

## CHAPTER 2 — MEASUREMENT OF TEMPERATURE

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## MEASUREMENT OF TEMPERATURE

## 2.1 General

## 2.1.1 Definition

Temperature is the condition which determines the direction of the net flow of heat between two bodies. In such a system, that body which overall loses heat to the other is said to be at the higher temperature.

## 2.1.2 Units and scales

The thermodynamic temperature ( $T$ ), with units of kelvin ( $K$ ), is the basic temperature. The kelvin is the fraction  $1/273.16$  of the thermodynamic temperature of the triple point of water. The temperature ( $t$ ), in degrees Celsius defined by equation (2.1), is used for most meteorological purposes:

$$t = T - 273.16 \quad (2.1)$$

A temperature difference of one degree Celsius ( $^{\circ}\text{C}$ ) unit is equal to one kelvin ( $K$ ) unit.

In the thermodynamic scale of temperature, measurements are expressed as differences from absolute zero ( $0\text{ K}$ ), the temperature at which the molecules of any substance possess no kinetic energy. The scale of temperature in general use since 1990 is the International Temperature Scale (ITS)-90 (see the annex), which is based on assigned values for the temperatures of a number of reproducible equilibrium states (see Table 1 of the annex) and on specified standard instruments calibrated at those temperatures. The ITS was chosen in such a way that the temperature measured against it is identical with the thermodynamic temperature, any difference being within the present limits of measurement accuracy. In addition to the defined fixed points of the ITS, other secondary reference points are available; the points of meteorological interest and the standard method for interpolating between them are given in Table 2 of the annex. Temperature on the ITS should be designated "degrees Celsius".

## 2.1.3 Meteorological requirements

## 2.1.3.1 GENERAL

Meteorological requirements for temperature measurements primarily relate to:

- (a) The air near the Earth's surface;
- (b) The surface of the ground;
- (c) The soil at various depths;
- (d) The surface levels of the sea and lakes;
- (e) The upper air.

These measurements are required, either jointly or independently and locally or globally, for input to numerical weather prediction models, for hydrological and agricultural purposes, and as indicators of climatic variability. Local temperature also has direct

physiological significance for the day-to-day activities of the world's population. Measurements of temperature may be required as continuous records or may be sampled at different time intervals. This chapter deals with requirements (a), (b) and (c).

## 2.1.3.2 ACCURACY REQUIREMENTS

The range, reported resolution, and required accuracy for temperature measurements are detailed in Chapter 1, Part I. In practice, it may not be economical to provide thermometers which meet the required performance directly. Instead cheaper thermometers, calibrated against a laboratory standard, are used with corrections being applied as necessary to their readings. It is necessary to limit the size of the corrections to keep residual errors within bounds. Also, the operational range of the thermometer will be chosen to reflect the local climatic range. As an example, the table below gives an acceptable range of calibration and errors for thermometers covering a typical measurement range.

Thermometer characteristic requirements

Thermometer type	Ordinary	Maximum	Minimum
Span of scale ( $^{\circ}\text{C}$ )	-30 to 45	-30 to 50	-40 to 40
Range of calibration ( $^{\circ}\text{C}$ )	-30 to 40	-25 to 40	-30 to 30
Maximum error	<0.2 K	$\pm 0.2\text{ K}$	$\pm 0.3\text{ K}$
Maximum difference between maximum and minimum correction within the range	0.2 K	0.3 K	0.5 K
Maximum variation of correction within any interval of $10^{\circ}\text{C}$	0.1 K	0.1 K	0.1 K

All temperature measuring instruments should be issued with a certificate confirming compliance with the appropriate accuracy or performance specification, or a calibration certificate which gives the corrections that must be applied to meet the required accuracy. This initial testing and calibration should be performed by a national testing institution or an accredited calibration laboratory. Temperature-measuring instruments should also be checked subsequently at regular intervals, the exact apparatus used for this calibration being dependent on the instrument or sensor to be calibrated.

## 2.1.3.3 RESPONSE TIMES OF THERMOMETERS

For routine meteorological observations there is no advantage in using thermometers with a very small time constant, since the temperature of the air continually fluctuates up to a degree or two within a few seconds. Thus, to obtain a representative reading with such a thermometer would require taking the mean of a number of

readings, whereas a thermometer with a larger time constant tends to smooth out the rapid fluctuations. Too long a time constant, however, may result in errors when long-period changes of temperature occur. It is recommended that the time constant, defined as the time required by the thermometer to register 63.2 per cent of a step change in air temperature, should be between 30 and 60 seconds in a wind speed of  $5 \text{ m s}^{-1}$ . The time constant is roughly inversely proportional to the square root of the wind speed.

#### 2.1.3.4 RECORDING THE CIRCUMSTANCES IN WHICH MEASUREMENTS ARE MADE

Temperature is one of the meteorological quantities whose measurements are particularly sensitive to exposure. For climate studies in particular, temperature measurements are affected by the state of the surroundings, by vegetation, by the presence of buildings and other objects, by ground cover, by condition and changes in design of the radiation shield or screen, and by other changes in equipment. It is important that records should be kept not only of the temperature data, but also of the circumstances in which the measurements are made. Such information is known as metadata — data about data.

#### 2.1.4 *Methods of measurement*

In order to measure the temperature of an object, a thermometer can be brought to the same temperature as the object (i.e. into thermodynamic equilibrium with it) and then the temperature of the thermometer itself can be measured. Alternatively, the temperature can be determined by a radiometer without need for thermal equilibrium.

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. Radiometric thermometers operate in the infrared part of the electromagnetic spectrum and are used, amongst other applications, for temperature measurements from satellites.

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

There are various standard texts on instrument design and laboratory practice for the measurement of temperature, such as Jones (1992).

##### 2.1.4.1 THERMOMETER EXPOSURE AND SITING

Radiation from the Sun, clouds, the ground and other surrounding objects passes through the air without appreciably changing its temperature, but a thermometer exposed freely in the open can absorb considerable radiation. As a consequence, its temperature may differ from the true air temperature, the difference depending on the

radiation intensity and on the ratio of absorbed radiation to dissipated heat. For 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 operational thermometers the temperature difference may reach 25 K under extremely unfavourable conditions. Therefore, in order to ensure that the thermometer is at true air temperature it is necessary to protect the thermometer from radiation by a screen or shield which also serves to support the thermometer. This screen also shelters it from precipitation while allowing the free circulation of air around it, and prevents accidental damage. Maintaining a free circulation may, however, be difficult to achieve under conditions of rime ice accretion. Practices for reducing observation errors under such conditions will vary and may involve the use of special designs of screens or temperature-measuring instruments.

In order to achieve representative results when comparing thermometer readings at different places and at different times, a standardized exposure of the screen and, hence, of the thermometer itself is also indispensable. For general meteorological work, the observed temperature should be representative of the free air conditions surrounding the station over as large an area as possible, at a height of between 1.25 and 2 m above ground level. The height above ground level is specified because large vertical temperature gradients may exist in the lowest layers of the atmosphere. The best site for the measurements is, therefore, over level ground, freely exposed to sunshine and wind and not shielded by, or close to, trees, buildings and other obstructions. 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 are expected to be more marked than in rural districts. Observations of temperature on the top of buildings are of doubtful significance and use because of the variable vertical temperature gradient and the effect of the building itself on the temperature distribution.

##### 2.1.4.2 TEMPERATURE STANDARDS

###### *LABORATORY STANDARDS*

Primary standard thermometers will be held and maintained at national standards laboratories. A national meteorological or other accredited calibration laboratory will have, as a working standard, a high-grade platinum resistance thermometer, traceable to the national standard. The accuracy of this thermometer may be 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  $1 \cdot 10^{-4} \text{ K}$ .

###### *FIELD STANDARDS*

The WMO reference psychrometer (WMO, 1992) is the reference instrument for determining the relationship between the air temperature measured by conventional surface instruments and the true air temperature. This

instrument has been designed to be used as a free standing instrument and not for deployment within a screen or shelter; it is the most accurate instrument available for evaluating and comparing instrument systems. It is not intended for continuous use in routine meteorological operations. It is capable of providing a temperature measurement with an uncertainty of  $\pm 0.04$  K (at the 95 per cent confidence level). See Chapter 4, Part I for further information.

## 2.2 Liquid-in-glass thermometers

### 2.2.1 General description

For routine observations of air temperature, including maximum, minimum and wet-bulb temperatures, liquid-in-glass thermometers are still commonly used. Such thermometers make use of the differential expansion of a pure liquid with respect to its glass container to indicate the temperature. The stem is a tube having a fine bore attached to the main bulb; 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 to be measured. The changes in volume of the liquid with respect to its container are indicated by changes in the liquid column; by calibration with respect to a standard thermometer, a scale of temperature can be marked on the stem, or on a separate scale tightly attached to the stem.

The liquid used depends on the required temperature range; mercury is generally used for temperatures above its freezing point ( $-38.3^{\circ}\text{C}$ ), while ethyl alcohol or other pure organic liquids are used for lower temperatures. The glass should be one of the normal or borosilicate glasses approved for use in 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. A narrower bore provides greater movement of liquid in the stem for a given temperature change, but reduces the useful temperature range of the thermometer for a given stem length. The thermometer should be suitably annealed before it is graduated in order to minimize the slow changes that occur in the glass with ageing.

There are four main types of construction for meteorological thermometers. These are:

- (a) The sheathed type with the scale engraved on the thermometer stem;
- (b) The sheathed type with the scale engraved on an opal glass strip attached to the thermometer tube inside the sheath;
- (c) The unsheathed type with the graduation marks on the stem and mounted on a metal, porcelain or wooden back carrying the scale numbers;
- (d) The unsheathed type with the scale engraved on the stem.

The stems of some thermometers are lens-fronted to provide a magnified image of the mercury thread. The best known example is the clinical thermometer designed for medical purposes, but lens-fronted thermometers are not widely used in meteorology.

Types (a) and (b) have the advantage over types (c) and (d) that their scale markings are protected from wear. For types (c) and (d), the markings may have to be reblacked from time to time; on the other hand, such thermometers are easier to make than types (a) and (b). Types (a) and (d) have the advantage of being less susceptible to parallax errors (see section 2.2.4).

Whichever type is adopted, the sheath or mounting should not be unduly bulky as it would keep the heat capacity low. At the same time, the sheath or mounting should be sufficiently robust to withstand the normal risks of handling and transit.

For mercury-in-glass thermometers, especially maximum thermometers, it is important that the vacuum above the mercury column be nearly perfect. All the thermometers should be graduated for total immersion with the exception of thermometers for soil temperature. Special requirements of thermometers for various purposes are dealt with hereafter under the appropriate headings.

#### 2.2.1.1 ORDINARY (STATION) THERMOMETERS

This is the most accurate instrument of all the meteorological thermometers. Usually it is a mercury-in-glass type. Its scale markings have a distance of 0.2 K or 0.5 K, and the scale is longer than that of the other meteorological thermometers.

The ordinary thermometer is used in a thermometer screen to avoid radiation errors. A support keeps it in vertical position with the bulb at the lower end. The form of the bulb is that of a cylinder or of an onion.

A pair of ordinary thermometers can be used as a psychrometer.

#### 2.2.1.2 MAXIMUM THERMOMETERS

The recommended type is a mercury-in-glass thermometer with a constriction in the bore between the bulb and the beginning of the scale. This constriction prevents the mercury column from receding with falling temperature. However, the thermometer can be reset intentionally by the observer by holding it firmly, bulb-end downwards, and swinging his arm until the mercury column is reunited. The maximum thermometer should be mounted at an angle of about two degrees from the horizontal with the bulb at the lower end to ensure that the mercury column rests against the constriction without gravity forcing it to pass. It is desirable to have a widening of the bore at the top of the stem to enable parts of the column which have become separated to be easily united.

#### 2.2.1.3 MINIMUM THERMOMETERS

The most common instrument is a spirit thermometer with a dark glass index, about 2 cm long, immersed in the spirit. Since some air is left in the tube of a spirit thermometer, a safety chamber should be provided at the upper end and it should be large enough to allow the instrument to withstand a temperature of  $50^{\circ}\text{C}$  without

damage. Minimum thermometers should be supported in a similar manner to maximum thermometers, in a near-horizontal position.

Various liquids can be used in minimum thermometers, such as ethyl alcohol, pentane and toluol. It is important that the liquid should be as pure as possible since the presence of certain impurities increases the tendency of the liquid to polymerize with exposure to light and after the passage of time; such polymerization causes a change in the calibration. In the case of ethyl alcohol, for example, the alcohol should be completely free of acetone.

Minimum thermometers are also exposed to obtain grass minimum temperature.

#### 2.2.1.4 SOIL THERMOMETERS

For measuring soil temperatures at depths of 20 cm or less, mercury-in-glass thermometers, with their stems bent at right angles, or any other suitable angle, below the lowest graduation, are in common use. The thermometer bulb is sunk into the ground to the required depth, and the scale is read with the thermometer *in situ*. These thermometers are graduated for immersion up to the measuring depth. Since the remainder of the thermometer is kept at air temperature, a safety chamber should be provided at the end of the stem.

For measuring temperature at depths of over 20 cm, mercury-in-glass thermometers, mounted on wooden, glass or plastic tubes with their bulbs embedded in wax or metallic paint, are recommended. The thermometer-tube assemblies are then suspended or slipped in thin-walled metal or plastic tubes sunk into the ground to the required depth. In cold climates, the tops of the outer tubes should extend above the ground to a height greater than the expected depth of snow cover.

The technique of using vertical steel tubes is unsuitable for the measurement of the diurnal variation of soil temperature, particularly in dry soil, and calculations of soil thermal properties based on such measurements could be significantly in error.

The large time constant due to the increased heat capacity enables the thermometers to be removed from the outer tubes and read before their temperature has had time to change appreciably from the soil temperature.

When the ground is covered by snow, and in order that the observer may approach the line of thermometers without disturbing the snow cover, it is recommended that a lightweight bridge be constructed parallel to the line of thermometers. The bridge should be designed so that the deck can be removed between readings without affecting the snow cover.

#### 2.2.2 Procedures for measurements

##### 2.2.2.1 READING ORDINARY THERMOMETERS

Thermometers should be read as rapidly as possible in order to avoid changes of temperature due to the presence of the observer. Since the liquid meniscus, or index,

and the thermometer scale are not in the same plane, care must be taken to avoid errors of parallax. These will occur unless the observer ensures that the straight line from his eye to the meniscus, or index, is at a right angle to the thermometer stem. Since thermometer scales are not normally subdivided to less than one-fifth of a whole degree, readings to the nearest tenth of a degree, which are essential in psychometry, must be made by estimation. Corrections for scale errors, if any, should be applied to the readings. Maximum and minimum thermometers should be read and set at least twice daily. Their readings should be compared frequently with those of an ordinary thermometer in order to ensure that no serious errors develop.

##### 2.2.2.2 MEASURING GRASS MINIMUM

The grass minimum temperature is the lowest temperature reached overnight by a thermometer freely exposed to the sky just above short grass. The temperature is measured with a minimum thermometer such as that described in section 2.2.1.3. The thermometer should be mounted on suitable supports so that it is inclined at an angle of about 2° from the horizontal with the bulb lower than the stem, 25 to 50 mm above the ground and in contact with the tips of the grass. When the ground is snow-covered, the thermometer should be supported immediately above the surface of the snow, as near to it as possible without actually touching it.

Normally, the thermometer is exposed at the last observation hour before sunset and the reading is taken next morning. The instrument is kept within a screen or indoors during the day. However, at stations where an observer is not available near sunset it may be necessary to leave the thermometer exposed throughout the day. In strong sunshine, such exposure of the thermometer can cause the spirit to distil and collect in the top of the bore. This effect can be minimized by fitting a cotton sock on a black metal shield over the safety chamber end of the thermometer; this shield absorbs more radiation and consequently reaches a higher temperature than the rest of the thermometer. Thus, any vapour will condense lower down the bore at the top of the spirit column.

##### 2.2.2.3 MEASURING SOIL TEMPERATURES

The standard depths for soil temperature measurements are 5, 10, 20, 50 and 100 cm below the surface; additional depths may be included. The site for such measurements should be a level plot of bare ground, about 75 cm<sup>2</sup>, are typical of the surrounding soil for which information is required. If the surface is not representative of the general surroundings, its extent should not be less than 100 m<sup>2</sup>. When the ground is covered with snow, it is desirable to measure the temperature of the snow cover as well. Where snow is rare, the snow may be removed before taking the readings and then replaced.

When describing a site for soil temperature measurements, the soil type, soil cover and the degree and direction of slope of the ground should be recorded. Whenever possible, the physical soil constants, such as bulk density, thermal conductivity and the moisture content at field capacity, should be indicated. The level of the water table (if within five metres of the surface) and the soil structure should also be included.

At agricultural meteorological stations, the continuous recording of soil temperatures and air temperatures at different levels in the layer adjacent to the soil (from ground level up to about 10 metres above the upper limit of prevailing vegetation) is desirable.

### 2.2.3 *Thermometer siting and exposure*

Both the ordinary thermometer as well as the maximum and minimum thermometers are always exposed in a thermometer screen placed on a support. The extreme thermometers are mounted on suitable supports so that they are inclined at an angle of about  $2^\circ$  from the horizontal, with the bulb being lower than the stem.

Siting and exposure of the grass minimum thermometer is as prescribed in section 2.2.2.2. At a station where snow is persistent and of varying depth it is possible to use a support which allows the thermometers to be raised or lowered to maintain the correct height above the snow surface.

### 2.2.4 *Sources of error in 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 and gross reading errors;
- (d) Changes in the volume of the bulb produced by exterior or interior pressure;
- (e) Capillarity;
- (f) Errors in scale division and calibration;
- (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.

#### 2.2.4.1 **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 quality of glass employed in the thermometer, and may be as much as 1 K — with the

best glass it should be only 0.03 K — and would be proportionately 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. Even with the best glass, the change may be about 0.01 K a year at first. For accurate work, and especially with inspectors' or check thermometers, the zero should be redetermined periodically and the necessary corrections applied.

#### 2.2.4.2 **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 is calibrated by immersing the thermometer either completely or only 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.

For meteorological applications, the most likely circumstance where this might be encountered is when checking the calibration of an ordinary thermometer in a vessel containing another liquid at a temperature significantly different from ambient and only the bulb or lower part of the stem is immersed.

#### 2.2.4.3 **PARALLAX AND GROSS READING ERRORS**

If the thermometer is not viewed in the plane which is perpendicular to the stem of the thermometer and passes through the top of the liquid column, parallax errors will arise. The error increases with the thickness of the stem of the thermometer and the angle between the actual and the correct line of sight. This error can be avoided only by taking great care when making an observation. With mercury-in-glass thermometers suspended vertically, as in an ordinary screen, the thermometer must be viewed at the horizontal level of the top of the mercury column.

Errors can also occur because the approach of the observer to read the thermometer usually disturbs the surroundings in some way. It is, therefore, necessary for the observer to make the readings to the nearest tenth of a degree as soon as possible. Gross reading errors are usually 1, 5 or  $10^\circ$  in magnitude. Such errors will be avoided if the observer rechecks the tens and units figure after making his initial reading.

#### 2.2.4.4 **ERRORS DUE TO DIFFERENTIAL EXPANSION**

The coefficient of cubical expansion of mercury is  $1.82 \cdot 10^{-4} \text{ K}^{-1}$ , and that of most glasses lies between

$1.0 \cdot 10^{-5}$  and  $3.0 \cdot 10^{-5} \text{ K}^{-1}$ . The expansion coefficient of the glass is, thus, an important fraction of that of mercury and cannot be neglected. 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 the stem being used, the scale value of unit length of the stem varies along the stem, and the thermometer has to be calibrated by the manufacturer against a standard thermometer before it can be used.

#### 2.2.4.5 ERRORS ASSOCIATED WITH SPIRIT THERMOMETERS

The expansion coefficients of the liquids used in spirit thermometers are very much larger than those of mercury and their freezing points are much lower (ethyl alcohol freezes at  $-115^\circ\text{C}$ ). Spirit is 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 disadvantages of liquid-in-glass thermometers, liquid thermometers, with the exception of mercury thermometers, have some peculiarities to themselves:

- (a) Adhesion of the spirit to the glass. Unlike mercury, 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;
- (b) 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 beginning 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;
- (c) Slow changes in the liquid. The organic liquids used tend to polymerize with age and exposure to light, with a consequent gradual diminution in liquid volume. 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 if dyes are used to colour the liquid to make it more visible.

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 chapter.

#### 2.2.5 Comparison and calibration in the field and laboratory

##### 2.2.5.1 LABORATORY CALIBRATION

Laboratory calibrations of thermometers should be carried out by national testing institutions or accredited calibration laboratories. For liquid-in-glass thermometers, a liquid bath should be employed, within which it should be possible to maintain the temperature at any desired values within the required range. The rate of temperature change within the liquid should not exceed the recommended limits and the calibration apparatus should be provided with a means of stirring the liquid. The reference thermometers and thermometers under test should be suspended independently of the container and should not touch the sides.

Sufficient measurements should be made to ensure that the corrections to be applied represent the performance of the thermometer under normal conditions with errors due to interpolation at any intermediate point not exceeding the non-systematic errors.

##### 2.2.5.2 FIELD CHECKS AND CALIBRATION

All liquid-in-glass thermometers experience gradual changes of zero. For this reason, it is desirable to check them at regular intervals, usually about once every two years. They should be stored in an erect position at room temperature for least 24 hours before starting the checking process.

The ice point may be checked by nearly filling a Dewar flask with crushed ice made from distilled water and by moistening it with more distilled water. The space between the ice pieces as well as the bottom of the vessel should be free from air. The water should remain 2 cm beneath the ice surface. An ordinary Thermos flask will accommodate the total immersion of most thermometers up to their ice point. The thermometers should be inserted so that the least possible part of the mercury or spirit column emerges from the ice. An interval of at least 15 minutes should lapse to allow the thermometer to take up the temperature of the melting ice before a reading of the indicated temperature is made. Each thermometer should be moved backwards and forwards through the mixture and immediately read to a tenth part of the scale interval. Further readings at five-minute intervals should be taken and a mean value computed.

Other points in the range can be covered by reference to a travelling standard or inspector's thermometer. Comparison should be made by immersing the reference thermometer and the thermometer, or thermometers to be tested, in a deep vessel of water. It is generally best to work indoors, especially if the Sun is shining, and best results will be obtained if the water temperature is at, or close to, ambient.

Each thermometer is compared with the reference thermometer; thermometers of the same type can be compared with each other. For each comparison, the

thermometers are held with their bulbs close together, are moved backwards and forwards through the water for about one 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 thermometers are calibrated for total immersion; provided the difference between the water and air temperature is not more than 5 K, the emergent stem correction should be negligible. Often, with the bulbs at the same depth, the tops of the column of mercury (or other liquid) in the reference thermometer and the thermometer under check 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 specified in the table in section 2.1.3.2.

Soil thermometers may be tested in this manner except that they 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 does not change by more than 1 K in 30 minutes, then the difference from the corrected reading of the reference thermometer should not exceed 0.25 K.

### 2.2.6 *Corrections*

When initially issued, thermometers should be provided with either a dated certificate confirming compliance with the accuracy requirement, or a dated calibration certificate giving the corrections which should be applied to the readings to achieve the required accuracy.

In general, if the errors at selected points in the range of a thermometer (e.g. 0°C, 10°C, 20°C) are all within  $\pm 0.05$  K, no corrections will be necessary and the thermometers can be used directly as ordinary thermometers in naturally ventilated screens and as maximum, minimum, soil or grass minimum thermometers. If the errors at these selected points are greater than 0.05 K, then a table of corrections should be available to the observer at the place of reading, together with unambiguous instructions on how these corrections should be applied.

Thermometers for which certificates would normally be issued are those:

- (a) For use in ventilated psychrometers;
- (b) For use by inspectors as travelling standards;
- (c) For special purposes for which application of corrections is justified.

For psychrometric use, identical thermometers should be selected.

### 2.2.7 *Maintenance*

#### 2.2.7.1 *BREAKAGE IN THE LIQUID COLUMN*

The most common fault encountered is the breaking of the liquid column, especially during transit. This is most likely to occur in spirit (minimum) thermometers. Other problems associated with these thermometers are adhesion of the spirit to the glass and the formation by distillation of drops of spirit in the support part of the bore.

A broken liquid column can usually be reunited by holding the thermometer bulb-end downward and tapping the thermometer lightly and rapidly against the fingers or something else which is elastic and not too hard. The tapping should be continued for some time (five minutes if necessary), and afterwards the thermometer should be hung, or stood upright in a suitable container, bulb downward, for at least one hour to allow any spirit adhering to the glass to drain down to the main column. If such treatment is not successful, then 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, while the stem is tapped or shaken 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 of bursting the thermometer if the spirit expands into the safety chamber.

#### 2.2.7.2 *SCALE ILLEGIBILITY*

Another shortcoming of unshathed liquid-in-glass thermometers is that with time their scale can become illegible. This can be corrected at the station by rubbing with a dark crayon or black lead pencil.

### 2.2.8 *Safety*

Mercury, which is the liquid most commonly in use in liquid-in-glass thermometers, is poisonous if swallowed or if the vapour is inhaled. If a thermometer is broken and the droplets of mercury are not removed there is some danger to health, especially in confined spaces. (Advice on cleaning up is given in Chapter 3, Part I in the section on mercury barometers.) There may also be restrictions on the carriage of mercury thermometers on aircraft, or special precautions which must be taken to prevent the escape of mercury in the event of a breakage. The advice of the appropriate authority or carrier should be sought.

## 2.3 *Mechanical thermographs*

### 2.3.1 *General description*

The types still commonly used are supplied with bi-metallic or Bourdon-tube sensors since these are relatively inexpensive, reliable and portable. However, they are not readily adapted for remote or electronic recording. Such thermographs incorporate a rotating

chart mechanism common to the family of classical recording instruments. In general, thermographs should be capable of operating over a range of about 60 K or even 80 K if they are to be used in continental climates. A scale value is needed such that the temperature can be read to 0.2 K without difficulty on a chart of reasonable size. To achieve this, provision should be made for altering the zero setting of the instrument according to the season. The maximum error of a thermograph should not exceed 1 K.

#### 2.3.1.1 BIMETALLIC THERMOGRAPH

In bimetallic thermographs, the movement of the recording pen is controlled by the change in curvature of a bimetallic strip or helix, one end of which is rigidly fixed to an arm attached to the frame. A means of fine adjustment of this arm should be provided so that the zero of the instrument can be altered when necessary. In addition, the instrument should be provided with a means of altering the scale value by adjusting the length of the lever which transfers the movement of the bimetal to the pen; this adjustment is best left to authorized personnel. The bimetallic element should be adequately protected from corrosion; this is best done by heavy copper, nickel or chromium plating, although a coat of lacquer may be adequate in some climates. A typical time constant of about 25 seconds is obtained at an air speed of 5 m s<sup>-1</sup>.

#### 2.3.1.2 BOURDON-TUBE THERMOGRAPH

The general arrangement is similar to that of the bimetallic type but its temperature-sensitive element is in the form of a curved metal tube of flat, elliptical section, filled with alcohol. The Bourdon tube is less sensitive than the bimetallic element and usually requires a multiplying level mechanism to give sufficient scale value. A typical time constant is about 60 seconds at an air speed of 5 m s<sup>-1</sup>.

#### 2.3.2 Procedures for measurements

In order to improve the resolution of the reading, thermographs will often be set, in different seasons, to one of two different ranges with corresponding charts. The exact date for changing from one set of charts to the other will vary according to the locality, but when the change is made the instrument will need to be adjusted. This should be done either in the screen on a cloudy, windy day at a time when the temperature is practically constant or in a room where the temperature is constant. The adjustment is made by loosening the screw holding the pen arm to the pen spindle and by moving the pen arm to the correct position and retightening the screws. The instrument should then be left as is before rechecking and any further adjustments made as necessary.

#### 2.3.3 Exposure and siting

These instruments should be exposed in a large thermometer screen.

#### 2.3.4 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 the chart can be kept to a minimum by suitably adjusting the gate suspension.

#### 2.3.5 Comparison and calibration

##### 2.3.5.1 LABORATORY CALIBRATION

There are two basic methods of laboratory calibration of bimetallic thermographs. These may be checked by fixing them in a position with the bimetallic element in a bath of water. Alternatively, the thermograph may be placed in a commercial calibration chamber equipped with an air temperature control mechanism, a fan, and a reference thermometer.

Comparisons should be made at two temperatures; from these, any necessary changes in the zero and magnification can be found. Scale adjustments should be performed by authorized personnel, and only after reference to the appropriate manufacturer's instrument handbook.

##### 2.3.5.2 FIELD COMPARISON

The time-constant of the instrument may be as low as 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, in general, not 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.

#### 2.3.6 Corrections

Thermographs would not normally be issued with correction certificates. If station checks show the instrument to have excessive errors and if these cannot be adjusted locally, then the instrument should be returned to an appropriate calibration laboratory for repair and recalibration.

#### 2.3.7 Maintenance

Routine maintenance will involve an inspection of the general external condition, the play in the bearings, the inclination of the recording arm, the set of the pen, and the angle between the magnification arm and recording arm. Such examinations should be performed in accordance with the recommendations of the manufacturer. In

general, the helix should be handled carefully to avoid mechanical damage and should be kept clean. The bearings of the spindle should also 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.

## 2.4 Electrical thermometers

### 2.4.1 General description

Electrical instruments are now in widespread use for measuring temperatures in meteorology. Their main virtue lies in their ability to provide an output signal suitable for use in remote indication, recording, storage, or transmission of temperature data. The most frequently used sensors are electrical resistance elements, semiconductor thermometers (thermistors) and thermocouples.

#### 2.4.1.1 ELECTRICAL RESISTANCE THERMOMETERS

A measurement of the electrical resistance of a material whose resistance varies in a known manner with the temperature of the material can be used to represent the temperature.

For small temperature changes, the increase in resistance of pure metals is proportional to the change in temperature, as expressed in equation 2.2:

$$R_T = R_0 [1 + \alpha (T - T_0)] \quad (2.2)$$

where  $(T - T_0)$  is small,  $R_T$  is the resistance of a fixed amount of the metal at temperature  $T$  in kelvins,  $R_0$  is its resistance at a reference temperature  $T_0$ , and  $\alpha$  is the temperature coefficient of resistance in the vicinity of  $T_0$ .

With  $0^\circ\text{C}$  as the reference temperature, equation 2.2 becomes:

$$R_T = R_0 (1 + \alpha \cdot t) \quad (2.3)$$

For larger temperature changes and for certain metallic alloys, equation 2.4 expresses the relationship more accurately:

$$R_T = R_0 [1 + \alpha (T - T_0) + \beta (T - T_0)^2] \quad (2.4)$$

With  $0^\circ\text{C}$  as the reference temperature, equation 2.4 becomes:

$$R_T = R_0 (1 + \alpha \cdot t + \beta \cdot t^2) \quad (2.5)$$

These equations give the proportional change in resistance of an actual thermometer, so that values for the coefficients  $\alpha$  and  $\beta$  can be found by calibration of the thermometer concerned.

A good metal resistance thermometer will satisfy the following requirements:

- Its physical and chemical properties will remain the same through the temperature measurement range;
- Its resistance will increase steadily with increasing temperature without any discontinuities in the range of measurement;
- External influences such as humidity, corrosion, or physical deformations will not alter its resistance appreciably;

- Its characteristics will remain stable over a period of two years or more;
- Its resistance and thermal coefficient should be large enough to be useful in a measuring circuit.

Pure platinum best satisfies the foregoing requirements. Thus, it is used for the primary standard thermometers needed for transferring the ITS-90 between instrument locations. Copper is a suitable material for use in secondary standards.

Practical thermometers are artificially aged before use and are commonly made from platinum alloys, nickel, or copper (and occasionally tungsten) for meteorological purposes. Usually they are hermetically sealed with either glass or ceramic. Nevertheless, their time constant is smaller than that of the liquid-in-glass thermometers.

#### 2.4.1.2 SEMICONDUCTOR THERMOMETERS

Another type of resistance element in common use is the thermistor. This is a semiconductor with a relatively large temperature coefficient of resistance, which may be either positive or negative depending upon the actual material. Mixtures of sintered metallic oxides are suitable for making practical thermistors, which usually take the form of small discs, rods, or spheres and are often glass-coated. The general expression for the temperature dependence of the resistance,  $R$ , of the thermistor is given in equation 2.6:

$$R = a \exp (b/T) \quad (2.6)$$

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

The advantages of thermistors from a thermometric point of view are:

- The large temperature coefficient of resistance enables the voltage applied across a resistance bridge to be reduced while attaining the same sensitivity, thus reducing or even eliminating the need to account for the resistance of the leads and its changes;
- The elements can be made very small, so their very low thermal capacities can yield a small time constant. However, very small thermistors with their low thermal capacity have the disadvantage that, for a given dissipation, the self-heating effect is greater than for large thermometers. Thus, care must be taken to keep the power dissipation small.

A typical thermistor has a resistance which varies by a factor of 100 or 200 over the temperature range  $-40$  to  $40^\circ\text{C}$ .

#### 2.4.1.3 THERMOCOUPLES

In 1821, Seebeck discovered that a very small contact electromotive force was set up at the place where two different metals touched. If a simple circuit is made with two metals and with the conjunction 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; a current will then flow. 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 depend on the types of metal joined and the temperature of the junction point, and may be empirically represented for any two metals by the expression:

$$(E_T - E_s) = \alpha(T - T_s) + \beta(T - T_s)^2 \quad (2.7)$$

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

$$E_n = E_1 - E_2 \quad (2.8)$$

$$E_n = a(T_1 - T_2) + b(T_1 - T_2)^2 \quad (2.9)$$

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  $a$ .

Thermocouples are made by welding or soldering together wires of the metals concerned. These junctions can be made very small and with negligible heat capacity.

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.

For meteorology, thermocouples are mostly used when a thermometer of very small time constant, of the order of one or two seconds, and capable of remote reading and recording is required, usually for special research tasks. A disadvantage, if the absolute temperature is required, is the necessity for a constant-temperature enclosure for both the cold junction and ancillary apparatus for the measurements of the electromotive force that have been set up; thermocouples are best suited for the measurement of differential temperatures, since this complication does not arise. Very high precision can be achieved with suitably sensitive apparatus, but frequent calibration is necessary. Copper-constantan or iron-constantan combinations are

suitable 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.

#### 2.4.2 Procedures for measurements

##### 2.4.2.1 ELECTRICAL RESISTANCES AND THERMISTORS

Electrical resistance and thermistor thermometers may be connected to a variety of electrical measurement circuits, many of which are variations of resistance bridge circuits in either balanced or unbalanced form. In a balanced bridge, a precision potentiometer is adjusted until no current flows in an indicator, the position of the potentiometer arm being related to the temperature. In an unbalanced bridge, the out-of-balance current may be measured by a galvanometer; however, this current is not simply a function of the temperature and depends in part on other effects. An alternative which avoids this situation is to use a constant current source to power the bridge and to measure the out-of-balance voltage to obtain the temperature reading.

In the case of remote measuring, it should be taken into consideration that the wire between the resistance thermometer and the bridge also forms a resistance which alters depending on the temperature. Suitable precautions can be taken to avoid such errors.

Digital voltmeters can be used in conjunction with a constant current source to measure the temperature-dependent voltage drop across the thermometer element; the output can be scaled directly in temperature. Also, the digital output can be stored or transmitted without loss of accuracy and, thus, be available for further use. The digital output of the digital voltmeters can be subsequently converted back to an analogue voltage, if desired, to feed a recorder, for example.

##### 2.4.2.2 THERMOCOUPLES

There are two main methods of measuring the electromotive force produced by thermocouples:

- (a) By measuring the current produced in the circuit with a sensitive galvanometer; and
- (b) By balancing the thermoelectric electromotive force with a known electromotive force, so that no current actually flows through the thermocouples themselves.

In method (a), the galvanometer is connected directly in series with the two junctions. Method (b) will generally be used if a measuring accuracy of better than 0.5 per cent is required. This procedure does not depend on the magnitude of, or changes in, the line resistance since no current flows in the balanced condition.

##### 2.4.3 Exposure and siting

The requirements relating to exposure and siting of electrical thermometers will, in general, be the same as for liquid-in-glass thermometers (see section 2.2.3). Exceptions include:

- (a) The measurement of extreme values. Separate maximum and minimum thermometers may no longer be required if the electrical thermometer is connected to a continuously operating data recording system;
- (b) The measurement of surface temperatures. The radiative properties of electrical thermometers will be different from liquid-in-glass thermometers. Electrical thermometers exposed as grass minimum (or other surface) thermometers will, therefore, record different values from similarly exposed conventional thermometers. These differences may be minimized by placing the electrical thermometer within a glass sheath;
- (c) The measurement of soil temperatures. The use of mercury-in-glass thermometers in vertical steel tubes is quite unsuitable for the measurement of the diurnal variation of soil temperature. It is possible to obtain readings which are much more representative by deploying electrical thermometers in brass plugs, inserted at the required depth into an undisturbed vertical soil face, the latter having been exposed by trenching. Electrical connections are brought out through plastic tubes via the trench, which is then refilled in such a way to restore, as far as possible, the original strata and drainage characteristics.

#### 2.4.4 Sources of error

##### 2.4.4.1 ELECTRICAL RESISTANCES AND THERMISTORS

The main sources of error in a temperature measurement made with electrical resistance thermometers are:

- (a) Self-heating of the thermometer element;
- (b) Inadequate compensation for lead resistance;
- (c) Inadequate compensation for non-linearities in the sensor or processing instrument;
- (d) Sudden changes in switch contact resistances.

Self-heating occurs because the passage of a current through the resistance element produces heat and, thus, the temperature of the thermometer element becomes higher than that of the surrounding medium.

The resistance of the connecting leads will introduce an error in the temperature reading. This will become more significant for long leads, e.g. when the resistance thermometer is located at some distance from the measuring instrument; the reading errors will also vary as the temperature of the cables changes. These errors can be compensated for by the use of extra conductors, ballast resistors, and an appropriate bridge network.

Neither the electrical resistance thermometer nor the thermistor is linear over an extended temperature range but may approximate a linear output if the range is limited. Provision must, therefore, be made to compensate for such non-linearities. This is most likely to be required for thermistors, to achieve a usable meteorological range of measurement.

Sudden changes in switch contact resistance can occur as switches age. They may be variable and can go undetected unless regular system calibration checks are performed (see section 2.4.5).

##### 2.4.4.2 THERMOCOUPLES

The main sources of error in the measurement of temperature using thermocouples are:

- (a) Changes in the resistances of the connecting leads with temperature. This effect may be minimized by keeping all the leads as short and as 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) Stray secondary thermal electromotive forces due to the use of metals which are different from the thermocouple metals in the connecting circuit. The temperature differences in the remainder of the circuit must, therefore, be kept as low as possible; this is especially important when the electromotive forces to be measured are small (periodical recalibration will be necessary to allow for this);
- (d) Leakage currents can occur from neighbouring power circuits. This can be minimized by suitable screening of the leads;
- (e) Galvanic currents can be set up if any leads or junctions are allowed to get wet;
- (f) 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 direct-reading instruments. This effect can be minimized by keeping the temperature of the galvanometer as near as possible to that at which the circuit was calibrated;
- (g) 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 errors will normally be small, provided the standard cell is treated correctly, and adjustments of the potentiometer current are made just before taking a temperature measurement.

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

#### 2.4.5 Comparison and calibration

##### 2.4.5.1 ELECTRICAL RESISTANCES AND THERMISTORS

The basic techniques and procedures for laboratory calibration and field checking of electrical thermometers will be the same as for liquid-in-glass thermometers (see section 2.2.5). In general, however, it will not be possible to bring the resistance thermometer indoors

since checks should include the thermometer's normal electrical leads. Checks will, therefore, have to be carried out with the thermometers in the screen. Accurate comparative measurements of the temperatures indicated by the electrical thermometer and a reference mercury-in-glass or local indicating resistance thermometer will be difficult to achieve unless two observers are present. Since the measurement instrument is an integral part of the electrical thermometer, its calibration may be checked by substituting the resistance thermometer by a pre-precision decade resistance box and by applying resistances equivalent to fixed 5 K temperature increments over the operational temperature range. The error at any point should not exceed 0.1 K. This work would normally be performed by a servicing technician.

#### 2.4.5.2 THERMOCOUPLES

The calibration and checking of thermocouples require the hot and cold functions to be maintained at accurately known temperatures. The techniques and instrumentation necessary to undertake this work are generally very specialized and will not be described here.

#### 2.4.6 Corrections

When initially issued, electrical thermometers should be provided with:

- (a) A dated certificate confirming compliance with the appropriate standard; or
- (b) A dated calibration certificate giving the actual resistance at fixed points in the temperature range. These resistances should be used when checking the precision of the measuring instrument or system interface prior to, and during, operation. The magnitude of the resistance difference from the nominal value should not, in general, be greater than an equivalent temperature error of 0.1 or 0.2 K.

#### 2.4.7 Maintenance

The regular field checks should identify any changes in system calibration. These may occur as a result of long-term changes in the electrical characteristics of the thermometer, of degradation of the electrical cables or their connections, of changes in contact resistance of switches or of changes in the electrical characteristics of the measuring equipment. Identification of the exact source and correction of such errors will require specialized equipment and training and should be undertaken only by a maintenance technician.

#### 2.5 Radiation shields

A radiation shield or screen should, as far as possible, be designed to provide an enclosure with an internal temperature which is both uniform and the same as that of the outside air. It should completely surround the thermometers and should exclude radiant heat and precipitation. Best results are obtained with forced ventilation, by drawing air over the thermometer

element with a fan; in this case, the shield may be made of highly polished metal, although thermally-insulating material is preferable. Thermally-insulating material must be used if the system relies on natural ventilation.

#### 2.5.1 Louvred screens

Most of the numerous varieties of the louvred screen rely on natural ventilation. The walls of such a screen should preferably be double-louvred and the floor should be made of staggered boards, but other types of construction may be found to meet the above requirements. The roof should be double-layered, with provisions for ventilation of the space between the two layers. In cold climates, owing to the high reflectivity of snow (up to 88 per cent), the screen should also have a double floor. At the same time, however, the floor should easily drop or tilt so that any snow entering the screen during a storm can be removed.

The size and construction of the screen should be such that it keeps the heat capacity as low as practicable and allows ample space between the instruments and the walls. The latter feature excludes all possibility of direct contact of the thermometer sensing elements with the walls, and is particularly important in the tropics where insolation may heat the sides to the extent that an appreciable temperature gradient is caused in the screen. Direct contact between the sensing elements and the thermometer mounting should also be avoided. The screen should be painted both inside and outside with white, non-hygroscopic paint.

When double walls are provided, the layer of air between them serves to reduce the amount of heat that would otherwise be conducted from the outer wall to the inner enclosure, especially in strong sunshine. When the wind is appreciable, the air between the walls is changed continually so that the conduction of heat inwards from the outer walls is further decreased.

Free circulation of air throughout the screen helps the temperature of the inner wall adapt to ambient air changes. In this way, the influence of the inner wall upon the temperature of the thermometer is reduced. Also, free circulation of air within the screen enables the thermometer to follow the ambient air changes more quickly than if radiative exchanges alone were operative. However, the air circulating through the screen spends a finite time in contact with the outer walls and may have its temperature altered thereby. This effect becomes 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 can be expected to be higher than the true air temperature on a day of strong sunshine and calm wind, and slightly lower on a clear, calm night, with errors perhaps reaching 2.5 and -0.5 K, respectively, in extreme cases. Additional errors may be introduced by cooling due to evaporation from a wet screen after rain.

All these errors also have a direct influence on the readings of other instruments inside the screen, such as hygrometers, evaporimeters, etc.

Errors due to variations in natural ventilation can be reduced if the screen is fitted with a suitably designed forced ventilation system which maintains a constant and known ventilation rate, at least at low wind speeds. Care should be taken in the design of such systems to ensure that heat from the fan or any electrical motors does not affect the screen temperature.

In general, only one door is needed, the screen being placed so that the Sun does not shine on the thermometers when the door is open at the times of observation. In the tropics, two doors are necessary for use during different periods of the year. Likewise, in polar regions (where the Sun is at a low angle) precautions should be taken to protect the interior of the screen from the direct rays of the Sun either by a form of shading or by using a screen which is mounted so that it can be turned to an appropriate angle while the door is open for readings.

Although most screens are still made of wood, some recent designs using plastic materials offer greater protection against radiation effects because of an improved louvre design which provides a better airflow. In any case, the screen and stand should be constructed of sturdy materials and should be firmly installed so that errors in maximum and minimum thermometer readings caused by wind vibration are kept to a minimum. In some areas where wind vibration cannot be entirely damped, elastic mounting brackets are recommended. The ground cover beneath the screen should be grass or, in places where grass does not grow, the natural surface of the area.

The screen should be kept clean and should be repainted regularly; in many places, repainting once every two years is sufficient, but in areas subject to atmospheric pollution it may be necessary to repaint at least once a year.

### 2.5.2 Other artificially ventilated shields

The main alternative to exposure in a louvred screen, either naturally or artificially ventilated, is to shield the thermometer bulb from direct radiation by placing it on the axis of two concentric cylindrical shields and drawing a current of air (with a speed between 2.5 and 10 m s<sup>-1</sup>) between the shields and past the thermometer bulb. This type of exposure is normal in aspirated psychrometers (see Chapter 4, Part I). In principle, the shields should be made of a thermally-insulating material, although in the Assmann psychrometer the shields are of highly polished metal to reduce the absorption of solar radiation. The inner shield is kept in contact with a moving stream of air on both sides so that its temperature, and consequently that of the thermometer, can approximate very closely to that of the air. Such shields are usually mounted with their axes in a vertical position; the amount of direct radiation from the ground entering through the base of such shields is small and can be reduced by extending the base of the shields appreciably below the thermometer bulb. Where the artificial ventilation is provided by an electrically-driven fan, care should be taken to prevent any heat from the motor and the fan from reaching the thermometers.

The design of the WMO reference psychrometer takes careful account of the effects of radiation and the use of artificial ventilation and shielding to ensure that the thermometer element is at equilibrium at the true air temperature (See Chapter 4, Part I).

#### References

- Jones, E. B., 1992: *Jones's Instrument Technology*. Volume 2: Measurement of temperature and chemical composition, Fourth edition, Butterworths-Heinemann, Oxford.
- World Meteorological Organization, 1992: *Measurements of Air Temperature and Humidity* (R. G. Wylie and T. Lalas). Technical Note No. 194, WMO-No. 759, Geneva.

## ANNEX

## DEFINING THE FIXED POINTS OF THE INTERNATIONAL TEMPERATURE SCALE (ITS)-90

The fixed points of the ITS-90 of interest to meteorological measurements are contained in Table 1, while secondary reference points of interest to meteorological measurements are contained in Table 2.

The standard method of interpolating between the fixed points uses formulae to establish the relation between indications of the standard instruments and the values of ITS-90. The standard instrument used from  $-259.34^{\circ}\text{C}$  to  $630.74^{\circ}\text{C}$  is a platinum resistance thermometer for which the resistance ratio  $R_{100}/R_0$  is 1.385 0;  $R_{100}$  is the resistance at  $100^{\circ}\text{C}$  and  $R_0$  is the resistance at  $0^{\circ}\text{C}$ .

From  $0^{\circ}\text{C}$  to  $630.74^{\circ}\text{C}$ , the resistance at temperature  $t$  is provided by the equation:

$$R_t = R_0 (1 + A \cdot t + B \cdot t^2) \quad (1)$$

where  $R_t$  is the resistance at temperature  $t$  of a platinum wire,  $R_0$  is its resistance at  $0^{\circ}\text{C}$  and  $A$  and  $B$  are constants which are found from measurements at  $R_t$  at the boiling point of water and the freezing point of zinc.

From  $-189.344\ 2$  to  $0^{\circ}\text{C}$ , the resistance at temperature  $t$  is provided by the equation:

$$R_t = R_0 (1 + A \cdot t + B \cdot t^2 + C \cdot (t-100) \cdot t^3) \quad (2)$$

where  $R_t$ ,  $R_0$ ,  $A$  and  $B$  are determined as for equation 1 above and  $C$  is found by measurement at the boiling point of oxygen.

TABLE 1  
Defining fixed points on the ITS

Equilibrium state	Assigned value of ITS	
	K	$^{\circ}\text{C}$
Equilibrium between the solid, liquid and vapour phases of argon (triple point of argon)	83.805 8	-189.344 2
Equilibrium between the solid, liquid and vapour phases of mercury (triple point of mercury)	234.315 6	-38.834 4
Equilibrium between the solid, liquid and vapour phases of water (triple point of water)	273.16	0.01
Equilibrium between the solid and liquid phases of gallium (freezing point of gallium)	302.914 6	29.764 6
Equilibrium between the solid and liquid phases of indium (freezing point of indium)	429.748 5	156.598 5

TABLE 2  
Secondary reference points and their temperatures on the ITS

Equilibrium state	Assigned value of ITS	
	K	$^{\circ}\text{C}$
Equilibrium between the solid and vapour phases of carbon dioxide (sublimation point of carbon dioxide) at standard atmospheric pressure $p_0$ (1 013.25 hPa). The temperature $t$ as a function of the vapour pressure of carbon dioxide is given by the equation: $t = [1.210\ 36 \times 10^{-2} (p-p_0) - 8.912\ 26 \times 10^{-6} (p-p_0)^2 - 78.464]^{\circ}\text{C}$ where $p$ is the atmospheric pressure in hPa, in the temperature range 194 to 195 K	194.686	-78.464
Equilibrium between the solid and liquid phases of mercury (freezing point of mercury) at standard atmospheric pressure	234.296	-38.854
Equilibrium between ice and air-saturated water (ice-point) at standard atmospheric pressure	273.15	0.00
Equilibrium between the solid, liquid and vapour phases of phenoxybenzene (diphenyl ether) (triple point of phenoxybenzene)	300.014	26.864