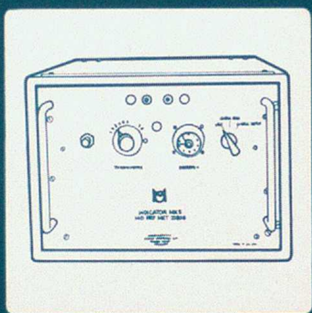
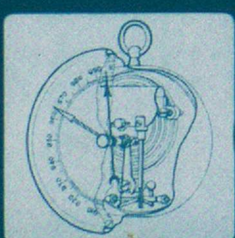
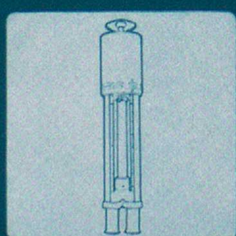
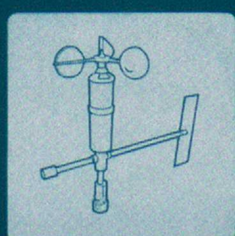
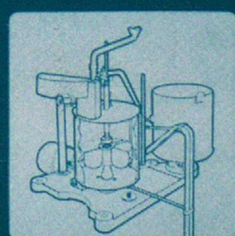
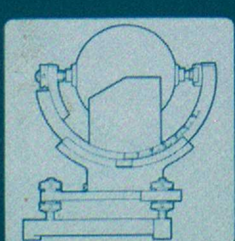
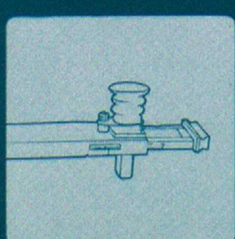
Meteorological Office

Handbook of Meteorological Instruments

Second Edition

2 Measurement of Temperature

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METEOROLOGICAL OFFICE

HANDBOOK OF METEOROLOGICAL INSTRUMENTS

SECOND EDITION

VOLUME 2

MEASUREMENT OF TEMPERATURE

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INTRODUCTION

The first edition of the *Handbook of meteorological instruments* was prepared by the Instruments Division of the Meteorological Office in 1953, to provide a comprehensive source of information on the design, installation, operation and maintenance of all instruments then in use at Meteorological Office stations. Since then numerous improvements have been made to existing instruments, and new instruments and instrument systems introduced into service. This revised edition, whilst retaining some of the original material, gives information on the more recently developed instruments, and records the modifications made to some of the instruments previously described. In general, only instruments currently in use are included and if information is required on older, obsolete, types reference should be made to the previous edition.

Initially, eight separate volumes, each dealing with a specific aspect of meteorological instrumentation for surface observations, are being presented as follows:

Volume 1 Measurement of Atmospheric Pressure
Volume 2 Measurement of Temperature
Volume 3 Measurement of Humidity
Volume 4 Measurement of Surface Wind
Volume 5 Measurement of Precipitation and Evaporation
Volume 6 Measurement of Sunshine and Solar and Terrestrial Radiation
Volume 7 Measurement of Visibility and Cloud Height
Volume 8 General Observational Systems

When complete, the set can be bound to form one book.

Although this handbook is intended primarily to provide information for Meteorological Office personnel about the instruments used at official stations, particulars of some other types are included to illustrate different principles. Where these other types are not described in detail, sources of fuller information are given. It is hoped that the book will also be helpful to users of meteorological instruments outside the Meteorological Office. These readers should, however, understand that certain instructions on procedures are for the guidance of Meteorological Office personnel.

In addition to giving, where applicable, instructions for the installation, operation, and maintenance of Meteorological Office pattern instruments, this handbook deals with accuracy and sources of error.

The general requirements of meteorological instruments, both indicating and recording, are:

(a) Accuracy
(b) Reliability
(c) Ease of reading and manipulation
(d) Robustness and durability
(e) Low cost of ownership.

Most meteorological instruments have to be maintained in continuous operation and many are partially or wholly exposed to the weather. These restrictions call for especially high standards of design and manufacture. The need for uniformity is one of the most important requirements for meteorological measurements. The decisions and recommendations of the World Meteorological Organization, which affect instrument practice, have therefore been followed as closely as possible.

CONTENTS

LIST OF DIAGRAMS

LIST OF PLATES

VOLUME 2
MEASUREMENT OF TEMPERATURE

1 GENERAL

Temperature is the condition which determines the flow of heat from one body to another. In a system of two bodies, that which loses heat to the other is said to be at the higher temperature. There are usually two distinct processes involved in measuring the temperature of a body: (1) a thermometer is brought to the same temperature as the object, i.e. into thermodynamic equilibrium with it, and then (2) the temperature of the thermometer is measured.

Meteorology requires the measurement, and often the continuous recording, of the temperature of:

(a) the air near the surface,
(b) the soil at various depths,
(c) the surface levels of the sea and lakes, and
(d) the upper air.

This volume deals with (a), (b) and (c).

1.1 Historical

The first application of an instrument to determine relative temperature dates from the time of Galileo (1564–1642) and consisted of a simple air thermometer. Spirit of wine was later used as the thermometric substance, but other liquids, such as linseed oil, were also used. Mercury did not come into general use until it was adopted by Fahrenheit in 1721–24. The method of making the expansion of the thermometric substance apparent was altered from the movement of the water column in the air thermometer to the movement of the liquid in a vertical tube attached to the bulb, whose upper end was open to the atmosphere. Later the modern form of liquid-in-glass thermometer was devised with a bulb full of liquid which expands into a sealed tube. The tube is normally as nearly as possible exhausted of air and all gases except that of the vapour of the contained liquid.

It was the original practice to fix one point of the scale only, and then mark the rest of the scale by equal fractions of the volume of the liquid thus registered; many different fixed points were used. The definite adoption of a graduation with a fixed number of divisions between two fixed points instead of using a fixed increment of a standard volume was due to Fahrenheit. He adopted several different sets of fixed points and scales, but eventually settled on zero as the lowest temperature he recorded in Danzig in the year 1709 and the temperature of the human body as 96. The zero was also approximately the temperature he recorded in an ice and salt mixture. This scale gave 32 as the ice-point of water and 212 as the boiling-point. The ice-point and boiling-point of water were later used as fixed points after their constancy and easy reproducibility had been established.

Réaumur formed the basis of his scale in 1730 when he used an alcohol thermometer, and observed that a volume of 1000 units at the ice-point became 1080 units at the temperature of boiling water. He marked his scale 0 at the ice-point and 80 at the boiling-point.

In 1736 Celsius proposed numbering the boiling-point of water 0 and the ice-point 100, but it was actually Christen who reversed the numerals and made the ice-point 0 and the boiling-point 100, and thus founded the Celsius (Centigrade) scale. Since the middle of the eighteenth century only three types of scale have been in common use (i.e. Reaumur, Fahrenheit and Celsius or Centigrade).

1.2 Units and scales of temperature

The basic temperature is the thermodynamic temperature (θ) the unit of which is the kelvin (K). The kelvin is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. In addition to the thermodynamic temperature, expressed in kelvins, use is also made of the Celsius temperature (T) defined by the equation

$$T = \theta - 273.15$$

The unit employed to express a Celsius temperature is the degree Celsius (°C), which is equivalent to the kelvin.

The thermodynamic scale of temperature is one on which measurements are made from absolute zero (0 K), the temperature at which the molecules of any substance possess no heat energy. The scale of temperature generally in use, however, is the International Practical Temperature Scale (IPTS) of 1968 which is based on the assigned values of the temperatures of a number of reproducible equilibrium states (defining fixed points), and on standard instruments calibrated at those temperatures. The IPTS was chosen in such a way that the temperature measured on it closely approximated to the thermodynamic temperature; the difference is within the limits of the present accuracy of measurement. As well as the defining fixed points of the IPTS, other secondary reference points are available; points of meteorological interest are given in Tables I and II.

Table I. *Defining fixed points of the IPTS*

Equilibrium state	Assigned value of IPT K	Assigned value of IPT °C
Equilibrium between the liquid and vapour phases of oxygen (boiling-point of oxygen) at standard atmospheric pressure (1013.25 mb).	90.188	−182.962
Equilibrium between the solid, liquid and vapour phases of water (triple point of water).	273.16	0.01
Equilibrium between the liquid and vapour phases of water (boiling-point of water) at standard atmospheric pressure p_0. The temperature T as a function of the vapour pressure of water is given by the equation $T = [100+2.7655 \times 10^{-2}(p-p_0)-1.13395 \times 10^{-5}(p-p_0)^2 +6.82509 \times 10^{-9}(p-p_0)^3]$ °C where p is the atmospheric pressure in mb.	373.15	100

Table II. *Secondary reference points and their temperatures on the IPTS*

Equilibrium state	IPT K	IPT °C
Equilibrium between the solid and vapour phases of carbon dioxide (sublimation point of carbon dioxide) at standard atmospheric pressure p_0 (1013.25 mb). The temperature T as a function of the vapour pressure of carbon dioxide is given by the equation $T = [1.21036 \times 10^{-2}(p-p_0)-8.91226 \times 10^{-6} (p-p_0)^2 -78.476]$ °C where p is the atmospheric pressure in mb.	194.674	−78.476
Equilibrium between the solid and liquid phases of mercury (freezing-point of mercury) at standard atmospheric pressure.	234.288	−38.862
Equilibrium between ice and air-saturated water (ice-point) at standard atmospheric pressure.	273.15	0.0
Equilibrium between the solid, liquid and vapour phases of phenoxybenzene (diphenyl ether) (triple point of phenoxybenzene)	300.02	26.87

The standard method of interpolating between the fixed points is by the use of formulae to establish the relation between indications of the standard instruments and values of IPT. The standard instrument used from −259.34 °C to 630.74 °C is a platinum resistance thermometer for which the resistance ratio R_T/R_0, where R_T is the resistance at temperature T and R_0 the resistance at 0 °C, is 1.39250 or greater at $T = 100$ °C.

Below 0 °C the resistance–temperature relation of the thermometer is found from a reference function and specified deviation equations. For temperatures between 0 °C and −183 °C the relation is in the form

$$R_T = R_0\,[A + BT + CT^3(T-100)]$$

where A is the resistance ratio given by the reference function and the constants B and C are determined by the measured deviations at the boiling-point of oxygen and the boiling-point of water.

From 0 °C to 630.74 °C the resistance–temperature relation is provided by the equation

$$R_T = R_0\,(1 + A_1T + B_1T^2)$$

where the constants R_0, A_1 and B_1 are determined by measurement of the resistance at the triple point of water, the boiling-point of water (or the freezing-point of tin) and the freezing-point of zinc.

On the Fahrenheit temperature scale the unit is the degree Fahrenheit (°F), and the ice- and boiling-points of water at standard atmospheric pressure are numbered 32 and 212 respectively, a span of 180 degrees. A temperature interval of one degree on the Fahrenheit scale is thus equal to a temperature interval of 5/9 of a degree on the IPTS. Thus if C is the temperature in degrees Celsius equivalent to a temperature F in degrees Fahrenheit,

$$F = \frac{9}{5}\,C+32,$$

or

$$C = \frac{5}{9}\,(F-32).$$

The Fahrenheit scale is still used by some countries for observational purposes but for reports for international exchange the Celsius scale has been adopted by the World Meteorological Organization.

1.3 General principles of thermometers

Theoretically any physical property of a substance which is a function of temperature can be used as the basis of a thermometer. The properties most widely used in meteorological thermometers are thermal expansion and the change in electrical resistance with temperature.

Thermometers which indicate the prevailing temperature are often known as 'ordinary' thermometers while those which indicate extreme temperatures over a period of time are called 'maximum' or 'minimum' thermometers.

Ordinary liquid-in-glass thermometers. Liquid-in-glass thermometers make use of the differential expansion of a liquid with respect to its glass container. A fine-bore tube (called the stem) is attached to the main bulb holding the liquid, and the volume of liquid in the thermometer is such that the bulb is filled completely but the stem is only partially filled at all temperatures which are to be measured. The changes in volume of the liquid with respect to its container are then shown by changes in position of the end of the liquid in the bore of the stem, and, by calibration with respect to a standard thermometer, a scale of temperature can be marked on the stem itself. The liquid used depends on the required temperature range; mercury is generally used for temperatures above its freezing-point (−38.8 °C) and for lower temperatures ethyl alcohol or other organic liquids are used. The glass should be one of the 'normal' or 'borosilicate' glasses approved for thermometers. The glass bulb is made as thin as is consistent with reasonable strength to facilitate the conduction of heat to and from the bulb and its contents. The narrower the bore the greater will be the movement of the liquid column for a given change in temperature and the smaller the span of temperature covered for a given stem length.

Maximum thermometers. The most common maximum thermometer is a mercury-in-glass thermometer with a plug or constriction in the bore below the lowest graduation. When the temperature falls the mercury column is not drawn back past the constriction, provided the thermometer is not inclined with the stem sloping upwards at an angle of more than about 10° to the horizontal. It is possible to shake the mercury past the constriction when the instrument has to be reset.

Minimum thermometers. The most usual device for indicating the minimum temperature is a glass thermometer filled with colourless spirit with a small index placed in the bore below the spirit surface. If the thermometer is tilted so that the bulb is higher than the stem the index will move along the bore until halted by the end of the spirit; surface tension stops the index breaking through the surface. In use, the thermometer is mounted approximately horizontally and, as the spirit contracts with falling temperature, the index is moved along the bore by the spirit. If, however, the temperature rises and the spirit expands the index remains stationary; the end of the index furthest from the bulb thus indicates the lowest temperature recorded since the instrument was last set. The thermometer can be reset by tilting the instrument so that the index moves to the end of the spirit column.

Bimetallic thermometers. The bimetallic thermometer element is a strip of metal (usually curved or in the form of a helix) which is made by welding together two bars of metals having different coefficients of expansion and rolling the resultant compound bar into a thin strip. When the temperature of the strip changes, the two metals expand or contract by different amounts and as a result the curvature of the strip varies. If one end of the strip is fixed and the other end is free to move, the resultant movement of the free end can be translated into the movement of a pointer, or other convenient device, for indicating the temperature.

Electrical resistance thermometers. A measurement of the electrical resistance of a mass of metal or other material whose resistance varies in a known manner with the temperature can be converted into temperature. The element may be either connected into a suitable electrical circuit, e.g. Wheatstone bridge, and the resistance of the element and its leads measured (as in the Meteorological Office electrical thermometer indicator Mk 5, see page 2–39), or the voltage across the element measured (as in the Meteorological Office digital temperature indicator Mk 1A, see page 2–41).

Thermo-couples. In a thermo-couple two different metals are joined together to make a continuous circuit; if one junction has a different temperature from the other, an electromotive force is set up in the circuit and a current flows. The magnitude of this force varies with the temperature difference between the junctions. Thus if one junction is kept at a fixed or reference temperature and the other junction is allowed to take up the temperature it is required to measure, the electromotive force developed in the circuit gives a measure of the difference in temperature between the hot and cold junctions, and the required temperature can be found. There are various combinations of metals which can be used in making a thermo-couple, the choice of combination depending on the temperature range, sensitivity and accuracy required.

1.4 Brief comparison of the different types of thermometers

A more detailed examination of the errors of the various types of thermometers will be found in the following sections, but a broad comparison of their relative usefulness may be of value.

Mercury-in-glass thermometers are standard instruments for determining the surface air, sea and soil temperatures. Their advantages lie in the simplicity of operation and the independence of ancillary apparatus. They can usually be read to 0.1 °C, and, after applying any necessary corrections, the reading should be accurate to this amount over most of the scale. Their main sources of error arise from slow changes in the glass of the bulb and parallax errors in reading the instrument. The range of temperature which can be covered is from near the freezing point of mercury to above the highest meteorological temperature likely to be encountered, i.e. from −39 °C upwards.

Spirit-in-glass thermometers are used as minimum thermometers and whenever the temperature is likely to fall below −39 °C. Although the coefficient of expansion of the spirit used, with respect to glass, is very much larger than that of mercury, the attainable accuracy is inferior to that obtained by a mercury thermometer of similar cost. They are subject to the following errors in addition to those of mercury thermometers:

(a) slow changes in the liquid, especially with exposure to light,
(b) adhesion of the spirit to the glass causing the thermometer to read low if the temperature falls rapidly, and
(c) breaking up of the liquid column by jolting or by a process of slow distillation into the upper part of the stem.

The time-constant (see below) of the spirit thermometer is usually greater than that of a mercury thermometer of similar dimensions.

The bimetallic principle is used in thermographs. Its advantages lie in its robustness and simplicity. Slow changes take place in the bimetallic strip, but these can be reduced by suitable treatment and any residual effect taken care of by the periodic checking of the zero. A thermograph of this type can be made to record all temperatures of meteorological interest, and it can be constructed so that its time-constant is less than that of a mercury-in-glass thermometer.

Electrical resistance thermometers are very suitable for remote temperature reading and recording; thermistors have the additional advantages of being very small and having generally larger changes of resistance with temperature (see page 2–32). Their main disadvantage is that ancillary apparatus is required besides the thermometer element and its leads. The Meteorological Office electrical thermometer indicator Mk 5 (see page 2–39) has a dial graduated in degrees and tenths of a degree Celsius and can be read to 0.05 °C. The Meteorological Office digital temperature indicator Mk 1A provides a read-out in degrees and tenths of a degree Celsius. Both instruments cover the whole range of meteorological temperatures and, as normally used in meteorology, have smaller time-constants than mercury-in-glass thermometers. Errors may be caused by the self-heating of the element by the electric current, if the ventilation rate is low and the instrument is used for continuous recording.

Thermo-couples are mostly used when a thermometer of very small time-constant and capable of remote reading and recording is required. A disadvantage, if absolute temperature is required, is the need of a constant-temperature enclosure for one junction and ancillary apparatus for the measurement of the electromotive force set up; thermo-couples are very suited to measurement of differential temperatures when this complication does not arise. The accuracy can be made very high with suitably sensitive apparatus.

1.5 Time-constants of thermometers

If the medium surrounding a thermometer undergoes a step change in temperature, the temperature of the thermometer does not change instantaneously to the new temperature of the medium but approaches it gradually. The time required for the temperature of the thermometer to change by a stated proportion of the step change is known as the 'response time'.

The rate at which the temperature of the thermometer approaches the temperature of the surrounding medium is given by

$$\frac{dT}{dt} = \frac{-1}{\tau}(T - T_m) \qquad \ldots\ldots (1)$$

where T = the temperature of the thermometer
T_m = the temperature of the medium, and
τ = a characteristic parameter with the dimension of time.

If T_m remains constant, equation (1) can be integrated and becomes

$$(T_0 - T) = (T_0 - T_m)(1 - e^{-t/\tau}) \qquad \ldots\ldots (2)$$

where T_0 = the temperature of the thermometer when $t = 0$.

The time for the thermometer to respond to 90 or 95 per cent of a step change is often given. In particular, however, by putting $t = \tau$ in equation (2), it is seen that τ is the time required for the thermometer to respond to $(1 - 1/e)$, i.e. 63.2 per cent of the step change. τ is referred to as the 'time-constant'.

A simplified theoretical treatment of the mechanism by which the temperature of the thermometer changes can be given as follows:

Suppose a mass, m, of the surrounding medium, air for example, flows past the thermometer bulb in unit time and in so doing has its temperature changed from its normal value, T_m, to that of the thermometer, T. Actually a mass of air larger than m will be affected by the thermometer, but the temperature change will not equal $(T_m - T)$ for the whole of that mass. Then the heat given up by the air in a short time, Δt, will be $mc_p \Delta t (T_m - T)$, where c_p is the specific heat at constant pressure. This is the amount of heat absorbed by the thermometer bulb, of thermal capacity C, in changing its temperature by an amount ΔT. Thus

$$C\Delta T = -mc_p(T - T_m)\,\Delta t$$

i.e.

$$\frac{\Delta T}{\Delta t} = -\frac{mc_p(T - T_m)}{C}$$

but

$$\frac{\Delta T}{\Delta t} = -\frac{1}{\tau}(T - T_m)$$

therefore

$$\tau = \frac{C}{mc_p}. \qquad \ldots (3)$$

The value of τ with the thermometer in air varies with the ventilation rate as would be expected from equation (3); m is in fact a function of ρu where ρ is the density of the air and u is the ventilation rate. It is found experimentally that τ can be represented by the form $\tau = K(\rho u)^{-n}$ where K is a constant and n is less than unity. Table III gives values of τ in seconds for a variety of thermometers together with the approximate value of n.

Table III. *Time-constants of various thermometers*

Thermometer	Bulb dimension	Ventilation rate	Time-constant	n
		m s^{-1}	s	
Mercury-in-glass	Spherical 11.2 mm diameter	4.6	56	0.48
Mercury-in-glass as wet bulb	Spherical 11.2 mm diameter	4.6	52	0.36
Mercury-in-glass	Spherical 10.65 mm diameter	4.6	50	0.43
Spirit-in-glass	Spherical 14.4 mm diameter	4.6	85	0.41
Bimetallic	Helical (station thermograph)	4.6	21	0.64
Electrical resistance element Mk 2	Cylindrical 100 mm long 6.3 mm diameter	5.0	32	0.5

The simple theory given above does not take into account the differences of temperature inside the bulb itself. The time-constant will depend on the conductivity of the various materials, and also on the transfer of heat through the bulb by internal convection (if possible). In general the smaller the ratio of the exposed surface to the total capacity of the bulb, the greater is the time-constant for any given ventilation rate. The type of surface and shape of the bulb also affect the effective value of m in equation (3). If the bulb is damp a further change occurs.

Response of thermometers when the temperature of the medium is changing at a constant rate. If the temperature of the surrounding medium is changing at a constant rate of β degrees per second, equation (1) becomes

$$\frac{dT}{dt} = -\frac{1}{\tau}\,[T - (T_m + \beta t)] \qquad \ldots (4)$$

where T_m is the value of the temperature of the surrounding medium at a time $t = 0$. If the temperature of the thermometer at $t = 0$ is T_0 then equation (4) gives

$$T - (T_m + \beta t) = (T_0 - T_m)\,e^{-t/\tau} - \beta\tau(1 - e^{-t/\tau}). \qquad \ldots (5)$$

The first term on the right gives the exponentially decreasing amount by which the indicated temperature is influenced by the initial temperature difference $(T_0 - T_m)$; the second term has two parts, one decreasing exponentially and the other being a constant. After an interval of time t, which is large compared with τ, both exponential terms may be neglected, and equation (5) reduces to

$$T - (T_m + \beta t) = -\beta\tau.$$

This result shows that the reading of the thermometer will differ from the true temperature by an amount $\beta\tau$, i.e. the thermometer will indicate what the actual temperature was at a time τ seconds previously.

Response of thermometers when the temperature fluctuates. If the temperature of the medium undergoes a simple harmonic variation about a mean temperature T_m, with a period s seconds and an amplitude a, equation (1) then becomes

$$\frac{dT}{dt} = -\frac{1}{\tau}\left[T - \left(T_m + a \sin\frac{2\pi t}{s}\right)\right],$$

or

$$\tau\frac{dT}{dt} + T = T_m + a \sin\frac{2\pi t}{s},$$

and the solution is $T - T_m = Be^{-t/\tau} + a\left[1 + \frac{4\pi^2\tau^2}{s^2}\right]^{-\frac{1}{2}} \sin\left[\frac{2\pi t}{s} - \lambda\right]$

where $\lambda = \tan^{-1}\dfrac{2\pi\tau}{s}$.

The value of B depends on the initial conditions but after a time t large compared with τ the term containing B becomes negligible. The response of the thermometer varies in a simple harmonic manner with the same period as the variation in temperature of the medium, but out of phase and with reduced amplitude.

Table IV gives the ratio of the amplitude of the thermometer response variation to the amplitude of the temperature variation of the medium and the phase angle by which the thermometer response is separated from the true variation for various values of s/τ.

Temperature fluctuations of period less than the time-constant are hardly indicated at all, and it is not until the period equals four times the time-constant that the response amplitude rises to half the true amplitude.

The fluctuations in temperature which actually occur in the atmosphere are not in fact simple harmonic variations but consist of temperature changes of irregular amplitude and

Table IV. *Response of thermometers to fluctuating temperatures*

Ratio of period to time-constant (s/τ)	0.2	0.4	0.6	0.8	1.0	2.0	4.0	6.0	10.0
Ratio of response to true amplitude	0.04	0.06	0.09	0.13	0.16	0.31	0.54	0.69	0.85
				degrees					
Phase difference (λ)	88	86	85	83	81	72	58	46	32

period. Such changes cannot easily be treated theoretically, but the rather more simple case of periodic fluctuations consisting of an abrupt change of temperature, then steady temperature for a period, followed by a further sudden change back to the original temperature has been considered by Bilham (1935). He showed that for a period of 1 second the amplitude of the thermometer's response is 0.23 of the actual amplitude (as compared with 0.16 for simple harmonic variations); the general features of Table IV are not changed, however.

The temperature of the air can fluctuate when the sun is shining and the wind speed is moderate. The question then arises as to what is required when measuring the air temperature at any instant. Usually it is the average temperature over a period of about 5–10 minutes, in which case the time-constant of the thermometer should not be less than about 30–60 seconds, as otherwise it will be unduly influenced by any short-period fluctuations about the average, and several readings would be required to obtain the mean. This applies especially to maximum thermometers, for the fluctuations are often most marked at the time of maximum temperature. The same considerations apply to minimum thermometers, although the fluctuations in temperature are usually neither so large nor rapid at the time of minimum temperature, because of the increased stability at this time in most situations.

2 EXPOSURE OF THERMOMETERS

2.1 Exposure of thermometers for measuring air temperature

Radiation from the sun, the clouds, the ground and the surrounding objects passes through the air without appreciably affecting the air temperature in the lower layers, but a thermometer, exposed freely in the open, usually absorbs the radiation to a considerable extent. As a consequence its temperature may differ from the true air temperature, such difference depending on the ratio of surface area to volume of the thermometer, on the nature and finish of the material of the thermometer, the intensity of the various kinds of radiation, the speed of the airflow past the thermometer, and other factors. With some thermometer elements, such as the very fine wire used in an open-wire resistance thermometer, the difference may be very small or even negligible, but with the more usual thermometers the difference may be as much as 25 °C under extremely unfavourable conditions. It is usual therefore to provide some form of screen or shield which will serve to support the thermometer, shield it from direct radiation from outside sources while allowing the free circulation of air around it, shield it from precipitation, and prevent accidental damage.

Ideal screen or shield. The conditions which an ideal screen should satisfy can be set out in the following form:

(a) The screen should be a 'uniform' temperature enclosure.

(b) The temperature of the inner walls of the enclosure should be the same as that of the external air, and should respond to the changing temperature of the air as rapidly as possible.

(c) The enclosure should completely surround the thermometer.

(d) The enclosure should be impervious to precipitation and radiant heat.

Conditions (c) and (d) are easily attained. Conditions (a) and (b), though generally difficult to attain, are approximated to in the screens and shields used by the provision of double walls or louvers with ample air circulation and by painting the screens white, or by polishing the outer surface of the shields so as to reflect the maximum amount of radiation. When double walls are provided, although the outer wall may be heated to a higher temperature than the external air by strong sunshine, the layer of air between the two walls will reduce the amount of heat conducted to the inner enclosure. When the wind is appreciable, or when artificial ventilation is provided, the air between the two walls is changed constantly, and the conduction of heat from the outer walls is further decreased.

The free circulation of air throughout the screen is also provided to help the temperature of the inner wall and the thermometer to change quickly when the air temperature itself changes. If radiation exchange alone were relied on to provide the mechanism for changing

the temperature of the thermometer, the resulting time-constant would normally be too large.

The air that circulates through the screen or shield will, however, spend a certain time in contact with the outer walls and may have its temperature altered by conduction. This effect is usually negligible when the wind or ventilation is strong, but may become appreciable when the wind is light and the temperature of the outer wall is markedly different from the air temperature. Thus the temperature of the air in a screen may be expected to be slightly higher than the true air temperature on a day of strong sunshine and calm wind and slightly lower on a clear calm night. These errors may be about +2.5 °C and –0.5 °C in the two extreme cases (see also page 2–12).

Location of the screen or shield. For general meteorological work the temperature required is that which is representative of the free air conditions over as large an area as possible surrounding the station, at, or close to, a height of 1.25 m above ground level. The height above ground level must be specified, as on many occasions large vertical temperature gradients exist in the lowest layers of the atmosphere. The best site for the screen, or shield, and thermometers is therefore over level ground, freely exposed to sun and wind and not shielded by, or close to, trees and buildings. The most unrestricted exposure available should be used. A site on a steep slope or in a hollow is subject to exceptional conditions and should be avoided. In towns and cities local peculiarities will be more marked than in rural districts, but the best site is an open situation with the screen at the normal height. Observations of temperature on the top of buildings may be of doubtful significance and use owing to the sometimes rapid variation of the temperature in the vertical, especially at night, and the effect of the building itself on the temperature distribution. At a station where snow is persistent and of varying depth it is possible to use a support which allows the screen to be raised or lowered to maintain the correct height above the snow surface.

Effect of ventilation rate. When a thermometer is exposed in a fast-moving airstream some of the kinetic energy of the moving air is converted into heat, leading to a purely local temperature rise. Any consequent error in the recorded temperature is negligible for surface observations.

Thermometer screens. Sparks (1972) reviewed the aspects of thermometer screen design, exposure and use that affect the temperature inside the screen. He also surveyed types of thermometer screens used by meteorological services.

Two main types of screen are used in the United Kingdom: an ordinary screen for exposing liquid-in-glass thermometers or electrical resistance thermometer elements, and a large screen to accommodate these instruments and in addition a thermograph and a hygrograph. The Meteorological Office patterns of large and ordinary screens are described below.

Large thermometer screen. The large thermometer screen (Plate I) is a rectangular wooden box provided with doors at the back and front; the sides, back and front are double-louvered, the roof is double and the base consists of overlapping boards separated vertically by an air space. A series of holes, of 25 mm diameter with brass liners, in the inner roof helps the air circulation between the inner and outer roofs. The two sides of the louvers act in a similar manner to double walls, and at the same time allow the air to circulate freely. The top of the screen is covered with sheet zinc, which is turned down at the edges, and the whole is painted with white gloss paint. The front door is hinged at the bottom and may be fastened by a brass turn, hasp and staple at the centre top. A suitable length of brass chain is fixed between the side posts and the door, so that the door comes to rest in an approximately horizontal position when opened to its fullest extent. The rear door is identical with the front door, except that the brass turn, hasp and staple are replaced by brass securing plates. These plates can be unscrewed when necessary if access to the rear of the screen is required. A rectangular metal clip, used to support the water reservoir, is secured to the side of the thermometer mounting. The dimensions of the clear rectangular space inside the screen are 990 mm (wide) by 290 mm (deep) by 420 mm (high).

The screen itself is supported on a stand consisting of four uprights of angle steel, with angle-steel cross-pieces and diagonal ties of mild-steel strip. Foot plates, 130 mm square, are provided at the base of each upright. All the members are supplied drilled, ready for assembly, together with the necessary nuts and bolts.

Installation of screen. A hole should be dug, 300 mm deep and of sufficient length and breadth to take the flat ends of the feet of the uprights. This depth should ensure that the base of the screen will be 1.1 m above the ground level, and thus that the bulbs of the dry- and wet-bulb thermometers will be 1.25 m above the ground. The front of the screen should face true north in the northern hemisphere (south in the southern hemisphere) to reduce to a minimum the risk of sunlight reaching the thermometer bulbs when the door is opened. The assembled stand should be placed in the hole, so that the top is level, and then the earth filled in and trodden down. The legs should be sufficiently rigid when in position to prevent shaking during gales; in very exposed situations, however, it is advisable to have the feet set in concrete. The ground cover beneath the screen should be grass, or, at places where grass does not grow, the natural earth surface of the district.

Once the stand is erected, the screen is fitted on to the top and fixed firmly in place by screws at each end.

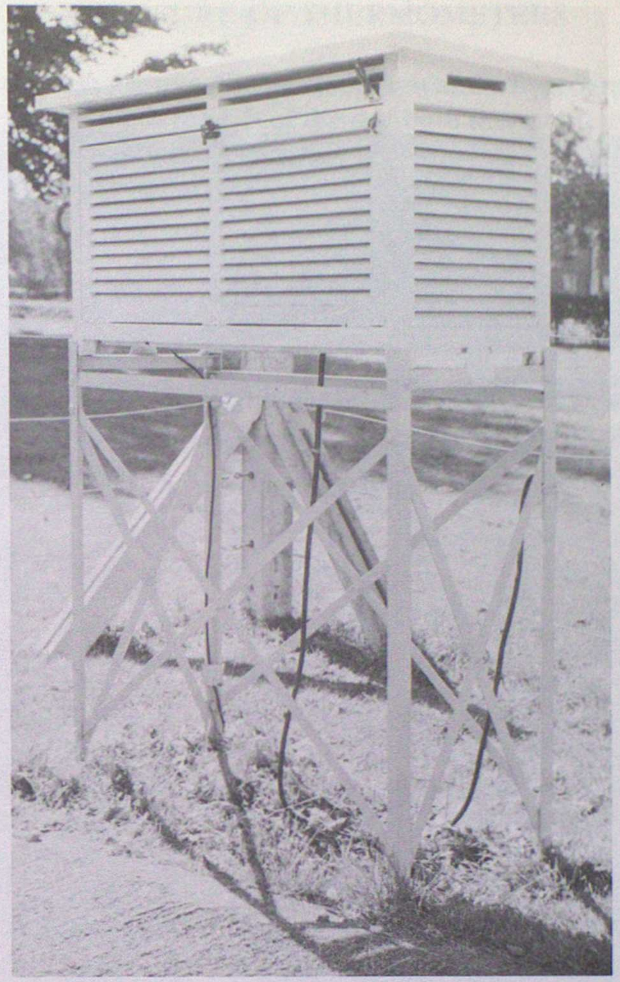
The mounting for the thermometers consists of a wooden framework fixed firmly in position inside the screen. The dry- and wet-bulb thermometers are suspended in a vertical position, 140 mm apart, with the buttons at the top of the thermometers resting in the supports on the upper cross-piece of the mounting. Brass clips hold the thermometers in grooves in the upper and lower cross-pieces. The grooves are sufficiently deep to take the sheathed thermometers but not deep enough to allow any movement, once the thermometers are in position. When in position the bulbs of the two thermometers are about 75 mm above the centre base board of the screen.

If electrical resistance thermometer elements Mk 2 are also to be mounted in the screen, a small wooden adapter block must be fitted to the back of the thermometer mounting. The adapter block, which has two small holes in it of suitable size for the thermometer elements, is fitted parallel with the top of the lower cross-piece so that when the thermometer elements are inserted they are behind the mercury-in-glass wet- and dry-bulb thermometers. If, alternatively, thermometer elements Mk 4A are to be mounted they are held in place by plastic-coated metal clips screwed directly to the back of the thermometer mounting. In both cases the lower ends of the thermometer elements should be about level with the bulbs of the mercury-in-glass thermometers.

The arrangement of the wet-bulb reservoir and the covering of the wet bulb are dealt with in Volume 3.

The mercury-in-glass maximum thermometer is laid in position on the upper two metal brackets on the lower cross-piece, and these are positioned so that the thermometer rests at an angle of 2° to the horizontal. The thermometer should be placed so that the bulb is at the lower end, i.e. with the bulb on the left when facing the front of the screen. The spirit-in-glass minimum thermometer is laid in position on the lower two metal brackets on the lower cross-piece. It also slopes at an angle of 2° to the horizontal, and the bulb should be lower than the stem. The thermometers are held firmly in place by the elasticity of the metal.

This arrangement, with the thermometers grouped closely together, reduces to a minimum the obscuring of one thermometer scale by other thermometers, and places the maximum and minimum thermometers in a readily available position for removal for the purpose of resetting. The wet bulb is also well away from the other three bulbs, and there is a space of at least 75 mm between each bulb and the walls of the screen. The firm fixing of the maximum and minimum thermometers is important, as any jolting in strong winds, or when the door of the screen is opened, might otherwise lead to a displacement of the index or mercury column. The reason for the slope of the maximum thermometer is to prevent the mercury column from moving along the bore when the thermometer is replaced in the screen after resetting. On the other hand too great a slope of the thermometer might introduce errors in the other direction, by allowing the mercury to pass back through the constriction when the temperature falls.



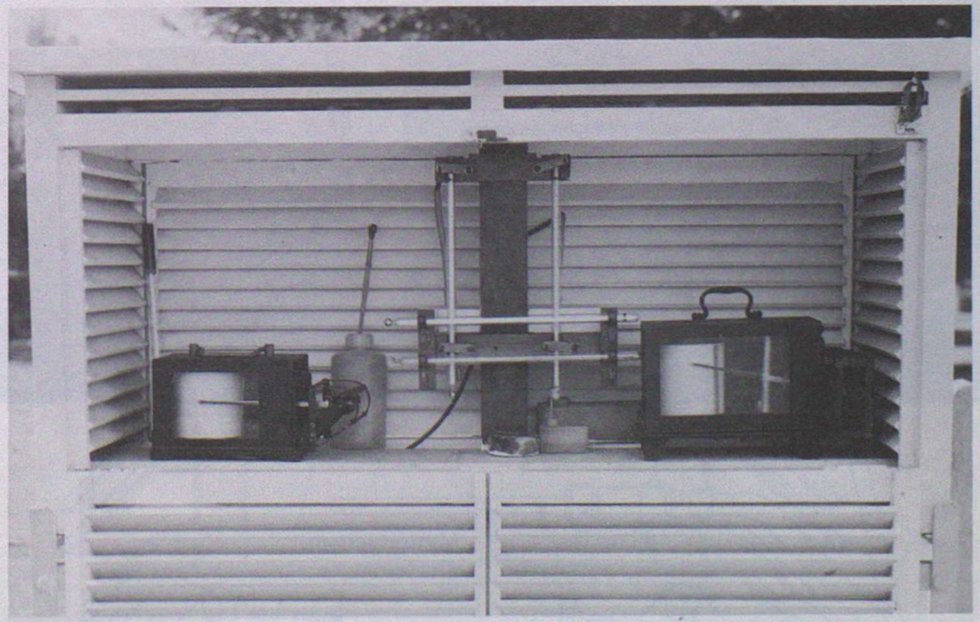


Plate I. Large thermometer screen.

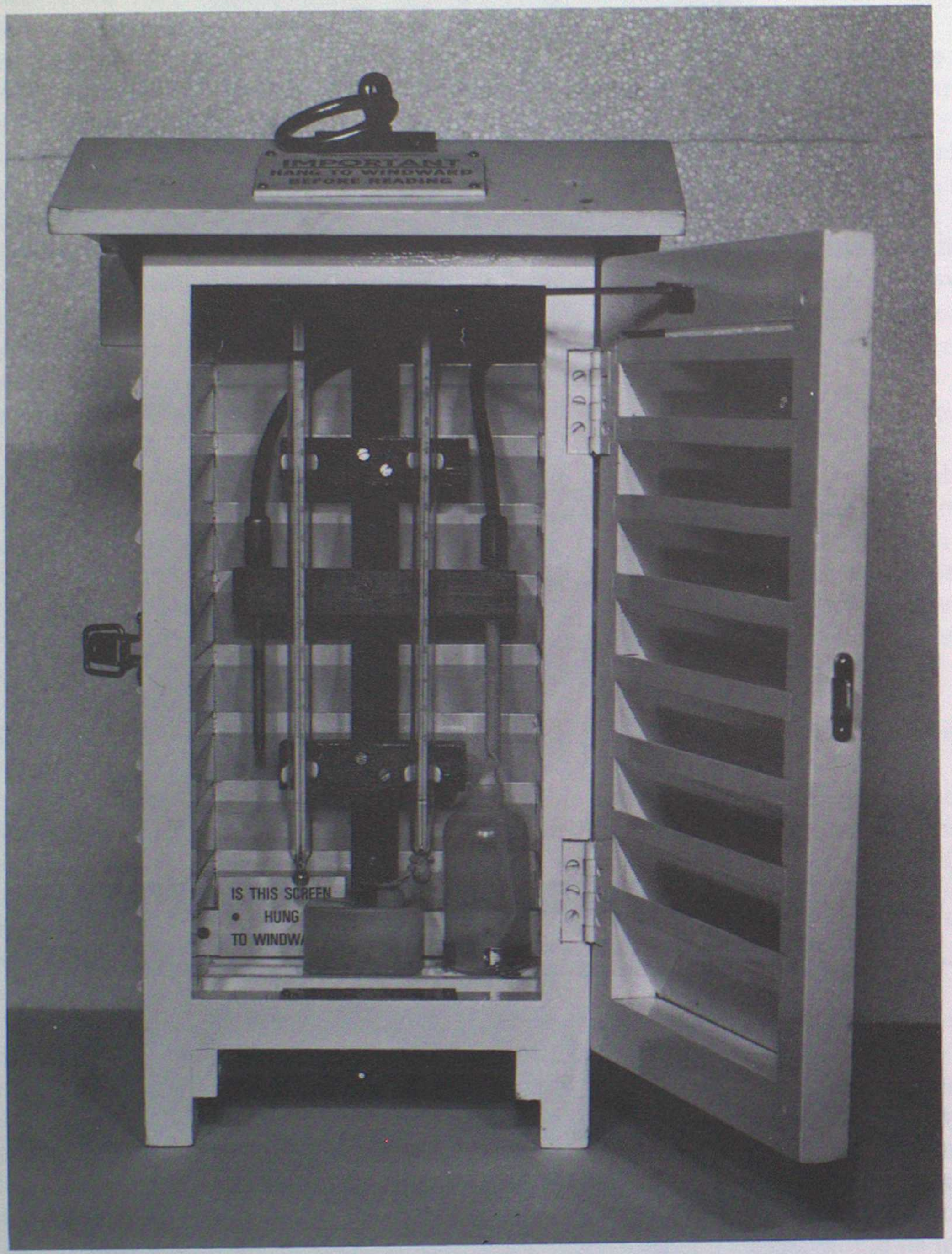


Plate II. Marine screen.

The screen will also house a bimetallic thermograph and a hygrograph. These rest on the centre board, the thermograph to the left of the dry-bulb thermometer and the hygrograph to the right of the wet-bulb thermometer.

The paint on the screen should be kept in good condition and renewed as necessary. A dirty screen absorbs much more radiation than a white screen, and thus the errors introduced by the heating of the screen are larger. It is advisable to wash the screen with soap and water regularly in the intervals between paintings.

Ordinary thermometer screen. The ordinary thermometer screen is similar to the large thermometer screen except that it has a clear inside width of 445 mm. Because of the narrower width the door louvers are made in one section without a central supporting post. The design of the stand, and its erection, is similar to that for the large screen.

Marine screens. The marine thermometer screen Mk 1B (Plate II) is designed mainly for use on board ship but is also used at some coastal stations where a suitable site for an instrument enclosure is unavailable. The screen can house a pair of mercury-in-glass thermometers or electrical resistance thermometer elements or both. If electrical resistance thermometer elements are housed in the screen they are permanently mounted. The sides and base of the screen have single louvers, and the outer roof is gabled with a small air space between it and the top of the screen proper. Five holes drilled in the top of the screen allow free circulation of air. The clear inside space is approximately 280 mm × 180 mm × 100 mm. In use the screen is usually mounted on brackets on the ship's rails or stanchions.

The ODAS (Oceanic Data Acquisition System) screen is also designed for use in a marine environment. It consists essentially of a series of glass fibre flanged discs, A in Figure 1,

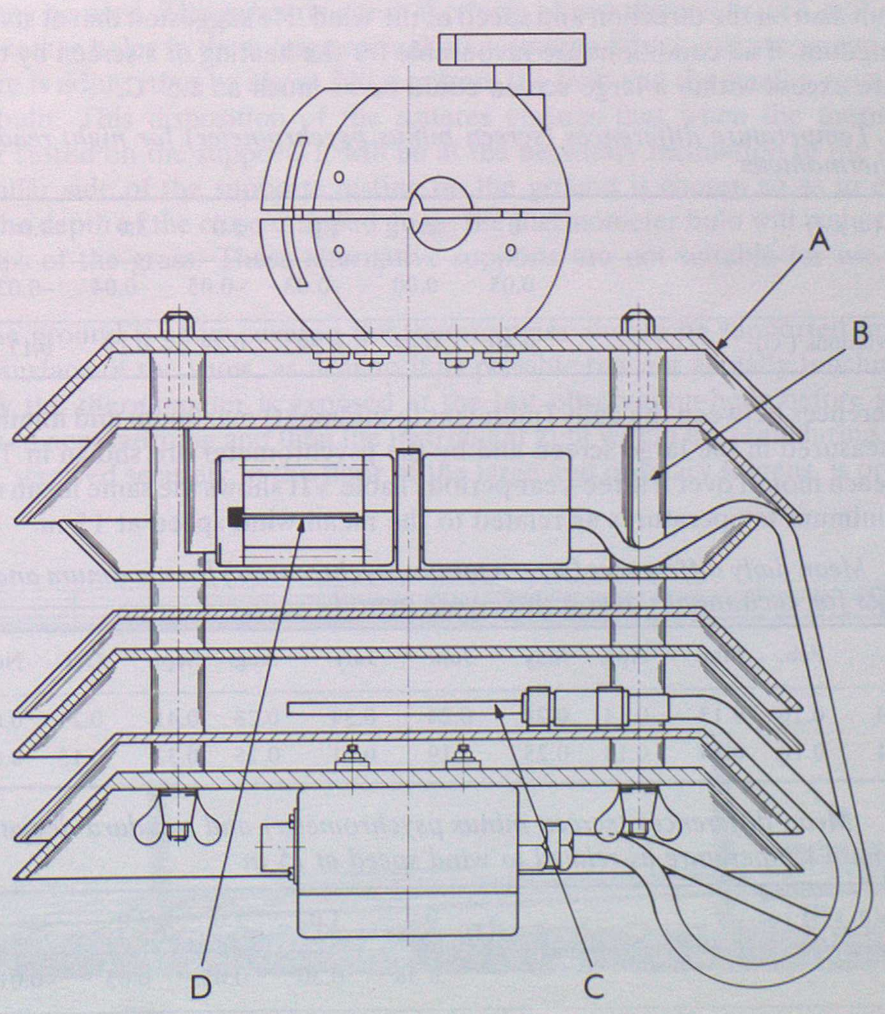


Figure 1. ODAS screen

mounted on top of one another and separated from each other by spacers, B. For unattended operation, e.g. on buoys, the screen usually houses an electrical thermometer element Mk 4A, C, and an electric humidity sensor, D. At attended locations a similar installation may be used or alternatively the screen can house a pair of electrical thermometer elements only. The screen is fitted with a clamp for mounting to a suitable support.

Errors caused by ordinary and large screens. Little work has been done on the problem of screen time-constants but observations by Langlo (1949) on a Norwegian screen suggest that $\tau = 24V^{-\frac{1}{2}}$, where τ is the time-constant in minutes and V the wind speed in m s^{-1}. An investigation by Bryant (1968) using an ordinary screen produced a time-constant given by $\tau = 8.2V^{-\frac{1}{2}}$. Painter (1977), by adapting Bryant's expression, suggested that the large thermometer screen could have a time-constant of approximately $12.2V^{-\frac{1}{2}}$ minutes. For a range of wind speeds at screen level of 0.5 to 10 m s^{-1} this expression gives a range of time-constants of 17 to 4 minutes for a large screen. By comparison, the aspirated psychrometer used by Painter had a time-constant varying between 100 and 130 seconds.

Painter compared readings at Kew from an electrical resistance thermometer element exposed in a large screen with those from an aspirated resistance psychrometer. To evaluate the relationship between temperatures from the two instruments when the screen was unaffected by solar radiation, temperature differences were obtained from hourly readings for all periods of darkness over a period of two years. The differences, some of which are shown in Table V, were classified according to the mean hourly wind speed at an effective height of 15 m. Painter also investigated the effect of solar radiation on the temperature in a large screen. It was found that the effect was dependent not only on the intensity of the solar radiation but also on the direction and speed of the wind. He suggested that at stations in the United Kingdom, if all conditions are favourable for the heating of a screen by the sun, the temperature excess within a large screen could be as much as 2.5 °C.

Table V. *Temperature differences (screen minus psychrometer) for night readings of the dry-bulb thermometer*

Wind speed (m s^{-1})	0	0.5	1.0	2.0	3.0	4.0	5.0
Mean (°C)	0.05	0.00	−0.03	−0.05	−0.04	−0.03	−0.02
Standard deviations (°C)	0.40	0.42	0.39	0.29	0.19	0.17	0.14

The differences between the daily (midnight to midnight) maximum and minimum temperatures measured in the large screen and by the psychrometer are shown in Table VI as means for each month over a three-year period. Table VII shows the same mean differences of daily minimum temperatures as related to the mean wind speed at 15 m.

Table VI. *Mean daily differences (screen minus psychrometer) for maximum and minimum temperatures for each month over a three-year period.*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Max	0.04	0.16	0.17	0.14	0.28	0.24	0.34	0.28	0.41	0.21	0.01	0.03
Min	0.11	0.18	0.14	0.15	0.25	0.19	0.21	0.25	0.32	0.15	0.08	0.08

Table VII. *Mean differences (screen minus psychrometer) and standard deviations of the daily minimum temperature as related to wind speed at 15 m*

Wind speed (m s^{-1})	0.0	1.0	2.0	3.0	4.0	5.0
Mean (°C)	0.38	0.30	0.05	0.05	−0.01	−0.04
Standard deviation (°C)	0.30	0.34	0.28	0.30	0.25	0.17

Other methods of exposure for measuring air temperature. The main alternative method of thermometer exposure consists of shielding the thermometer bulb from direct radiation by placing it on the axis of two concentric cylindrical shields and drawing a current of air between the shields and past the thermometer bulb. This type of exposure is normal in aspirated psychrometers (see Volume 3). The shields are normally of highly polished metal to reduce their absorption of radiation. As the inner shield is kept in contact with a moving stream of air on both sides, its temperature, and consequently that of the thermometer, should approximate very closely to the temperature of the air. The shields are usually mounted with their axes vertical; the amount of direct radiation from the ground entering through the base of the shields is small and can be reduced by extending the base of the shields appreciably below the thermometer bulb.

In the whirling, or sling, psychrometer there is no direct protection from radiation. The thermometer is mounted on a light frame, attached to a handle, so that it can be rapidly whirled by the observer. The details of this method are given in Volume 3.

2.2 Exposure of thermometers for measuring grass, bare soil and concrete slab minimum temperatures. The grass minimum temperature is the lowest temperature reached overnight over short grass freely exposed to the sky. The most open position available should therefore be chosen, and the grass kept short by mowing as necessary. The temperature is measured with a minimum thermometer such as that described on page 2–28. The thermometer may be mounted on two Y-shaped forks (Figure 2) so that it is inclined at about 2° to the horizontal with the bulb lower than the stem, 25 mm to 50 mm above the ground and in contact with the tips of the grass. Alternatively, special grass minimum thermometer supports may be used. The supports are in the form of two different-sized rubber squares, having off-centre holes in them large enough to accommodate the thermometer stem. The large square is adjusted to be about 290 mm from the bulb and the smaller square 110 mm from the bulb. This disposition of the squares ensures that when the thermometer is exposed or stored on the supports it will be at the necessary inclination to the horizontal. The particular side of the supports resting on the ground is chosen so as to ensure that whatever the depth of the close-cropped grass, the thermometer bulb will be just in contact with the tips of the grass. These alternative supports are not suitable for use at 'windy' sites.

When the ground is snow-covered the thermometer should be supported immediately above the surface of the snow, as near to it as possible but not actually touching it.

Normally the thermometer is exposed at the last observation-hour before sunset, the reading taken next morning and then the instrument kept within a screen during the day. A cork stand, screwed securely to the floor of the large and ordinary screens, is provided for

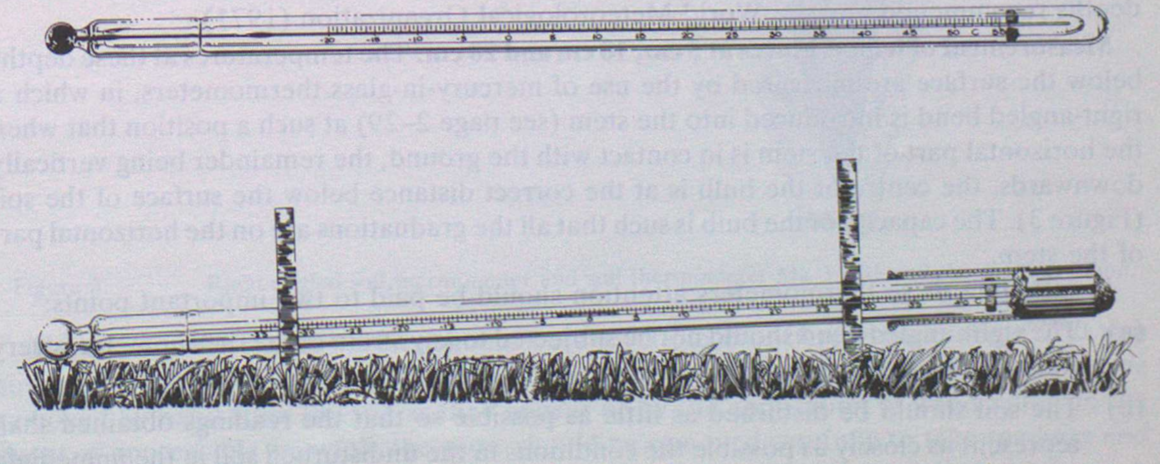


Figure 2. Maximum and minimum thermometers

this purpose. The stand is positioned, so that it cannot interfere with the airflow, on the right-hand side of the screen. The thermometer should be propped vertically, bulb downwards, in the hole of the stand. If special grass minimum thermometer supports are being used, the thermometer with supports attached may be stored in the front well on the floor of the screen.

At stations where an observer is not available around sunset it may be necessary to leave the thermometer exposed throughout the day. Exposure of the thermometer to strong sunshine can cause the spirit to distil and collect in the top of the bore. This is prevented or minimized by the fitting of a cotton sock and a black metal shield over the safety chamber end of the thermometer. The shielded end of the thermometer absorbs more radiation than the rest of the thermometer and consequently reaches a higher temperature. Vapour is thus prevented from condensing in the upper part of the bore, and any vapour which has already condensed there evaporates and condenses lower down the bore at the top of the spirit column.

At certain selected stations a minimum thermometer is used for measuring minimum temperature on bare soil or on a concrete slab or both.

(a) *Bare soil minimum temperature*. The thermometer should be laid on level bare soil with the stem having a slight slope downwards towards the bulb. Small pegs should be placed in the ground at each side of the thermometer, but not near the bulb, to prevent accidental movement. When the ground is snow-covered the thermometer should rest on top of level snow.

(b) *Concrete slab minimum temperature*. The thermometer, fitted with an anti-condensation shield, is exposed in the centre of a concrete slab with sides 1 m by 600 mm, and 50 mm thick. The slab, light grey in colour and conforming to BS 368, is laid horizontally, smooth side uppermost, flush with the ground in an open position. The thermometer should be placed so that the bulb is in the centre of, and in contact with, the surface of the slab, and with the stem parallel to the longer side of the slab. To hold the thermometer firmly in position, a PVC-coated phosphor-bronze spring-clip is provided. To accommodate this spring-clip, the concrete slab should be drilled and plugged to take a suitably sized round-headed brass woodscrew; the plug should be positioned so that the provisions above as to the thermometer's placement are met. The spring-clip fastens around the thermometer stem just below the anti-condensation shield and, additionally, provides a downward slope to the bulb of approximately 2°.

When the ground is snow-covered, the concrete slab should be swept clear of snow at the time of setting the thermometer.

2.3 Exposure of thermometers for measuring soil temperatures

Soil temperature is usually measured at one or more standard depths which, in the United Kingdom, are 5 cm, 10 cm, 20 cm, 30 cm, 50 cm and 1 m. Except for 30 cm these are the depths recommended by the World Meteorological Organization (1971).

Measurement of temperatures at 5 cm, 10 cm and 20 cm. The temperatures at these depths below the surface are measured by the use of mercury-in-glass thermometers, in which a right-angled bend is introduced into the stem (see page 2–29) at such a position that when the horizontal part of the stem is in contact with the ground, the remainder being vertically downwards, the centre of the bulb is at the correct distance below the surface of the soil (Figure 3). The capacity of the bulb is such that all the graduations are on the horizontal part of the stem.

In installing these thermometers attention should be paid to two important points:

(a) The right-angled bend should not be subjected to any strain as the thermometer is very weak at this point.

(b) The soil should be disturbed as little as possible so that the readings obtained shall represent as closely as possible the conditions in the undisturbed soil in the immediate neighbourhood.

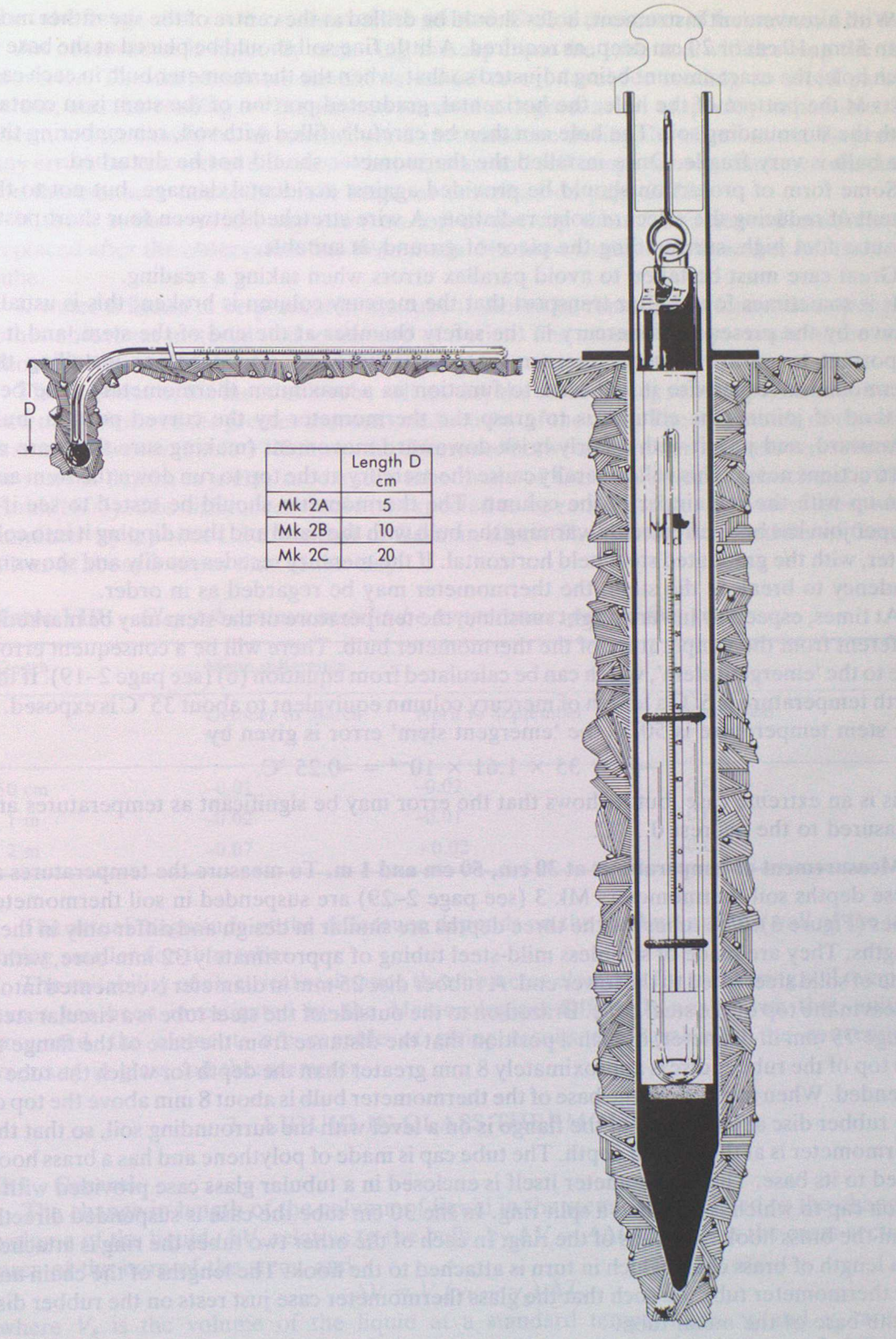


Figure 3. **Right-angled soil thermometer and soil thermometer Mk 3 with soil thermometer tube.**

The site for the thermometers should be a level piece of bare ground about 750 mm square, typical of the surrounding soil for which information is required; weeds should be removed by hand from the site as they appear or by the application of weed-killer. In the event of appreciable snowfall, the snow should be removed carefully to take readings and afterwards replaced as far as possible.

With a convenient instrument, holes should be drilled at the centre of the site rather more than 5 cm, 10 cm or 20 cm deep, as required. A little fine soil should be placed at the base of each hole, the exact amount being adjusted so that, when the thermometer bulb in each case rests at the bottom of the hole, the horizontal, graduated portion of the stem is in contact with the surrounding soil. The hole can then be carefully filled with soil, remembering that the bulb is very fragile. Once installed the thermometer should not be disturbed.

Some form of protection should be provided against accidental damage, but not to the extent of reducing the effect of solar radiation. A wire stretched between four short posts, about a foot high, surrounding the piece of ground, is suitable.

Great care must be taken to avoid parallax errors when taking a reading.

It is sometimes found after transport that the mercury column is broken; this is usually shown by the presence of mercury in the safety chamber at the end of the stem, and it is important to ensure that the mercury column is properly joined before installing the thermometer (otherwise it will tend to function as a maximum thermometer). The best method of joining the column is to grasp the thermometer by the curved portion, bulb downward, and jerk it with a fairly brisk downward movement (making sure there are no obstructions near). This will generally cause the mercury at the top to run down the stem and join up with the remainder of the column. The thermometer should be tested to see if a proper join has been effected by warming the bulb with the hand and then dipping it into cold water, with the graduated stem held horizontal. If the mercury recedes readily and shows no tendency to break in the stem, the thermometer may be regarded as in order.

At times, especially in very bright sunshine, the temperature of the stem may be markedly different from the temperature of the thermometer bulb. There will be a consequent error, due to the 'emergent stem', which can be calculated from equation (6) (see page 2–19). If the earth temperature is 5 °C a length of mercury column equivalent to about 35 °C is exposed. If the stem temperature is 50 °C the 'emergent stem' error is given by

$$-45 \times 35 \times 1.61 \times 10^{-4} = -0.25 \text{ °C}.$$

This is an extreme case, but it shows that the error may be significant as temperatures are measured to the nearest 0.1 °C.

Measurement of temperatures at 30 cm, 50 cm and 1 m. To measure the temperatures at these depths soil thermometers Mk 3 (see page 2–29) are suspended in soil thermometer tubes (Figure 3). The tubes for the three depths are similar in design and differ only in their lengths. They are made of seamless mild-steel tubing of approximately 32 mm bore, with a cone of solid steel fitted to the lower end. A rubber disc 25 mm in diameter is cemented into a recess in the top of the steel cone. Brazed on to the outside of the steel tube is a circular steel flange 75 mm in diameter, in such a position that the distance from the base of the flange to the top of the rubber disc is approximately 8 mm greater than the depth for which the tube is intended. When in position, the base of the thermometer bulb is about 8 mm above the top of the rubber disc and the base of the flange is on a level with the surrounding soil, so that the thermometer is at the correct depth. The tube cap is made of polythene and has a brass hook fitted to its base. The thermometer itself is enclosed in a tubular glass case provided with a nylon cap to which is attached a split ring. In the 30 cm tube the case is suspended directly from the brass hook by means of the ring. In each of the other two tubes the ring is attached to a length of brass chain which in turn is attached to the hook. The lengths of the chain and the thermometer tube are such that the glass thermometer case just rests on the rubber disc at the base of the metal tube.

The site chosen for the thermometers should be uniform and horizontal in all directions to a distance at least equal to the depth of the deepest thermometer bulb. The site should be well exposed to sunshine and any grass should be kept reasonably short.

A tube for the required depth must be set vertically in the ground, a pilot hole first being made without disturbing the surrounding ground. The cap should then be removed from the tube and the tube inserted into the pilot hole. A wooden block should be placed over the rim of the tube to protect it and a mallet or hammer used to drive the tube into the ground until the tube flange rests on the surface of the ground. Only a minimum of force should be used.

An observation is made by removing the cap from the tube and withdrawing the thermometer. The thermometer should be raised to eye-level for reading to avoid parallax errors, and the reading, to the nearest tenth of a degree, made as quickly as possible. The thermometer should be screened from direct sunshine during the observation. To prevent any errors on account of differences between air and soil temperatures, the time-constant of the thermometer has to be made large, as described on page 2–29.

If there is snow cover, any snow on top of the cap should be removed carefully and replaced after the observation has been made. No snow should be allowed to fall inside the tube.

If water is found to be present in the tube it should be removed by means of a sponge or other absorbent material tied to the end of a stick. The cause of the presence of the water should be investigated and action taken to prevent its recurrence.

The presence of the metal soil-tube will modify the surrounding soil temperature to a small extent by virtue of the greater thermal conductivity of the tube. The magnitude of this effect is small, however. Table VIII shows the difference between the mean temperatures recorded at various depths in a clay tube and a tube made of German silver (Kleinschmidt, 1935; Kuhl, 1907). The differences would be expected to be rather greater for a steel tube, whose conductivity is about 1.5 times that of German silver. The thermal conductivity of German silver is about 5 times that of the clay.

Table VIII. *Clay-tube minus metal-tube temperature, period five years*

Depth	Mean difference		
	October to March °C	April to September °C	Whole year °C
50 cm	−0.01	−0.02	−0.02
1 m	−0.02	−0.01	−0.02
2 m	−0.07	+0.02	−0.03

The actual magnitude of the difference depends on the thickness of the wall of the tube, being smaller for thin tubes.

The suitability of electrical resistance thermometer elements for measuring soil temperatures has been investigated by the Meteorological Office. It was shown that, suitably mounted, the elements are capable of giving results comparable to the conventional mercury-in-glass soil thermometer.

3 LIQUID-IN-GLASS THERMOMETERS

3.1 General

The change in length of the column of liquid in the stem, Δl, is related to the change in volume of the liquid, ΔV, relative to the bulb, by $\Delta V = A\Delta l$ where A is the cross-sectional area of the bore of the stem, and

$$\Delta V = V_s(\gamma_l - \gamma_g)\,\Delta T,$$

where V_s is the volume of the liquid at a standard temperature, γ_l and γ_g are the coefficients of cubical expansion of the liquid and the glass respectively, and ΔT is the change in temperature.

Thus $\Delta l = V_s \dfrac{(\gamma_l - \gamma_g)}{A}\Delta T.$

In the above discussion the expansion of the bore has been neglected.

Meteorological Office liquid-in-glass thermometers have one or other of the two types of stem shown in Figure 4. Whirling psychrometer thermometers are of type (a), having a fine circular bore and a 'lens front' which produces a magnified image of the mercury column when viewed normal to the lens. All other thermometers are of type (b), having a similar bore to type (a) but a plain round stem. The bore in type (b) is much larger for spirit thermometers than for mercury thermometers. In all thermometers there is a strip of enamel behind the bore to serve as a suitable background against which to view the liquid column. The enamel is usually yellow, but may be white in whirling psychrometer thermometers.

The scale is engraved directly on the thermometer stem which for ordinary, maximum and minimum thermometers is enclosed in a protective cylindrical glass sheath.

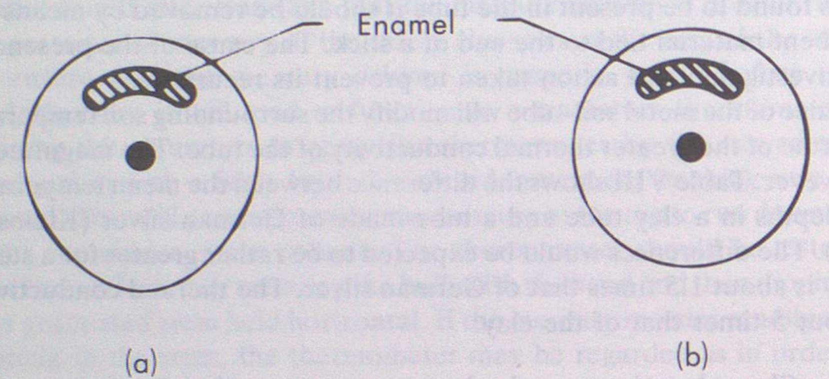


Figure 4. Cross-sections of thermometer stems.

3.2 Errors of liquid-in-glass thermometers

The main sources of error common to all liquid-in-glass thermometers are:

(a) elastic errors,

(b) errors caused by the emergent stem,

(c) parallax errors,

(d) changes in the volume of the bulb produced by exterior or interior pressure,

(e) capillarity,

(f) errors in scale division and calibration, and

(g) inequalities in the expansion of the liquid and glass over the range considered.

The last three errors can be minimized by the manufacturer and included in corrections to be applied to the observed values. Some consideration needs to be given to the first three errors. Error (d) does not usually arise when the thermometers are used for meteorological purposes.

Elastic errors. There are two kinds of elastic errors, reversible and irreversible. The first is of importance only when a thermometer is exposed to a large range of temperature in a short period of time. Thus, if a thermometer is checked at the steam-point and shortly afterwards at the ice-point, it will read slightly too low at first and then the indicated temperature will rise slowly to the correct value. This error depends on the make of glass employed in the thermometer, and may be as much as 1 °C, but with the best glass it should be only 0.03 °C, and would be proportionally less for smaller ranges of temperature. The effect is of no importance in meteorological measurements, apart from the possibility of error in the original calibration.

The irreversible changes may be more significant. The bulb of the thermometer tends to contract slowly over a period of years, and thus causes the zero to rise. The greatest change will take place in the first year and then the rate of change will gradually decrease. This alteration can be reduced by heat treatment of the bulb and by using the most suitable glass,

but even with the best glass the change may be about 0.01 °C a year at first. For accurate work, and especially with inspector's thermometers, the zero should be redetermined periodically and the necessary corrections applied.

Errors caused by the emergent stem. A thermometer used to measure the air temperature is usually completely surrounded by the air at approximately uniform temperature, and it is calibrated by immersing the thermometer either completely or to the top of the mercury column (i.e. calibrated by complete or partial immersion). When such a thermometer is used to determine the temperature of a medium which does not surround the stem, so that the effective temperature of the stem is different from that of the bulb, an error will result. If a length, l_e mm, of the mercury column is out of the medium whose temperature, T, is required, and the mean temperature of the emergent column is T_e, then the difference between the correct and actual position of the end of the mercury column is

$$\frac{l_e A\,(\gamma_l - \gamma_g)\,(T - T_e)}{A} = l_e(\gamma_l - \gamma_g)\,(T - T_e),$$

where γ_l, γ_g and A have the same definitions as given on page 2–17. The expansion of the bore has again been neglected.

If the mean length of 1 °C on the scale is y mm then the error in degrees Celsius, ΔT, is given by

$$\Delta T = \frac{l_e(\gamma_l - \gamma_g)\,(T - T_e)}{y}$$

$$= n(\gamma_l - \gamma_g)\,(T - T_e), \qquad \ldots (6)$$

where n is the number of degrees whose length equals l_e mm. The value of $(\gamma_l - \gamma_g)$ is approximately 1.6×10^{-4} °C^{-1} for most mercury thermometers and 9.1×10^{-4} °C^{-1} for spirit thermometers. In any numerical evaluation of ΔT it is usually difficult to measure T_e, the mean temperature of the stem. The error rarely exceeds a few tenths of a degree even in extreme cases.

Errors due to parallax. If the thermometer is not viewed with the eye in the plane which is perpendicular to the stem of the thermometer and passes through the top of the mercury column, parallax errors will arise (see Figure 5). The error increases with the thickness of the stem of the thermometer and the angle between the actual line of sight and the correct line of

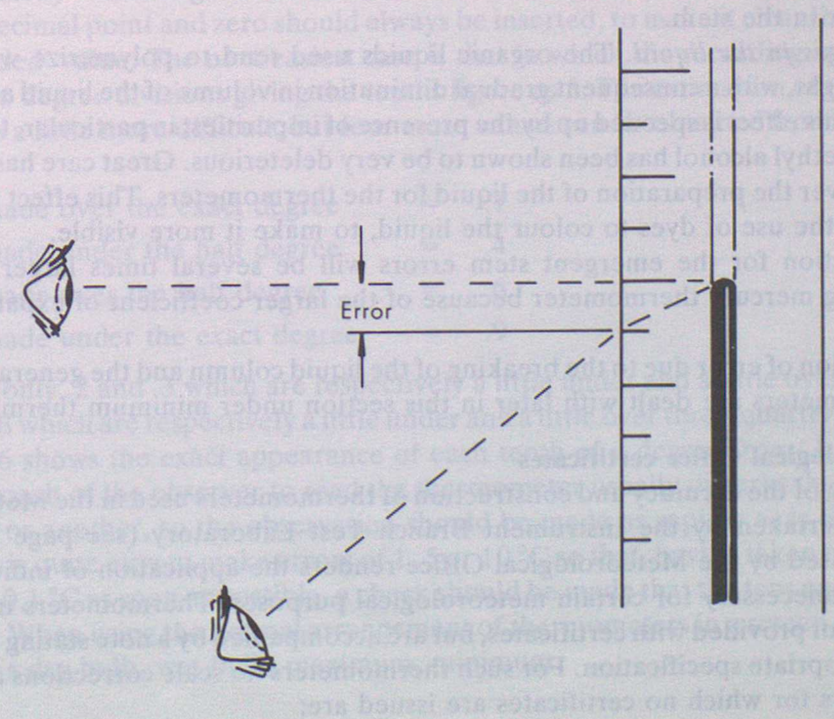


Figure 5. Illustrating error due to parallax.

sight. This error can be avoided only by taking great care when making an observation. With thermometers suspended vertically, as in an ordinary screen, the thermometer must be viewed at the horizontal level of the top of the mercury column.

Mercury thermometers. The coefficient of cubical expansion of mercury is 1.82×10^{-4} °C^{-1}, and that of most glasses lies between 1.0×10^{-5} and 3.0×10^{-5} °C^{-1}. The expansion coefficient of the glass is thus an important fraction of that of mercury and γ_g cannot be neglected in the equation linking Δl and ΔT. As neither the coefficients of cubical expansion of mercury and glass nor the cross-sectional area of the bore of the stem are strictly constant over the range of temperature and length of stem being used, the scale value of unit length of the stem varies along the stem, and the thermometer has to be calibrated against a standard thermometer before it can be used.

The mercury used to fill the thermometer should be chemically clean and free from gases, and after it has been introduced into the thermometer a vacuum is normally produced in the stem before sealing, although in some ordinary thermometers an inert gas such as nitrogen is placed in the stem above the mercury. Mercury thermometers are limited to measuring temperature above the freezing-point of mercury (–38.8 °C).

Spirit thermometers. The expansion coefficients of the liquids used in spirit thermometers are very much larger than that of mercury, and their freezing points are much lower (ethyl alcohol freezes at −115 °C). They are used in minimum thermometers because they are colourless and because their larger expansion coefficient enables a larger bore to be used. Spirit thermometers are less accurate than mercury thermometers of similar cost and quality. Beside having the general errors of liquid-in-glass thermometers (page 2–18) they have errors peculiar to themselves.

Adhesion of the spirit to the glass. Unlike mercury the organic liquids generally wet the glass, and therefore, when the temperature falls rapidly, a certain amount of the liquid may remain on the walls of the bore, causing the thermometer to read low. The liquid gradually drains down the bore if the thermometer is suspended vertically.

Breaking of the liquid column. Drops of the liquid often form in the upper part of the thermometer stem by a process of evaporation and condensation. These can be reunited with the main column, but errors may be caused at the start of the process before it is noticed. The column is also often broken during transport. This error is reduced during manufacture by sealing off the thermometer at its lowest temperature so that it contains the maximum amount of air in the stem.

Slow changes in the liquid. The organic liquids used tend to polymerize with age and exposure to light, with a consequent gradual diminution in volume of the liquid and lowering of the zero. This effect is speeded up by the presence of impurities; in particular, the presence of acetone in ethyl alcohol has been shown to be very deleterious. Great care has, therefore, to be taken over the preparation of the liquid for the thermometers. This effect may also be increased by the use of dyes to colour the liquid, to make it more visible.

The correction for the emergent stem errors will be several times larger than for a corresponding mercury thermometer because of the larger coefficient of expansion of the liquid.

The reduction of error due to the breaking of the liquid column and the general care of the spirit thermometers are dealt with later in this section under minimum thermometers.

3.3 Meteorological Office certificates

Verification of the accuracy and construction of thermometers used in the Meteorological Office is undertaken by the Instrument Branch Test Laboratory (see page 2–55). The control exercised by the Meteorological Office renders the application of individual scale corrections unnecessary for certain meteorological purposes. Thermometers intended for such use are not provided with certificates, but are accompanied by a note stating compliance with the appropriate specification. For such thermometers no scale corrections are applied. Thermometers for which no certificates are issued are:

(a) Ordinary, sheathed for use in naturally ventilated screens.

(b) Maximum, minimum and grass or concrete minimum.

(c) Soil.

(d) Sea temperature.

Thermometers for which certificates are issued are those:

(a) For use in ventilated psychrometers.

(b) For use by inspectors.

(c) For special purposes for which application of corrections is justified.

Ordinary sheathed thermometers for which no certificates are issued are divided, by selection, into two categories. These are:

Category A when errors at 0, 10 and 20 °C are all within the limits ±0.05 °C, and

Category B when the error at one or more of the points 0, 10 and 20 °C is outside the limits ±0.05 °C but within the limits of the appropriate British Standard.

For easy identification, Category A thermometers are marked with red paint on the top button. Any pair of these ordinary thermometers in the same category may be used, without corrections, for psychrometric purposes.

The tolerances quoted in the following pages are intended primarily for acceptance purposes. It should be appreciated that these tolerances, when applied to an individual thermometer, may be exceeded with time. Regular checking is therefore necessary (see page 2–31), so that uncertificated thermometers may be exchanged if necessary or certificated thermometers may be supplied with updated corrections.

3.4 General notes on making temperature observations

The thermometers should be kept clean and the bulbs bright. After cleaning a dry bulb 10–15 minutes should be allowed to elapse before any readings are taken. Care should always be taken to avoid errors due to parallax when making the actual readings.

Most thermometers are usually required to be read to the nearest 0.1 °C. It is essential that the observer should acquire skill in estimating tenths of a degree rapidly and accurately. The simplest case occurs when the end of the index or column of liquid in the thermometer coincides exactly with a degree division such as 17, in which case the reading is recorded as 17.0. The decimal point and zero should always be inserted, to make it clear that the entry is not a 'rounded' value. The next easiest case is that in which the recording is just half-way between two degree divisions giving the tenths figure as 5. The estimation of the intermediate tenths is a little more difficult, but four more values can be obtained from the following rules:

A shade over the exact degree	=	.1
A shade under the half degree	=	.4
A shade over the half degree	=	.6
A shade under the exact degree	=	.9

This leaves only .2 and .3 which are respectively a little under and a little over one-quarter, and .7 and .8 which are respectively a little under and a little over three-quarters. As a further aid Figure 6 shows the exact appearance of each tenth of a degree from .1 to .9.

The approach of the observer to read the thermometer usually disturbs the surroundings in one way or another, so the observation should be made as rapidly as is consistent with accuracy. It is quite easy to make errors of 1, 5 or 10 °C so that, having taken the readings to the nearest 0.1 °C as soon as possible, a check should be made that the tens and units figures are correct. When using the normal arrangement of thermometers in a screen the best order of reading is dry bulb, wet bulb, maximum, minimum.

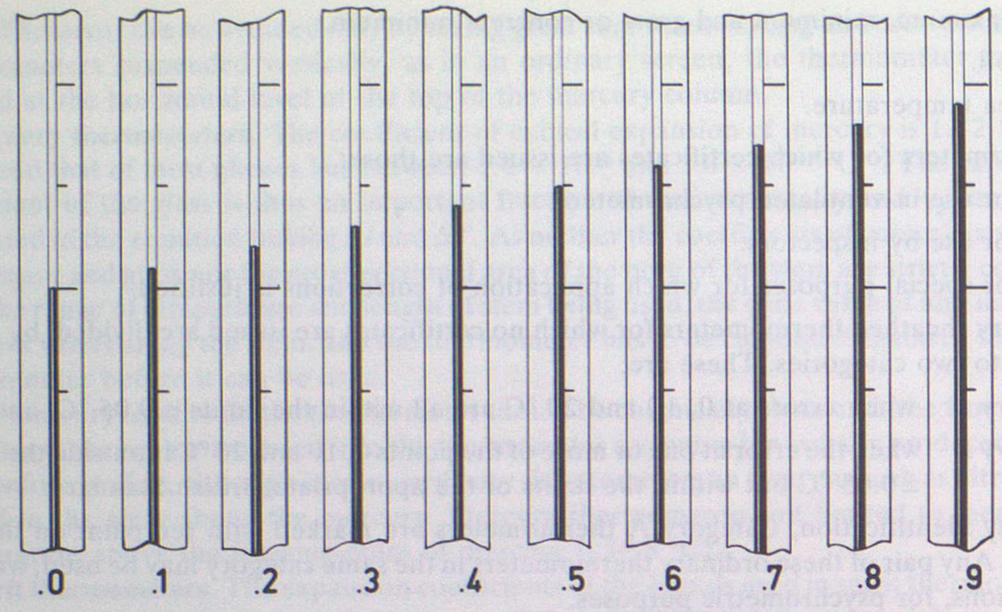


Figure 6. Estimating tenths of a degree.

3.5 Ordinary thermometers (mercury-in-glass and spirit-in-glass)

Sheathed type mercury-in-glass Ord 1/C, Ord 2/C, Ord 3/C and spirit-in-glass Ord 4/C. The specification of these thermometers is that given in BS 692 *Meteorological thermometers* issued by the British Standards Institution. They are sheathed thermometers of the mercury-in-glass type (Figure 7), except for Ord 4/C, evacuated above the mercury, graduated on the stem and protected by a glass sheath. They are graduated for total immersion and graduation marks are made for each half-degree Celsius. Each 5 °C is figured, a minus sign being placed above negative figures.

The dimensions of these thermometers are given in Table IX, and the details of the ranges covered, the maximum errors allowed in the various parts of the range, and the restrictions on the magnitude of the rate of change or error along the stem are given in Table X.

Table IX. *Dimensions for meteorological thermometers*

Dimensions		Type: Ordinary mm	Maximum mm	Minimum mm
Overall length		315 to 330	315 to 345	315 to 345
Length of scale, minimum		190	190	190
Stem diameter		5 to 6.5	5 to 6.5	5 to 6.5
Length of parallel portion of bore above and below scale, minimum		10	10	10
Bulb diameter:				
Spherical type	Ord 1/C, Ord 2/C, Ord 3/C	8.5 to 11.5	8.5 to 11.5	not greater than 16.5
	Ord 4/C	11.5 to 14		
Distance from bottom of bulb to bottom of scale, minimum		50	50	50

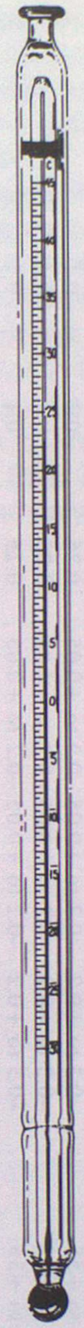


Figure 7. Ordinary thermometer.

The stem is protected by an outer glass sheath not greater than 14 mm in outside diameter and hermetically sealed to the stem at a point near the bulb. The top end of the stem is securely supported inside the sheath by a ring of rubber or cork, not exceeding 4 mm in width, fitted inside the sheath and over the stem and placed so as not to obscure the graduated scale. The end of the sheath is finished in the form of a button, as shown in Figure 7, so that it can be easily and securely suspended from the clip at the top of the thermometer stand in the large and ordinary screens.

From Tables IX and X it will be seen that the scale is such that there is less than 0.4 °C mm^{-1}. This is sufficiently open to allow the position of the end of the liquid column to be read to the nearest 0.1 °C.

Table X. *Ranges and tolerances for meteorological thermometers (Celsius scale)*

Designation	Filling	Range	Maximum error (°C) at any point				Maximum error (°C) in an interval of 10 °C (see Note 2)		
		°C	Below –40 °C	–40 °C to below 0 °C	0 °C to 25 °C	Above 25 °C	Below 0 °C	0 °C to 25 °C	Above 25 °C
Ord 1/C	Mercury	–20 to +55	. .	–0.3 to +0.2	–0.2 to +0.05	–0.2 to +0.05	0.25	0.1	0.1
Ord 2/C	Mercury	–30 to +45	. .	–0.3 to +0.2	–0.2 to +0.05	–0.2 to +0.05	0.25	0.1	0.1
Ord 3/C	Mercury	–40 to +35	. .	–0.3 to +0.2	–0.2 to +0.05	–0.2 to +0.05	0.25	0.1	0.1
Ord 4/C	Spirit	–55 to +20	±0.6	±0.25	±0.1	. .	0.25	0.1	. .
Max 1/C	Mercury	–10 to +65	. .	–0.3 to +0.2	–0.2 to +0.05	–0.2 to +0.05	0.25	0.1	0.1
Max 2/C	Mercury	–20 to +55	. .	–0.3 to +0.2	–0.2 to +0.05	–0.2 to +0.05	0.25	0.1	0.1
Max 3/C	Mercury	–30 to +45	. .	–0.3 to +0.2	–0.2 to +0.05	–0.2 to +0.05	0.25	0.1	0.1
Max 4/C	Mercury	–40 to +35	. .	–0.3 to +0.2	–0.2 to +0.05	–0.2 to +0.05	0.25	0.1	0.1
Min 1/C	Spirit	–25 to +50	. .	±0.25	±0.1	±0.25	0.25	0.1	0.25
Min 2/C	Spirit	–35 to +40	. .	±0.25	±0.1	±0.25	0.25	0.1	0.25
Min 3/C	Spirit	–50 to +25	±0.6	±0.25	±0.1	. .	0.25	0.1	. .
Min 4/C	Spirit	–70 to +15	±0.6	±0.25	±0.1	. .	0.25	0.1	. .

Note 1. The range of the Ord 3/C and Max 4/C thermometers extends down to –40 °C because the mercury usually remains fluid at this temperature, due to supercooling below its freezing-point of –38.8 °C.

Note 2. The maximum error in an interval of 10 °C refers to the algebraic difference between the errors at opposite ends of the interval; thus 0.1 °C means that the change of error in any interval of 10 °C does not exceed 0.1 °C.

Note 3. The tolerances for the mercury-in-glass thermometers permit greater minus errors than plus errors in order to allow for the tendency of the zero of these thermometers to rise slowly with time.

3.6 Thermometers for aspirated psychrometers

The thermometers used in aspirated psychrometers are of the mercury-in-glass type with a cylindrical bulb and unsheathed stem. A flanged non-ferrous cap is cemented on to the top of the stem and a cylindrical non-ferrous sleeve near the bottom of the stem (Figure 8). Both the cap and the sleeve are chromium plated.

There are three different temperature ranges, 0 °C to 55 °C (Mk 3A), –15 °C to +40 °C (Mk 3B) and –35 °C to + 20 °C (Mk 3C). The graduation marks are for every 0.5 °C, with longer lines at each 1 °C, and are figured at each 5 °C. A minus sign is placed above negative figures. No graduation mark is hidden by the sleeve. Table XI gives the main dimensions, permissible errors at a point and permissible rate of change of error over an interval of 10 °C.

The scale span of 55 °C is at least 145 mm in length (i.e. less than 0.4 °C mm^{-1}). This is sufficiently open to allow reading to the nearest 0.1 °C.

The metal sleeve is securely cemented to the stem of each thermometer in such a position that its upper edge is 210 mm ± 2 mm from the upper edge of the cap. The external diameters of the sleeve and cap are such that they fit closely into place in the psychrometer.

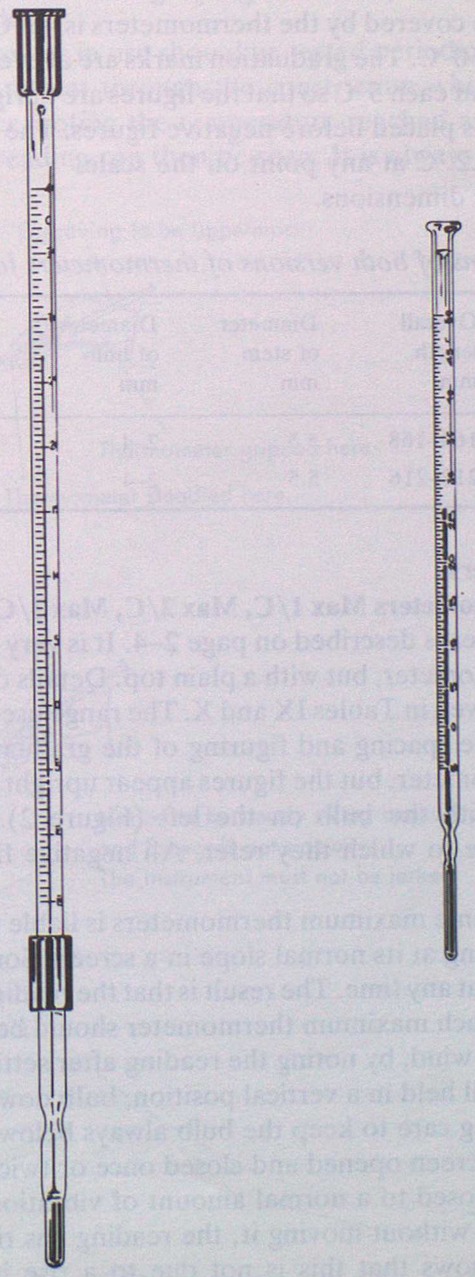


Figure 8. Thermometers for aspirated and whirling psychrometers.

Table XI. *Main dimensions and permissible errors of thermometers for aspirated psychrometers*

Overall length	Diameter of stem	Diameter of bulb	Length of bulb	Scale length	Permissible error at a point (°C)		Permissible change in error (°C) over an interval of 10 °C	
					below 0 °C	at or above 0 °C	below 0 °C	above 0 °C
mm	mm	mm	mm	mm				
280 ± 8	6 + 1.0 − 0.5	4 ± 0.5	19 ± 4	⩾145	−0.3 to +0.2	−0.2 to +0.05	0.25	0.1

3.7 Thermometers for whirling psychrometers

The thermometers used in whirling psychrometers are of the mercury-in-glass type with a cylindrical bulb, unsheathed stem, a lens magnifying front and a button top (Figure 8).

The range of temperature covered by the thermometers is −5 °C to +50 °C; later versions cover the range −15 °C to +50 °C. The graduation marks are at every 0.5 °C, with longer lines at each 1 °C, and are figured at each 5 °C so that the figures are upright when the thermometer is horizontal. A minus sign is placed before negative figures. The thermometers should not be in error by more than 0.2 °C at any point on the scale.

Table XII gives the main dimensions.

Table XII. *Main dimensions of both versions of thermometers for whirling psychrometers*

Temperature range °C	Overall length mm	Diameter of stem mm	Diameter of bulb mm	Length of bulb mm	Scale length mm
−5 to +50	164–168	5.5	2–4	15–22	80–105
−15 to +50	212–216	5.5	2–4	15–22	105–130

3.8 Maximum thermometers

Sheathed maximum thermometers Max 1/C, Max 2/C, Max 3/C, Max 4/C. The principle of the maximum thermometer is described on page 2–4. It is very similar in construction to the ordinary sheathed thermometer, but with a plain top. Details of the dimensions, ranges, and permissible errors are given in Tables IX and X. The range used should be chosen to suit the conditions expected. The spacing and figuring of the graduation marks are similar to those of the ordinary thermometer, but the figures appear upright when the thermometer is in a horizontal position, with the bulb on the left (Figure 2). The figures are placed symmetrically about the line to which they refer. All negative figures have a minus sign placed before them.

The mercury column of some maximum thermometers is liable to run up the bore a little when the thermometer is lying at its normal slope in a screen. Some thermometers do this only under vibration, others at any time. The result is that the readings, if taken in the normal manner, may be too high. Each maximum thermometer should be tested, preferably on an overcast morning with some wind, by noting the reading after setting, to the nearest 0.1 °C, while the thermometer is still held in a vertical position, bulb downward. It should then be replaced in the screen, taking care to keep the bulb always below the stem of the thermometer, and the door of the screen opened and closed once or twice in the usual manner so that the thermometer is exposed to a normal amount of vibration. If, after observing the reading of the thermometer without moving it, the reading has risen by more than 0.1 or 0.2 °C and the dry bulb shows that this is not due to a rise in temperature, this will demonstrate that the mercury column has risen.

To obtain correct readings from thermometers which show this fault the thermometer should be removed from the stand and tilted slowly until the bulb is about 150 mm below the opposite end, and then the reading taken. This will ensure that the mercury column has run back to the constriction.

Setting maximum thermometers. Difficulty is sometimes experienced by manufacturers in making the constriction exactly the right size. If the constriction is too wide the thermometer acts as an ordinary thermometer. If the constriction is too narrow difficulty may be experienced in resetting the thermometer. However, if maximum thermometers are reset as follows it will be found that even with a narrow constriction the mercury column can be reset. Figure 9 illustrates the recommended way of holding the thermometer. The motion should be a steady swing backwards and forwards, not sideways, and without any jerking. This should be done in a place free from obstructions. The mercury column should be as close as possible to the bulb, i.e. resting against the constriction, at the beginning of the swing. If it is not it may strike violently against the constriction when the thermometer is swung and cause damage to the stem at that point. A tiny crack may occur which does not reach the surface, but may be sufficient to cause the thermometer to act partially as an ordinary thermometer when the temperature falls.

The maximum thermometer in use should be tested periodically, to see that the mercury column does not in fact retreat through the constriction when the temperature falls, by warming the thermometer, noting the temperature reached and leaving it in a horizontal position. Any change in reading can then be seen. It is always important to check that the

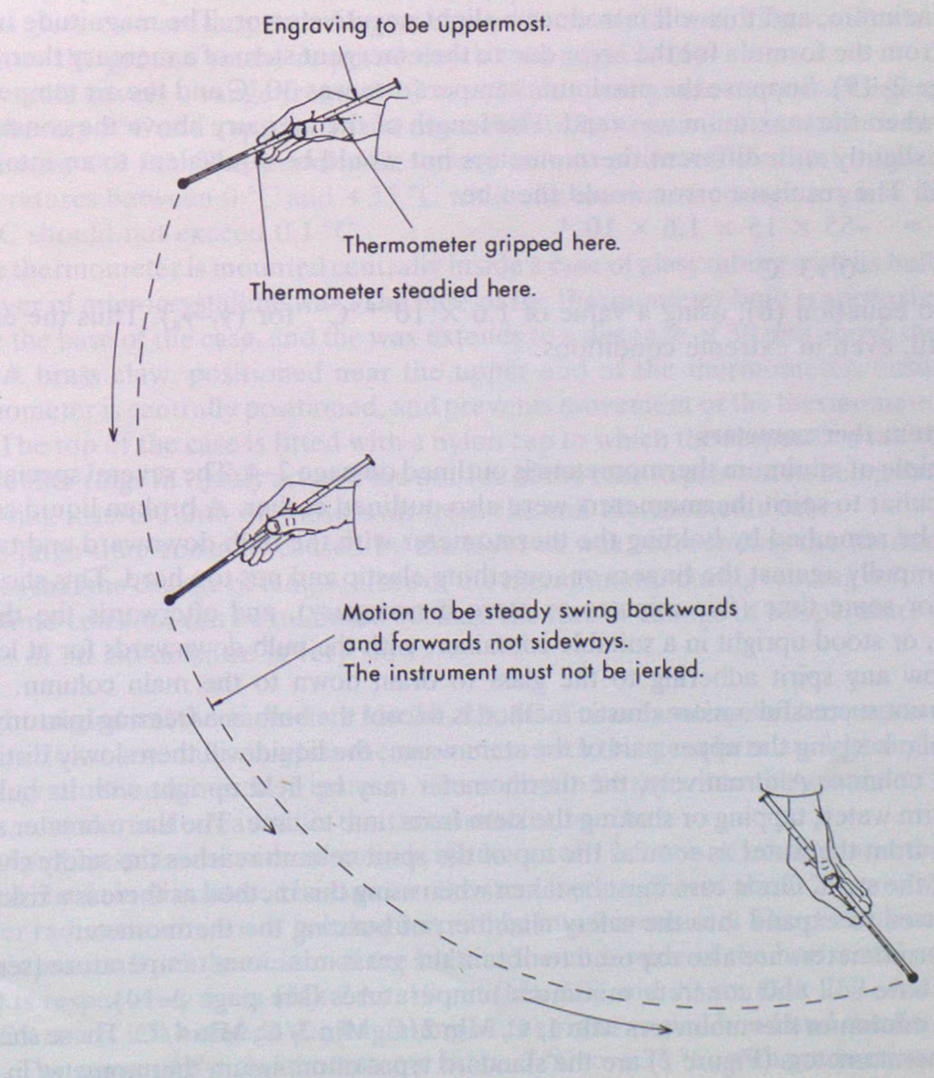


Figure 9. Setting the maximum thermometer.

reading of the maximum thermometer is at least as high as the highest dry-bulb reading recorded since the thermometer was last set. After setting, the reading of the maximum thermometer should be compared with the dry-bulb reading; the difference should not exceed 0.2 °C.

If, after careful checking at the time of observation, the reading of the maximum (or minimum) thermometer is found to be inconsistent with the readings of the dry bulb since the thermometer was last supposed to have been set, the cause of the discrepancy may be one of the following:

(a) An error in one of the readings of the dry bulb at one of the preceding observations covering the period under consideration.

(b) An incorrect resetting of the maximum (or minimum) thermometer at the beginning of the period.

(c) An actual discrepancy between readings correctly taken owing to a defect in one of the instruments.

Which of these alternatives is applicable can be decided only by a careful examination of the instruments and the circumstances of the case. For example, it is usually easy to find out if a large error has been made in the readings of the dry bulb by comparison with a thermograph, comparison with surrounding stations, or by comparison with readings at other hours at the station.

Errors in maximum thermometers due to change in temperature since the maximum. The length of the mercury column above the constriction will contract when the temperature falls from the maximum, and this will introduce a slight negative error. The magnitude may be calculated from the formula for the error due to the emergent stem of a mercury thermometer (see page 2–19). Suppose the maximum temperature was 30 °C and the air temperature only 15 °C when the maximum was read. The length of the mercury above the constriction would vary slightly with different thermometers but would be equivalent to an interval of about 55 °C. The resultant error would then be:

$$\text{error} = -55 \times 15 \times 1.6 \times 10^{-4}$$
$$= -0.13\ ^{\circ}\text{C}$$

according to equation (6), using a value of $1.6 \times 10^{-4}\ ^{\circ}\text{C}^{-1}$ for $(\gamma_l - \gamma_g)$. Thus the error is usually small, even in extreme conditions.

3.9 Minimum thermometers

The principle of minimum thermometers is outlined on page 2–4. The several special types of error peculiar to spirit thermometers were also outlined earlier. A broken liquid column can usually be remedied by holding the thermometer with the bulb downward and tapping lightly and rapidly against the fingers or something elastic and not too hard. This should be continued for some time (five minutes or more if necessary), and afterwards the thermometer hung, or stood upright in a suitable container, with the bulb downwards for at least an hour to allow any spirit adhering to the glass to drain down to the main column. If this treatment is not successful a more drastic method is to cool the bulb in a freezing mixture of ice and salt, while keeping the upper part of the stem warm; the liquid will then slowly distil back to the main column. Alternatively, the thermometer may be held upright with its bulb in a vessel of warm water, tapping or shaking the stem from time to time. The thermometer should be removed from the water as soon as the top of the spirit column reaches the safety chamber at the top of the stem. Great care must be taken when using this method as there is a risk, if the spirit is allowed to expand into the safety chamber, of bursting the thermometer.

These thermometers are also exposed to obtain the grass minimum temperature (see page 2–13), and bare soil and concrete minimum temperatures (see page 2–14).

Sheathed minimum thermometers Min 1/C, Min 2/C, Min 3/C, Min 4/C. These sheathed minimum thermometers (Figure 2) are the standard types of minimum thermometer in use in the Meteorological Office, and in general construction they conform with the other sheathed thermometers. Details of the dimensions, etc. are given in Tables IX and X. One main difference between these thermometers and the mercury sheathed thermometers is that an elongated safety chamber is provided, so that the temperature of the thermometer may be raised to 50 °C without damage. This is necessary if the thermometer is to be used as a grass minimum thermometer. The bulbs on these thermometers are larger than the bulbs on the ordinary and maximum thermometers, and this, together with the fact that alcohol has a much lower thermal conductivity than mercury, means that the time-constant of the thermometer is appreciably greater than that of the other sheathed types. This is not a serious drawback as the rate of change of temperature is usually small near the time of minimum temperature.

When replacing the thermometer in the screen it should be inserted stem first and the bulb should be kept higher than the stem during the process. As with the maximum thermometers after resetting, the temperature indicated should not differ by more than 0.2 °C from the dry bulb. If the instrument is reading low it is probable that some of the spirit has passed to the top of the stem. This should be remedied as set out above. The notes dealing with discrepancies between the readings of the maximum and minimum thermometer and the readings of the dry bulb over the same period (page 2–28) should be carefully studied.

3.10 Soil thermometers

Ordinary soil thermometer Mk 3. The ordinary soil thermometer Mk 3 consists of an unsheathed mercury-in-glass thermometer mounted within a clear glass case, and is used for measuring the temperature of the soil at depths of 30 cm or more. In practice the thermometer and glass case are suspended by a chain within a metal tube (Figure 3) which has been sunk into the ground to the required depth (see page 2–16).

The scale covers a range from −7 °C to +38 °C, with graduation markings every 0.5 °C figured every 5 °C and a spacing of not more than 0.35 °C mm^{-1}. This makes it easy to read to the nearest 0.1 °C. The permissible errors at any point on the scale are ±0.1 °C for temperatures between 0 °C and +35 °C while the maximum change in error in an interval of 5 °C should not exceed 0.1 °C.

The thermometer is mounted centrally inside a case of glass tubing with its bulb embedded in a layer of microcrystalline wax. The base of the thermometer bulb is approximately 8 mm above the base of the case, and the wax extends to a distance of 38 mm above the base of the case. A brass claw, positioned near the upper end of the thermometer, ensures that the thermometer is centrally positioned, and prevents movement of the thermometer, within the case. The top of the case is fitted with a nylon cap to which the suspension may be attached. Two rubber rings fit tightly around the outside of the case to prevent its being damaged when it is being inserted into or withdrawn from the soil thermometer tube.

The large time-constant caused by the layer of wax surrounding the thermometer bulb ensures that the change of temperature of the thermometer during reading is very small. This large time-constant can be tolerated because the rate of change of temperature of the soil at depths of 30 cm or more is very slow.

Right-angled soil thermometers Mk 2A, 2B, 2C. For measuring soil temperatures at depths of up to 20 cm, mercury-in-glass thermometers with the stem bent at right angles below the lowest graduation are used (Figure 3). The bulb can be sunk into the ground to the required depth, and the scale read with the thermometer *in situ*.

The bulb is spherical with an outside diameter of 12.5 mm ±1.5 mm, and the stem is 6.3 mm ±1.3 mm in diameter. The curve in the stem has a radius of about 25 mm; with curves of smaller radius the chance of breakage would be much increased. The dimension D in Figure 3 (the distance from the centre of the bulb to the underside of the horizontal portion of the stem) is respectively 5 cm (Mk 2A), 10 cm (Mk 2B) and 20 cm (Mk 2C). A distance of at least 25 mm is left between the beginning of the right-angled bend and the first graduation mark. The range of the thermometer is from −7 °C to +38 °C, with graduation marks every 0.5 °C, figured every 5 °C and with the graduations spaced so that there is no more than 0.4

°C mm⁻¹. These thermometers are not graduated for total immersion, as are all the other thermometers described, but only for immersion up to the beginning of the right-angled bend (i.e. for an immersion of (D – 25 mm)).

The remainder of the thermometer is kept at air temperature, a safety chamber being provided at the end of the stem. The permissible errors at a point and the permissible rate of change of error along the scale are the same as those for the ordinary soil thermometer Mk 3 (page 2–29).

3.11 Inspector's thermometers

The Meteorological Office inspector's thermometer (Figure 10) is an unsheathed mercury-in-glass type with a cylindrical bulb. It is filled above the mercury with inert gas at a suitable pressure. Graduations are for every 0.1 °C, partially figured at each 1 °C and fully

Figure 10. Inspector's thermometer.

figured at each 5 °C. Graduation lines are longer at each 0.5 °C and 1.0 °C. The thermometer covers a span of only 30 °C and is available in two ranges, –5 °C to + 25 °C (temperate) and +10 °C to +40 °C (tropical).

Each thermometer is graduated for total immersion, and is provided with an enlarged safety chamber at the top of the stem. The total length of the scale (30 °C) is at least 190 mm long, i.e. there is less than 0.2 °C mm⁻¹. This provides for an exceptionally open scale, and, together with the 0.1 °C graduations, enables measurement to be made to the nearest 0.05 °C and if necessary to the nearest 0.01 °C. The general dimensions of the thermometer are as follows:

Length of stem: not exceeding 300 mm.
External diameter of bulb: 5.5 mm ±1.5 mm.
External diameter of stem: 5.5 to 7.0 mm.

The permissible errors at any point are –0.15 to +0.05 °C, and the permissible change of error over an interval of 5 °C is 0.1 °C. The measurements for the Meteorological Office certificate are made with an uncertainty of 0.02 °C, but the corrections are given to the nearest 0.01 °C. These errors should always be taken into account when using the thermometer. The graduations on the thermometer may in time become faint. If so, they can be re-blackened by rubbing the stem with dark crayon or black lead pencil.

Inspector's thermometers should be returned to the Instrument Branch Test Laboratory for recalibration at intervals not exceeding two years.

3.12 Checking of thermometers

It was mentioned on page 2–18 that all liquid-in-glass thermometers experience gradual changes of zero. For this reason it is desirable, if possible, to check them at regular intervals, usually about once every two years.

The inspector's thermometer is used for checking ordinary sheathed thermometers for use in naturally ventilated screens by immersing the inspector's thermometer and the thermometer, or thermometers, to be tested in a deep vessel of water; it is generally better to work indoors especially if the sun is shining. The water should be at a temperature not above 20 °C.

Each ordinary thermometer is compared with the inspector's thermometer, and ordinary thermometers of the same category are also compared with each other. For each comparison the two thermometers (inspector's plus ordinary, or two ordinary) are held with their bulbs close together, and the thermometers moved backwards and forwards through the water for about a minute and then read. It must be possible to read both thermometers without changing the depth of immersion; subject to this the bulbs should be as deep in the water as possible. Most Meteorological Office thermometers are calibrated for total immersion, but provided the difference between the water and air temperature is not more than 5 °C the emergent stem correction is negligible. Usually, with the bulbs at the same depth, the tops of the columns of mercury in an ordinary sheathed thermometer and an inspector's thermometer will not be very close together. Particular care should therefore be taken to avoid errors of parallax. These comparisons should be made at least three times for each pair of thermometers. For each set of comparisons the mean of the differences between readings should not exceed the tolerances given in Table XIII.

Table XIII. *Tolerances for checking ordinary sheathed thermometers*

Category	Difference between psychrometric pairs °C	Difference from corrected reading of inspector's thermometer °C
A	0.15	0.2
B	0.3	0.3

Soil thermometers Mk 3 may be tested in a similar manner to ordinary sheathed thermometers except that soil thermometers should be left in the water for at least 30 minutes to allow the wax in which the bulbs are embedded to take up the temperature of the water. The large time-constant of the soil thermometer makes it difficult to get a good check unless the temperature of the water can be held very steady. If the test is carefully made in water whose temperature is not changing by more than 1 °C in 30 minutes the difference from the corrected reading of the inspector's thermometer should not exceed 0.25 °C.

4 ELECTRICAL RESISTANCE THERMOMETERS

4.1 General

For small temperature changes the increase in specific resistance of pure metals is proportional to the change in temperature, i.e.

$$R_T = R_s \{ 1 + \alpha (T - T_s)\},$$

where R_T is the specific resistance* at temperature T, R_s is the specific resistance at some standard temperature T_s and α is the temperature coefficient of resistance. For large intervals of temperature and for some alloys a more exact relationship must be used, e.g.

$$R_T = R_s \{1 + \alpha (T - T_s) + \beta(T - T_s)^2\}.$$

The values of α and β, for any particular resistance element, are determined by calibration.

Table XIV shows representative values of R_s (at 0 °C), and corresponding values of α for some common metals and alloys.

The choice of suitable material for a thermometer element depends on many factors, such as a large value of α, ability to maintain its characteristics over a long period, resistance to corrosion, and uniformity of various samples. The metals most commonly used are platinum, nickel, tungsten and copper. For fundamental standards, and for all thermometers which are expected to keep their calibration over extended periods, platinum is the most suitable. For secondary instruments nickel is satisfactory, and copper can be used for applications in which a close approach to linearity in the relation between resistance and temperature is desirable.

Table XIV. *Values of the specific resistance (at 0 °C) and the temperature coefficients of resistance of some common metals and alloys*

Substance	$R_s \times 10^6 \Omega$cm	$\alpha \times 10^4$ °C^{-1}
Copper	1.56	43
Iron	8.9	65
Nickel	6.14	68
Platinum	9.81	39.2
Silver	1.51	41
Tungsten	4.9	48
Constantan	48	±0.2
Manganin	42	0.1
Nichrome	103	1

Another type of resistance element which can be used is a thermistor, which may have a positive or negative temperature coefficient. In general the resistance R of a thermistor can be expressed by the equation

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

where a and b are constants and T is the temperature of the thermistor in kelvins.

* The specific resistance (or resistivity) of a conductor is the resistance between parallel faces of a cube of the conductor of unit dimensions. The value of specific resistance is usually given in units of ohm/cm.

Their advantages from the thermometric point of view are:

(a) Their change in resistance with temperature is much larger than that of metals. A typical element with a negative temperature coefficient has a resistance of about 80 ohms at 40 °C, 1100 ohms at 0 °C and 62 500 ohms at −80 °C. Also the proportional change in resistance given by

$$\frac{1}{R}\frac{dR}{dT} = \frac{-b}{T^2}$$

at about 10 °C is 4.5×10^{-2} °C^{-1} compared with 3.8×10^{-3} °C^{-1} for platinum. This enables the voltage across a Wheatstone bridge to be reduced for a given sensitivity. Problems of accounting for lead resistances and their changes are reduced, or even eliminated.

(b) The elements can, if necessary, be made very small and thus have a very low thermal capacity and a small time-constant. The self-heating effect, for a given power dissipation, in these small elements is, however, larger than that in a large element, so that the power dissipated has to be kept small.

The changes in resistance with temperature for some metals and for a typical thermistor are shown in Figure 11.

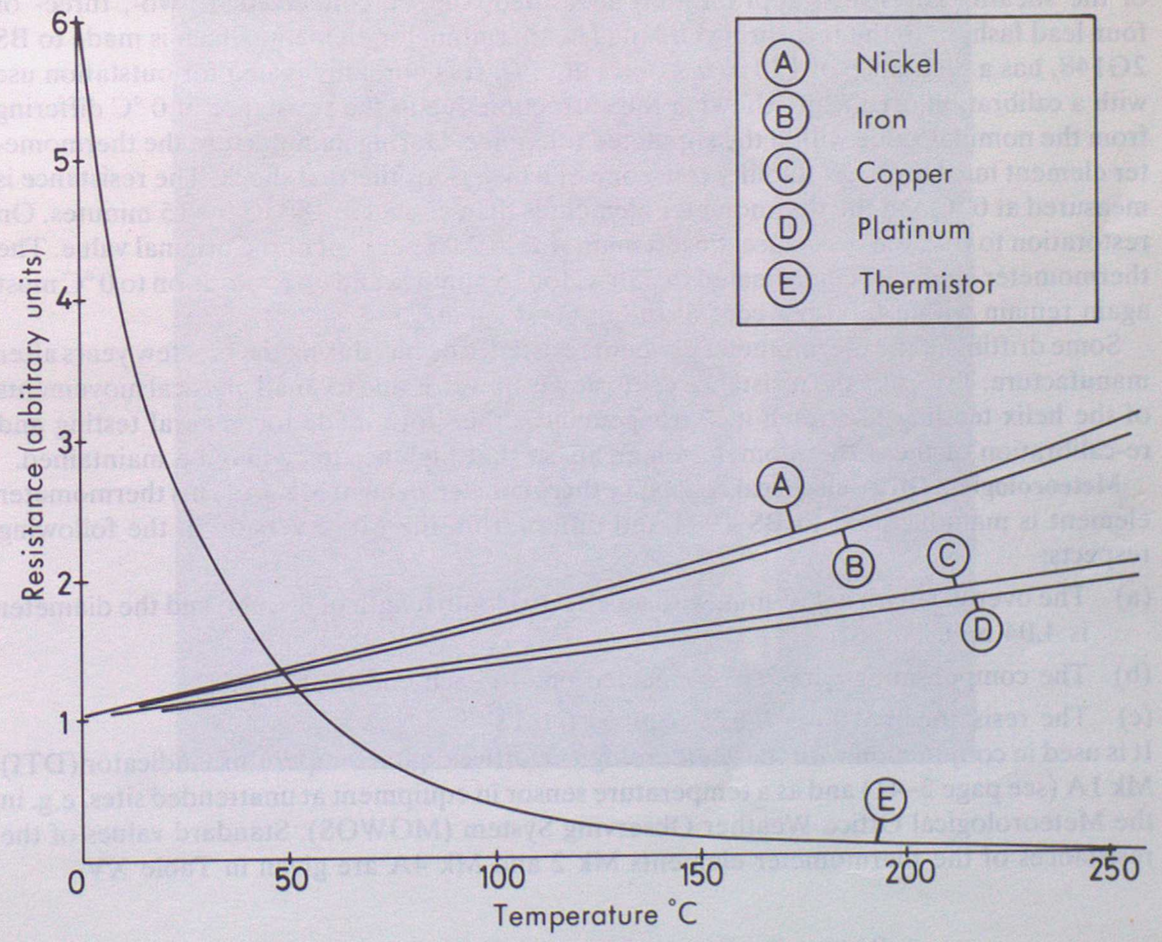


Figure 11. Variation of resistance with temperature.

4.2 Electrical resistance thermometer elements

Electrical resistance thermometer elements usually consist of a coil wound on an insulating former which is protected by a sheath of suitable shape and size. For meteorological work the sheath should be waterproof to protect the winding. If a very small time-constant is required, a thin wire stretched on an insulating frame in the open can be used. This is practically insensitive to radiation, but only small currents should be used or the self-heating effect would be appreciable. The heating effect varies sharply with the wind speed, and can be used to measure the latter.

Meteorological Office electrical resistance thermometer element Mk 2. This thermometer element (Plate III) is used, in conjunction with the Meteorological Office electrical thermometer indicator Mk 5 (see page 2–39), for measuring air temperatures in the range –50 °C to 50 °C. The thermometer element consists of a helix of pure platinum wire set into a cylindrical ceramic former about 25 mm in length. The platinum helix is attached to the ceramic in a virtually strain-free condition by intruding molten glass so that about 30 per cent of the circumference of the helix is fixed to the ceramic walls. Connected to the helix is a pair of silver-covered copper wires, 0.5 mm in diameter, which exit from the ceramic former and surrounding stainless steel sheath as flying leads for connecting to the measuring circuit. A similar pair of wires, joined together on the former, are for connecting to the compensating leads. In later versions, for protection of the leads at the point of exit, a four-lead cable is used. The thermometer element and connecting wires are hermetically sealed in a stainless steel sheath about 118 mm long with an effective thermometer bulb length of 100 mm and diameter 6.3 mm; the flying leads, or cable ends, extend about 70 mm beyond the sealed end of the sheath. The leads, appropriately identified, can be connected in two-, three- or four-lead fashion to the measuring circuit. The thermometer element, which is made to BS 2G148, has a resistance of 130 ± 0.3 ohms at 0 °C. It is normally issued for outstation use with a calibration certificate, showing the correction due to the resistance at 0 °C differing from the nominal value within the stipulated tolerance. During manufacture the thermometer element must undergo stability tests, one of which is for thermal shock. The resistance is measured at 0 °C and the thermometer element is then cooled to –80 °C for 15 minutes. On restoration to 0 °C the resistance must remain within 0.05 per cent of the original value. The thermometer element is then heated to 250 °C for 15 minutes and on restoration to 0 °C must again remain within 0.05 per cent of the original value.

Some drifting of the thermometer element resistance occurs during the first few years after manufacture. Typically the resistance drifts slowly upwards due to small physical movements of the helix tending to stretch it. Arrangement is therefore made for general testing and re-calibration of these thermometer elements so that high accuracy may be maintained.

Meteorological Office electrical resistance thermometer element Mk 4A. This thermometer element is manufactured to BS 1904 and differs from the Mk 2 version in the following respects:

(a) The overall length is 115 mm, with an effective bulb length of 80 mm, and the diameter is 4.04 mm.

(b) The compensating wires are connected one to each end of the helix.

(c) The resistance is 100 ± 0.075 ohms at 0 °C.

It is used in conjunction with the Meteorological Office digital temperature indicator (DTI) Mk 1A (see page 2–41) and as a temperature sensor in equipment at unattended sites, e.g. in the Meteorological Office Weather Observing System (MOWOS). Standard values of the resistances of the thermometer elements Mk 2 and Mk 4A are given in Table XV.

4.3 Thermometer leads

The leads connecting the resistance thermometer element to its measuring circuit need to be of low resistance relative to the resistance of the thermometer element. In this way changes in the resistances of the leads, due to temperature variations, may be kept to a minimum. When, however, the leads are long it may be impractical to meet this requirement. The use of compensating leads overcomes this problem, reducing or eliminating the effect of change in lead resistance upon the temperature reading of the indicator. Either three-leads compensation or four-leads compensation is usually employed.

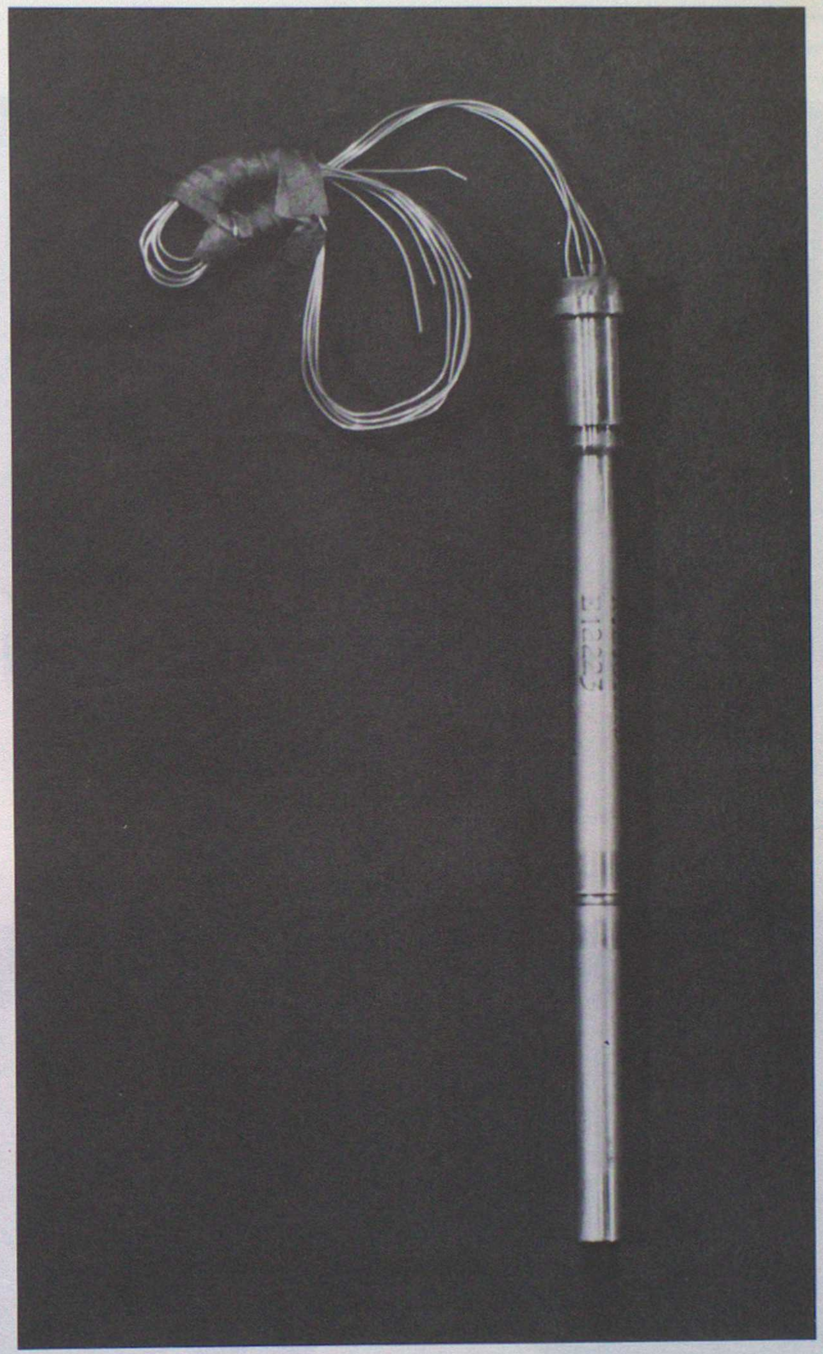


Plate III. Electrical resistance thermometer element Mk 2.

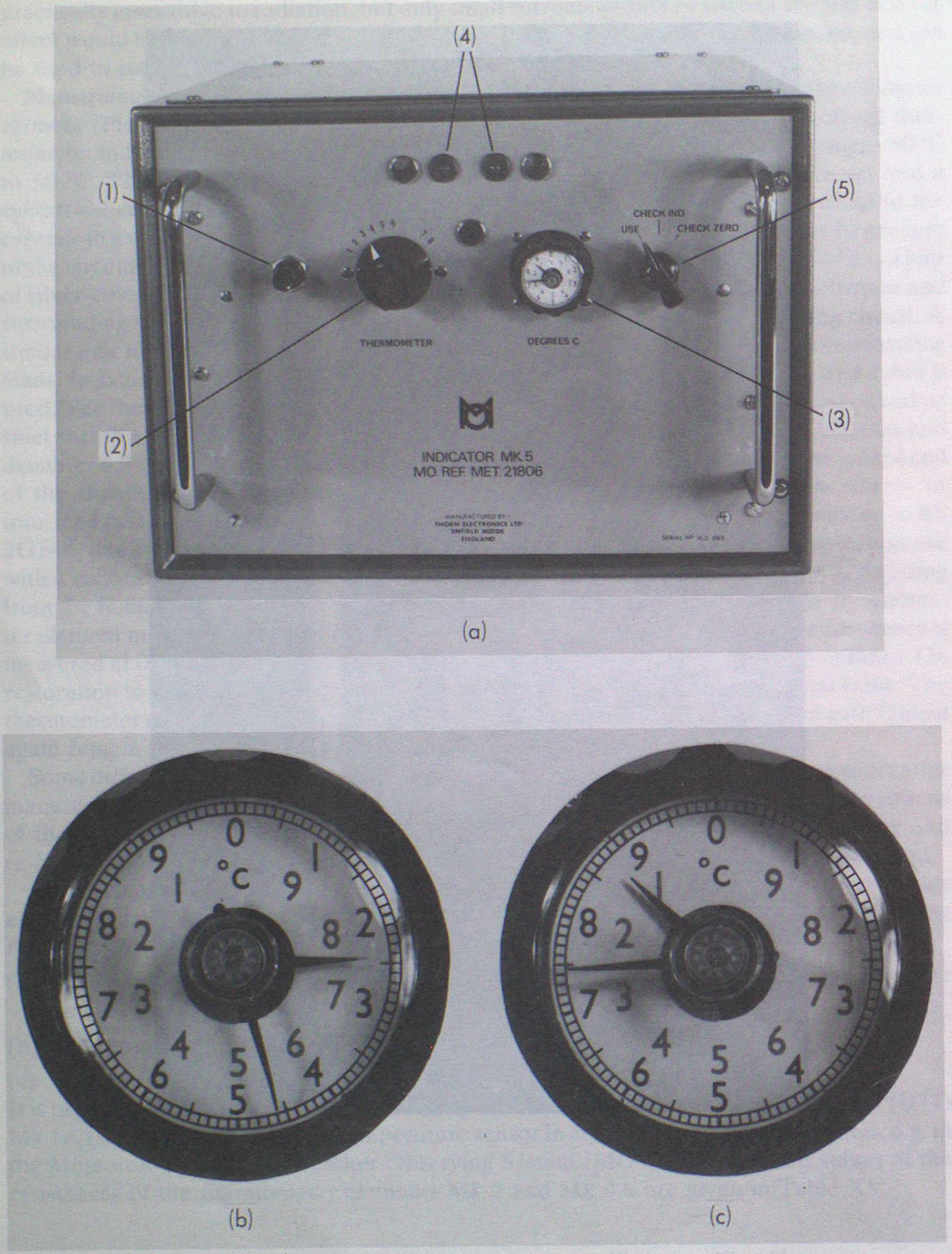


Plate IV. Electrical resistance thermometer indicator Mk 5.

Table XV. *Standard values of the resistance of the Meteorological Office electrical resistance thermometer element (a) Mk 2 and (b) Mk 4A.*

Temperature	Resistance (ohms)		Temperature	Resistance (ohms)	
°C	(a)	(b)	°C	(a)	(b)
−60	98.75	76.33	0	130.00	100.00
−50	104.01	80.31	+10	135.15	103.90
−40	109.24	84.27	+20	140.29	107.79
−30	114.45	88.22	+30	145.21	111.67
−20	119.65	92.16	+40	150.51	115.54
−10	124.83	96.09	+50	155.60	119.39

Three-leads compensation. Three equal leads l_1, l_2 and l_3 (Figure 12) are connected to the thermometer element and bridge circuit. The lead l_3 is in arm R_3, l_1 is in the thermometer element arm R_T, and l_2 is connected between the thermometer element and the indicator. If l_1 and l_3 are of equal resistance, temperature changes will affect both leads equally. If $R_1 = R_2$ and $R_3 = R_T$ when the bridge is balanced, arms R_3 and R_T will be affected equally by changes in the resistance of the leads.

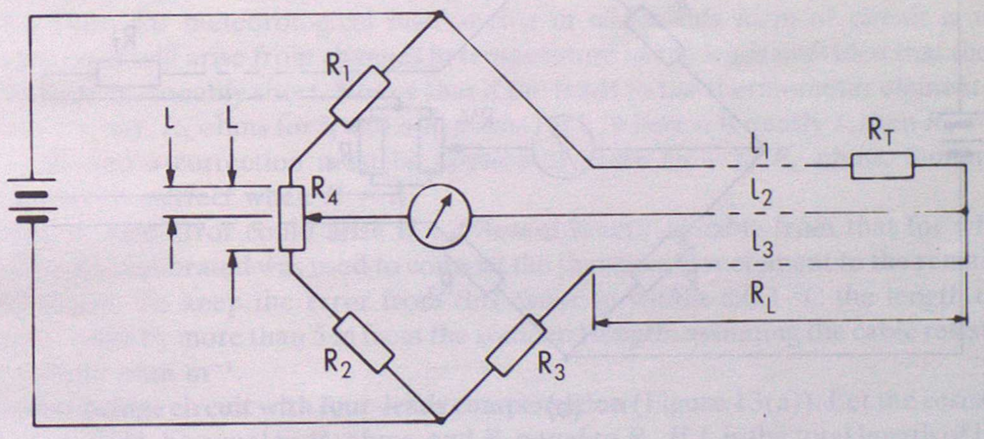


Figure 12. Balanced-bridge circuit with three-leads compensation.

Four-leads compensation. Two identical pairs of leads l_1 and l_2, and l_3 and l_4 (Figure 13(a)) are connected in arms R_3 and R_T respectively. The leads in arm R_3 are joined together at a point near the thermometer element; those in arm R_T are connected to the thermometer element. Both pairs are in the same outer cover so that l_1 and l_2 compensate for changes in the resistance of l_3 and l_4 due to temperature variation.

4.4 Measurement of resistance

Resistance thermometer elements may be used with a variety of electrical circuits, the most common of which are developments of the Wheatstone bridge in either balanced or unbalanced form. With a balanced bridge the deflexion of the indicator is adjusted to zero, the degree of adjustment being related to the temperature. With an unbalanced bridge the actual deflexion is taken as a measure of the temperature.

An alternative to either of these methods is a four-leads system using a constant-current source. The current is fed to the thermometer element via one pair of leads and the voltage across the thermometer element sensed via the remaining pair of leads.

Balanced-bridge circuit with three-leads compensation (Figure 12). By suitable adjustment of the contact on the slide wire the current through the indicator can be reduced to zero. Let the resistance of leads l_1 and l_3 be equal to R_L ohms. If L is the total length of the

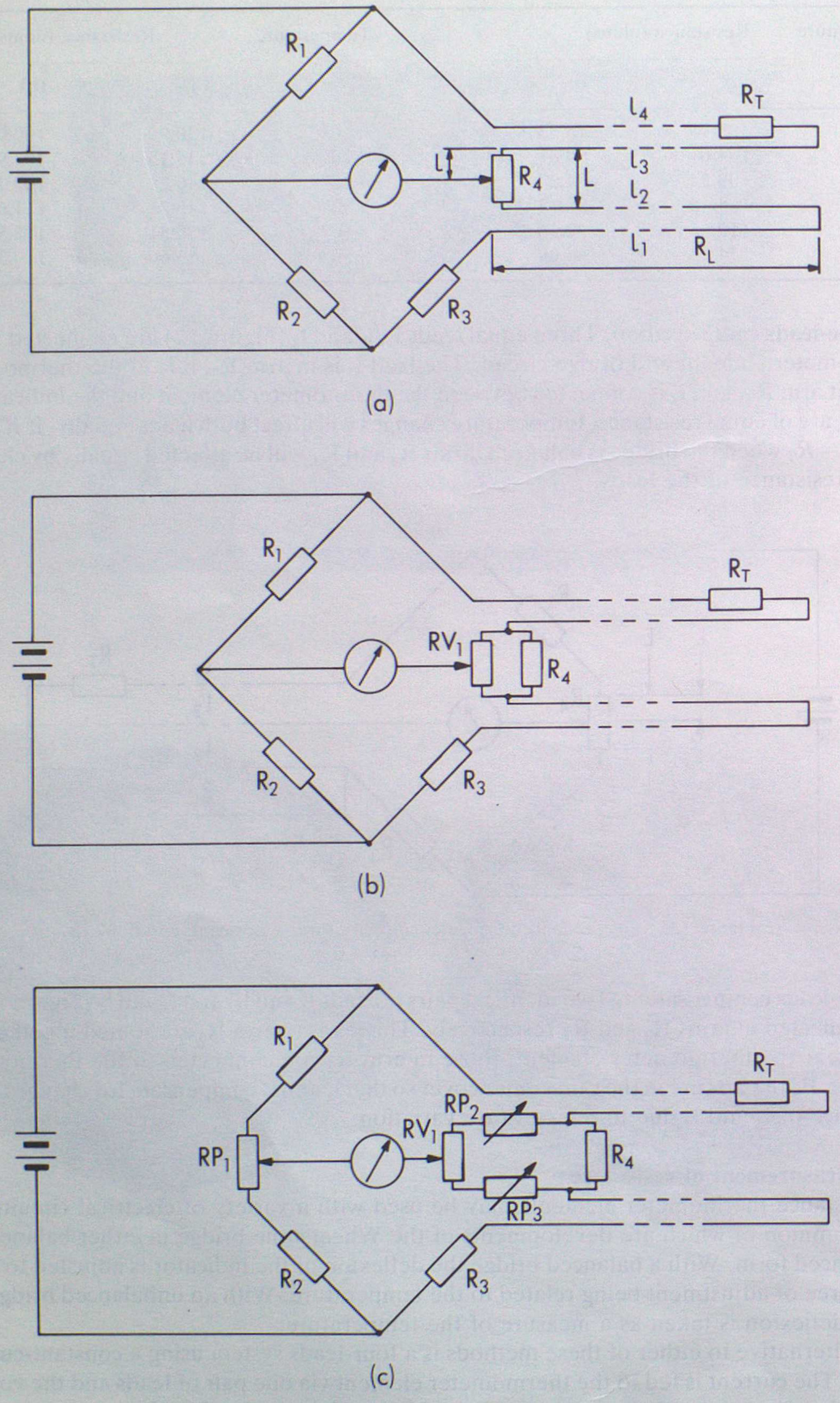


Figure 13. Balanced-bridge circuit with four-leads compensation.

slide wire of resistance R_4, then the resistance of a length l in the arm R_1 is $(l/L)R_4$. When the bridge is balanced

$$\frac{R_1 + (\frac{l}{L})R_4}{R_2 + (\frac{L-l}{L})R_4} = \frac{R_T + R_L}{R_3 + R_L} = K \text{ (say)} \qquad \ldots (7)$$

R_1, R_2 and R_3 are the values of the resistances shown in Figure 12, R_T being the resistance of the thermometer element.

From equation (7) $R_T = KR_3 + (K-1)R_L$. The position of the contact gives the value of K. When $K = 1$ the resistances of the leads have no effect on the point of balance and compensation is perfect; as R_1 is normally made equal to R_2 this is when the contact is in the centre of R_4. At other points of contact the compensation is not perfect. With a platinum thermometer element K could vary from about 0.80 to 1.20 for a temperature range of −50 °C to +50 °C. If T is the temperature of the thermometer element as indicated by the position of the contact on the bridge wire the value of $\partial T/\partial R_L$ is $(K-1)\,\partial T/\partial R_T$, which is $1.93(K-1)$ °C ohm^{-1} for a platinum thermometer element of resistance 130 ohms at 0 °C. The maximum value of this is about 0.4 °C ohm^{-1} change in the resistance of the leads for the values of K given above. Ten metres of copper cable of the type normally used in connecting thermometer elements has a resistance of about 0.4 ohms which may change by 0.08 ohm for a lead temperature change of 40 °C; this corresponds to a maximum temperature error of about 0.04 °C. Thus, for meteorological instruments in which this form of circuit is used no significant error will arise from changes in temperature of the leads provided that the length of lead is kept reasonably short. Notice that if the leads to the thermometer element are not equal but are, say, R_L ohms for l_3 and $\alpha\, R_L$ ohms for l_1, where α is nearly 1, then $R_T = KR_3 + (K - \alpha)\, R_L$ and a correction must be applied of value $(\alpha - 1)\, R_L$ ohms. Similarly, the compensation is perfect when $K = \alpha$.

A more serious error could arise if a different length of cable from that for which the instrument was calibrated was used to connect the thermometer element to the remainder of the instrument. To keep the error from this cause to within ±0.1 °C the length of cable should not differ by more than 5 m from the standard length, assuming the cable resistance to be about 0.05 ohm m^{-1}.

Balanced-bridge circuit with four-leads compensation (Figure 13(a)). Let the resistance of leads l_1, l_2, l_3 and l_4 be equal to R_L ohms, and R_1 equal to R_2. If L is the total length of the slide wire of resistance R_4 then the resistance of a length l in arm R_T is $(l/L)R_4$. When the bridge is balanced

$$\frac{R_1}{R_2} = \frac{R_T + (\frac{l}{L})R_4 + 2R_L}{R_3 + (\frac{L-l}{L})R_4 + 2R_L} = 1,$$

$$R_T = R_3 + \frac{R_4}{L}(L - 2l) \qquad \ldots (8)$$

and thus is independent of changes in lead resistance provided the leads are of equal resistance.

Let a change ΔR in R_T require a change in l of Δl, then

$$(R_T + \Delta R) = R_3 + \frac{R_4}{L}\,[L - 2(l + \Delta l)]. \qquad \ldots (9)$$

From equations (8) and (9)

$$\Delta R = -2\Delta l\,\frac{R_4}{L}$$

$$\text{or } \Delta l\,\frac{R_4}{L} = \frac{-\Delta R}{2}.$$

Thus a reduction in R_T requires the balance point of R_4 to be moved to such a position that the portion of R_4 included in arm R_T is increased by half the change in R_T. The resistance of arm R_2 is decreased by a similar amount. If the value of R_T increases the balance point is moved in the opposite direction. Movement of the balance point is therefore determined solely by the change in value of R_T and is not influenced by the absolute magnitude.

A Wheatstone bridge circuit can also be used by omitting the slide wire and measuring the out-of-balance current through the galvanometer. This current will bear a definite relation to the resistance of the thermometer element and thus to the temperature, but it will also depend on the electromotive force supplied to the bridge and the sensitivity of the galvanometer, which is dependent to a certain extent on the temperature of the galvanometer. In practice errors from these sources may be eliminated by using a constant-current source to power the bridge, and measuring the out-of-balance voltage to obtain a temperature reading. Theoretically, a constant-voltage source can be used as an alternative to a constant-current source, and the current kept sensibly constant by using very large resistances, compared with the resistance of the thermometer element, in the two arms of the bridge.

4.5 Errors due to self-heating of the resistance element

The passage of the current through the resistance element produces heat, and thus the temperature of the thermometer element becomes higher than that of the surrounding medium. The heat generated per second is given by I^2R/J, where I is the current through the resistance R and J is the mechanical equivalent of heat. Then, if a mass m of air, of temperature T and specific heat at constant pressure c_p, flows past the thermometer element per unit time and takes up the temperature of the element $(T + \Delta T)$, the amount of heat taken away from the thermometer in unit time is $mc_p\Delta T$, and this equals I^2R/J when equilibrium is established. Therefore

$$\Delta T = \frac{I^2R}{mc_pJ} .$$

The time-constant of the thermometer element τ is, however, given by equation (3):

$$\tau = \frac{C}{mc_p}$$

and therefore $$\Delta T = \frac{\tau}{C}\frac{I^2R}{J},$$

where C is the thermal capacity of the thermometer element.

For the Meteorological Office electrical resistance thermometer element Mk 2 the self-heating effect measured in a stirred bath of ice and water at 0 °C is approximately as follows:

Current (milliamperes)	Self-heating (degrees Celsius)
1.0	0.007
2.0	0.027
3.0	0.047
4.0	0.077
5.0	0.117

In still air and with a current of 1 mA, ΔT is about 0.05 °C, while for a current of 5 mA it is about 0.25 °C.

One way of measuring the error due to self-heating is by a simple test (due to Ribaud). Holding the medium at a constant temperature, find the indicated temperature with a current I flowing (one cell across the bridge, say). Suppose this temperature be T_1, differing from T, the true temperature of the medium, by amount d due to the self-heating effect. Then use a current $2I$ (using two cells across the bridge) and measuring the new temperature, T_2, which should be approximately $T + 4d$, since the heating effect of the current is proportional to I^2.

The required temperature T is then given by

$$T = \frac{4T_1 - T_2}{3} \text{ and } d = \frac{T_2 - T_1}{3}$$

This analysis only holds when the currents through the element are reasonably small.

4.6 Meteorological Office electrical thermometer indicator Mk 5

This instrument is used with the electrical resistance thermometer element Mk 2 for accurate measurements of temperature, and temperature differences, e.g. wet-bulb depressions, over the range –50 °C to + 50 °C. By selective switching, provision is made for the measurement and direct reading, in degrees Celsius, of up to six thermometer elements positioned at distances not exceeding 900 m, and for two thermometer elements within 18 m. A clock-type dial, registering from a precision potentiometer, provides a scale length of 8 mm °C^{-1}, i.e. about three times more open than the scale of an ordinary mercury-in-glass thermometer.

For temperature measurement the resistance of a remote thermometer element is compared with that of a precision resistor (reference resistor) and any resulting difference in value is measured and adjusted, with a precision potentiometer, to balance the bridge. Balance of the bridge is indicated by two small neon lamps glowing simultaneously. The instrument is powered by a 12-volt dry battery, or external 24-volt d.c. source, and controlled by a press-button switch; it is housed in a steel case which can be panel-mounted, wall-mounted or bench-mounted. The front panel (Plate IV) carries the power supply button-switch (1), thermometer element selector switch (2), balancing potentiometer (3), balance-indicating neon lamps (4) and checking switch (5).

Circuit description. The indicator uses a modified form of the four-lead balanced-bridge circuit described previously (page 2–37), together with a voltage regulator, a 15 Hz resistance-capacity oscillator, a detector, tuned amplifiers and a power amplifier. The voltage regulator stabilizes the supply to the various circuits, and the 15 Hz oscillator output is power amplified and fed to the measuring bridge and neon indicator circuit. The change in value with temperature of R_T is known accurately when R_T is the resistance of a platinum resistance thermometer element. The movement of the balance point on R_4 can therefore be calibrated directly in temperature. The value of the resistance required for R_4 is relatively low and the use of a rotary potentiometer would result in inadequate discrimination. However, as balance is achieved when no current flows through the detector, it is only necessary to determine the point on R_4 at which the voltage is exactly equal to that at the junction of R_1 and R_2. This is achieved by connecting a relatively high-resistance potentiometer RV_1 in parallel with R_4 and connecting the detector to the slider of RV_1. R_4 may then be a fixed resistor (Figure 13(b)). The temperature calibration of R_4 will also hold good for RV_1, and may be transferred to RV_1 without loss of accuracy.

The value of R_4 must allow for the parallel resistance of RV_1 and is so chosen that the required temperature range is slightly exceeded when RV_1 is on its lower limit. The range is then reduced to the exact value by adjustment of the series resistors RP_2 and RP_3. The ratio arms are brought to equality by the inclusion of a small potentiometer RP_1 between R_1 and R_2, the detector being taken to its slider (Figure 13(c)).

If the two pairs of leads, thermometer element and compensating, differ in resistance, this difference must be kept small; when 130 ohm thermometer elements are used a maximum difference of 0.3 ohm is permitted.

By using a low-frequency (15 Hz) a.c. supply thermo-electric effects are avoided, and the effects of lead capacitance minimized. Although the capacitances of the thermometer element leads and the compensating leads are similar, the positioning of R_3 at the bridge end of the compensating lead reduces the effect of lead capacitance in that arm of the bridge.

Therefore when lead lengths of more than about 18 m are used R_3 is short circuited and a fixed resistor of the same value is connected at the thermometer element end of the compensating lead. The detector circuit accepts and amplifies out-of-balance signals from the bridge and passes them to the 15 Hz selective amplifier which is also coupled to the neon indicator circuit. One or other of the neons will glow in response to the particular phase of the out-of-balance signal thus indicating the direction the precision potentiometer should be turned to achieve balance of the bridge. Potentiometers in the neon indicating circuit are pre-adjusted so that both neons will glow when the bridge is balanced, i.e. when output signal is zero.

Installation. User stations are not equipped with the special test equipment needed to verify the accurate setting up of the bridge resistors and the associated compensating leads connecting the indicator to the remote thermometer elements. Installation of the entire system is undertaken by the Meteorological Office Operational Instrumentation Branch. Detailed test procedures are carried out to prove the system. After the system is considered satisfactory the users should not change thermometer element leads or resistors.

Method of use. The thermometer elements are housed in ordinary or large screens (in marine screens on Ocean Weather Ships) and mounted with the wet and dry bulbs close to the corresponding bulbs of mercury-in-glass thermometers so that comparison can be readily made when required. A specially adapted thermometer mount is provided to accommodate both mercury-in-glass thermometers and thermometer elements. The indicator is suitably positioned within the observing office.

The dial of the indicator (Plate IV) has two scales, outer and inner. The outer scale is graduated in black from 0 to 99 clockwise, and figured at each 10. The 'twelve o'clock' position represents 0 °C and the 'six o'clock' position +50 °C. The inner scale is figured in red from 0 to 9 anticlockwise; the 'six o'clock' position represents –50 °C. The small hand makes one revolution for 100 °C. When it is to the right of zero the temperature is positive and the reading is taken from the black figuring in tens of degrees Celsius; when it is to the left of zero the temperature is negative and the reading is taken anticlockwise from the red figuring in tens of degrees Celsius. The large hand makes one revolution for 10 °C and the reading is taken from the black graduations, clockwise from zero in units and tenths of a degree Celsius positive and anticlockwise from zero in units and tenths of a degree Celsius negative.

The procedure for measuring and reading temperatures from the dial of the indicator (Plate IV(a)) is:

(a) Turn switch (5) to the 'USE' position.
(b) Turn switch (2) to the selected thermometer element.
(c) Press switch (1) and allow 10 seconds to elapse for the bridge circuits to stabilize then, still depressing the switch, commence the reading.
(d) Refer to the neon indicator lamps (4). With the bridge unbalanced only one of the neons will be glowing. If this is the right-hand one, turn the knob (3) anticlockwise, if the left-hand one, turn clockwise. The bridge is balanced when both neons are glowing. The temperature of the selected thermometer element should then be read from the dial.

Examples of positive and negative temperatures as registered on the dial are shown at (b) and (c) in Plate IV. At (b) the small hand is at a point between 20 °C and 30 °C on the outer scale (black, positive) but nearer to 20 °C, and the large hand is pointing directly to 4.6 °C; indicated temperature is 24.6 °C. At (c) the small hand is at a point between –10 °C and –20 °C on the inner scale (red, negative) but nearer to –10 °C and the large hand is pointing to 7.5 °C on the outer scale which, read anticlockwise from 0 °C is –2.5 °C; indicated temperature is –12.5 °C. The procedure for measuring temperature differences is exactly the same as that for the direct measurement of temperature. If the indicator is used for psychrometry, connection of the thermometer elements can be arranged so that depressions of the wet bulbs give positive readings on the dial.

The indicator should be checked at weekly intervals to ensure that the bridge balance point is correctly maintained. Switch (5) is set to 'CHECK IND' to verify that the two neons glow with equal brightness; if necessary the brightness may be adjusted by suitably resetting the adjacent potentiometers. It is possible to set the brightness of the neons so that the 'dead space', i.e. the point between glow and no glow, is 0.02 °C or less and in any case it should not exceed 0.2 °C. Switch (5) is then set to 'CHECK ZERO' and the bridge should balance at 0 °C. If the balance is not within ±0.1 °C the batteries should be changed.

Accuracy and sources of error. The main source of error results from fitting a non-linear thermometer element to a linear dial-scale. The thermometer element non-linearity is partly overcome by placing the precision resistor in the thermometer screen so that changes of temperature affect it and the thermometer element in like manner. The temperature coefficient of the resistor is such that the resulting small changes of its resistance compensate for the residual thermometer element resistance. The Mk 5 indicator dial is truly linear except insofar as individually manufactured dials may be engraved slightly in error. The dial itself can only be read to about ± 0.05 °C so some setting-up error must also be allowed for. Pre-issue checks are carried out to make sure that no gross errors are likely to occur. The dry-bulb temperature as measured by the bridge must be within ± 0.2 °C of the true value for the nominal range –20 °C to +40 °C for various combinations of lead and bridge temperatures. The measurement of temperature differences up to 15 °C must be accurate to within ± 0.1 °C when one thermometer element is held at a nominal temperature of 10 °C. The other sources of error lie in the development of sudden variable switch contact resistances as the switches age and in undetected changes in the zero correction applied to the thermometer elements. For this reason it is normal practice to undertake comparisons against regularly checked mercury-in-glass thermometers which change their calibration only very slowly. Some typical values of the errors encountered in the system are shown in Table XVI.

Table XVI. *Errors of the Mk 5 indicator and resistance thermometer element Mk 2*

Temperature (°C)		–25	–10	0	10	20	30	45
Thermometer error	$\bar{x}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	s	±0.013	±0.005	±0.000	±0.005	±0.011	±0.016	±0.024
Systematic non-linearity	$\bar{x}$	+0.06	+0.01	0.00	–0.02	–0.02	–0.05	–0.10
	s	±0.033		±0.000		±0.014		±0.008
Dial non-linearity	$\bar{x}$	+0.038	+0.008	+0.000	+0.004	–0.001	–0.000	–0.021
	s	±0.053	±0.025	0.000	±0.026	±0.038	±0.040	±0.044
Setting-up error	$\bar{x}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	s	±0.05	±0.05	±0.05	±0.05	±0.05	±0.05	±0.05
Overall mean error	$\bar{x}$	+0.10	+0.02	0.00	–0.02	–0.02	–0.05	–0.12
	s	±0.064		±0.05		±0.042		±0.051

$\bar{x}$ = mean s = standard deviation

4.7 Meteorological Office digital temperature indicators (DTIs) Mk 1A and Mk 1B

The Meteorological Office DTI Mk 1A (Plate V) is basically an integrating digital voltmeter, scaled in temperature, used to indicate temperatures sensed by electrical resistance thermometer elements Mk 4A. The instrument uses a constant-current source which is fed to the thermometer element via one of the two pairs of leads connecting the DTI to the thermometer element. The voltage across the thermometer element is sensed, via the second pair of connecting leads, by an amplifier where it is integrated for a fixed period and then compared with a reference voltage before being indicated on a seven-segment gas-discharge display. The non-linearity of the thermometer element is compensated for by causing the reference voltage to decrease in a 'continuous' manner as the input increases. This matches the reduction in sensitivity (ohms °C^{-1}) with increase in temperature. A counting system of Binary Coded Decimal (BCD) decades continuously counts clock pulses from an oscillator and the number to be displayed is transferred to BCD stores, followed by decoder-drivers to power the display. The inclusion of stores provides a flicker-free display and allows a BCD output when required. Analogue to digital conversion takes place approximately twice per second and the instrument automatically recalibrates to zero between conversions.

Provision is made for inputs from up to eight thermometer elements via a separate selector unit (Plate V), which incorporates a facility for the zero adjustment of individual thermometer elements.

The display consists of three digits, a decimal point and, for negative temperatures, a minus sign. Leading zeros are not suppressed; e.g. a temperature of 1.5 °C is displayed as 01.5 °C. The display range is from –99.9 °C to 99.9 °C although optimum calibration is attained between –30.0 °C and 40.0 °C. The display can be read from up to 10 m away or in direct sunlight.

The DTI Mk 1B is intended for use where the illumination from a permanently lit display might prove obtrusive. The display and selector units are mounted in a single cabinet, and a blanking switch is incorporated by which the display may be switched off whilst leaving the system powered.

Analogue to digital conversion. The system used to provide analogue to digital conversion is based on the 'dual-slope' technique. In the dual-slope technique the measurement is a voltage-to-time conversion with a constant sample time. The unknown voltage, V, is determined by a two-stage operation, the first stage of which occurs in a fixed time $T = 1/f$, where f is the mains frequency. During time T a capacitor (operational amplifier) is charged at a rate proportional to V (Figure 14). After time T the input of the operational amplifier is switched to a reference voltage, of opposite polarity to V, and the capacitor discharged at a constant rate giving time intervals, for pulses to flow to the clock, proportional to the magnitude of V, e.g. $t_1 \propto V_1$, $t_2 \propto V_2$, etc.

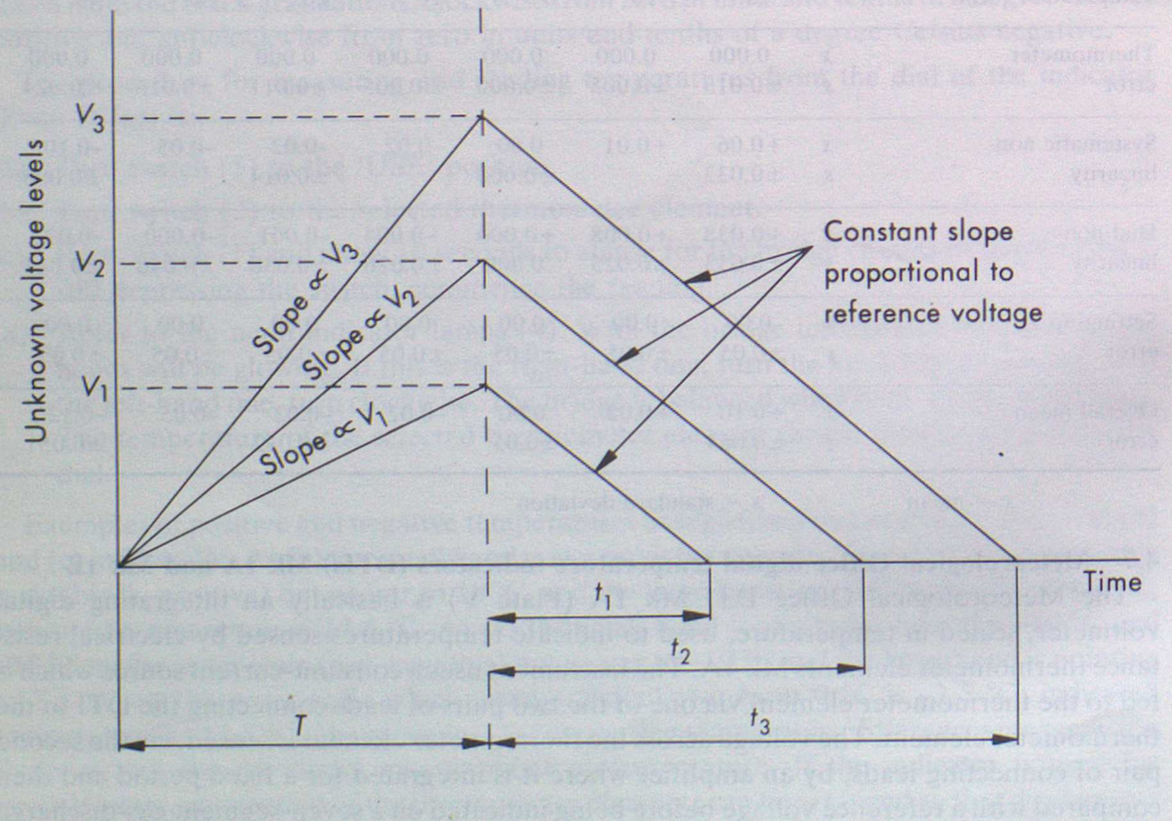


Figure 14. Voltage–time relationships in a dual-slope voltmeter.

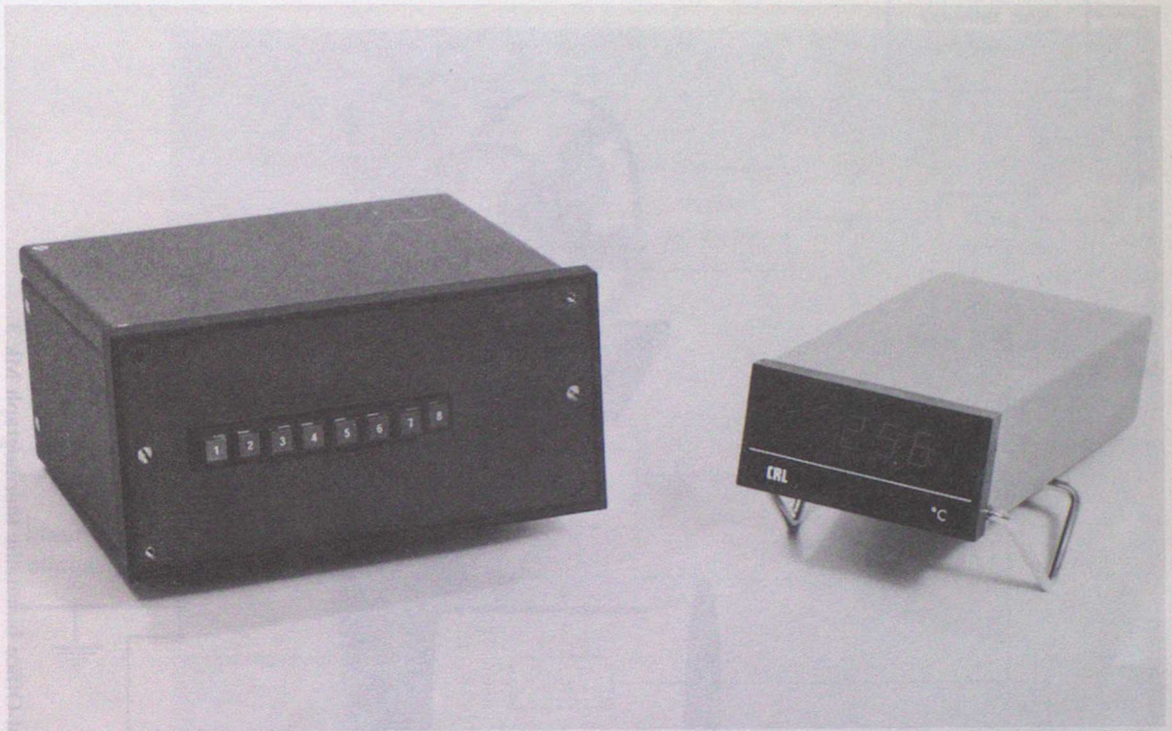


Plate V. Meteorological Office digital temperature indicator Mk 1A.

Plate VI. Meteorological Office bimetallic thermograph Mk 3.

Figure 15 shows a simplified schematic diagram for a dual-slope digital voltmeter. The dual-slope instrument has good accuracy, stability and simplicity but the reading rate is limited to half the power-line frequency.

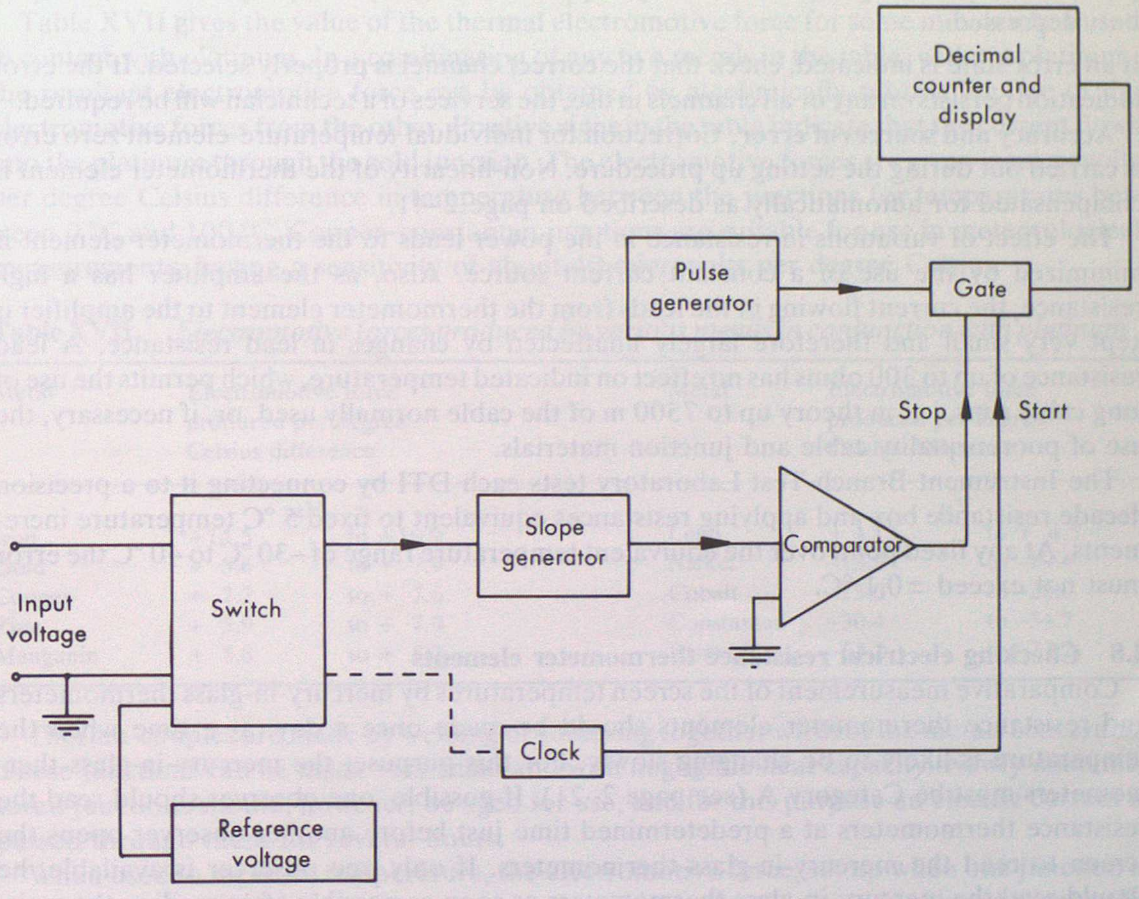


Figure 15. Schematic diagram of a dual-slope digital voltmeter.

In the DTI Mk 1A integration is achieved by the use of a small toroidal transformer, the primary of which is driven by the output of an operational amplifier. The voltage appearing at the transformer secondary is an accurate reproduction of the signal applied to the amplifier until such time as the transformer saturates. The integral of the system is essentially the flux of the transformer, though only saturation flux is detected. In each conversion period, the flux is taken from saturation level by the input signal and returned to saturation level by the reference voltage.

Installation. User stations do not have the equipment necessary to perform installation and setting-up procedures. Installation of the entire system is undertaken by the Meteorological Office Operational Instrumentation Branch.

Method of use. The thermometer elements Mk 4A are housed in a large, ordinary or marine screen, and the display and selector units are suitably positioned within the observing office. Once the instrument has been installed and set up the only operation required by the user is to press the appropriate push-button on the front of the selector unit. The display will stabilize within 2 seconds of selecting a channel.

If the mains supply to the instrument is interrupted for more than a few seconds, 30 minutes must be allowed to elapse after the supply is reconnected before readings are taken. In view of this it is recommended that the instrument be left switched on permanently unless it is expected to remain unused for a week or more.

If the display shows the central digit blanked an error state exists, which may be due to either

(a) the selection of a channel to which no thermometer element is connected, or

(b) no channel being selected, as may happen accidentally if a push-button is not fully depressed.

If an error state is indicated, check that the correct channel is properly selected. If the error indication persists on any or all channels in use, the services of a technician will be required.

Accuracy and sources of error. Correction for individual temperature-element zero error is carried out during the setting up procedure. Non-linearity of the thermometer element is compensated for automatically as described on page 2–41.

The effect of variations in resistance in the power leads to the thermometer element is minimized by the use of a constant current source. Also, as the amplifier has a high resistance, the current flowing in the leads from the thermometer element to the amplifier is kept very small and therefore largely unaffected by changes in lead resistance. A lead resistance of up to 300 ohms has no effect on indicated temperature, which permits the use of long cable runs, i.e. in theory up to 7500 m of the cable normally used, or, if necessary, the use of poorer-quality cable and junction materials.

The Instrument Branch Test Laboratory tests each DTI by connecting it to a precision decade resistance box and applying resistances equivalent to fixed 5 °C temperature increments. At any fixed point over the equivalent temperature range of –30 °C to 40 °C the error must not exceed ±0.1 °C.

4.8 Checking electrical resistance thermometer elements

Comparative measurement of the screen temperatures by mercury-in-glass thermometers and resistance thermometer elements should be made once a day, at a time when the temperature is likely to be changing slowly. For this purpose, the mercury-in-glass thermometers must be Category A (see page 2–21). If possible, one observer should read the resistance thermometers at a predetermined time just before another observer opens the screen to read the mercury-in-glass thermometers. If only one observer is available, he should read the mercury-in-glass thermometers as soon as possible after reading the resistance thermometers.

5 THERMO-COUPLES

5.1 General

It was discovered in 1821 by Seebeck that a place where two different metals touched a very small contact electromotive force was set up. If a simple circuit is made with two metals and with the junctions at the same temperature there will be no resultant electromotive force in the circuit because the two electromotive forces, one at each junction, will exactly oppose and cancel one another. If the temperature of one junction is altered, the two electromotive forces no longer balance and there is a net electromotive force set up in the circuit, and a current flows. When there are several junctions, the resultant electromotive force is the algebraic sum of the individual electromotive forces. The magnitude and sign of the contact electromotive force set up at any one junction depends on the type of metals joined and the temperature of the junction point, and may be empirically represented for any two metals by the expression

$$(E_T - E_s) = \alpha\,(T - T_s) + \beta(T - T_s)^2,$$

where E_T is the contact electromotive force at a temperature T and E_s is the electromotive force at some standard temperature T_s, α and β being constants. If there are two junctions, at temperatures T_1 and T_2, the net electromotive force E_n (the thermal electromotive force) is given by $(E_1 - E_2)$, where E_1 is the contact electromotive force at temperature T_1 and E_2 is the contact electromotive force at temperature T_2. E_n can also be represented by a quadratic formula of the type given for $(E - E_s)$ to a good approximation:

$$E_n = E_1 - E_2$$
$$= a(T_1 - T_2) + b(T_1 - T_2)^2$$

where a and b are constants for the two metals concerned. For most meteorological purposes, it is often possible to neglect the value of b, as it is always small compared with a.

Table XVII gives the value of the thermal electromotive force for some metals when used in contact with platinum. In a combination of any two metals in the table, without platinum, the resultant electromotive force can be obtained by algebraically subtracting one of the electromotive forces from the other. Positive signs in the table indicate that the current flows into the platinum through the cold junction. The electromotive forces are given in microvolts per degree Celsius difference in temperature between the junctions for temperatures between 0 °C and 100 °C. Copper–constantan junctions are suitable for use in meteorological measurements, having a sensitivity of about 40 microvolts per degree Celsius.

Table XVII. *Electromotive forces produced by various metals in conjunction with platinum*

Metal	Electromotive force produced per degree Celsius difference		Metal	Electromotive force produced per degree Celsius difference	
	μV			μV	
Iron	+14.5	to +19.9	Lead	+ 4.1	to + 4.5
Gold	+ 5.6	to + 7.9	Nickel	–13.9	to –19.4
Copper	+ 7.2	to + 7.6	Cobalt	–15.0	to –20.0
Zinc	+ 5.9	to + 7.9	Constantan	–30.4	to –34.7
Manganin	+ 5.8	to + 8.3	Bismuth	–63.2	to –72.2

Thermo-couples are made by welding or soldering together wires of the metals concerned. These junctions can be made very small and with negligible heat capacity. Newly manufactured junctions should, however, be aged for use, and for this purpose an electric current is passed through them for several hours.

When used to measure temperature, the electromotive force, set up when one junction is maintained at a standard known temperature and the other junction is allowed to take the temperature whose value is required, is measured. This electromotive force can be directly related to the difference in temperature between the two junctions by previous calibration of the system, and thus the unknown temperature is found by adding this difference algebraically to the known standard temperature.

5.2 Methods of measurement of the electromotive force

There are two main methods of measuring the electromotive force produced: (a) by measuring the current produced in the circuit with a sensitive galvanometer, and (b) by balancing the thermo-electric electromotive force with a known electromotive force, so that no current actually flows through the thermo-couples themselves. In (a) the galvanometer is connected directly in series with the two junctions (Figure 16). It should be noted that if the leads from A and B to the galvanometer are not of the same metal as used in the thermo-couple leads to these points the temperature of the junctions at A and B should be the same, or a subsidiary thermo-electromotive force may be set up and vitiate the results. The deflexion of the galvanometer will depend on the resistance of all parts of the circuit and on the sensitivity of the instrument. It will be best to calibrate the circuit at several temperatures over the range required. The change in resistance of the thermo-couple with temperature will be allowed for in this way, but the temperature of the external leads and the galvanometer itself should be kept as constant as possible. If it is not possible to keep the temperature of the leads approximately constant, the resistance of the galvanometer itself will have to be made high compared with the remaining resistance in the circuit, so that changes in the remaining resistance will have comparatively little effect on the current produced (i.e. the galvanometer would be acting as a voltmeter).

The principle of the potentiometer circuit is shown in Figure 17. The resistance AB is a uniform wire connected in series with a cell, a switch and a variable resistance. There is thus a uniform drop of potential along the wire when the switch is closed. Enclosed in the thermo-couple circuit is a portion, AC, of this wire (where C is a movable contact) and this circuit is so arranged that the potential drop along AC and the thermo-electric electromotive force tend to drive currents in opposite directions through the galvanometer. The position of C is adjusted until the galvanometer shows no deflexion. The thermo-electric electromotive force is then equal to the potential drop along AC which is given by $(AC/AB)U$, where U is the total potential drop along the resistance AB. U is normally standardized to some known value before the circuit is used by inserting a standard cell in place of the thermo-couple and,

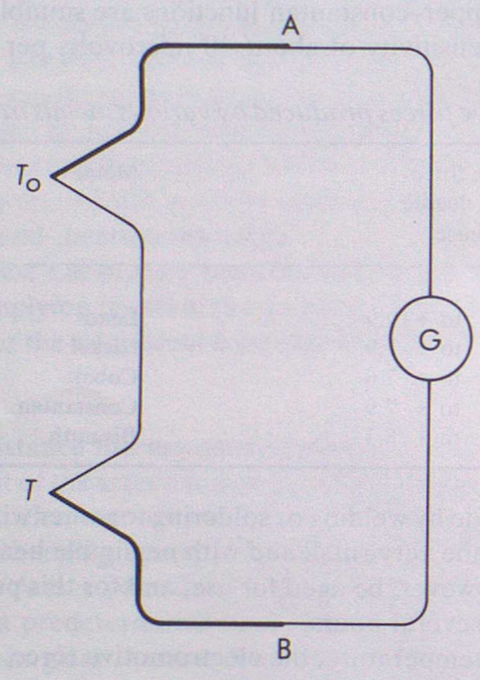


Figure 16. Simple circuit for measuring thermo-electric electromotive forces.

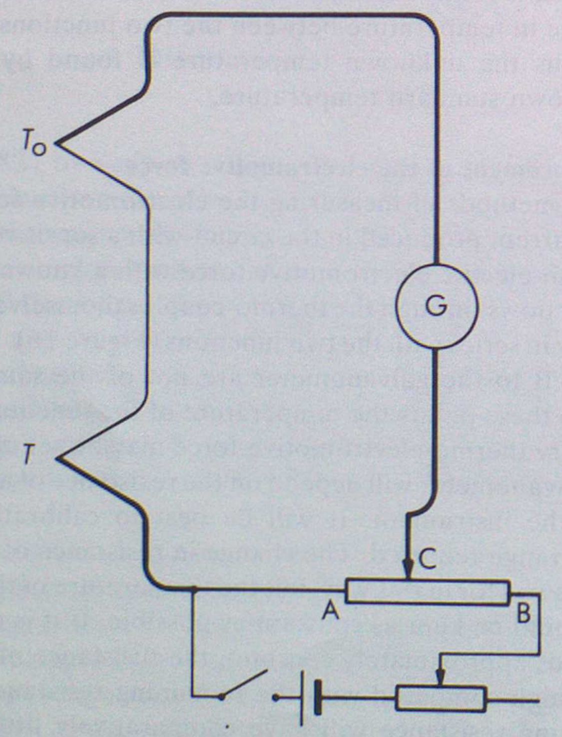


Figure 17. Potentiometer method of measuring thermo-electric electromotive forces.

with the contact C at the extreme end B, adjusting the variable resistance in series with the battery and AB until there is no deflexion in the galvanometer. In this way no current passes through the thermo-couple at the point of balance and, consequently, variations in the temperature of the leads can have no effect on the result.

5.3 Sources of error

The main sources of error in the measurement of the temperature difference between the hot and cold junction are:

(a) Changes in the resistances of the connecting leads with temperature. This effect only applies to the first method described above, and may be minimized by keeping all the leads as short and compact as possible and well insulated.

(b) Conduction along the leads from the junction when there is a temperature gradient in the vicinity of the temperature measuring point.

(c) Since different metals (besides the thermo-couple metals) often have to be used in connecting the circuit there is the possibility that stray secondary thermal electromotive forces will be set up. The temperature differences in the remainder of the circuit must therefore be kept as low as possible. This is specially important when the electromotive forces to be measured are small.

(d) In the course of time the metals of the thermo-couple may undergo chemical changes, resulting in changes in the electromotive forces produced. Periodical re-calibration will be necessary to allow for this.

(e) Leakage currents can occur from neighbouring power circuits. This can be cut down by suitable screening of the leads.

(f) Galvanic currents can be set up if any leads or junctions are allowed to get wet.

(g) Changes in temperature in the galvanometer alter its characteristics (chiefly by changing its resistance). This will not affect the readings by the potentiometric method to any degree, but will affect the direct-reading instruments. This can be minimized by keeping the temperature of the galvanometer as near as possible to that at which the circuit was calibrated.

(h) In the potentiometric measurement, changes in the electromotive force of the standard cell against which the potentiometer current is adjusted and changes in the potentiometer current between adjustments, will cause corresponding errors in the measured electromotive force. These will normally be small, provided the standard cell is treated properly and adjustments of the potentiometer current are made just before taking a temperature measurement.

Errors (a) and (g) emphasize the superiority of the potentiometric method when a very high degree of accuracy is required.

5.4 Application to meteorological instruments

The main advantage of thermo-couples for meteorological work is that they can be made very small, and thus with a very small time-constant (of the order of a second or two) and a very low sensitivity to radiation. Copper–constantan or iron–constantan are suitable combinations of metals for meteorological work as the electromotive force produced per degree Celsius is higher than with the rarer and more expensive metals which are normally used at high temperatures. It is often advantageous to obtain a higher electromotive force by using more than one set of thermo-couple junctions in series. This will reduce the error due to stray electromotive forces and other outside causes. The cold junction can be conveniently immersed in a container filled with melting ice (with precautions against short-circuiting). Its temperature is then known accurately.

Although the potentiometric method is more accurate it is usually less convenient, and a circuit of the direct-reading kind is normally used. Provided the precautions outlined above are taken, this can be made a convenient and accurate method of measuring temperature.

6 BIMETALLIC THERMOGRAPHS

6.1 Theory of the bimetallic strip

Consider a bimetallic strip AC of length l (Figure 18), clamped at one end and composed of thicknesses h_1 and h_2 of metals I and II. Let E be the value of Young's modulus and α be the coefficient of expansion of the metals, with subscripts 1 and 2 for the two metals. Let 2ψ be the angle subtended by the bimetal at the centre of curvature O of strip (∠COA in Figure 18). Then it can be shown that the small movement ΔS in the end C caused by a small change in temperature ΔT is given approximately by

$$\Delta S = \left\{\frac{l^2 A}{2(h_1 + h_2)}\right\}(\alpha_2 - \alpha_1)\left\{\frac{f(\psi)}{\psi}\right\}\Delta T,$$

where

$$\frac{1}{A} = \frac{1}{2} + \frac{E_1 h_1^3 + E_2 h_2^3}{6(h_1 + h_2)^2}\left\{\frac{1}{E_1 h_1} + \frac{1}{E_2 h_2}\right\}$$

and

$$f(\psi) = \left\{\frac{\psi^2 + \sin^2\psi - 2\psi\cos\psi\sin\psi}{\psi^2}\right\}^{\frac{1}{2}}.$$

Also $\Delta\psi$, the change in ψ for a change in temperature of ΔT, is given by

$$\Delta\psi = \frac{1A}{2(h_1 + h_2)}(\alpha_2 - \alpha_1)\Delta T \qquad \ldots (10)$$

The value of $f(\psi)/\psi$ has been tabulated and some values are given in Table XVIII.

Table XVIII. *Value of $f(\psi)/\psi$ for different values of ψ*

	0°	30°	60°	120°	180°	360°
$f(\psi)/\psi$	1.000	0.970	0.885	0.601	0.318	0.159

The sensitivity is greatest for a straight bimetallic strip, inversely proportional to the thickness of the strip, proportional to the square of the total length of the strip and proportional to the difference in the coefficients of expansion of the two metals. The stiffness of the strip is also important in the design of the instrument for, other things being equal, the greater the stiffness the better the record, because there is more force available to overcome friction in the mechanism. It can be shown that the displacement S of the end of the strip caused by a couple of bending moment M is given by

$$S = \frac{l^2 f(\psi) 6M}{\psi E (h_1 + h_2)^3},$$

where $E = \frac{1}{2}(E_1 + E_2)$, i.e. the stiffness (proportional to $1/S$) is proportional to $(h_1 + h_2)^3$, while the deflection due to a change in temperature is inversely proportional to $(h_1 + h_2)$. The time-constant, which will be approximately proportional to the mass of metal, will vary directly as $(h_1 + h_2)$. A compromise has thus to be reached between these factors in any given design.

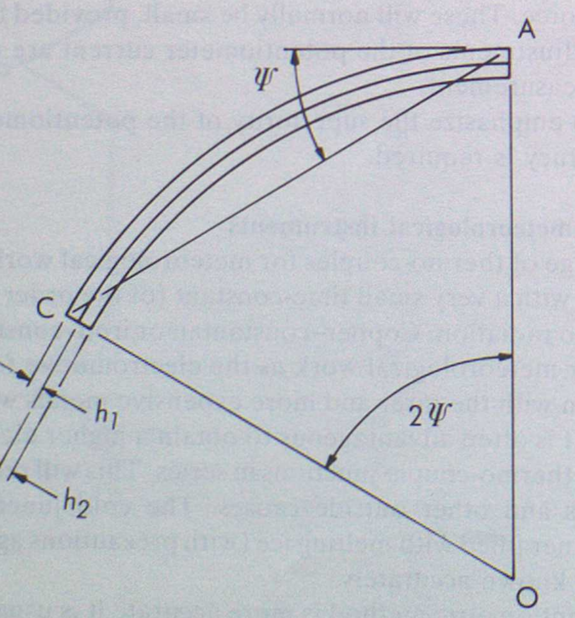


Figure 18. Principle of the bimetallic strip.

The bimetallic principle for indicating temperature has many applications but its use in surface meteorology is mainly limited to applications in thermographs.

6.2 Sources of error

Newly manufactured bimetallic strips are liable to an ageing process which results in a decrease of sensitivity (dS/dT), and for this reason only 'well aged' bimetallic strips are used (made by repeated heating and cooling of the strip over the entire measuring range contemplated). An extra change can also be brought about sometimes by frequent sudden large temperature changes, which result in a zero error and also a further decrease in sensitivity. These changes do not, however, occur in normal practice although they may occur during calibration. If the strip is cooled considerably below its lower temperature limit there is a risk that the welding may be damaged and the strip rendered useless.

6.3 Meteorological Office bimetallic thermograph Mk 3

The main base of the Meteorological Office bimetallic thermograph is a gun-metal casting providing support for the clock and drum and also the support for two arms which serve as the framework to carry the temperature element (Plate VI). The temperature element consists of a bimetallic strip, coiled in the form of a left-handed helix with the metal with the greatest coefficient of expansion on the outside. One end of the helix is rigidly anchored to a setting arm, which in turn is secured to one arm of the frame by a hexagonal nut and bush bearing. A setting screw enables the setting arm to be rotated about the horizontal axis passing through the centre of the helix against the pressure of a phosphor bronze spring. Coinciding with the horizontal axis of the helix is a phosphor bronze spindle which can revolve freely on pointed phosphor bronze pivot screws, one of which passes through the bush bearing and the other through the opposite arm of the frame. This spindle also passes through a hole drilled at right angles to the axis of a small brass pillar which is fixed rigidly by a screw to the free end of the helix. Another screw ensures that the pillar cannot rotate relative to the spindle. The pen arm is carried by a normal Meteorological Office pattern gate suspension (see Appendix 1) which is attached to the end of the spindle. A small screw normally fixes the suspension rigidly to the spindle, but if loosened it enables the position of the pen arm to be altered relative to the spindle.

As the temperature changes, the end of the helix rotates around its axis and at the same time causes the spindle and pen arm to rotate. Adjustment of the setting screw causes the whole helix to rotate about the axis and also alters the position of the pen arm. Several alternative positions are provided for attaching the pillar to the end of the helix; they enable the total length of the helix in use to be altered within certain limits. Changing the length of the helix alters the value of $d\psi/dT$ (see equation (10)), and consequently the scale value of the instrument can be adjusted. The helix is copper-plated and cellulosed as a protection against corrosion. A perforated brass cage is fixed to the main casting to protect the helix against accidental mechanical damage without obstructing the free flow of air. The clock is mounted on the main base, has either a daily or weekly movement, and carries an 'S' type drum (or one of similar external dimensions). The outer case, made of sheet copper, is hinged to the main base along the end furthest from the helix and does not cover the helix and cage. It has a glass window opposite the drum and is provided with a brass carrying handle. The pen may be lifted from the chart when necessary by a pen-lifter arm.

Installation. The instrument should be exposed in a large thermometer screen on the base board to the left of the thermometers.

Method of use. Two different ranges, with corresponding charts, are used in the British Isles; the winter chart has a range from −25 °C to + 20 °C and the summer chart from −10 °C to +35 °C. The proper date for changing from one set of charts to the other varies somewhat with the locality; for the London area, for example, the changes should normally be made about the middle of October and the middle of April. When changing from one set of charts to the other the instrument has to be readjusted. This should be done either with the instrument in a screen on a cloudy, windy day at a time when the temperature is practically constant, or in a room whose temperature is constant. A new chart should be fitted to the drum, taking care that corresponding lines on the overlapping and underlying portions are coincident and that the chart is as near to the bottom flange of the drum as possible (with the base of the chart touching it in at least one place). The pen should be replaced on the chart, and then the instrument left for a period of half an hour or more to reach equilibrium with its surroundings. If it is exposed in a room a position out of direct sunlight should be chosen and a thermometer suspended with its bulb close to the helix. The thermometer should then be read (the ordinary dry-bulb thermometer should be used if the thermograph is in the screen) and the pen arm adjusted until the indicated temperature on the chart is the same as that of the thermometer. This adjustment should be done roughly at first, by loosening the screw holding the pen arm to the pen-arm spindle, moving the pen arm to approximately the correct position and then tightening the screw. Any necessary fine adjustment can be carried out by use of the setting screw. After making the adjustment once, the thermograph should be left for a further period undisturbed, and then the result checked. Some further slight adjustment may be necessary because of the effect of the observer on the thermograph when making the previous adjustment. This secondary effect should, however, be small and easily corrected. The temperature at which the setting is made should lie about the middle of the range of the new chart if possible. The general instructions for autographic instruments with regard to time marking, fitting of charts on to drums, changing of charts, care of pens, tabulating the charts, winding the clock, and general cleanliness (see Appendix 1) should be carefully followed. Time marking can be done by carefully depressing the pen arm slightly with the finger. As in all autographic instruments the pressure of the pen on the chart should be reduced to the minimum necessary to give a clear record.

The time-constant of the instrument is roughly one-half that of the ordinary mercury thermometer, so that routine comparisons of the readings of the dry bulb and the thermograph at fixed hours will not in general produce exact agreement even if the instrument is working perfectly. A better procedure is to check the reading of the instrument on a suitable day at a time when the temperature is almost constant (usually a cloudy, windy day), or alternatively to compare the minimum readings of the thermograph trace with the reading of the minimum thermometer exposed in the same screen. Any necessary adjustment can then be made by means of the setting screw.

A useful way to obtain a check on the scale value of the instrument is to plot the readings of the dry bulb at the main hours of observation against the observed readings of the thermograph. There will be some scatter, but the best fitting line should be at an angle of 45° to either axis. If this is not so, the scale value will be in error and the slope of the line will give the amount of the error. This can be corrected by altering the point of attachment of the end of the helix to the column connecting it to the pen-arm spindle. If the scale is too contracted (i.e high temperature registering too low and low temperature registering too high) the point of attachment has to be moved nearer to the free end of the helix. If, on the other hand, the scale is too expanded (high temperature registering too high and low temperature registering too low) the point of attachment of the column should be moved away from the free end of the helix. This adjustment is not easy to carry out at an outstation, because of the difficulty of testing to see if the required result is obtained. If the first adjustment is not quite correct it is usually fairly simple to get the correct result by proportion.

Maintenance and repair. The helix should be handled carefully to avoid mechanical damage, and should be kept clean. The bearings of the spindle should be kept clean, and oiled at intervals by the sparing use of a little clock oil. The instrument is very simple mechanically, and, provided precautions are taken to keep the friction to a minimum and to prevent corrosion, it should give good service.

Accuracy and sources of error. In the thermograph mechanism itself, friction is the main source of error. One cause of this is bad alignment of the helix with respect to the spindle. Unless accurately placed the helix acts as a powerful spring, and, if rigidly anchored, it pushes the main spindle against one side of the bearings. With modern instruments this should not be a serious problem. Friction between the pen and chart can be kept to a minimum by suitable adjustment of the gate suspension (see Appendix 1). When new instruments are tested, the maximum permissible error at any point is ±0.5 °C.

7 MEASUREMENT OF SEA SURFACE TEMPERATURE

7.1 General

The sea surface temperature may be measured using one of three main methods:

(a) A bucket is lowered overboard to obtain a sample of sea water, the temperature of which is then measured. The temperature measured is approximately the average temperature of the uppermost 150 mm deep layer of the sea surface.

(b) The temperature of the sea water in the engine-room intake is measured. This is the temperature at a depth that will vary with the size of the vessel and its loading, and may be as deep as 15 m. The difference in temperature between the surface and the depth of the intake may be appreciable when the sea is calm and the sun is shining brightly. Intake readings are also liable to certain siting errors. For these reasons, whenever practicable, the bucket method is preferable.

(c) A hull sensor, containing a platinum resistance thermometer, is mounted on the inside of the ship's hull below the water-line. The depth will vary with the loading of the vessel. Temperature measurement may be made remotely with either a manually balanced bridge indicator, such as the Mk 5 indicator (see page 2–39), or an automatic digital temperature indicator, such as the DTI Mk 1B (see page 2–41).

7.2 Thermometers for use with sea-temperature buckets

Mounted thermometer Mk 3 (Plate VII). For extra strength and robustness unsheathed mercury thermometers may be mounted on a plastic mount. These thermometers have spherical bulbs and the top of the stem is made in the form of a nib to fasten in the top of the mounting. They are used in conjunction with a canvas bucket.

The scale is engraved on the stem with graduation marks every 0.5 °C; the graduation marks for every 5 °C are also reproduced and figured on the mount, on the right hand side of the thermometer stem. The graduation marks on the stem of the thermometer are always used in observing the units and tenths of a degree, the marks on the mount being used only for the fives figure. If there is any slight discrepancy between the graduation marks on the mount and the corresponding marks on the thermometer stem, the mark on the stem should always be taken as correct. In addition to the normal graduation marks there are etched on the side of the stem, in very small numerals at the appropriate places, such of the following graduation marks as fall within the range of the thermometer:

−20 °C, 0 °C, and +40 °C.

These marks are used by the Instrument Branch Test Laboratory when testing the thermometers, and can also be used to ensure that the thermometer has not been fixed to the wrong mount. Apart from the length (246 mm) the thermometer complies with the British

Standard for the Ord/2C meteorological thermometer, the essential requirements of which are set out in Table X.

The graduation marks on this thermometer are exposed to the atmosphere and the blacking may need renewing at intervals by rubbing the stem of the thermometer with a dark coloured crayon or a black lead pencil, and wiping off the surplus.

Mount. The mount is made of unbreakable rigid plastic. It is rectangular in shape apart from a slightly curved top edge. The length of the mount is 246 mm, width 35 mm, and thickness 4 mm; the long edges are bevelled. Two nickel clips hold the thermometer in position, and the nib at the end of the thermometer stem is let into a hole at the top of the mount and fixed with plaster of Paris. When the thermometer is in position the distance from the bottom of the mount to the bottom of the thermometer bulb is between 2.5 and 3.8 mm. Two small holes are drilled in the top of the mount and are used to attach it to a thermometer protector.

Sea-temperature thermometers Mk 2 and Mk 3 (Figure 19). Both thermometers are of the mercury-in-glass type with cylindrical bulbs, the Mk 3 having a button on the top. The scale covers a range from –5 °C to +35 °C with graduation marks every 0.5 °C, figured every 5 °C. All negative figures have a minus sign placed above them. The permissible errors are similar to those for thermometers for aspirated psychrometers (see page 2–26).

7.3 Thermometer protector

The thermometer protector (Plate VII) is used as a protective support for the mounted thermometer. It consists of a recessed mahogany stock with a brass reservoir provided at the base into which the bulb of the thermometer dips. The thermometer mount rests with its base on a brass support on the bottom of the stock, and is held at its upper end by a brass clamping plate which is screwed to a metal fitting passing over the top of the stock. A spring attached to the clamping plate grips the mount firmly. When the thermometer has to be removed for any reason the clamping plate should first be taken out by unscrewing the two fixing screws.

7.4 Thermometer sheath

The thermometer sheath (Figure 19) acts as a protective container for a Mk 2 sea-temperature thermometer. It is made of a length of brass tubing, closed at each end by a threaded solid brass plug. The inner surface of each plug is fitted with a neoprene buffer. Rubber grummets provide additional support for the thermometer when fitted in the sheath. A cutaway, in the form of a long slot, allows reading of the fitted thermometer and two diametrically opposed small slots assist circulation of the water around the thermometer bulb. A polythene washer is fitted to the plug at the bottom of the sheath and acts as a retaining flange when the thermometer–sheath assembly is being withdrawn from the bucket for reading.

7.5 Sea-temperature buckets

Meteorological bucket Mk 2A (Plate VII). The meteorological bucket Mk 2A consists simply of a canvas bucket with a wooden base, fitted with a lid which is kept closed by means of a spring. When the bucket is trailed through the sea the lid is opened by the water pressure and the bucket is filled. The lid reduces the loss of water when the bucket is being hauled to the ship's deck and also reduces the rate of heat loss due to evaporation from the water surface.

Method of use. The bucket should be let into the water forward of all outlet pipes after making fast to the deck rail or other firm support the rope connected to the bucket handle. After letting the bucket trail in the water for at least 30 seconds, keeping the bucket just below the sea surface as far as possible, it should be withdrawn quickly, placed in the shade and out of the wind, the thermometer inserted in the bucket and the water stirred. The temperature recorded by the thermometer should then be read to the nearest 0.1 °C when it attains a steady value (after about 30 seconds). The bulb of the thermometer should be kept

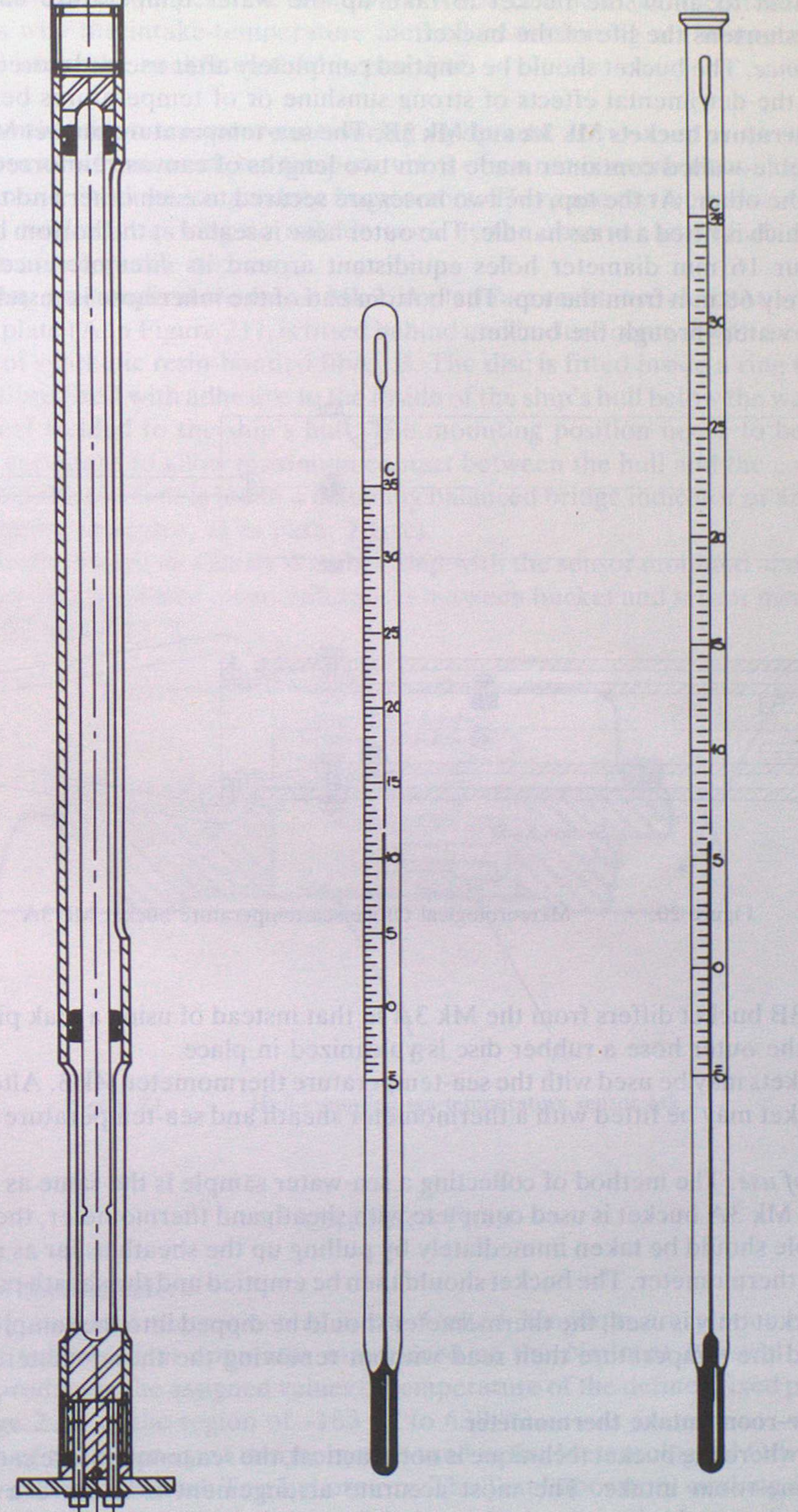


Figure 19. Thermometer sheath and sea-temperature thermometers Mk 2 and Mk 3.

well beneath the surface of the water throughout with continuous stirring, and the reading should be taken without undue delay as soon as the temperature of the thermometer becomes steady or the rate of change of temperature becomes less than 0.1 °C min^{-1}. The thermometer should not be withdrawn from the water until the reading has been taken. It is not advisable to keep the bucket trailing for longer than one minute as this period is more than sufficient to allow the bucket to take up the water temperature and any longer immersion shortens the life of the bucket.

Maintenance. The bucket should be emptied completely after use and stored under cover, away from the detrimental effects of strong sunshine or of temperatures below freezing.

Sea-temperature buckets Mk 3A and Mk 3B. The sea-temperature bucket Mk 3A (Figure 20) is a double-walled container made from two lengths of canvas-reinforced rubber hose one inside the other. At the top, the two hoses are secured to each other and to a gun-metal mouth to which is fitted a brass handle. The outer hose is sealed at the bottom by a teak plug, and has four 16 mm diameter holes equidistant around its circumference with centres approximately 68 mm from the top. The bottom end of the inner hose is castellated to assist the flow of water through the bucket.

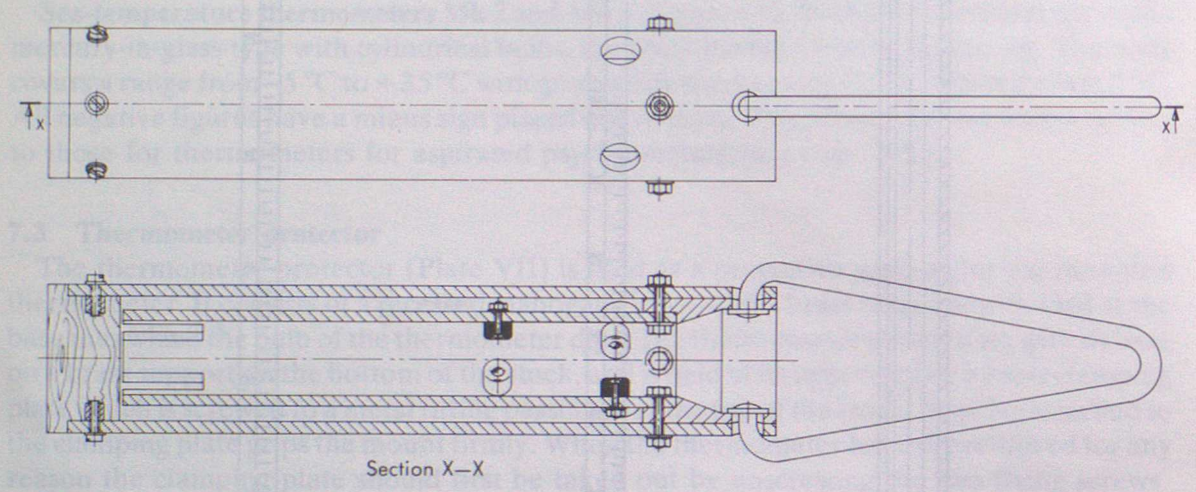


Figure 20. Meteorological Office sea-temperature bucket Mk 3A.

The Mk 3B bucket differs from the Mk 3A in that instead of using a teak plug to seal the bottom of the outer hose a rubber disc is vulcanized in place.

Both buckets may be used with the sea-temperature thermometer Mk 3. Alternatively the Mk 3A bucket may be fitted with a thermometer sheath and sea-temperature thermometer Mk 2.

Method of use. The method of collecting a sea-water sample is the same as with a canvas bucket. If a Mk 3A bucket is used complete with sheath and thermometer, the temperature of the sample should be taken immediately by pulling up the sheath as far as necessary and reading the thermometer. The bucket should then be emptied and the sheath pushed back in.

If the bucket only is used, the thermometer should be dipped into the sample for about 30 seconds and the temperature then read without removing the thermometer.

7.6 Engine-room intake thermometer

On ships where the bucket technique is not practical, the sea temperature can be measured at the engine-room intake. The most accurate arrangement is to have a thermometer permanently inserted in a pocket in the main inlet pipe as near as possible to the ship's side. In cases where the thermometer is a ship's fitting, it is essential that its accuracy be checked against an official tested instrument and corrections made for any index error that is found.

Alternatively a thermometer can be held in water issuing from a tap in the intake, taking care that the bulb is completely immersed for long enough to ensure that a correct reading is obtained. In many engine-rooms the intake pipe is inconveniently situated, and great care has to be taken to avoid parallax errors. The thermometer or the tap for taking water samples

may also be situated a long way from the ship's side and in a very heated part of the engine-room, so that the temperature of the water is not the true sea temperature. This is one of the reasons why the intake-temperature method of measuring sea temperature is not recommended when the bucket method is practical.

7.7 Hull-mounting sea-temperature measuring equipment

The use of buckets to measure sea temperature is often not convenient or easy, while the engine-room intake method can produce large errors. There are obvious advantages therefore in using a method requiring no outside work by the observer and which can provide measurements of acceptable accuracy.

Hull-mounting sea-temperature sensor Mk 2. A platinum resistance element, wound in the form of a thin plate (A in Figure 21), is fitted behind and in close contact with a copper plate let into a disc of synthetic resin-bonded fibre, B. The disc is fitted inside a ring C, either of resin-bonded fibre fixed with adhesive to the inside of the ship's hull below the water-line, or of stainless steel welded to the ship's hull. The mounting position needs to be as free as possible from curvature to allow maximum contact between the hull and the copper plate. The output from the element is fed to a manually balanced bridge indicator or an automatic digital temperature indicator, as in para. 7.1 (c).

Accuracy. Trials aboard an Ocean Weather Ship with the sensor mounted about 460 mm below the water-line produced mean differences between bucket and sensor measurements of between 0.02 and 0.15 °C.

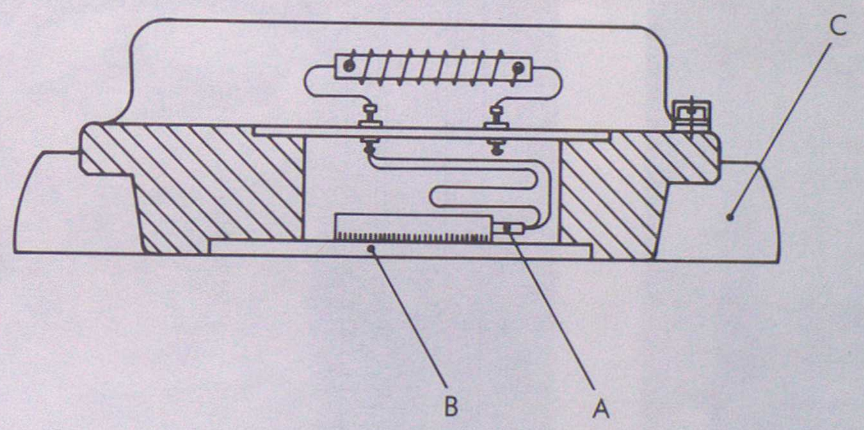


Figure 21. Hull-mounting sea-temperature sensor Mk 2.

8 CALIBRATION

8.1 Standard thermometers

The primary standard thermometers in the United Kingdom are platinum resistance thermometers calibrated in apparatus maintained at the National Physical Laboratory (NPL), for reproducing the assigned values of temperature of the defined fixed points of the IPTS (see page 2–2) in the region of −183 °C to 630 °C.

Verification of the accuracy of thermometers used in the Meteorological Office is undertaken by the Instrument Branch Test Laboratory. The Test Laboratory working standard is a high-grade platinum resistance thermometer whose accuracy is checked periodically in a water triple-point cell (the triple point of water is exactly defined and can be reproduced in a triple-point cell with an uncertainty of 1×10^{-4} °C). The Meteorological Office water triple-point cell was manufactured at the NPL, and is similar to cells maintained at the NPL for use in the calibration of primary standard thermometers. When compared with a reference cell at the NPL the equilibrium temperatures of the two cells differed by 1×10^{-4} °C or less.

The cell (Figure 22) consists of a glass tube surrounded over most of its length by a glass flask. The tube and flask are in contact only at the neck of the flask, where they are sealed together. The space between the tube and the flask is almost filled with distilled water and sealed off under vacuum. The remaining space subsequently fills with water vapour.

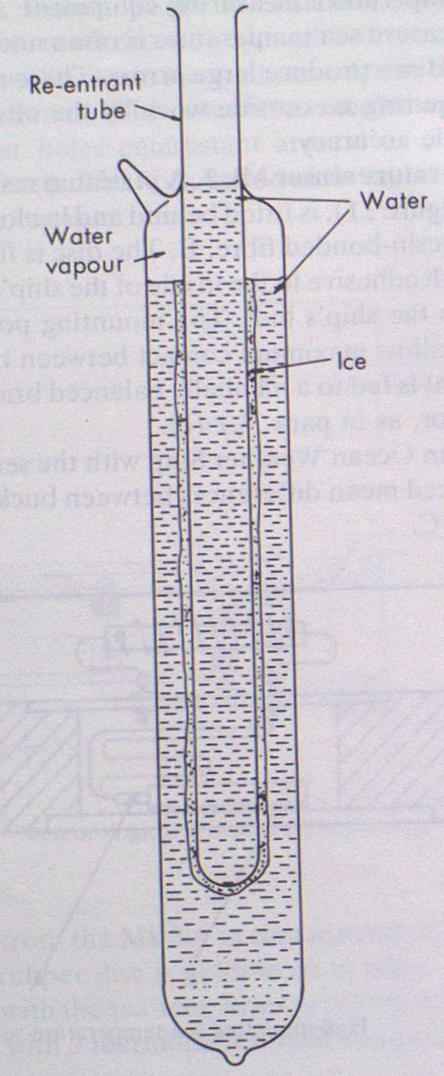


Figure 22. Water triple-point cell.

The cell is prepared for use by the following sequence of operations:

(a) The cell is cooled to 0 °C by immersing it in an ice bath.

(b) The re-entrant tube is cooled well below 0 °C by filling it with finely powdered solid CO_2. In so doing a fairly uniform sheath of ice, several millimetres thick, is formed round the tube over most of its length.

(c) The remaining CO_2 is then tipped out and the tube filled with water at, typically, 20 °C. This causes a thin layer of ice, adjacent to the tube, to melt.

(d) The water is sucked out of the tube and replaced with ice-cold water.

(e) The cell is returned to the ice bath and left to attain its equilibrium temperature.

The water in the re-entrant tube will take up the triple-point temperature and ensure good thermal contact between the thermometer being calibrated and the walls of the cell.

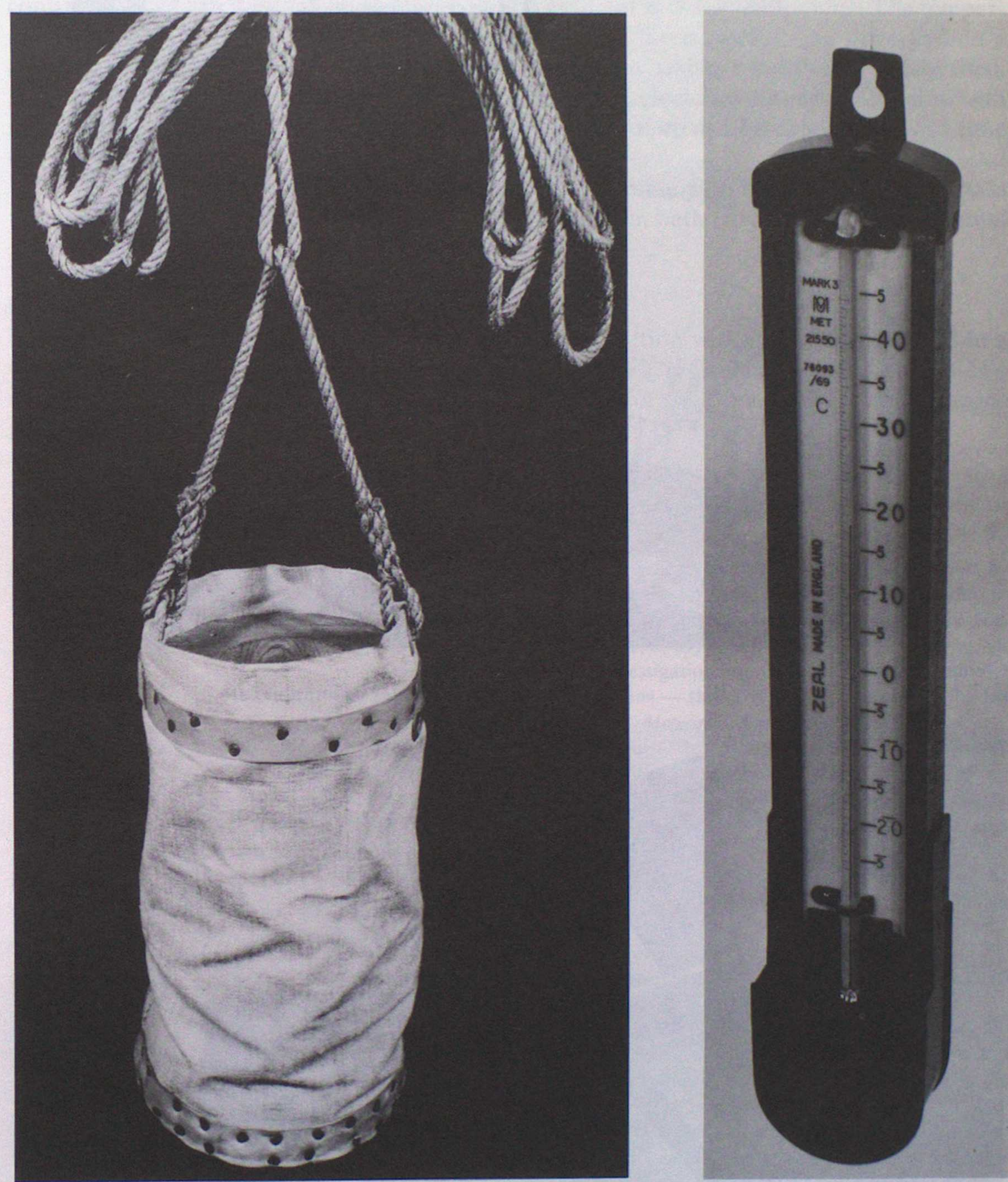


Plate VII. Meteorological Office sea-temperature bucket Mk 2A, mounted thermometer Mk 3 and thermometer protector.

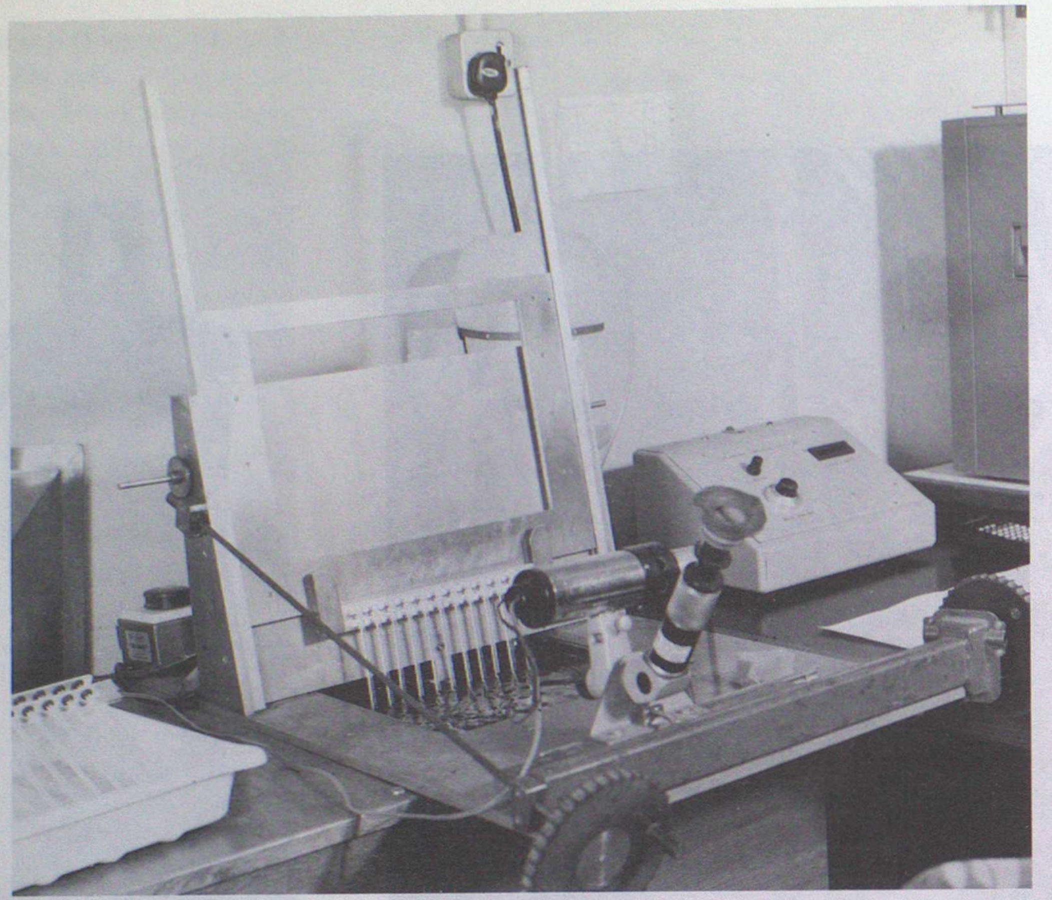


Plate VIII. Liquid-in-glass thermometer calibration bath.

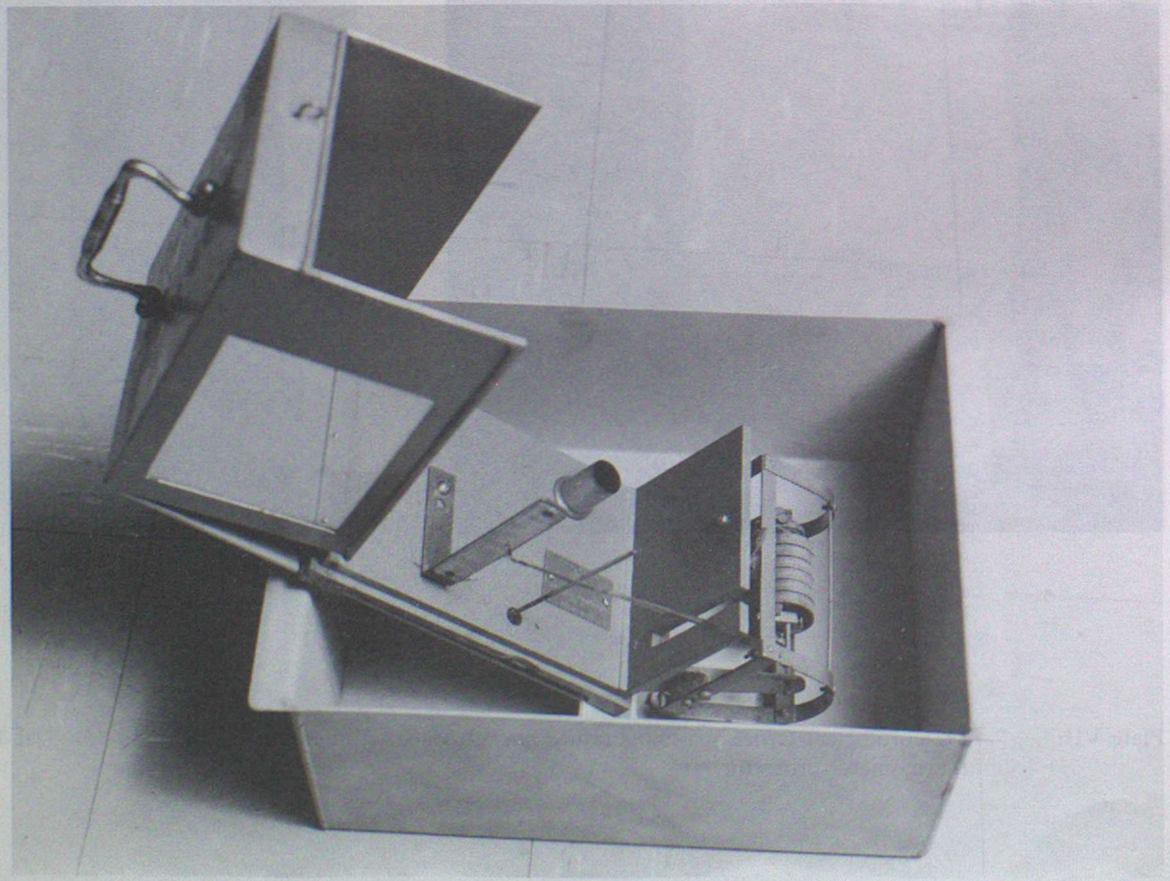


Plate IX. Thermograph checking bath.

8.2 Calibration of thermometers

Liquid-in-glass thermometers are calibrated at temperatures between −20 °C and +50 °C by immersion in a thermostatically controlled paraffin bath (Plate VIII). The bath is continuously agitated to reduce any temperature gradient to a negligible value. The temperature of the bath is measured by the working standard thermometer, and displayed on a recorder to enable the operator to determine when a stable condition is established. Readings of the thermometers being tested are made at selected points and compared with simultaneous readings of the working standard. Batches of up to 12 thermometers at a time can be dealt with in this manner.

Resistance thermometer elements are calibrated by immersion in an ice bath (to obtain the nominal resistance) followed by immersion in a steam bath (to obtain the fundamental interval).

8.3 Checking of thermographs

Bimetallic thermographs are checked by fixing in position with the helix immersed in a water bath (Plate IX). Comparisons are made against a reference thermometer at two temperatures, usually about 0 °C and 28 °C. From these comparisons any necessary changes in the zero and magnification can be determined.

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APPENDIX 1

METEOROLOGICAL RECORDING INSTRUMENTS — GENERAL CONSIDERATIONS CONCERNING CONSTRUCTION, MAINTENANCE AND OPERATION

CONTENTS

LIST OF DIAGRAMS

LIST OF PLATES

APPENDIX 1

A.1 RECORDING METHODS

A.1.1 Introduction

The effect of friction on the accuracy of a recording instrument is generally larger and more serious than in a comparable indicating instrument, especially when a pen, writing continuously on paper, is used to record the results. The friction between the pen and the paper is usually much larger than the total amount of friction in the bearings of the instrument; the concept of adequate control thus arises.

The effect of friction is to impose a certain force on the indicating mechanism in the opposite direction to that in which the variable element is causing the mechanism to move. This force causes the reading of the instrument to be in error by a certain amount. The 'control' of the instrument may be defined as the force which must be applied to the indicating mechanism at the point where it is recording (e.g. at the pen) to keep the indication constant when the value of the element which is being recorded changes by one unit. This is equal to the force required to move the indicating mechanism over one unit of the scale provided the measured element remains constant. The greater the control the less will be the effect of friction and the more detailed will be the record. In any case the control should be such that the maximum effect of the friction on the reading should be less than the least change it is desired to record. If this is not so, the errors will be markedly different for rising and falling values of the element recorded and there will be 'lost motion' when the variable element reaches a maximum or minimum value.

A.1.2 Recording charts

There are several methods by which the indication of an instrument can be made to give a permanent record. In the majority of these the record is in the form of a line on a sheet of paper, and is measured by reference to the position of the line on the paper. The properties of the paper are thus of some importance.

Good chart paper is manufactured so that its fibres lie largely in one direction ('downboard'). These fibres are hygroscopic and swell slightly in a lateral direction when they absorb water. Thus it is found that an instrument chart changes its dimensions when it is soaked in water, or to a somewhat lesser extent when the humidity changes, and the magnitude of the change in any direction depends on the direction of the fibres. All Meteorological Office charts are cut with the time-scale 'downboard', and it is found that the change in length in this direction when the chart is immersed in water after being in a normal room atmosphere is about 0.2–0.3 per cent. On the other hand the change in length in a direction perpendicular to this is 2.5–3.0 per cent, i.e. 10 times as much. The chart will not of course become soaked in normal use, but experiments have shown that the changes in dimensions are very nearly as much when the charts are exposed in a humidity chamber and the relative humidity is altered from about 50 per cent to about 100 per cent. The change in length 'downboard' is 0.1–0.2 per cent, and the change in length in a perpendicular direction is 1.5–2 per cent.

In very accurate work it is thus necessary to have two datum lines drawn on the chart at fixed positions; these can be used as base lines to enable zero errors (due to chart slipping or being inserted wrongly) and changes in scale value (due to the chart altering in size before the record was made) to be measured and allowed for.

A.1.3 Pen recorders

In most meteorological instruments using pen recording the pen rests lightly on a chart wrapped around a vertical cylindrical drum. The drum is rotated at a constant speed, and as the element to be recorded varies the pen moves up and down the chart. To reduce friction, it is necessary to adjust the pressure of the pen on the chart to the minimum consistent with a clear record. This is achieved in many Meteorological Office instruments by means of the gate suspension (Figure A1). The pen arm is suspended in a small gate, A, so that it can rotate freely about the gate axis. The gate itself is fixed to a collar, B, and can be rotated about an axis parallel to the pen arm, i.e. its inclination to the vertical plane containing the pen arm can be varied. When the axis of the gate is in this vertical plane there is no tendency for the pen arm to move in one direction or the other, but when the gate is inclined to the vertical plane there is a component of the weight of the pen arm which exerts a moment about the gate axis and causes the pen either to press on the chart or to fall away from it. The pressure between the pen and the paper can thus be adjusted to a suitable value which remains practically independent of the position of the pen on the chart provided the pen arm is perpendicular to the pen-arm spindle. It is normally found that an inclination of the gate axis of about 10° to the vertical is quite sufficient.

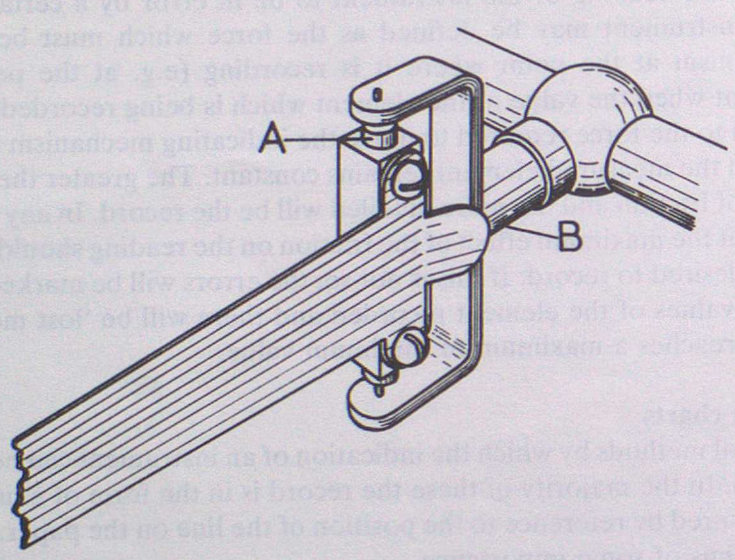

Figure A1. Gate suspension for pen arm.

There are two main ways in which the changes in the variable element being recorded are converted into changes of the position of the pen. In the first, the point of support of the pen arm is moved in a direction perpendicular to the time axis on the chart; the hour lines on the chart are straight lines and the length of the pen arm is immaterial. In the second, the changes in the variable element are converted into angular movements of a spindle on which the pen arm is mounted; the hour lines are approximately arcs of circles, with radii equal to the length of the pen arm (measured from the axis of the pen-arm spindle to the point of the pen) and with their centres on the plane through the pen-arm spindle parallel to the time axis. The true hour lines are not exactly arcs of circles because the pen writes on a cylinder and not on a plane surface.

It is necessary to ensure that the chart is printed for the correct pen-arm length and for the correct position of the pen-arm spindle. When replacing the pen on the pen arm, or fitting a new pen arm, every care must be taken to ensure that the effective pen-arm length is correct. The displacement of the pen at the end of the pen arm for a given angular movement is proportional to the length of the pen arm, so that an error of 8 mm in the length of a pen arm which should be 160 mm long will give an error of 5 per cent in the deflexion of the pen, and in the scale value on the chart at that point. The correct charts for all standard Meteorological Office instruments have identifying numbers, and these should always be quoted when

requesting stocks. If a non-standard chart has to be supplied specially, the data given should include the length of the pen arm and the position of the pen-arm axis, if the hour lines are not straight.

Pens. Various types of pen are used on the standard Meteorological Office instruments; the chief ones are illustrated in Figure A2. The type in normal use on the commoner instruments is shown at (a); it consists of a simple triangular reservoir attached to a short holder which can be slid over the end of the pen arm; it can hold more than sufficient ink for at least a normal week's record on any standard sized drum. Preferred alternatives for use on certain instruments are shown in (b) for the tilting-siphon rain-gauge, and in (c) for the thermograph and barograph. Both (b) and (c) are disposable items consisting of an ink reservoir fitted with a fibre nib; either pen will provide at least a year's normal record.

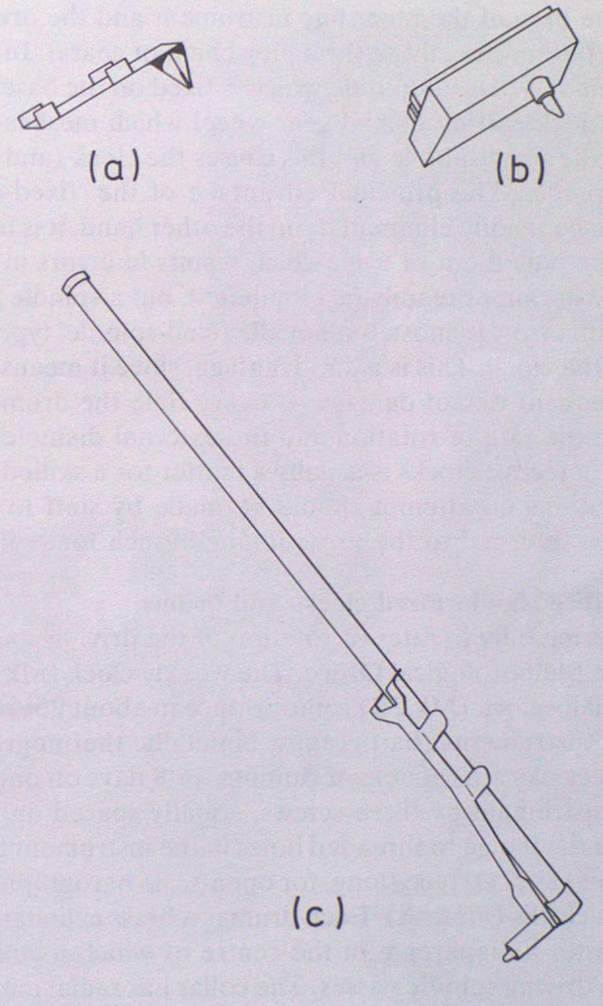

Figure A2. Instrument pens.

A.1.4 Electrosensitive paper

Recorders using various types of electrosensitive paper are also used. Paper is coated with zinc oxide so that when a small current passes from a stylus to the paper the zinc oxide coating is reduced to free zinc and a marking results. This process produces a fine, clean and dry trace resistant to smudging.

A.1.5 Electrical recorders

Devices for balancing potentiometric or bridge recorders have various forms, some manual, some self-balancing. Whatever the method used the principle is the same. A galvanometer, or an electronic circuit, is arranged to detect when the system is out of balance. Where a galvanometer is used, the position of the galvanometer pointer is detected either manually or electrically, and the slide-wire contact moved to the point of balance. Where an electronic circuit is used to detect the out-of-balance it is usual for the output of the detecting circuit to control the direction of rotation of a reversible motor which moves the slide-wire contact and positions the pen arm or pointer.

A.1.6 Clocks, drums and time-scales

Most meteorological recording instruments are fitted with 'daily' or 'weekly' clocks, i.e. clocks which cause the drum to rotate once in about 25½ hours and once in about 7⅓ days respectively. The overlap is necessary to allow some margin for the time of changing the chart, and to prevent the trace from crossing the join when the pen is near the top or bottom of the chart (on those instruments in which the hour lines are curved).

There are two possible ways of using the clock to drive the drum. In the 'fixed-clock' type the clock is screwed to the base of the recording instrument and the drum attached to the main spindle of the clock (either directly or through a chain of gears). In the 'fixed-spindle' type the clock is supported on a central spindle which is fixed on the base of the instrument. The main spindle of the clock carries a small gear wheel which meshes with another gear wheel rigidly attached to the fixed spindle and this causes the clock (and attached drum) to rotate round the fixed spindle. The principal advantage of the 'fixed-clock' type is that backlash in the system can be readily eliminated; on the other hand, it is found that the main spindle of the clock can be pulled out of true, which results in errors in the record. In the 'fixed-spindle' type backlash cannot readily be eliminated, but a spindle slightly out of true does not result in significant error. In most, but not all, 'fixed-spindle' type clocks the drum is permanently attached to the clock. This is a disadvantage, since it means that the clock will be handled — with consequent risk of damage — every time the drum is removed.

Time-scales depend on the rate of rotation and the external diameter of the drum.

The repair of faulty or defective clocks is usually a matter for a skilled clock repairer. At Meteorological Office stations no attempt should be made by staff to repair a defective clock; the clock should be returned to the provisioning branch for replacement.

A.1.7 Meteorological Office standardized clocks and drums

Two 'fixed' clocks differing only in rates of rotation of the driving spindles, serve as the standardized clocks of the Meteorological Office. The weekly clock (Mk 2A) rotating once in about 7⅓ days and the daily clock (Mk 2B) rotating once in about 25½ hours are used with the commoner recording instruments (barographs, bimetallic thermographs, hygrographs and rain recorders). Both clocks are capable of running for 8 days on one full winding. The clock is attached to the instrument by three screws, equally spaced on a circle of 89 mm diameter, passing through the flange to threaded holes in the instrument base. Two standardized drums, 'S' type (short) and 'O' type (long, for open-scale barographs), are for use with either of the standardized clocks (Plate A). Each drum is a brass cylinder, of defined height and diameter, provided with a diaphragm in the centre of which a collar is screwed and through which the clock's driving spindle passes. The collar has radial teeth on its underside which engage with similar teeth on a collar attached to a clutch drive on the driving spindle of the clock; a knurled nut secures the drum to the driving spindle of the clock. The object of the clutch drive is to facilitate the setting of the drum to its correct position when fitted to the clock. The drum is flanged around its base and the chart is held in position by two clips. In addition to the chart clips the 'O' type drum has two small pins screwed into its side, lying in the same line as the chart clips. These pins help to keep the chart in position where the two ends overlap. The 'S' type is 93 mm in diameter, so that it gives a time-scale of 11.4 mm h^{-1} with a daily clock. When used with a weekly clock Mk 2A the clock is adjusted to rotate once in 7 days 7.2 hours, giving a time-scale of 1.67 mm h^{-1}. The 'O' type drum is not normally used with a daily clock, but if it were the time-scale would be 17.2 mm h^{-1}. Used with a weekly clock Mk 2A, the clock is adjusted to rotate once in 7 days 8 hours, giving a time-scale of 2.5 mm h^{-1}. (The difference between a time of rotation of 7 days 8 hours and 7 days 7.2 hours is negligible for most purposes.) The standardized clocks and drums are completely

Plate A. Standard Meteorological Office clocks and drums.

interchangeable, i.e. any clock can be used with any drum. The weekly clocks can be regulated over a range of 2¼ hours in the 7 days and the daily clock over a range of 20 minutes in the 24 hours.

A.2 CORRECTION OF RECORDING INSTRUMENTS

It is important to ensure correct timing of any part of the recorded trace, and to be able to make an estimate of any errors in the record itself. There are three main causes of error that can affect the timing of the record:

(a) Backlash between the drum and the spindle on which it is mounted. This defect is not serious with clocks of the standard Meteorological Office pattern or similar types. It delays the starting of the record and causes a constant error once the record has started.

(b) An error in the clock rate (or the use of an unsuitable time-scale on the chart). If the difference is small the rate of revolution of the drum can be adjusted to the correct value (given by the time-scale on the chart) by means of the clock regulator. Small errors may occur, however, owing to the variability of the clock rate, e.g. with temperature changes.

(c) Errors due to the change in length of the chart with humidity variations (see page A–3). These are small in charts which are cut from the paper in the correct direction, but are serious if the chart is cut in the wrong direction.

In order that errors of this kind may be recognized it is essential to make accurate time marks on the records themselves. Although it is preferable that the time marks be made at about the same time each day, it is not essential provided the exact time at which the mark is made is known. The actual time (it suffices for most records if it is correct to the nearest minute) should be entered in the register. On weekly charts one time mark a day would suffice. On daily charts it is preferable to have more than one, the first being made at least half an hour but not more than 2 hours after starting the record, and another after about a further 8–12 hours. It is often convenient to make a time mark coincide with an hour mark and to note the timing error.

On most instruments a time mark may be made by depressing the pen between 3 mm and 6 mm and then releasing it. These limits should not be exceeded, as the careless depression of the pen can often disturb the calibration of the instrument or even strain some of the parts beyond their elastic limits.

On some instruments, e.g. barographs, a simple mechanical device is provided which enables time marks to be made without opening the case of the instrument. If a reading of the record has to be obtained at the same time as the time mark it should be made just before the time mark and not after it.

Recording instruments are generally less accurate than the comparable indicating instruments, and they cannot often be made absolute. It is therefore usual to compare their readings with those of an indicating instrument at several of the main observation hours throughout the day. In some recording instruments, e.g. the barograph, this will give immediately the error of the record or the necessary correction to the record, assuming that the indicating instrument is correct. It should be noted that the error is equal, but opposite in sign, to the correction. The mean correction for the day can therefore be ascertained and applied to any tabulated readings taken from the record.

No instrument responds immediately to changes in the element that is being measured, and different instruments respond at different rates. Comparisons should therefore be made only when the measured element is constant or changing very slowly, or mean values should be taken over a period in which any errors due to the different time-constants may be expected to cancel out.

Another possible procedure is to plot the readings of the recording and indicating instruments against one another; the points obtained should lie on or about a line at 45° to each axis passing through the origin. If the best-fitting straight line does not pass through the origin a zero error is indicated, and if the slope is not 45° there is an error in the scale value of one instrument, usually the recording instrument.

A.3. OPERATIONAL PROCEDURE

Some general instructions on the method of handling recording instruments are given below. These are supplementary to the more particular instructions given for each individual instrument.

A.3.1 Changing the chart

Remove the pen from the old chart, noting the correct time to the nearest minute (this serves as an extra time mark). Clean the pen if necessary and top with ink. See that the ink is flowing sufficiently freely to give a legible trace, but not so freely as to give a thick trace. It is rarely advisable to fill the reservoir completely. Remove the old chart and wrap the new chart round the drum so that it fulfils the following conditions (these are absolutely necessary if good and reliable records are to be obtained):

(a) The chart should fit tightly round the drum.
(b) The lines of equal scale value should be parallel to the flange at the bottom of the drum, i.e. corresponding lines on the beginning and end of the chart in the overlap portion should coincide.
(c) The bottom of the chart should be as close to the flange as possible and touching it in at least one place (if the chart is not cut quite correctly it may not be possible for it to touch the flange in all places and still comply with the other conditions cited).
(d) The end of the chart should overlap the beginning and not vice versa.

When the chart is fitted properly the spring clips should hold it in place. The clock can then be wound and the new record started. When setting the pen to the correct time the final adjustment should be made by moving the drum in the opposite direction to its normal motion to take up any backlash in the gear train, i.e. the drum should be moved from a time on the chart in advance of the actual time back to its correct position. Once they have been correctly set most recording instruments should not require readjustment more often than three or four times a year. If careful examination, extending over a period, shows that readjustment is necessary this may be done at the time a chart is changed, and a note should be made on the chart and in the register.

A.3.2 Writing up the chart

Before being filed away, the record should have inserted on it the following particulars: date (including the year), name of the station, its position, its height above mean sea level, actual time of each of the time marks, readings of the control instruments when the time marks were made, and time at which the record began and ended. If a reliable estimate of the mean errors in the record has been made, covering the period of the chart, this should be indicated. The reasons for any abnormal features, e.g. failure to ink, clock stopping, etc., should also be recorded if known.

A.3.3 Care at each main observation hour

See that the instrument is recording properly and read it. If necessary, a time mark should be made.

A.3.4 General hints (including cleaning)

Special care should always be taken to keep instruments clean. This not only improves their performance (by reducing friction) but also lengthens their useful life (by preventing

corrosion) and improves their appearance. General methods of cleaning the different materials most often used in instruments are as follows:

(a) *Plain brass or copper parts.* Unlacquered brass or copper parts may be kept bright by the use of jeweller's rouge applied with an oily rag or by metal polish applied sparingly. The polish should not be allowed to reach any bearing surfaces. The inside of a rain-gauge funnel should however only be rubbed with a dry rag.
(b) *Lacquered brass or copper parts.* These should be cleaned with a soft chamois leather. No polish should be applied, but where there is exposure to damp a little petroleum jelly may be used with advantage.
(c) *Polished woodwork.* This should be cleaned with a soft chamois-leather. A little linseed oil may be rubbed in with a soft cloth if necessary.
(d) *Glass and porcelain.* The dirt should be cleaned off with a moist rag or chamois-leather.
(e) *Bearings, pinions and hinges of instrument cases.* These should be lubricated sparingly with a touch of clock oil. Refer also to the detailed instructions for the instrument.
(f) *Ball races.* These should be treated in accordance with the detailed instructions for each instrument.
(g) *Steel parts.* These should be cleaned with an oily rag and protected from rust with a trace of petroleum jelly. If, in spite of care, rust appears, the part should be carefully cleaned with a fine emery cloth or carborundum cloth.
(h) *Painted woodwork.* In dusty localities woodwork should be brushed periodically, and at stations affected by smoke or soot a thorough cleaning with soap and water should be carried out once a month.
(i) *Painted surfaces liable to inking.* The ink should be removed while wet with a damp cloth. Older stains should be removed by the application of a small quantity of whiting applied with a damp cloth. Methylated spirit may be used with the whiting if there is no risk of this getting on to lacquered brass or polished woodwork.
(j) Naphthalene balls are effective in keeping insects from the interior of instruments exposed out of doors, e.g. recording rain-gauges.

Special care must be given to keeping the end of the pen arm and the fitting which actually supports the pen free from ink, or else corrosion may set in. This may lead to the use of a pen arm which is too short and thus give rise to faulty records.

APPENDIX 2

The International Systems of units (SI)

The International System (SI) consists of seven 'base units' together with two 'supplementary units'. From these are formed others known as 'derived units'. The base and supplementary units, and some of the derived units, have been given names and symbols. The symbols are printed in lower case except when derived from the name of a person; for example m (metre), but A (ampere). Symbols are not pluralized (1 m, 10 m) nor do they take a full stop. The names of the units do not, however, take capitals (except of course at the beginning of a sentence), although they may be pluralized; for example, 1 kelvin, 10 kelvins.

The *base units* are:

metre (symbol m)	the unit of length
kilogram (symbol kg)	the unit of mass
second (symbol s)	the unit of time
ampere (symbol A)	the unit of electrical current
kelvin (symbol K)	the unit of thermodynamic temperature, defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
candela (symbol cd)	the unit of luminous intensity
mole (symbol mol)	the unit of the amount of a substance which contains the same number of molecules as there are atoms in exactly 12 grams of pure carbon.

The two *supplementary units* are:

radian (symbol rad)	the measure of a plane angle
steradian (symbol sr)	the measure of a solid angle.

A few of the *derived units* are:

Quantity	*Name of unit*	*Symbol*	*Expressed in base units*
frequency	hertz	Hz	$1\ \mathrm{Hz} = 1\ \mathrm{s^{-1}}$
force	newton	N	$1\ \mathrm{N} = 1\ \mathrm{kg\ m\ s^{-2}}$
pressure	pascal	Pa	$1\ \mathrm{Pa} = 1\ \mathrm{N\ m^{-2}}$
work	joule	J	$1\ \mathrm{J} = 1\ \mathrm{N\ m}$
power	watt	W	$1\ \mathrm{W} = 1\ \mathrm{J\ s^{-1}}$

(1 newton = 10^5 dynes, 1 pascal = 10^{-2} millibars, 1 joule = 10^7 ergs.)

Multiplying prefixes

The multiples and sub-multiples of the units are not arbitrarily related to the units, as is usual in the British system,

e.g. 1 pound = 16 ounces = 7000 grains
1 yard = 3 feet = 36 inches,

but are formed by means of multiplying prefixes which are the same irrespective of the unit to which they are applied.

The names and values of the prefixes, and some examples of their use, are given below. Because the prefixes cover such an astronomical range it is not normally necessary to consider more than a selection of them applied to any one unit.

Prefix name	*Prefix symbol*	*Factor by which the unit is multiplied*	
tera	T	10^{12} =	1 000 000 000 000
giga	G	10^{9} =	1 000 000 000
mega	M	10^{6} =	1 000 000
kilo	k	10^{3} =	1000
hecto	h	10^{2} =	100
deca	da	10^{1} =	10
deci	d	10^{-1} =	0.1
centi	c	10^{-2} =	0.01
milli	m	10^{-3} =	0.001
micro	μ	10^{-6} =	0.000 001
nano	n	10^{-9} =	0.000 000 001
pico	p	10^{-12} =	0.000 000 000 001
femto	f	10^{-15} =	0.000 000 000 000 001
atto	a	10^{-18} =	0.000 000 000 000 000 001

Examples:
gigahertz (GHz), megawatt (MW), kilometre (km), centimetre (cm), milligram (mg), microsecond (μs), nanometre (nm), picofarad (pF).

NON-SI UNITS

The following non-SI units are in current use in the Meteorological Office and may be found in publications of the Office.

1. **Pressure**

The millibar is used as the unit of pressure in meteorology. Despite the recommended abbreviation mbar, the Meteorological Office will continue to use mb (1 mb = 1 hPa, where h = hecto = 10^2). The WMO preferred unit is the hPa, though it has yet to be promulgated.

2. **Temperature**

The unit degree Celsius (symbol °C) continues to be used.

Celsius temperature = temperature (in kelvins) minus 273.15 K (note that the sign ° is no longer used with K).

3. **Distance**

There is a continuing requirement for some distances to be measured in nautical miles (symbol n. mile).

Because the nautical mile varies with latitude, an internationally agreed International Nautical Mile is preferred. This has been in use in the United Kingdom since 1970. The International Nautical Mile is defined as 1852 m (6076.12 feet).

4. **Height**

Heights other than cloud heights are expressed in metres. Because of the requirements of aviation the heights of cloud will continue for the time being to be expressed in feet (1 foot = 0.3048 m).

5. **Speed**

The derived SI unit is the metre per second ($\mathrm{m\ s^{-1}}$). However, the World Meteorological Organization recommends the use of the knot for horizontal wind speed for the time being (1 knot = 1 nautical mile per hour $\approx 0.5\ \mathrm{m\ s^{-1}}$). The symbol kn for knot is recommended to avoid confusion with the symbol for kilotonne and will be used in Meteorological Office publications.

6. **Time**

Units other than SI, such as day, week, month and year, are in common use.

7. **Direction**

Direction is measured in degrees clockwise from north and refers to the true compass.

8. **Cloud amounts**

The use of 'okta' (one eighth of the area of the sky) for the measurement of cloud amount is authorized by the World Meteorological Organization.

APPENDIX 3

Terminology

In metrology (the field of knowledge concerned with measurement) confusion often arises in the usage of terms. These differences may range from subtle changes of meaning of common terms to the misuse of everyday terms, extracted from dictionaries, by ascribing to them specific meanings applicable only in certain areas of use.

Whilst by no means comprehensive, the following list represents terms occurring most frequently in this volume. For a more complete glossary of terms reference should be made to British Standards Institution publication BS 5233 from which these definitions are extracted.

Accuracy (of a measuring instrument). The quality which characterizes the ability of a measuring instrument to give indications equivalent to the true value of the quantity measured. The quantitative expression of this concept should be in terms of uncertainty.

Analogue (measuring) instrument. Measuring instrument in which the indication is a continuous function of the corresponding value of the quantity to be measured, e.g. mercury-in-glass thermometer.

Calibration. All the operations for the purpose of determining the values of the errors of a measuring instrument.

Conventional true value (of a quantity). A value approximating to the true value of a quantity such that, for the purpose for which that value is used, the difference between these two values can be neglected.

Correction. A value which must be added algebraically to the indicated value (uncorrected result) of a measurement to obtain the measured value (corrected result).

Detector. A device or substance which responds to the presence of a particular quantity without necessarily measuring the value of that quantity.

Digital (measuring) instrument. Measurement instrument in which the quantity to be measured is accepted as, or is converted into, coded discrete signals and provides an output and/or display in digital form.

Discrimination (of a measuring instrument). The property which characterizes the ability of a measuring instrument to respond to small changes of the quantity measured. *Note*. In some fields of measurement the term 'resolution' is used as synonymous with 'discrimination', but attention is drawn to 'sensitivity'.

Error (of indication, or of response) *of a measuring instrument*. The difference $v_i - v_c$ between the value indicated by (or the response of) the measuring instrument v_i and the conventional true value of the measured quantity v_c.

Hysteresis (of a measuring instrument). That property of a measuring instrument whereby it gives different indications, or responses, for the same value of the measured quantity, according to whether that value has been reached by a continuously increasing change or by a continuously decreasing change of that quantity.

Index. A fixed or movable part of the indicating device (e.g. recording pen, a pointer) whose position with reference to the scale marks enables the indicated value to be observed.

Indicating instrument. Measuring instrument which is intended to give, by means of a single unique observation, the value of a measured quantity at the time of that observation. An indicating instrument may have either continuous or discontinuous variation of indication.

Indication (or *response*) *of a measuring instrument*. The value of the quantity measured, as indicated or otherwise provided by a measuring instrument.

Maximum permissible error (of a measuring instrument). The extreme values of the error (positive or negative) permitted by specifications, regulations etc., for a measuring instrument.

Quantity (measurable). An attribute of a phenomenon or a body which may be distinguished qualitatively and determined quantitatively.

Range (of a measuring instrument). The interval between the lower and upper range-limits, e.g. a thermometer may have a range −40 °C to +60 °C.

Repeatability (of measurement). A quantitative expression of the closeness of successive measurements of the same value of the same quantity carried out by the same method, by the same observer, with the same measuring instruments, at the same location at appropriately short intervals of time.

Repeatability (of a measuring instrument). The quality which characterizes the ability of a measuring instrument to give identical indications, or responses, for repeated applications of the same value of the measured quantity under stated conditions of use.

Reproducibility (of measurement). The quantitative expression of the closeness of the agreement between the results of measurements of the same value of the same quantity, where the individual measurements are made under different defined conditions, e.g. by different methods, with different measuring instruments.

Resolution. See *Discrimination*.

Response. See *Indication*.

Response time (of a measuring instrument).* The time which elapses after a step change in the quantity measured, up to the point at which the measuring instrument gives an indication equal to the expected indication corresponding to the new value of the quantity, or not differing from this by more than a specified amount.

Scale. The array of indicating marks, together with any associated figuring, in relation to which the position of an index is observed. The term is frequently extended to include the surface which carries the marks or figuring.

Sensitivity (of a measuring instrument). (a) The relationship of the change of the response to the corresponding change of the stimulus (it is normally expressed as a quotient), or (b) the value of the stimulus required to produce a response exceeding, by a specified amount, the response already present due to other causes, e.g. noise.

Sensor. The part of a measuring instrument which responds directly to the measured quantity.

Span. The algebraic difference between the upper and lower values specified as limiting the range of operation of a measuring instrument, e.g. a thermometer intended to measure over the range −40 °C to +60 °C has a span of 100 °C.

Standard. A measuring instrument, or measuring apparatus, which defines, represents physically, conserves or reproduces the unit of measurement of a quantity (or a multiple or sub-multiple of that unit) in order to transmit it to other measuring instruments by comparison.

Primary standard. A standard of a particular quantity which has the highest class of metrological qualities in a given field.

Secondary standard. A standard the value of which is determined by direct or indirect comparison with a primary standard.

Reference standard. A standard, generally the best available at a location, from which the measurements made at the location are derived.

Working standard. A measurement standard, not specifically reserved as a reference standard, which is intended to verify measuring instruments of lower accuracy.

*For the purposes of this handbook, where a response time is quoted it refers to the time necessary for a measuring instrument to register 90 per cent of a step change in the quantity being measured. The time taken to register 63.2 per cent of a change is given the preferred title 'time-constant'.

Transfer standard. A measuring device used to compare measurement standards, or to compare a measuring instrument with a measurement standard by sequential comparison.

Travelling standard. A measuring device, sometimes of special construction, used for the comparison of values of a measured quantity at different locations.

Systematic error. An error which, in the course of a number of measurements of the same value of a given quantity, remains constant when measurements are made under the same conditions and remains constant or varies according to a definite law when the conditions change.

Transducer (measuring). A device which serves to transform, in accordance with an established relationship, the measured quantity (or a quantity already transformed therefrom) into another quantity or into another value of the same quantity, with a specified accuracy, and which may be used separately as a complete unit.

Uncertainty of measurement. That part of the expression of the result of a measurement which states the range of values within which the true value or, if appropriate, the conventional true value is estimated to lie.

INDEX

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