CHAPTER CONTENTS

CHAPTER 2. MEASUREMENT OF TEMPERATURE

2.1 GENERAL

2.1.1 Definition

WMO (1992) defines temperature as a physical quantity characterizing the mean random motion of molecules in a physical body. Temperature is characterized by the behaviour whereby two bodies in thermal contact tend to an equal temperature. Thus, temperature represents the thermodynamic state of a body, and its value is determined by the direction of the net flow of heat between two bodies. In such a system, the body which overall loses heat to the other is said to be at the higher temperature. Defining the physical quantity temperature in relation to the "state of a body" however is difficult. A solution is found by defining an internationally approved temperature scale based on universal freezing and triple points.[1] The current such scale is the International Temperature Scale of 1990 (ITS-90),[2] in which temperature is expressed as t_{90} (Celsius temperature) or T_{90} (kelvin temperature). For the meteorological range (–95 °C to +60 °C), t_{90} is defined by means of a well-specified set of platinum resistance thermometers calibrated at a series of defining fixed points and using specified interpolation procedures (BIPM, 1989, 1990).

For meteorological purposes, temperatures are measured for a number of media. The most common variable measured is air temperature (at various heights). Other variables are ground, soil, grass minimum and seawater temperature. WMO (1992) defines air temperature as "the temperature indicated by a thermometer exposed to the air in a place sheltered from direct solar radiation". Although this definition cannot be used as the definition of the thermodynamic quantity itself, it is suitable for most applications.

2.1.2 Units and scales

The thermodynamic temperature (T), with units of kelvin (K) (also defined as "kelvin temperature"), 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 (or "Celsius temperature") defined by equation 2.1, is used for most meteorological purposes (from the ice-point secondary reference in Table 2.A.2 in the annex):

$$t/°\mathrm{C} = T/\mathrm{K} - 273.15 \tag{2.1}$$

A temperature difference of one degree Celsius (°C) unit is equal to one kelvin (K) unit. Note that the unit K is used without the degree symbol.

In the thermodynamic scale of temperature, measurements are expressed as differences from absolute zero (0 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 ITS-90 (see the annex), which is based on assigned values for the temperatures of a number of reproducible equilibrium states (see Table 2.A.1 in 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 to the thermodynamic temperature, with any difference being within the present limits of measurement uncertainty. In addition to the defining fixed points of the ITS, other secondary reference points are available (see Table 2.A.2 in the annex). Temperatures of meteorological interest are obtained by interpolating between the fixed points by applying the standard formulae in the annex.

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[1] The authoritative body for this scale is the International Bureau of Weights and Measures/Bureau International des Poids et Mesures (BIPM), Sèvres (Paris); see http://www.bipm.org. BIPM's Consultative Committee for Thermometry (CCT) is the executive body responsible for establishing and realizing the ITS.

[2] Practical information on ITS-90 can be found on the ITS-90 website: http://www.its-90.com.

2.1.3 Meteorological requirements

2.1.3.1 *General*

Meteorological requirements for temperature measurements primarily relate to the following:

(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 relating to (a), (b) and (c).

2.1.3.2 *Accuracy requirements*

The range, reported resolution and required uncertainty for temperature measurements are detailed in Part I, Chapter 1, of this Guide. In practice, it may not be economical to provide thermometers that meet the required performance directly. Instead, cheaper thermometers, calibrated against a laboratory standard, are used with corrections being applied to their readings as necessary. 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.

Example of possible thermometer characteristics

Thermometer type	*Ordinary*	*Maximum*	*Minimum*
Span of scale (˚C)	–30 to 45	–30 to 50	– 40 to 40
Range of calibration (˚C)	–30 to 40	–25 to 40	–30 to 30
Maximum error	< 0.2 K	0.2 K	0.3 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 ˚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 uncertainty or performance specification, or a calibration certificate that gives the corrections that must be applied to meet the required uncertainty. This initial testing and calibration should be performed by 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 or lag coefficient, since the temperature of the air continually fluctuates up to one or two degrees within a few seconds. Thus, obtaining 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% of a step change in air temperature, should be 20 s. The time constant depends on the airflow over the sensor.

2.1.3.4 ***Recording the circumstances in which measurements are taken***

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 the condition of, and changes in, the design of the radiation shield or screen, and by other changes in equipment (WMO, 2011). It is important that records should be kept not only of the temperature data, but also of the circumstances in which the measurements are taken. Such information is known as metadata (data about data; see Part I, Chapter 1, Annex 1.C).

2.1.4 **Measurement methods**

In order to measure the temperature of an object, a thermometer can be brought to the same temperature as the object (namely, into thermodynamic equilibrium with it), and the temperature of the thermometer itself can then be measured. Alternatively, the temperature can be determined by a radiometer without the 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, among other applications, for temperature measurements from satellites. A special technique to determine the air temperature using ultrasonic sampling, developed to determine air speeds, also provides the average speeds of the air molecules, and as a consequence its temperature (WMO, 2002*a*).

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 thermometry, such as Jones (1992) and Middleton and Spilhaus (1960). Considering the concepts of thermometry, care should be taken that, for meteorological applications, only specific technologies are applicable because of constraints determined by the typical climate or environment.

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, with 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. However, 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 that 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. Precipitation on the sensor will, depending on the local airflow, depress the sensor temperature, causing it to behave as a wet-bulb thermometer. Maintaining free circulation may, however, be difficult to achieve under conditions of rime ice accretion. Practices for reducing observational errors under such conditions will vary and may involve the use of special designs of screens or temperature-measuring instruments, including artificial ventilation. Nevertheless, in the case of artificial ventilation, care should be taken to avoid unpredictable influences caused by wet deposition in combination with evaporation during precipitation, drizzle, fog, and the like. An overview of concepts of temperature measurement applicable for operational practices is given by Sparks (1970).

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 air 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. Sites on steep slopes or in hollows are subject to exceptional conditions and should be avoided. In towns and cities, local peculiarities are expected to be more marked than in rural districts. Temperature observations 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.

The siting classification for surface observing stations on land (see Part I, Chapter 1, Annex 1.B of this Guide) provides additional guidance on the selection of a site and the location of a thermometer within a site to optimize representativeness.

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 uncertainty of this thermometer may be checked periodically in a water triple-point cell. The triple point of water is defined exactly and can be reproduced in a triple-point cell with an uncertainty of $1 \cdot 10^{-4}$ 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 and is capable of providing a temperature measurement with an uncertainty of 0.04 K (at the 95% confidence level). See Part I, Chapter 4, 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 which has 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[3] is generally used for temperatures above its freezing point (–38.9 °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, as follows:

(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.

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 reblackened 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). An overview of thermometers, designed for use in meteorological practices is given by HMSO (1980).

Whichever type is adopted, the sheath or mounting should not be unduly bulky as this would keep the heat capacity high. At the same time, the sheath or mounting should be sufficiently robust to withstand the normal risks associated with 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 thermometers should be graduated for total immersion, with the exception of thermometers for measuring soil temperature. The special requirements of thermometers for various purposes are dealt with hereafter under the appropriate headings.

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[3] Advice concerning the safe use of mercury is given in Part I, Chapter 3, 3.2.7. The Minamata Convention on Mercury of the United Nations Environment Programme entered into force in October 2013 and will have a significant impact on the use of mercury for meteorological applications.

2.2.1.1 ***Ordinary (station) thermometers***

This is the most accurate instrument of all meteorological thermometers. Usually it is a mercury-in-glass-type thermometer. Its scale markings have an increment 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 a vertical position with the bulb at the lower end. The form of the bulb is that of a cylinder or an onion.

A pair of ordinary thermometers can be used as a psychrometer if one of them is fitted with a wet-bulb[4] sleeve.

2.2.1.2 ***Maximum thermometers***

The recommended type for maximum thermometers 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 temperatures. However, observers can reset by holding it firmly, bulb-end downwards, and swinging their arm until the mercury column is reunited. A maximum thermometer should be mounted at an angle of about 2° from the horizontal position, 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***

As regards 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 which should be large enough to allow the instrument to withstand a temperature of 50 °C without being damaged. 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 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 the expansion of the mercury.

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.

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[4] Wet-bulb temperatures are explained in Part I, Chapter 4.

The technique of using vertical steel tubes is unsuitable for measuring 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 because they will conduct heat from the surface layer.

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 **Measurement procedures**

2.2.2.1 ***Reading ordinary thermometers***

Thermometers should be read as rapidly as possible in order to avoid changes of temperature caused by the observer's presence. Since the liquid meniscus, or index, and the thermometer scale are not on the same plane, care must be taken to avoid parallax errors. These will occur unless the observer ensures that the straight line from his/her 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 degree, readings to the nearest tenth of a degree, which are essential in psychrometry, 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 temperatures***

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 position, 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 covered with snow, 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 the 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, exposing the thermometer in this way 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^2) and 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^2. 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 the ground's slope 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 5 m 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 m above the upper limit of prevailing vegetation) is desirable.

2.2.3 Thermometer siting and exposure

Both ordinary thermometers and maximum and minimum thermometers are always exposed in a thermometer screen placed on a support. Extreme thermometers are mounted on suitable supports so that they are inclined at an angle of about 2° from the horizontal position, with the bulb being lower than the stem.

The siting and exposure of grass minimum thermometers 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 that 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 the following:

(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 the 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, namely reversible and irreversible errors. The first is of importance only when a thermometer is exposed to a large temperature range 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 the glass employed in the thermometer, and may be as much as 1 K (with glass of the highest quality 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 thermometer bulb 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, after which the rate of change will gradually decrease. This alteration can be reduced by subjecting the bulb to heat treatment and by using the most suitable glass. Even with glass of the highest quality, the change may be about 0.01 K per year at first. For accurate work, and especially with inspector or check thermometers, the zero should be redetermined at the recommended intervals and the necessary corrections applied.

2.2.4.2 *Errors caused by the emergent stem*

A thermometer used to measure air temperature is usually completely surrounded by air at an approximately uniform temperature, and is calibrated by immersing the thermometer either completely or only to the top of the mercury column (namely, 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 temperature 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 on the plane that is perpendicular to the stem of the thermometer, parallax errors will arise. The error increases with the thickness of the thermometer stem 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 observers usually disturb the surroundings in some way when they approach to read the thermometer. It is, therefore, necessary for observers to take the readings to the nearest tenth of a degree as soon as possible. Gross reading errors are usually 1°, 5° or 10° in magnitude. Such errors will be avoided if observers recheck the tens and units figure after taking their initial reading.

2.2.4.4 *Errors due to differential expansion*

The coefficient of cubical expansion of mercury is $1.82 \cdot 10^{-4}$ K^{-1}, and that of most glass lies between $1.0 \cdot 10^{-5}$ and $3.0 \cdot 10^{-5}$ 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 °C). Spirit is used in minimum thermometers because it is colourless and because its larger expansion coefficient enables a larger bore to be used. Spirit thermometers are less accurate than mercury thermometers of similar cost and quality. In addition to having the general disadvantages of liquid-in-glass thermometers, spirit thermometers have some peculiarities to themselves:

(a) Adhesion of the spirit to the glass: Unlike mercury, organic liquids generally wet the glass. 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 errors caused by breakage in the liquid column and the general care of 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 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 being calibrated should be suspended independently of the container and fully immersed, and should not touch the sides.

Sufficient measurements should be taken 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 (see Part IV, Chapter 4).

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. The thermometers should be stored in an upright position at room temperature for at least 24 h before the checking process begins.

The ice point may be checked by almost filling a Dewar flask with crushed ice made from distilled water and 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 as little of the mercury or spirit column as possible emerges from the ice. An interval of at least 15 min should elapse to allow the thermometer to take up the temperature of the melting ice before a reading of the indicated temperature is taken. 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 5 min 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 thermometer. Comparison should be made by immersing the reference thermometer and the thermometer, or thermometers, to be calibrated in a deep vessel of water. It is generally better to work indoors, especially if the sun is shining, and the best results will be obtained if the water is at, or close to, ambient temperature.

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, moved backwards and forwards through the water for about 1 min, 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 that 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 columns of mercury (or other liquid) in the reference thermometer and the thermometer being checked will not be very close together. Particular care should therefore be taken to avoid parallax errors.

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 calibrated in this manner, but should be left in the water for at least 30 min 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 conduct a satisfactory check unless the temperature of the water can be kept very steady. If the calibration is carefully carried out in water whose temperature does not change by more than 1 K in 30 min, the difference from the corrected reading of the reference thermometer should not exceed 0.25 K.

2.2.6 **Corrections**

When initially issued, thermometers identified by a serial number should be provided with either a dated certificate confirming compliance with the uncertainty requirement, or a dated calibration certificate giving the corrections that should be applied to the readings to achieve the required uncertainty.

In general, if the errors at selected points in the range of a thermometer (for example, 0 °C, 10 °C, 20 °C) are all within 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, 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 laboratory calibration references;

(d) For special purposes for which the 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 (5 min if necessary), and afterwards the thermometer should be hung, or stood, upright in a suitable container, bulb downward, for at least 1 h to allow any spirit adhering to the glass to drain down to the main column. If such 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 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 unsheathed liquid-in-glass thermometers is that with time their scale can become illegible. This can be corrected at the station by rubbing the scale with a dark crayon or black lead pencil.

2.2.8 Safety

Mercury, which is the liquid most commonly used in liquid-in-glass thermometers, is poisonous if swallowed or if its 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 after a breakage is given in Part I, Chapter 3, in section 3.2 on mercury barometers.) There may also be restrictions on the carriage of mercury thermometers on aircraft, or special precautions that 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 of mechanical thermographs still commonly used are supplied with bimetallic 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 classic 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 reasonably sized chart. To achieve this, provisions 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 finely adjusting 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 that 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 s is obtained at an air speed of 5 m s^{-1}.

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 6 s at an air speed of 5 m s^{-1}.

2.3.2 Measurement procedures

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. However, 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, 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, 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 for the laboratory calibration of bimetallic thermographs. They 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 an instrument to have excessive errors, and if these cannot be adjusted locally, 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, and a check of the chart-drum clock timing. 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 using a small amount of clock oil. The instrument is mechanically very simple and, provided that precautions are taken to keep the friction to a minimum and prevent corrosion, it should give good service.

2.4 ELECTRICAL THERMOMETERS

2.4.1 General description

Electrical instruments are in widespread use in meteorology for measuring temperatures. 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:

$$R_T = R_0\left[1+\alpha\left(T-T_0\right)\right] \tag{2.2}$$

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

With 0 °C as the reference temperature, equation 2.2 becomes:

$$R_T = R_0 \left(1 + \alpha \cdot t\right) \tag{2.3}$$

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

$$R_T = R_0 \left[1 + \alpha \left(T - T_0\right) + \beta \left(T - T_0\right)^2\right] \tag{2.4}$$

With 0 °C as the reference temperature, equation 2.4 becomes:

$$R_T = R_0 \left(1 + \alpha \cdot t + \beta \cdot t^2\right) \tag{2.5}$$

These equations give the proportional change in resistance of an actual thermometer, so that values for the coefficients α and β can be found by calibration of the thermometer concerned. Based on these results, the inverse function, namely, t as a function of R, can be derived. Such a function may be expressed in terms of a power series of $(R_0 - R_T)$, namely, $t = t\ (R_0 - R_T) = c_1\ (R_0 - R_T) + c_2\ (R_0 - R_T)^2 + \dots$

A good metal resistance thermometer will satisfy the following requirements:

(a) Its physical and chemical properties will remain the same through the temperature measurement range;

(b) Its resistance will increase steadily with increasing temperature without any discontinuities in the range of measurement;

(c) External influences such as humidity, corrosion or physical deformations will not alter its resistance appreciably;

(d) Its characteristics will remain stable over a period of two years or more;

(e) 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. Platinum thermometers are also used for secondary standards and for operational sensors.

Practical thermometers are artificially aged before use and are commonly made from platinum alloys, nickel and occasionally tungsten for meteorological purposes. Usually they are hermetically sealed in a ceramic sheath. Their time constant is smaller than that of 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:

$$R = a \exp\left(b/T\right) \tag{2.6}$$

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

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

(a) 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;

(b) 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 °C to 40 °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 metals joined and the temperature of the junction point, and may be empirically represented for any two metals by the expression:

$$\left(E_T - E_S\right) = \alpha\left(T - T_S\right) + \beta\left(T - T_S\right)^2 \tag{2.7}$$

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, 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 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:

$$E_n = E_1 - E_2 \tag{2.8}$$

$$E_n = a\left(T_1 - T_2\right) + b\left(T_1 - T_2\right)^2 \tag{2.9}$$

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, a measurement is taken of 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. 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.

In meteorology, thermocouples are mostly used when a thermometer of very small time-constant, of the order of 1 or 2 s, 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 has been set up; thermocouples are best suited for the measurement of differential temperatures, since this complication does not arise. Very high accuracy 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 rarer and more expensive metals, which are normally used at high temperatures.

2.4.2 Measurements procedures

2.4.2.1 *Electrical resistance thermometers*

Electrical resistance 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, an accurate potentiometer is adjusted until no current flows in an indicator, with 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 that 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;

(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 uncertainty of better than 0.5% 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 the exposure and siting of electrical thermometers will, in general, be the same as those for liquid-in-glass thermometers (see section 2.2.3). Exceptions include the following:

(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 because of heat conduction from the surface. It is possible to obtain readings that 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 resistance thermometers***

The main sources of error in a temperature measurement taken with electrical resistance thermometers are the following:

(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, for example, 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 using extra conductors, ballast resistors and an appropriate bridge network. To reduce errors, it is highly recommended to use four-wire platinum resistance thermometers.

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 the following:

(a) Changes in the resistances of the connecting leads with temperature. This effect 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) Stray secondary thermal electromotive forces due to the use of metals that 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 that the standard cell is treated correctly, and that 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 resistance thermometers***

The basic techniques and procedures for the 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 a 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 an accurate 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 junctions 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 (which have a serial number) should be provided with either:

(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 uncertainty of the measuring instrument or system interface before 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, degradation of the electrical cables or their connections, changes in the contact resistance of switches or 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 be designed to provide an enclosure with an internal temperature that is both uniform and the same as that of the outside air. It should completely surround the thermometers and exclude radiant heat, precipitation and other phenomena that might influence the measurement.

Screens with forced ventilation, in which air is drawn over the thermometer element by a fan, may help to avoid biases when the microclimate inside the screen deviates from the surrounding air mass. Such a deviation only occurs when the natural wind speed is very low ($< 1 \text{ m s}^{-1}$). When such artificial ventilation is used, care should be taken to prevent the deposition of aerosols and rain droplets on the sensor which decrease its temperature towards the wet-bulb temperature. Manufacturers of artificially ventilated radiation shields are encouraged to provide a clear indication (such as an LED light) of the fan status directly on the screen or on the control unit or data logger to allow maintenance staff to check whether the fan is functioning properly by visual inspection. Additionally, the fan status and preferably the fan speed should be provided in the data output for automatic monitoring purposes.

As a shield material, highly polished, non-oxidized metal is favourable because of its high reflectivity and low heat absorption. Nevertheless, thermally insulating plastic-based material is preferable because of its simple maintenance requirements. Thermally insulating material must be used if the system relies on natural ventilation.

The performance of a screen (response behaviour and microclimate effects introducing unwanted biases) depends predominantly on its design, in which care must be taken to ensure both radiation protection and sufficient ventilation. Since the start of meteorological temperature measurements, very diverse types of screens have been designed. Following the introduction of temperature measurements taken in automatic weather stations, the variety of these designs has increased significantly (see WMO, 1998*a*). Because of differences in specific applications, the degree of automation and climatology, it is difficult to recommend one specific type of design suitable for worldwide measurements. Nevertheless, many investigations and intercomparisons on designs and their performance have been carried out. A clear overview of screen designs is given by WMO (1972). Results of thermometer screen intercomparisons are reported by Andersson and Mattison (1991), Sparks (2001), WMO (1998*b*, 1998*c*, 1998*d*, 2000*a*, 2000*b*, 2002*b*, 2002*c*, 2002*d*, 2011) and Zanghi (1987).

An international standard (ISO/DIS 17714) defines most relevant screen types and describes the methods to determine or compare screen performances (ISO, 2007).

2.5.1 **Louvred screens**

Most of the numerous varieties of 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%), 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 between the thermometer sensing elements and 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.

The 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, the 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, and the like.

Errors due to variations in natural ventilation can be reduced if the screen is fitted with a suitably designed forced ventilation system that 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 an electrical motor does not affect the screen temperature.

In general, only one door is needed, with 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 inside 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 that 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 repainted regularly; in many places, repainting the screen once every two years is sufficient, but in areas subject to atmospheric pollution it may be necessary to repaint it at least once a year.

2.5.2 Other artificially ventilated shields

The main alternative to exposure in a louvred screen, which is 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^{-1}) between the shields and past the thermometer bulb. This type of exposure is normal in aspirated psychrometers (see Part I, Chapter 4). In principle, the shields should be made of a thermally insulating material, although in the Assmann psychrometer the shields are made 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. When the artificial ventilation is provided by an electrically driven fan, care should be taken to prevent any heat from the motor and 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 Part I, Chapter 4).

ANNEX. DEFINING THE FIXED POINTS OF THE INTERNATIONAL TEMPERATURE SCALE OF 1990

The fixed points of the International Temperature Scale of 1990 (ITS-90) of interest to meteorological measurements are contained in Table 2.A.1, while secondary reference points of interest to meteorological measurements are contained in Table 2.A.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 the ITS-90 (BIPM, 1990). The standard instrument used from –259.34 °C to 961.78 °C is a platinum resistance thermometer.

An alternative practical method for ITS-90 approximation in platinum resistance thermometer calibration (determination of R_0, A , B and C, see equation below) is to obtain resistance-temperature data by making a comparison with a calibrated standard platinum resistance thermometer at numerous temperatures in the range of interest and then fit a polynomial to the data by a least-squares technique.

The relationship between the resistance of the platinum resistance thermometer under calibration and the temperature measured with a reference thermometer is described with an interpolation equation. The Callendar–Van Dusen equation is generally accepted as the interpolation equation for industrial platinum resistance thermometers (defined in the IEC 60751, see IEC (2008)) rather than for standard platinum resistance thermometers:

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

where R_t is the resistance at temperature t of a platinum wire, R_0 is its resistance at 0 °C (ice point) and A, B and C ($C = 0$ for $t > 0$ °C) are constants which are found using the least-squares method on the data acquired during the calibration.

Table 2.A.1. Defining fixed points on the ITS-90

Equilibrium state	*Assigned value of ITS*	
	K	*˚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)	273.160 0	0.01
Equilibrium between the solid and liquid phases of gallium (melting 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.A.2. Secondary reference points and their temperatures on the ITS-90

Equilibrium state	*Assigned value of ITS*	
	K	*˚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: $t = [1.210\,36 \cdot 10^{-2} (p - p_0) - 8.912\,26 \cdot 10^{-6}(p - p_0)_2 - 78.464]$ °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	273.150	0.00
Equilibrium between the solid, liquid and vapour phases of phenoxybenzene (diphenyl ether) (triple point of phenoxybenzene)	300.014	26.864

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