change. You should have observed in the Practicals that the measured differential was considerably larger than the normal figure. This was mainly due to the large thermal lag between the platinum probe and the actual detecting element which has the effect of 'attenuating' the temperature variations at the heat bar. Thus a 12°C change at the bar represents a 5°C change at the bimetal, for instance. For the optimum control accuracy, therefore, the detecting element should be in good thermal contact with the medium to be controlled.

The applications of thermostats are well known and numerous. Domestic water heaters, washing machines, dishwashers, refrigerators, etc all use them in temperature control applications. They are used in the same role in many similar industrial applications.

The other main area of application is to over-temperature protection, where the switch operates only under abnormal conditions of temperature and then removes the cause of those conditions, e.g by switching off power, or alternatively gives some kind of audible or visible alarm.

TYPICAL RESULTS AND ANSWERS **ASSIGNMENT 22**

Question 22.1

As the contacts of a bimetal normally closed switch are pressed together the temperature needed to separate the contacts increases. To produce an increased temperature the heater must be on for a greater part of the time so the duty ratio *increases.*

Question 22.2

The operation of the heater section of the control circuit of fig 5.22.8 is that while the reed switch is open (cold) the amplifier input is at +15V and hence also the output, placing about 25-30V across the heater. When the switch closes at the operating temperature the amplifier input and output go to −15V, thus reducing the heater power to near zero.

Note that in the latter condition the 220Ω resistor has 30V across it dissipating about 4W.

Exercise 22.1

Fig E5.22.9 is a typical graph obtained from this Practical.

Time (min)	Temp. (°C)	Aux heater Time (min)	Aux heater Action	Time (min)	Temp. (°C)	Aux heater Time (min)	Aux heater Action
0	22.9		ON	18	43.8	17:20	ON
1	23.8			19	43.4		
2	26.3			20	44.6		
3	29.8			21	46.5	20.20	OFF
4	33.6			22	47.0		
5	37.4			23	46.2		
6	41.1	6:40	OFF	24	44.8		
7	44.6			25	43.4	24:35	ON
8	46.7			26	43.9		
9	46.7			27	45.4		
10	45.8	10:35	ON	28	46.9	27:40	OFF
11	44.3			29	46.7		
12	43.1			30	45.6		
13	43.7	13.55	OFF	31	44.0	30:45	ON
14	45.4			32	43.5		
15	46.8			33	44.6		
16	46.5			34	46.4		
17	45.4			35	47.1	34:35	OFF

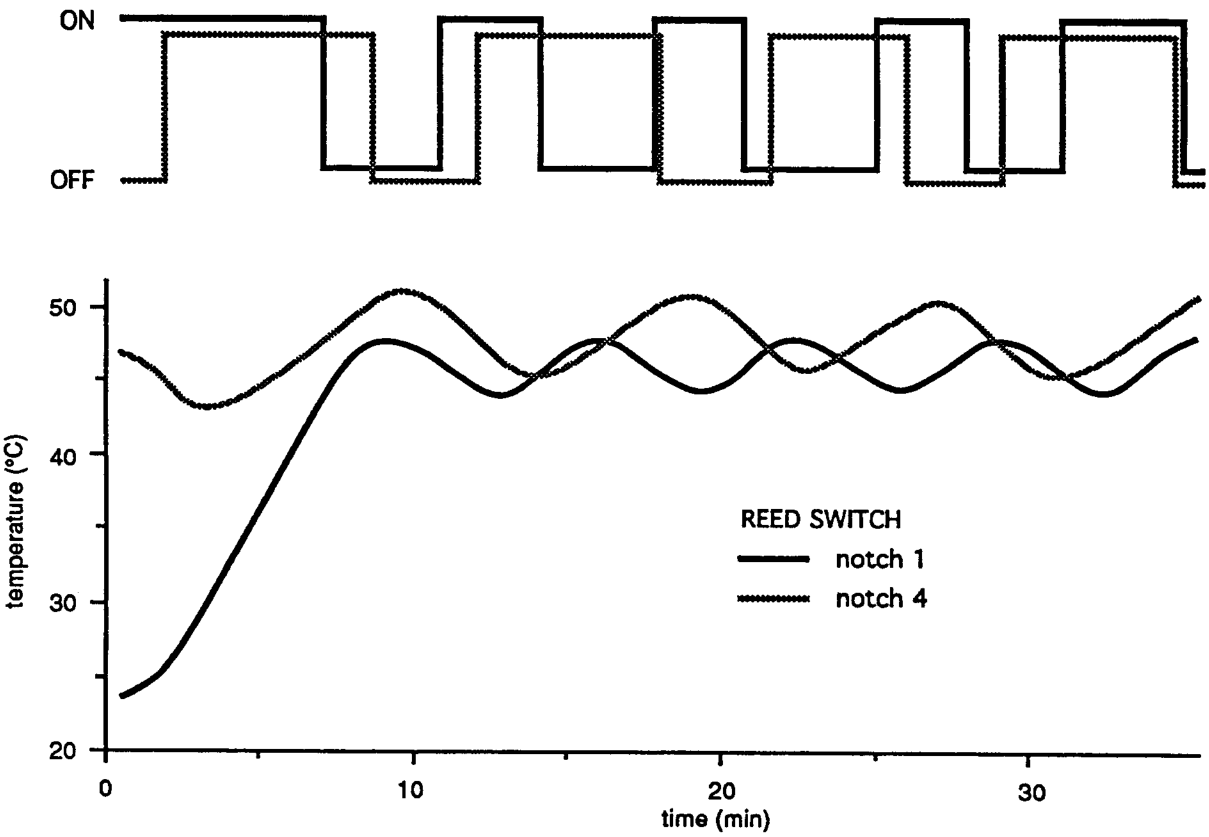
Ambient temperature 22°C

Reed switch at Notch 1

Time (min)	Temp. (°C)	Aux heater Time (min)	Aux heater Action	Time (min)	Temp. (°C)	Aux heater Time (min)	Aux heater Action
0	46.1		OFF	18	50.1		
1	44.9	1:35	ON	19	49.8		
2	42.7			20	48.4		
3	42.2			21	46.4	21:10	ON
4	43.0			22	44.6		
5	44.3			23	45.5		
6	45.9			24	46.8		
7	47.6			25	48.0	25:40	OFF
8	49.2	8:10	OFF	26	49.6		
9	50.4			27	49.3		
10	49.7			28	47.9	28:55	ON
11	48.0	11:50	ON	29	45.9		
12	45.9			30	44.5		
13	44.5			31	44.7		
14	44.7			32	45.7		
15	45.8			33	47.2		
16	47.2			34	48.7	34:15	OFF
17	48.7	17:30	OFF	35	50.0		

Ambient temperature 22°C
Reed switch at Notch 4

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 22



E5 22.8

Question 22.3

The average total cycle time is about 7 minutes at Notch 1 and 9 minutes at Notch 4.

Question 22.4

Duty Ratio $= \dfrac{\text{ON Time}}{\text{OFF Time}}$ and is typically unity but may vary between different equipments.

Question 22.5

The temperature differential is about 4°C at Notch 1 and 6°C at Notch 4.

Question 22.6

The mean temperature is about 45°C at Notch 1 and 47°C at Notch 4.

Question 22.7

Careful examination of the temperature readings show that for about 1 to 1.5 minutes after the switch closes or opens the temperature continues to rise or fall respectively.

This is due to the time taken for temperature changes to propogate from the source to the detector.

A good analogy is the phase difference which occurs between a sinusoidal voltage across a series RC circuit and the current through the circuit.

The current lags behind the voltage such that when the voltage (heat source) is decreasing the current (detected temperature) is still increasing. See fig 5.22.13.

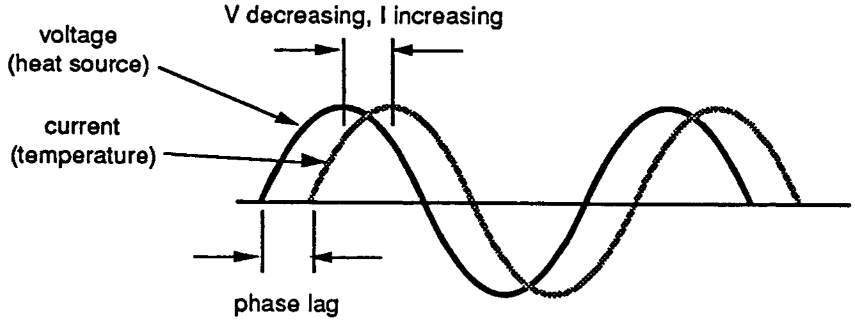


Fig 5.22.13 Thermal lag analogy

Question 22.8

The detector temperature at which the reed switch closes is about 44°C at Notch 1 and 46°C at Notch 4.

These values and those given in the answer to Question 22.5 are close to the nominal figures. However the results depend very much on the accuracy to which the temperature measurement circuitry is initially set up and also to any variation in ambient temperature during the measurement period. A wide variation in values is possible.

Another cause of operating temperature discrepancy is the relatively poor thermal contact between the bar and the reed switch magnets compared with that between the bar and the platinum detector. The increased differential is caused by thermal lag between the bar and the switch causing temperature changes to be effectively attenuated. This is a simplification of what is in reality a complex heat flow situation.

Question 22.9

When the reed is moved to Notch 4 the duty ratio may increase from near unity to about 1.5.

Question 22.10

The mean temperature remains roughly as before. An increased duty ratio is caused by a higher mean heater power needed to keep a more remote point at the same temperature.

Exercise 22.2

A typical graph for the bimetal switch is shown in fig E5.22.9.

The observed operating temperature and differential (9°C) are slightly greater than the specified figures of 45°C and 5°C respectively. The comments made in the answer to Question 22.8 apply here also. The duty ratio this time is about 0.5 and the cycle time is similar at 9:30 minutes.

When moved to Notch 4 the duty ratio becomes nearer to 1.

TYPICAL RESULTS AND ANSWERS   ASSIGNMENT 22

Time (min)	Temp. (°C)	Aux heater Time (min)	Aux heater Action	Time (min)	Temp. (°C)	Aux heater Time (min)	Aux heater Action
0	24.8		ON	21	45.6		
1	26.3			22	43.7		
2	30.2			23	41.3	22:35	ON
3	35.1			24	42.9		
4	40.1			25	45.9		
5	44.6			26	49.4	26:00	OFF
6	48.8			27	51.6		
7	52.4	6:25	OFF	28	50.7		
8	52.5			29	48.9		
9	50.9			30	46.9		
10	48.9			31	44.8		
11	46.4			32	43.0		
12	44.7			33	41.9	32:10	ON
13	42.8			34	44.1		
14	41.7	13:20	ON	35	47.3		
15	44.2			36	50.7	35:30	OFF
16	47.0			37	50.8		
17	50.4	16:35	OFF	38	49.3		
18	50.8			29	47.3		
19	49.4			40	45.3		
20	47.6						

Ambient temperature 22°C
Bimetal thermostat at Notch 1

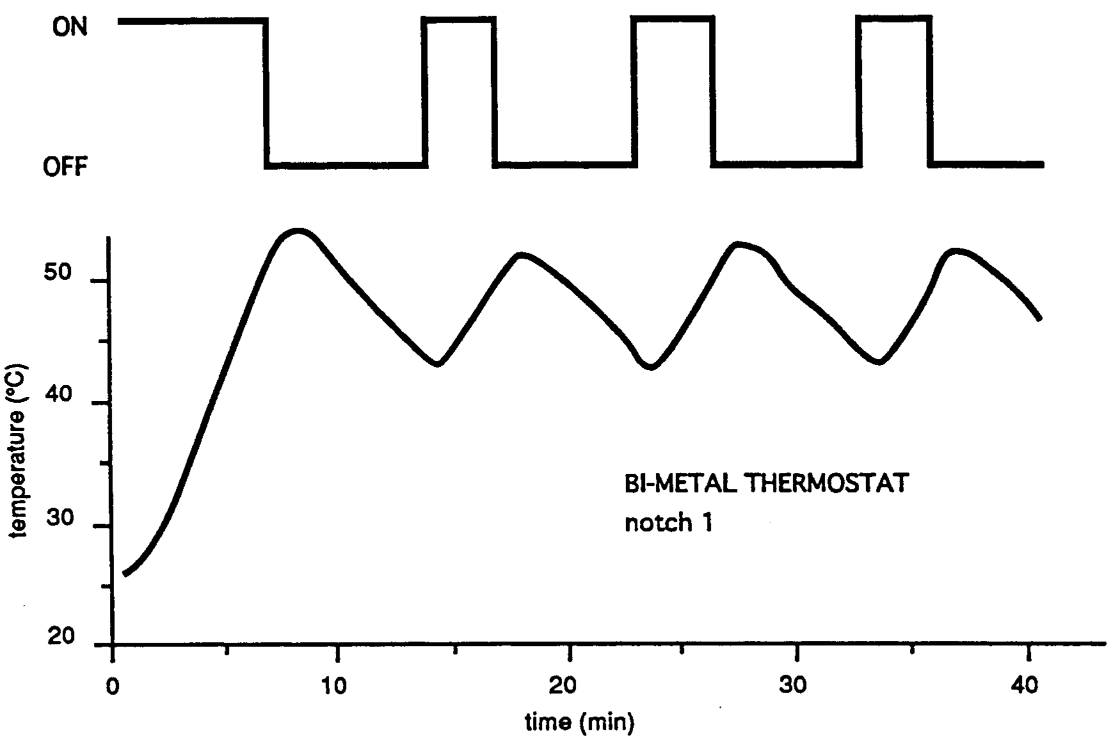

ON
OFF
50
40
30
20
temperature (°C)
BI-METAL THERMOSTAT
notch 1
0
10
20
30
40
time (min)

Fig E5.22.9

CONTINUOUS TEMPERATURE CONTROL — ASSIGNMENT 23

CONTENT

A system for the continuous control of temperature is designed and constructed. The operation of the system is assessed.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941M	Measurements Package
1	–	Heat Bar
1	–	Transducer - thermistor with flying leads. White sleeve.
1	–	Transducer Mount
1	–	Power Supply ±15V dc *(eg Feedback PS446)*
1	–	Variable Power Supply 0-10V dc
2	–	* DC Voltmeter 15V
1	–	* Ohmeter

* Alternatively multimeters may be used.

PRACTICALS

23.1 Design of Thermistor Network

23.2 Heater Calibration

23.3 Closed-loop Control

23.4 Dynamic Response

23.5 Auxiliary Heater as Fine Control

CONTINUOUS TEMPERATURE CONTROL

ASSIGNMENT 23

OBJECTIVES

When you have completed this assignment you will:

- Have studied the design requirements of a continuous temperature control system.
- Have constructed a working system and investigated its operating characteristics.
- Have determined the dynamic response of the system.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Be familiar with the use of the heat bar and preferably have completed Assignment 18, The Heat Bar – Familiarisation.
- Understand the operation of an on-off temperature control system and preferably have completed Assignment 22, On-Off Temperature Control.
- Recognise the characteristic behaviour of a thermistor and preferably have completed Assignment 20, The Thermistor.

INTRODUCTION

For some applications a control system in which the degree of heater power could be varied continuously instead of simply being switched on or off may be preferable. The basic idea of such a system is very simple and is illustrated in fig 5.23.1

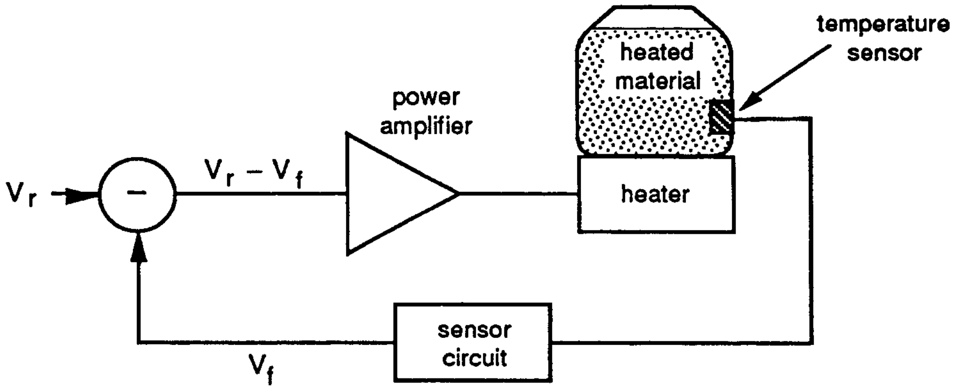


Fig 5.23.1 Simple temperature control

In fig 5.23.1 V_r is a reference voltage and is compared with a feedback voltage V_f, proportional to the measured temperature, to produce a voltage of $(V_r - V_f)$. This voltage drives a power amplifier supplying energy to the heater. If V_r is greater than V_f the heater power is increased until the temperature rises sufficiently to bring V_f up to V_r, when the heater power reduces to a value just sufficient to make good the losses and maintain the temperature constant. If V_r reduces the power reduces and allows the material to cool until once again V_f equals V_r.

You should be able to see that if the amplifier is sufficiently sensitive only a very small input will be needed to control the heater over its full range so that at balance V_r and V_f will be very nearly equal. Thus by controlling V_r we can control V_f and hence the temperature of the material.

In the system you are going to construct a thermistor detector will be used as it has a good sensitivity. The first thing we must therefore do is to design a suitable energising network.

PRACTICAL 23.1

Design of Thermistor Network

In the Practical Aspects section of Assignment 20, the use of a resistor R_C in parallel with the thermistor was shown to provide a nearly linear relation between temperature and resistance Now consider fig 5.23.2

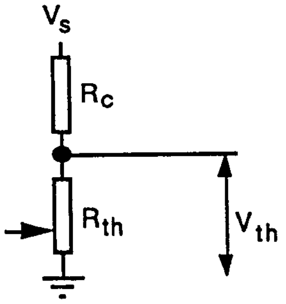


Fig 5.23.2

Assuming negligible load will be imposed upon the voltage V_{th} we can write:

$$V_{th} = \frac{V_s R_{th}}{R_c + R_{th}}$$

$$= \frac{V_s}{R_c} \cdot \left(\frac{R_c R_{th}}{R_c + R_{th}} \right)$$, multiplying numerator and denominator by R_C

The term in brackets is the parallel combination of R_C and R_{th} and if R_C is properly chosen will be linearly related to temperature. Also V_S and R_C are constants. In Assignment 20 it is shown that a value for R_C of 400Ω would give good linearity for the thermistor over the normal range of measurement from 22°C to 100°C.

If you have not already done so, carry out the following exercise

to find the relation between θ and $\frac{R_c R_{th}}{R_c + R_{th}}$

Exercise 23.1

Take the curve of R against θ given in the results for Practical 20.2 (see fig E5.20.15) and, using $R_c = 400\Omega$, and $R = R_{th}$, calculate $\frac{R_c R_{th}}{R_c + R_{th}}$ for various values of R_{th} between 22°C and 100°C; then plot the results on the same axes.

You should obtain a relatively straight line result.

Assignment 20 showed that the thermistor mounted in air had a dissipation constant of about 2.0mV per °C. Thus to ensure that errors due to self-heating do not exceed, say 2°C it is necessary to keep the maximum dissipation down to about 4.0mW.

Question 23.1

At what value of R_{th} does maximum dissipation occur in the circuit of fig 5.23.2?

Exercise 23.

Using the answer to Question 23.1 find the voltage across the thermistor for 4.0mW dissipation and hence determine what is the maximum value of V_s allowable.

You should have found that V_s is about 2.5V.

Finally, knowing the values of V_s, R_c and using your graph $\frac{R_c R_{th}}{R_c + R_{th}}$ against θ you are in a position to calculate figures for a graph of V_{th} against θ for the circuit in fig 5.23.2.

Exercise 23.3

Calculate $V_{th} = \frac{V_s}{R_c} \left(\frac{R_c R_{th}}{R_c + R_{th}} \right)$ for different values of θ, looking up the values of $\frac{R_c R_{th}}{R_c + R_{th}}$ from your first graph.

Plot V_{th} against θ as in fig 5.23.3. Also calculate the slope of the curve in V/°C; this is the sensitivity of the sensor.

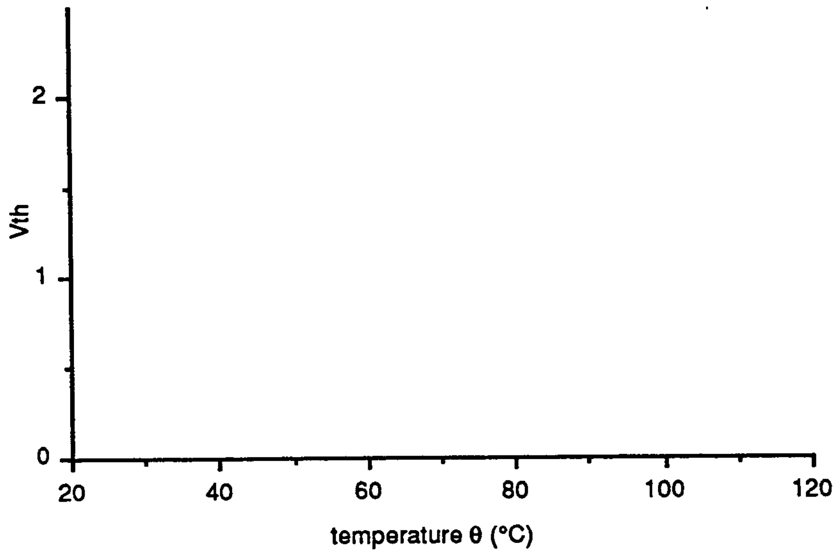


Fig 5.23.3

Now that you have a suitable calibrated detector the next step is to calibrate the heater system to discover how variations in the voltage applied to the heater will vary the temperature at some selected point on the heat bar.

PRACTICAL 23.2

Heater Calibration

Mount the thermistor probe in the transducer mount and position it at Notch 1. Set up the circuit shown in fig 5.23.4 but before connecting to the variable resistor R_S (R47) set it to 400Ω, the chosen value for R_C.

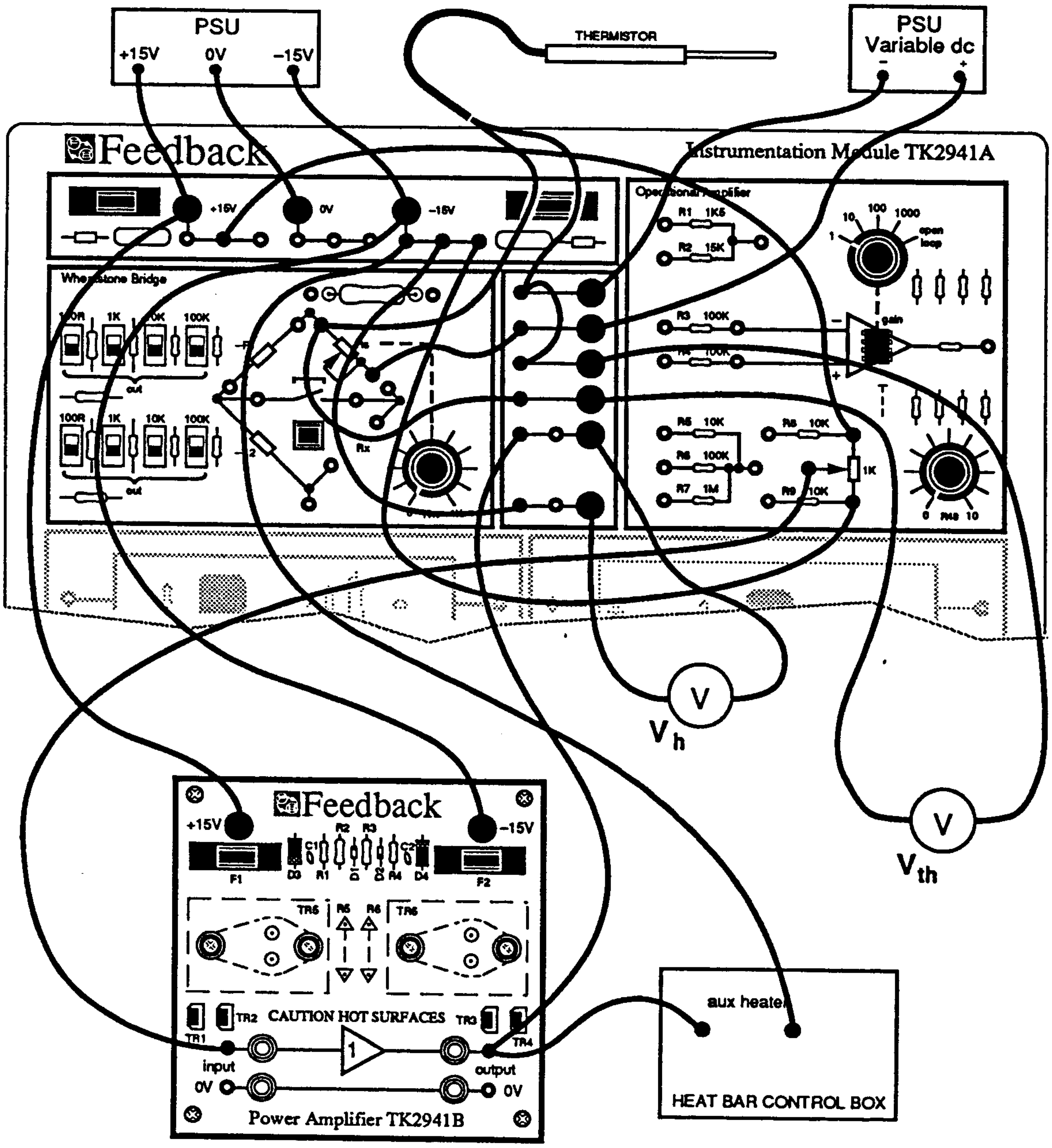


Fig 5.23.4

Ensure that the Operational Amplifier potentiometer control knob R49 is fully counter-clockwise and that the variable voltage supply is at zero setting. Switch on both power supplies and set the variable supply to your value of V_s, ie 2.5V.

Note the values of V_{th} and V_h and enter them in your own copy of the table shown in fig 5.23.5.

V_h (V)	V_{th} (V)	θ (°C)

Fig 5.23.5

Now increase V_h in steps of 2V by adjusting R49 until V_h reaches a minimum value. After each adjustment wait about 5 to 10 minutes for the heat bar temperature to stabilise and read V_{th}.

Exercise 23.4

From your graph θ against V_{th} determine θ for each value of V_{th} and plot θ against V_h as in fig 5.23.6

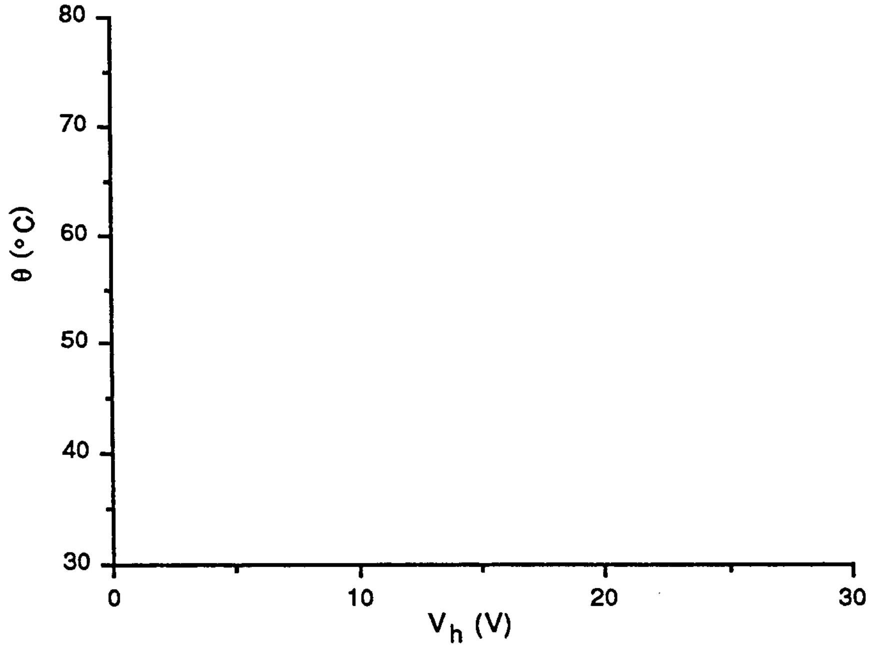


Fig 5.23.6 Heater calibration

Question 23.2 ***Is the graph of fig 5.23.6 linear?***

Question 23.3 ***If it is not, what do you think is the main reason?***

Whilst the graph of V_h against θ gives us insight into the behaviour of the heat bar and heater, for the purpose of controlling the temperature we are actually more interested in how the sensor output V_{th} varies with the heater input V_h.

Exercise 23.5

Plot V_h against V_{th} as in fig 5.23.7.

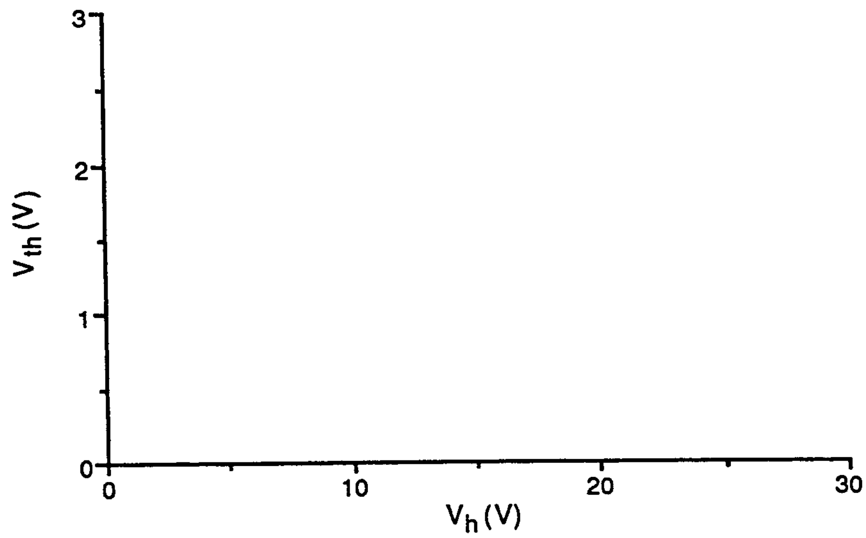


Fig 5.23.7

Question 23.4 ***Is the graph of fig 5.23.7 linear?***

Question 23.5 ***Did you expect it to be so?***

Question 23.6 ***What is the maximum temperature you can obtain at the probe position using the auxiliary heater only?***

Question 23.7 ***What changes would you expect to the graphs of fig 5.23.6 and fig 5.23.7 if the thermistor probe were positioned further from the heater eg at Notch 2 or 3?***

Remembering fig 5.23.1, the next step must be to produce a reference voltage V_r together with a means of subtracting from it the sensor output V_h.

Question 23.8

What circuit do you already have available to carry out the subtraction?

Of course it is the Operational Amplifier in TK2941A which may be used as a differential amplifier, and all we need to do is provide a suitable reference input from a potentiometer to one of the inputs whilst applying the sensor voltage to the other. But which voltage goes to which input?

Consider fig 5.23.8.

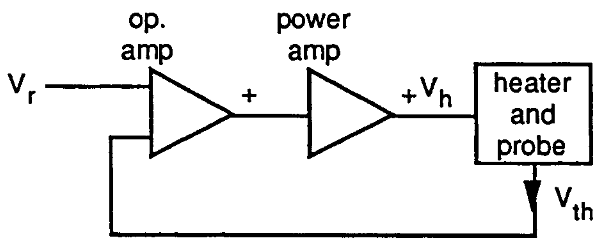


Fig 5.23.8

An increase in the output of the differential amplifier causes an increase in V_h and, from your graph of fig 5.23.7, a reduction in V_{th}.

Question 23.9

What sign must be attached to the V_{th} input of the differential amplifier so that this reduction of V_{th} causes a reduction of the amplifier output, as needed for negative feedback?

For the reference voltage, V_r, we need to generate a voltage which can be varied over the range of V_{th} found in fig 5.23.7 and it would be desirable to see that clockwise rotation of the potentiometer corresponded to an increase in temperature. Since V_{th} reduces with increasing temperature, so must V_r. The circuit of fig 5.23.9 gives a range for V_r from 2.5V to about 1.2V, enough to cover the possible range of temperatures using the auxiliary heater only. Check this for your own measurements from the graph of fig 5.23.7. The complete circuit can now be drawn as in fig 5.23.10.

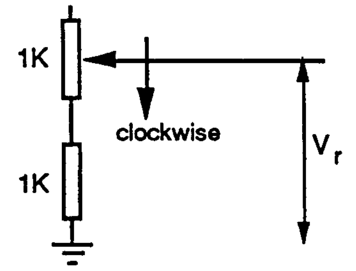


Fig 5.23.9

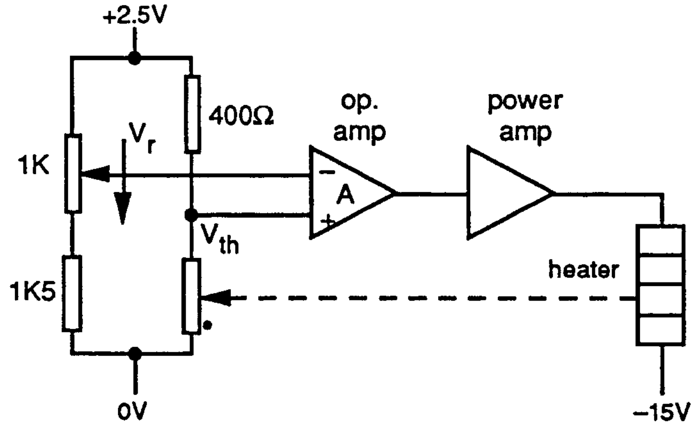


Fig 5.23.10 Complete control circuit

The only factor not yet determined is the gain A of the differential amplifier. This will affect the accuracy of control because if A is large only a very small difference ($V_r - V_{th}$) will be needed to bring about a large change of heater voltage V_h to rectify any tendency for the temperature to change. If A is small, on the other hand, a large difference will be needed so that larger fluctuations of temperature will take place to produce the same correcting effect. Also the temperature will not correspond to the expected value as determined by the setting of V_r – there will be an 'offset'. In the next Practical we shall try to see the effect of varying A upon the offset between V_r and V_{th}.

PRACTICAL 23.3

Closed-loop Control Construct the circuit of fig 5.23.10, corresponding to the module set-up of fig 5.23.11.

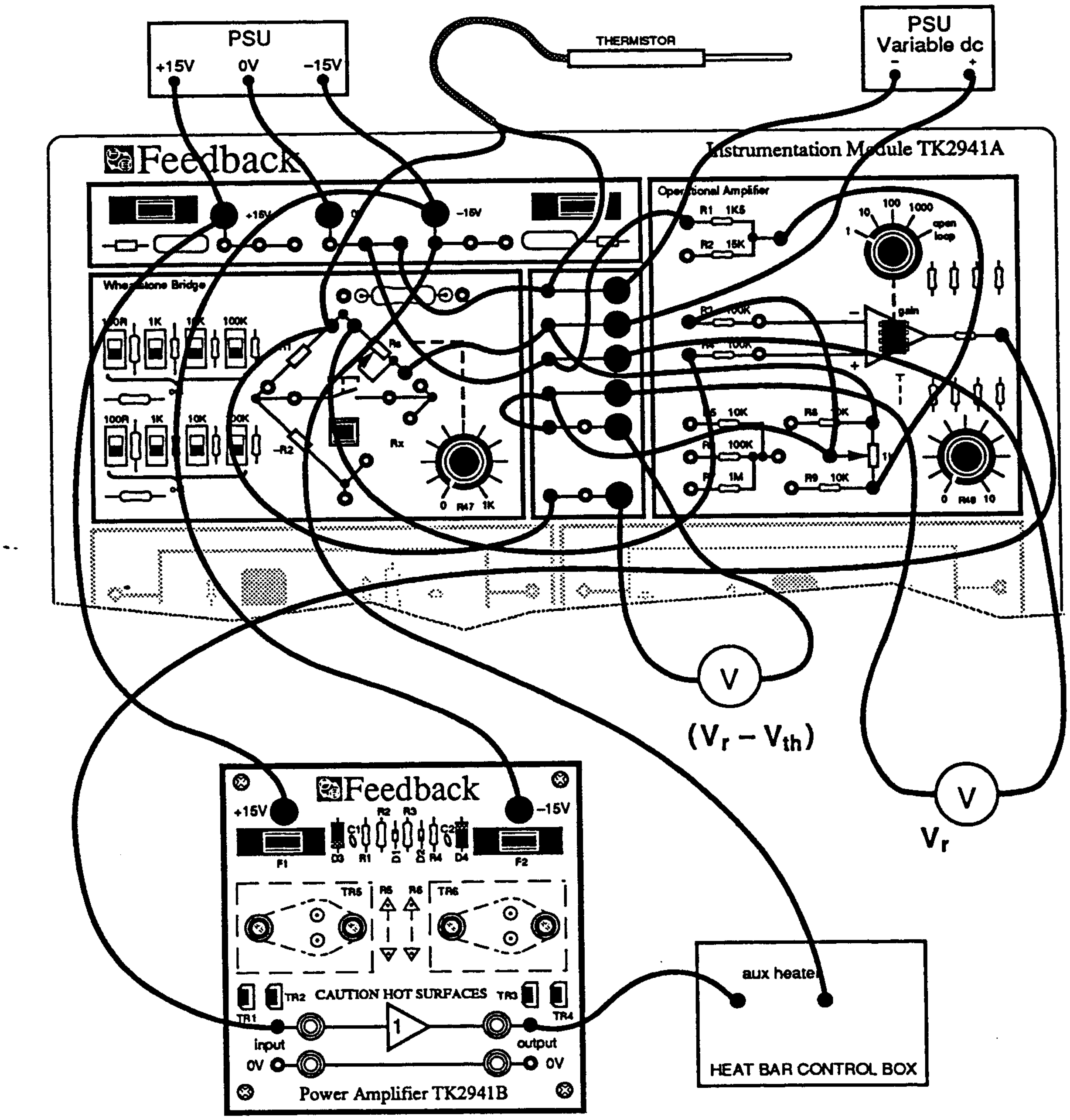


Fig 5.23.11

Switch on both power supplies.

The variable dc voltage should still be set to 2.5V as before. Set the gain control on the Operational Amplifier to 10. Adjust R49 to give a reference voltage somewhere in the middle of the range of V_{th} found in fig 5.23.7, approximately 1.6V and note from the graph of V_{th}/θ, fig E5.23.3, what temperature this corresponds to, say 50°C.

Wait until the temperature has stabilised – you can observe this by watching the V_{th} meter until it no longer shows change. This may take 30 minutes or more at the initial heating. When steady, record the values of ($V_r - V_{th}$) and V_r in your own copy of the table shown in fig 5.23.12. Repeat the experiment for a temperature near the bottom of the range, say 30°C and one near the top, say 70°C.

You may need to reduce the variable dc voltage slightly to obtain a V_r to correspond to a temperature of 70°C.

		gain = 10			gain = 1000		
desired temp (°C)	V_r (V)	$V_r - V_{th}$ (V)	V_{th} (V)	actual temp. (°C)	$V_r - V_{th}$ (V)	V_{th} (V)	actual temp. (°C)

Fig 5.23.12

Exercise 23.6 ***From V_r and ($V_r - V_{th}$) in your table, calculate V_{th} and look up the actual temperature from your plot of V_{th}/θ. Enter these values in the table.***

Question 23.10 ***Is there an appreciable difference between the desired and actual temperatures?***

Question 23.11 ***If so, is it constant or does it vary with the setting? Can you explain the results?***

Now set the amplifier gain to 1000 and repeat the tests, completing a table as before.

Question 23.12 ***How do the results compare with the previous ones?***

Question 23.13 ***What do you conclude from the comparison?***

As anticipated, you should find that the higher gain gives much closer control over the temperature. Although we have only been varying the amplifier gain A it should be easy to see that the sensitivities of other parts of the circuit are equally important. For instance, if the thermistor output for a given temperature change were reduced, this would also reduce the accuracy of control. In other words, all parts of the control loop, the heater, the sensor and the amplifiers contribute to the 'loop gain' of the system, and this is a most important concept. Let us estimate from our graphs what will be the value of this gain for different settings of A. Imagine the loop broken by disconnecting the sensor output from the amplifier input, as in fig 5.23.13.

For an input V_{in}, the output V_{th} is V_{in} times the product of all the gain factors in the loop. The power amplifier has a voltage gain of unity and the relation between V_{th} and V_h can be estimated from the graph of V_h/V_{th}.

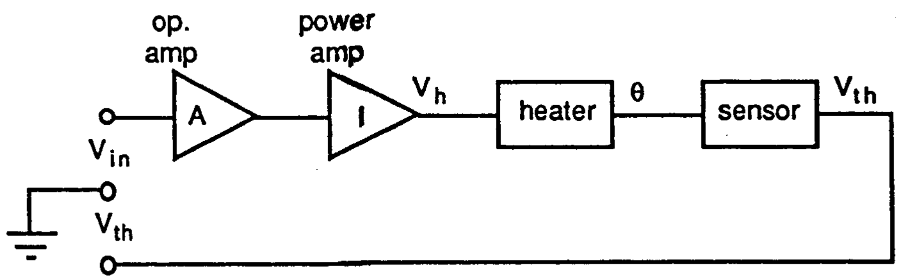


Fig 5.23.13

Exercise 23.7 ***On your graph of V_h/V_{th}, fig 5.23.7, draw a best straight line approximation over the range of the graph and estimate its slope, representing $\frac{V_{th}}{V_h}$. Then find the loop gain $A' = \frac{V_{th}}{V_h}$ for A = 1, 10, 100, 1000.***

You should find that quite a high value of A is needed to obtain a reasonable value of loop gain. As a rough guide only, for a temperature to be controlled with an accuracy of 1% requires a loop gain of about 100.

Question 23.14 ***Do your results for A = 1000 support this estimate of accuracy?***

Question 23.15 ***From your results, what is the range of temperatures over which effective control can be exercised by the system under investigation?***

PRACTICAL 23.4

Dynamic Response

First read the Practical Aspects section, which explains that static control accuracy and stability are to some extent conflicting requirements.

Then, with the same set-up as used in Practical 23.3, set the temperature to some point in the mid-range, say 50°C. Remove the meters from V_r and $(V_r - V_{th})$ and instead connect a meter between the amplifier output and ground so as to observe the variations of V_h, the heater voltage. Better still, if one is available, monitor V_h with a chart recorder since this will give a clearer picture of the behaviour and will provide a permanent record.

Obviously V_h will reflect changes in V_r or in V_{th} or both, but multiplied by the forward gain A of the amplifier, making changes easier to observe.

Start with A = 100 and wait until V_h becomes steady. Then cause a small disturbance to the system, which can be done in one of two ways.

- Make a small change in V_r, say to 55°C.
- Impose a thermal load on the system, for example by mounting the calibration tank full of cold water close alongside the thermistor probe.

Now observe how V_h changes to deal with the altered conditions.

You may have to continue observations for 15 minutes or so to see the full effect of each change, as this is the settling time of the system.

Now change the gain to 1000 and see what response you obtain for a small disturbance. Finally change the gain to 'open loop' and see what happens.

You should find that the responses are similar to those shown in fig 5.23.14. For gain 100 V_h approaches its steady value with a small over-shoot — this approximates to what is known as a 'critically damped' response. For gain 1000 V_h executes several quite large oscillations, which decreases in amplitude until finally only random variations are apparent but which initially may be so large as to cause the amplifier to limit. Finally with gain 'open loop' (ie about 10,000) V_h executes continuous oscillation between the limits, showing that the system is unstable.

It is worth noting that although the system is unstable with the highest gain the resulting changes in V_{th} are very small and may represent an acceptable temperature fluctuation. Of course this situation is virtually the same as in an on-off control as described in Assignment 22, the mean temperature being determined by the ratio of on time to off time. This is shown in fig 5.23.14.

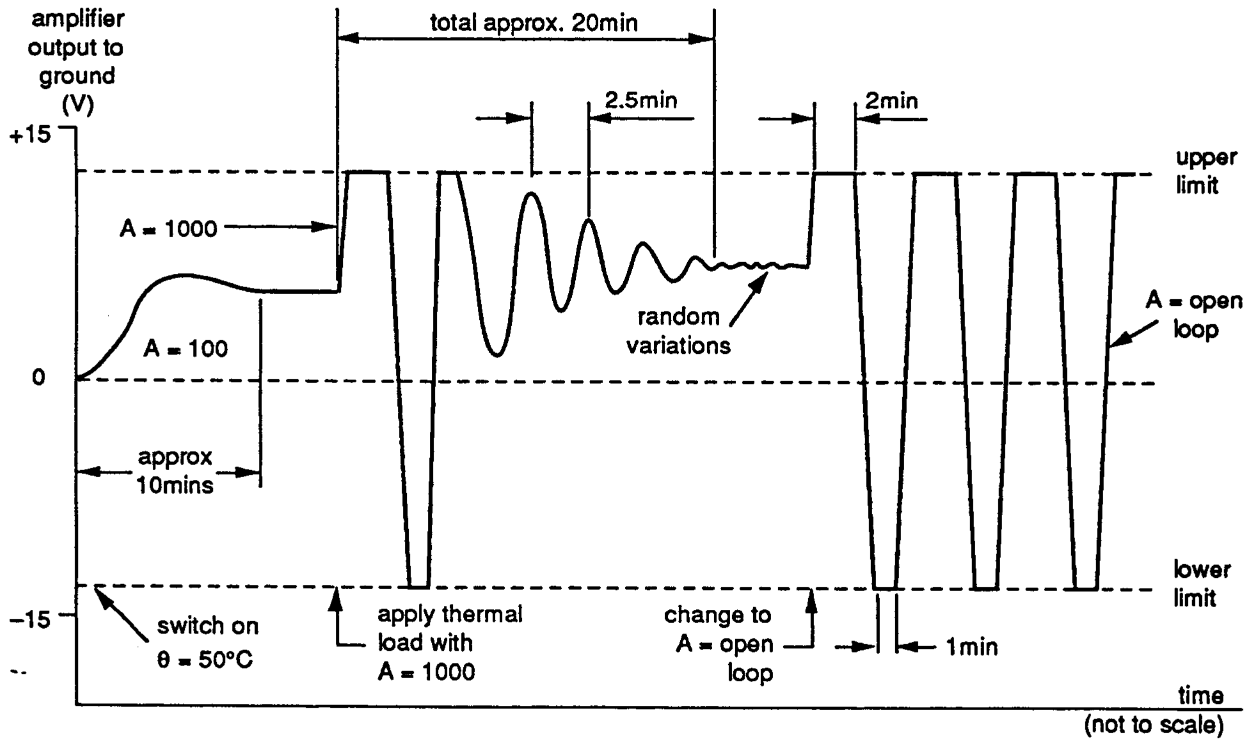


Fig 5.23.14

PRACTICAL 23.5

Auxiliary heater as Fine Control

With care it is possible to use the auxiliary heater to perform a fine control at a point further along the bar, using the main heater to establish a base temperature and the auxiliary one to raise this a few degrees.

Remember that:

- The range and loop gain of control will be less the further from the heater is the sensor because the auxiliary heater has a smaller heating effect at greater distance.
- The auxiliary heater can only raise the temperature, not lower it.

The procedure is to mount the sensor at the desired control point, say Notch 13, set the V_r control to minimum temperature so as to turn the auxiliary heater off and then switch on the main heater. When the bar has stabilised, adjust V_r until V_h comes within its operating range; then, with A = 1000 it should be possible to achieve steady, controlled conditions at a temperature which can be determined by noting V_r.

PRACTICAL ASPECTS

The full theory of feedback control systems is outside the scope of this manual but some of the practical difficulties and their solutions can be briefly considered here.
You have seen how a high loop gain is desirable from the point of view of accuracy, so is there any reason why the gain should not be increased indefinitely? Unfortunately if this were done a point would be reached, depending upon the time delays and lags in the system, where it would become unstable and start to oscillate continuously. This is often referred to as hunting. The achievement of accurate control without instability is the business of the control engineer, as is the achievement of as fast a response as possible to changes in setting.

One method of obtaining virtually zero deviation (difference between set value and actual value) under steady state conditions, is to use a degree of 'integral' control. In this the correcting signal is the time integral of the deviation exists, a gradually increasing correction signal is generated as in fig 5.23.15.

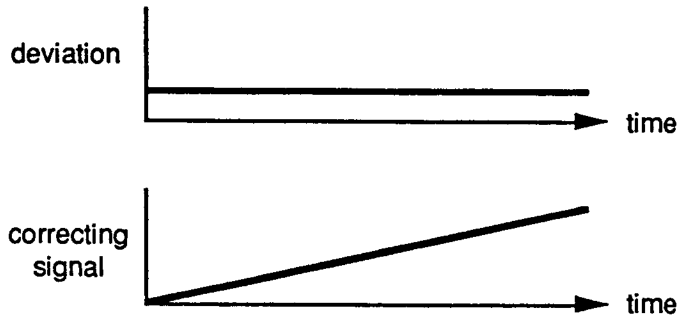


Fig 5.23.15

As the correcting signal increases the deviation must reduce until it eventually becomes zero and the correcting signal is then constant. Thus the effect of integral control is effectively to provide an infinite loop gain to steady signals but this does not have the same tendency to cause instability that a high gain would normally do because the gain of an integrator reduces with increasing frequency.

For the same reason a control system relying heavily upon integral control may be slow to respond to change of setting or changes in working conditions (eg ambient temperature). In this case a measure of 'derivative' control is introduced. In this the controlling signal responds to the rate of change of the deviation or the reference input.

To obtain the optimum performance from a control system it is usual to provide a mixture of 'proportional' control (this is what you have just been experimenting with) and 'integral' or 'derivative' control, and sometimes all three are used in what is usually referred to as a 'three term controller'. Sometimes the various terms are separately generated, perhaps electronically, and then summed together before applying the correcting signal. This is called a 'non-interacting' controller. In other applications, particularly pneumatic systems, the three terms are not easily separable and tend to interact with one another so that an adjustment of one affects one or both of the others. The process of setting up the different amounts of each type of control to achieve best performance is sometimes called 'tuning the system' and there are various ways of going about it.

Applications of control systems of this kind appear in every branch of industry, but particularly in the process industries such as chemical, petroleum etc and in all kinds of heat treatment plant. Temperature, of course, is not the only quantity controlled in this way but together with flow rate and liquid level it is one of the most important physical variables in industrial applications.

Obviously, there are many practical problems to be overcome when controlling the temperature of a large bulk of material. Fig 5.23.16 shows a vessel of liquid heated by base heaters,

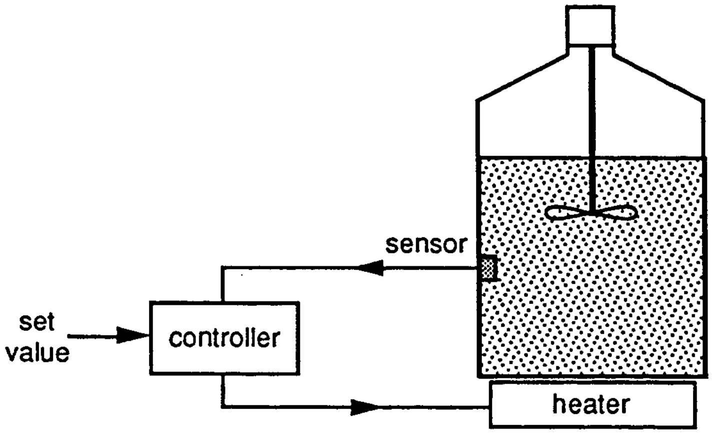


Fig 5.23.16

First of all it is meaningless to speak of the temperature of liquid in a vessel unless all parts of the liquid are at the same temperature, so adequate agitation must be provided to distribute the heat rapidly through the vessel. This in itself may not be enough, however, because heat loss from the liquid surface and through the vessel walls will inevitably mean that the liquid is cooler in these regions than elsewhere. To overcome this the vessel must be totally enclosed in an efficient thermal insulating jacket — this also saves heating energy, of course. Sometimes the heating element is combined with this insulation to give 'jacket heating'.

Another source of disturbance could occur when the vessel is topped up if the incoming liquid is at a different temperature from that already in the vessel.

Exercise 23.1 A typical plot of $\frac{R_c R_{th}}{R_c + R_{th}}$ against θ for $R_c = 400\Omega$ is given in fig 5.23.17 and shows good linearity.

Temperature θ (°C)	R = R_{th} at θ°C	Resistance $\frac{R_c R_{th}}{R_c + R_{th}}$ ($R_c = 400\Omega$) (Ω)
22	2000	333
30	1530	317
40	1100	293
50	780	264
60	575	236
70	430	207
80	310	175
90	200	133
100	130	98

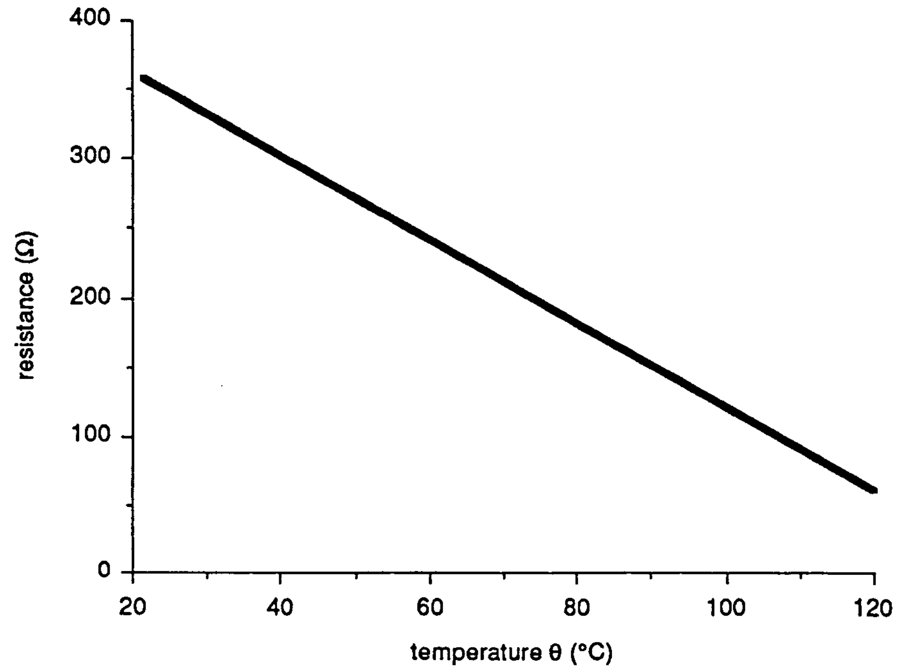


Fig 5.23.17

Question 23.1

In the circuit of fig 5.23.2, maximum thermistor dissipation occurs when $R_{th} = R_c$ (Maximum Power Transfer law).

Exercise 23.2

For P_{th} = 4.0mW and $R_{th} = R_c = 400\Omega$, the voltage across R_{th} is given by:

$$P = \frac{V^2}{R}$$

$$\therefore V_{th} = \sqrt{P_{th} R_{th}}$$

$$= \sqrt{4.10^{-3} . 400}$$

$$= \sqrt{1.6}$$

$$= \sqrt{1.24V}$$

Hence the maximum value of V_s is 2 x 1.24 = 2.5V approx.

Exercise 23.3 A typical plot of V_{th}/θ is given in fig E5.23.3 and has a slope of 18.75mV/°C.

Temperature θ (°C)	V_s (V)	R_c (Ω)	$\frac{R_c R_{th}}{R_c + R_{th}}$ (Ω)	$V_{th} = \frac{V_s}{R_c}\left(\frac{R_c R_{th}}{R_c + R_{th}}\right)$ (V)
30	2.5	400	320	2.0
40	2.5	400	290	1.8125
50	2.5	400	260	1.625
60	2.5	400	230	1.4375
70	2.5	400	200	1.25
80	2.5	400	170	1.0625
90	2.5	400	140	0.875
100	2.5	400	110	0.6875

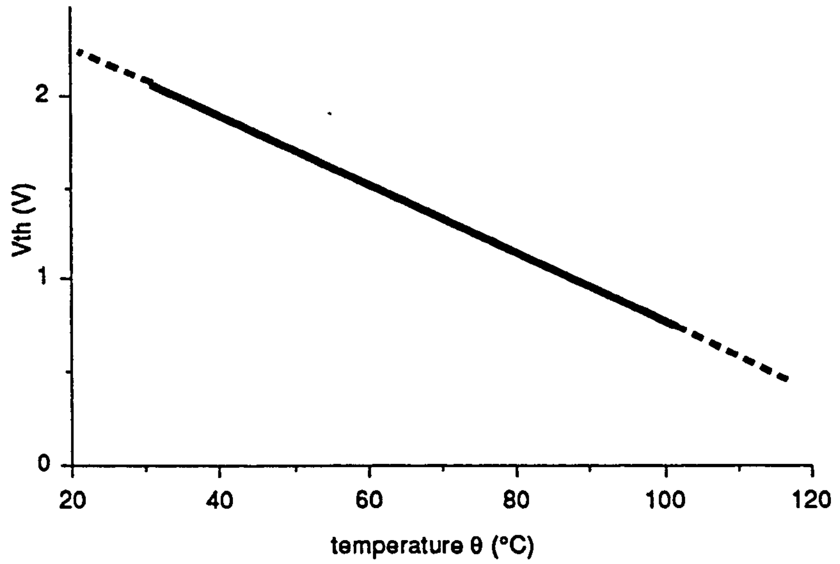


Fig E5.23.3

Exercise 23.4

A typical plot of θ/V_h obtained from the results of the practical and by reference to fig E5.23.3 is shown in E5.23.6.

V_h (V)	V_{th} (V)	θ (°C)
24.0	1.22	73.5
22.0	1.28	68
20.0	1.38	62
18.0	1.50	56
16.0	1.54	54
14.0	1.61	51
12.0	1.69	47
10.0	1.75	43.5
8.0	1.81	40
6.0	1.87	37
4.0	1.92	35
2.0	1.97	32

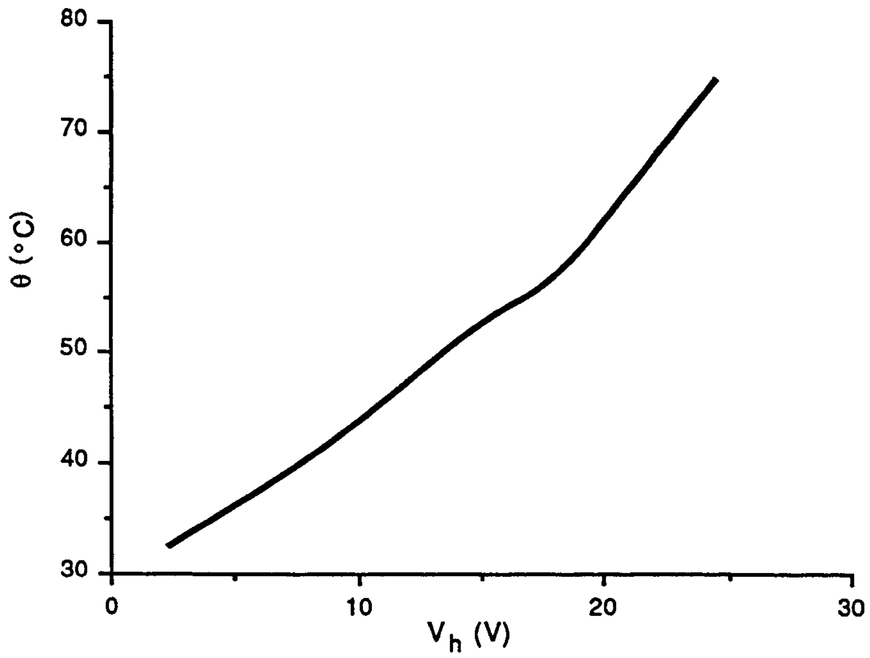


Fig E5.23.6

Question 23.2

The graph of fig E5.23.6 is not very linear.

Question 23.3

The main reason is that the temperature is related to the heater power, which is proportional to V_h^2 but there is the added factor of increased heat loss at higher temperatures, which tends to counteract the square law effect, thus producing the results obtained.

Exercise 5.23.5

A typical plot of V_h/V_{th} is given in fig E5.23.7 and shows also the best straight line approximation and slope figure.

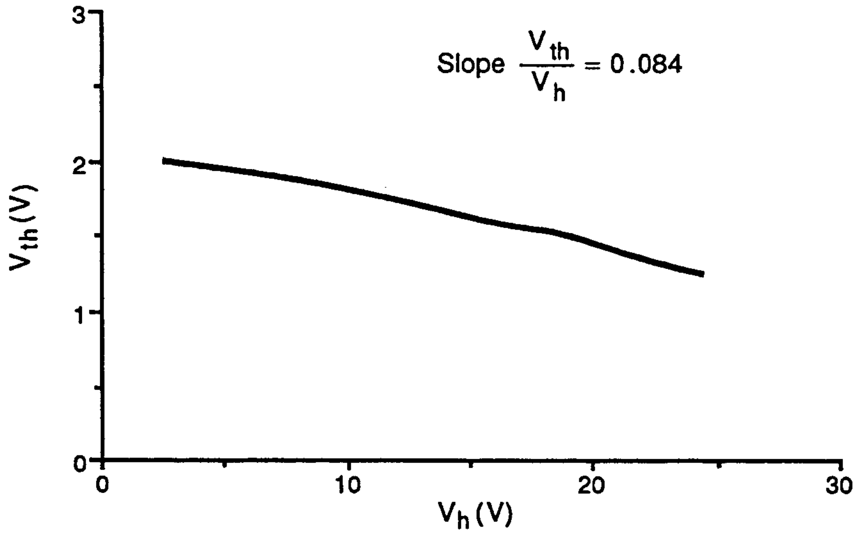


Fig E5.23.7

Question 23.4

The graph of fig 5.23.7 is not very linear.

Question 23.5

In view of the non-linearity of the θ/V_h graph and the linearity of the V_{th}/θ graph, this was to be expected.

Question 23.6

The maximum temperature obtainable with the probe close up to the auxiliary heater is typically 72°C at normal room temperature of 25°C.

Question 23.7

If the thermistor were moved further along the bar the graphs of θ/V_h and V_{th}/V_h would have reduced slope but would commence from the same point at room temperature. Thus lesser maximum temperatures would be achieved and the overall 'gain' of the heater-sensor combination would be reduced.

Question 23.8

The circuit available to carry out subtraction of V_{th} from V_r is the operational amplifier in TK2941A.

Question 23.9

Such a reduction of V_{th} must cause a reduction of V_h. V_{th} must connect to the + input of the amplifier since this produces an output in the same sense as the input. This is later shown in fig 5.23.10.

Typical results for V_r and $(V_r - V_{th})$ for A = 10 and 1000 are given in fig E5.23.12.

		gain = 10			gain = 1000		
desired temp (°C)	V_r (V)	$V_r - V_{th}$ (V)	V_{th} (V)	actual temp. (°C)	$V_r - V_{th}$ (V)	V_{th} (V)	actual temp. (°C)
30	2.0	+0.207	1.793	41.0	+0.216	1.784	41.0
50	1.625	–0.070	1.695	46.5	+0.015	1.610	50.5
70	1.25	–0.254	1.504	56.0	+0.002	1.248	70

Fig E5.23.12

Exercise 23.6

The values of V_{th} and θ are entered in the table above.

Question 23.10

There is a large difference between the desired and actual temperature for gain = 10 except at about 50°C.

Question 23.11

The error is present throughout the range, being 11°C at 30°C and 14°C at 70°C. This is because the change in V_{th}, amplified by a gain of 10, is insufficient to vary V_h enough to cause the necessary temperature change. Note that the error at 30°C is positive whilst at 50°C it is negative. Somewhere between, at about 45°C, the zero error point occurs.

Question 23.12

With gain = 1000 the deviations at the upper temperature are much smaller but still increase slightly with temperature, as they are bound to in a purely proportional control system,. The inaccuracy of the lowest temperature may be expected from the non-linearity of the θ/Resistance graph at temperatures between 20 and 40°C.

Question 23.13

The conclusion from the comparison is that a high forward gain is necessary to achieve accuracy.

Exercise 23.7

The straight line approximation is shown on fig E5.23.7 and its slope V_{th}/V_h is typically about 0.08, giving loop gains of 0.08, 0.8 and 80 for A = 1, 10, 100 and 1000 respectively.

Question 23.14

For A = 1000 the loop gain of 80 suggests a percentage error of about 8%. If the zero error point is at, say 40°C then at 70°C the rise is 25°C and 8% of this is about 2°C. The measured deviation is 0.2°C so the agreement is good.

Question 23.15

The effective range of temperature control with the sensor close to the heater is evidently from about 40°C to 70°C.