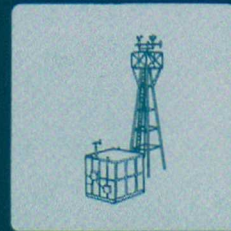
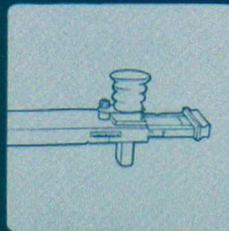
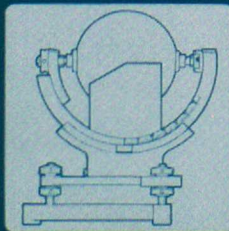
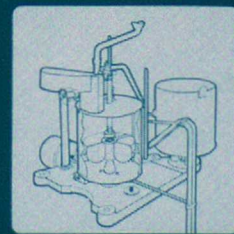
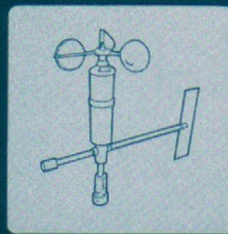
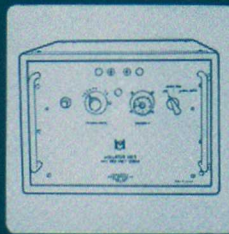
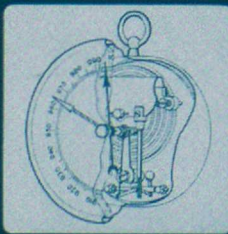
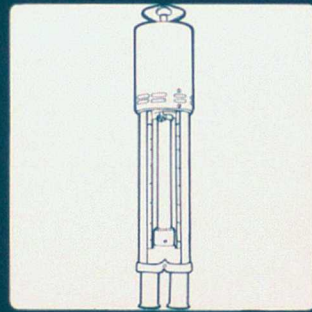


Meteorological Office

Handbook of Meteorological Instruments

Second Edition

3 Measurement of Humidity



HMSO

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METEOROLOGICAL OFFICE

HANDBOOK OF METEOROLOGICAL INSTRUMENTS

SECOND EDITION

VOLUME 3

MEASUREMENT OF
HUMIDITY

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INTRODUCTION

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

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

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

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

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

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

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

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

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

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VOLUME 3 MEASUREMENT OF HUMIDITY

1 GENERAL

1.1 Definitions

Hygrometry, considered in its broadest sense, is concerned with the measurement of the water content of solids, liquids and gases. In meteorology, concern is with the water vapour content of atmospheric air and there are various ways in which this may be specified. The most common are:

- mixing ratio (or humidity mixing ratio),
- specific humidity (or moisture content),
- vapour pressure,
- vapour concentration (or density of water vapour),
- dew-point and frost-point, and
- relative humidity.

Mixing ratio. The mixing ratio, r , is defined as the ratio of the mass of water vapour, m_v , to the mass of dry air, m_a , with which it is associated.

$$r = \frac{m_v}{m_a}$$

Specific humidity. The specific humidity, q , which is sometimes known as the moisture content or mass concentration, is defined as the ratio of the mass of water vapour, m_v , to the mass of moist air, $m_v + m_a$, with which it is associated.

$$q = \frac{m_v}{m_v + m_a} = \frac{r}{1 + r} \quad \dots (1)$$

Vapour pressure. The water vapour in the atmosphere behaves like any of the other gases present in that it exerts a pressure which makes up part of the total pressure of the air. This partial pressure of the water vapour is known as the vapour pressure, e , and may be measured in any of the usual units of pressure. It may be considered for meteorological purposes to be independent of the presence or absence of other gases. The relation between the vapour pressure and the mixing ratio is

$$e = \frac{r}{0.622 + r} P,$$

where p is the atmospheric pressure, and 0.622 represents the ratio of the density of water vapour to that of air at the same temperature and pressure,

$$\text{or } r = \frac{0.622e}{p - e}.$$

Similarly

$$q = \frac{r}{1 + r} = \frac{0.622e}{p - 0.378e}.$$

If an enclosed space is maintained at constant temperature in contact with a plane surface of pure water, the vapour pressure in the space rises to a maximum value which is characteristic of that temperature and which increases as the temperature increases. This maximum value of the vapour pressure is called the saturation vapour pressure.

When the air temperature is below 0 °C it is possible to have saturation over either a supercooled liquid water surface or an ice surface, and different values of the saturation vapour pressure are found in the two cases. The two conditions can be represented by e_w and e_i ; e_w refers to saturation over liquid water and applies to all temperatures up to the critical temperature of water (about 370 °C), and e_i refers to saturation over ice at temperatures of 0 °C or below. At 0 °C e_w and e_i are equal at atmospheric pressures usually encountered in meteorology. The values of e_w and e_i given in the *Hygrometric tables* (Meteorological Office, 1961) are those with reference to a plane surface of pure water or ice; over a curved surface the saturation vapour pressure changes, becoming higher over a convex surface and lower over a concave surface. It is also less over a solution of an electrolyte than the corresponding value over pure water at the same temperature. Very thin surface films of grease can also produce detectable reductions in the saturation vapour pressure over a water surface.

The deviation of the behaviour of water vapour from the laws governing a perfect gas can usually be neglected for meteorological purposes. It can also be noted that when e is small compared with p then

$$r \approx q \approx \frac{0.622e}{p}$$

The values of e_w and e_i can be found in *Hygrometric tables* for all temperatures likely to be met in meteorological observations at ground level in this country, but if the values at other temperatures are required these can be found in *Physical and chemical constants* by Kaye and Laby (1973), where the values are given in kilonewtons per square metre, and not in millibars, for temperatures up to 360 °C, or in the *Smithsonian meteorological tables* (1968), or can be calculated using the Meteorological Office humidity slide-rule Mk 6 or Mk 6A.

Vapour concentration. The vapour concentration, d_v , which is sometimes known as the absolute humidity, or vapour density, is defined as the ratio of the mass of water vapour, m_v , to the volume, V , occupied by the moist air with which it is associated:

$$d_v = \frac{m_v}{V}$$

It is thus equivalent to the density of the water vapour, and can be calculated from the vapour pressure and the temperature. If the vapour pressure is given in millibars and the temperature T in kelvins then

$$d_v = \frac{216.7e}{T} \text{ g m}^{-3}.$$

Dew-point and frost-point. If the actual vapour pressure in the air is e it is possible to find a temperature T_d such that the value of e_w at this temperature is equal to e . This temperature, T_d , is known as the dew-point of the air and will in general be equal to or less than the actual air temperature, T . It is the temperature to which the air has to be cooled at constant pressure before it becomes saturated with respect to liquid water; in saturated conditions the dew-point and air temperature are equal.

When the vapour pressure is less than 6.108 mb (the value of e_w at 0 °C) it is possible to find a somewhat similar temperature, T_f , such that the value of e_i at this temperature is equal to e . This temperature is called the frost-point (or hoar-frost point) of the air and is higher than the corresponding dew-point. It is the temperature to which the air has to be cooled at constant pressure before it becomes saturated with respect to ice (when $e = 6.108$ mb, $T_d = T_f = 0$ °C). The Meteorological Office practice is always to record and report the dew-point, unless it is specifically stated otherwise.

If the air is supersaturated with respect to ice at air temperatures below 0 °C (i.e. e is greater than the corresponding value of e_i at the air temperature T) the frost-point T_f will be higher than T and similarly, if the air is supersaturated with respect to liquid water, T_d will be higher than T .

Supersaturation with respect to ice, at temperatures below 0 °C, frequently occurs in the atmosphere, but supersaturation with respect to liquid water is probably rare and of only local occurrence.

Relative humidity. The relative humidity, U , is defined as the ratio (expressed as a percentage) of the actual vapour pressure to the saturation vapour pressure at the air temperature T , i.e.

$$U = 100 \frac{e}{e_T} \text{ per cent}$$

where e_T is the saturation vapour pressure at temperature T .

At air temperatures below 0 °C there are then two possible values of U :

$$U_w = 100 \frac{e}{e_w}$$

and
$$U_i = 100 \frac{e}{e_i}$$

The practice of the Meteorological Office is to calculate and report U_w , i.e. the relative humidity with reference to saturation over liquid water, at all temperatures.

The above definitions are similar to those of the World Meteorological Organization *Technical Regulations* (1975), except that in the latter the factor 0.622 is refined to 0.62198.

1.2 Hygrometers

A hygrometer is an instrument used to measure the amount of water vapour in the air. The following main types of hygrometer have been grouped according to their methods or principles of operation. For various reasons, e.g. size, these hygrometers are not necessarily all suitable for routine meteorological observations.

(1) Methods depending on the addition or removal of water vapour

(a) *Gravimetric method* (Wexler, 1961). The gravimetric method provides a measurement of the vapour concentration of a sample of air. This is obtained by first removing the water vapour in the sample with a drying agent and determining its mass (m_v) by direct weighing, and then measuring the volume (V) of the associated air. The measurements of m_v and V can be made with great accuracy, which makes the method suitable as a reference standard.

(b) *Volumetric and pressure methods* (Bongards, 1926). At constant temperature, the removal of the water vapour from a sample of air causes a change in volume (at constant pressure) or pressure (at constant volume) of the sample, which are measures of the partial volume or partial pressure (e) respectively of the water vapour.

The gravimetric, volumetric and pressure methods can also be used to measure the saturation deficit of a sample of air, i.e. the difference between the saturation and actual water vapour contents, by the addition of water vapour. In either mode, all three methods are normally confined to laboratory use.

(c) *Diffusion hygrometer* (Greinacher, 1944, 1954). If P is the atmospheric pressure, p_a the partial pressure of the air and p_v the partial pressure of the water vapour, then $P = p_a + p_v$. In one version of the diffusion hygrometer a thin porous membrane or plate is set into the wall of an otherwise sealed chamber containing a desiccant. The membrane preferentially permits diffusion of air, thus maintaining the pressure inside the chamber at p_a . The pressure difference (p_v) between the chamber and the ambient atmosphere is measured with a differential manometer connected to the chamber.

Similarly, if the chamber contains a wetting agent instead of a desiccant, the pressure difference between the chamber and the ambient atmosphere is directly proportional to the saturation deficit.

The instrument is very sensitive to temperature changes, which may give rise to false readings, and responds relatively slowly to humidity changes.

(d) *Psychrometer*. If evaporation takes place from a body of water into a stream of air, the temperature of the water decreases until a steady state is reached. The initial temperature of the air and the steady-state temperature of the water provide a measure of the humidity of the air, and the psychrometer is an instrument for obtaining these two temperatures. In its basic form the psychrometer consists of two thermometers, the bulb of one being bare and dry (known as the dry bulb), the bulb of the other (known as the wet bulb) being covered with a piece of thin wet material or a film of water or ice.

The psychrometer is normally used with either natural ventilation, as in a large screen (see Volume 2), or forced ventilation, as in the aspirated psychrometer Mk 3 (see page 3-14).

It is a simple, comparatively inexpensive instrument which can be used to give intermittent or continuous indication, or continuous recording of dry- and wet-bulb temperatures.

(2) Equilibrium sorption methods

Certain materials interact with water vapour and undergo a change in a chemical or physical property that is sufficiently reversible and reproducible for use as an indicator or sensor of ambient humidity. Water vapour may be adsorbed or absorbed by the sensor, adsorption being the taking up of one substance at the surface of another and absorption the penetration of a substance into the body of another.

(a) *Electric hygrometers*. The electric hygrometer utilizes the change in an electrical parameter, usually resistance or capacitance, with change in relative humidity. As measurements are made in terms of electrical quantities the instruments are suitable for remote indication or recording. The sensor can be made very small and relatively inexpensive though the need for associated measuring circuitry may add appreciably to the overall cost. Some sensors are sufficiently reproducible in manufacture to dispense with the need for individual calibration and to permit interchange without undue loss of accuracy.

Most sensors are temperature-dependent and, unless automatic temperature compensation is incorporated in the instrument design, calibration is necessary over a range of temperatures and each humidity measurement will require a corresponding temperature measurement. Time-constants vary considerably between the types of sensors but are usually a matter of a few seconds to a few minutes depending on temperature; sensors depending on adsorption have smaller time-constants than those depending on absorption. With some sensors the time-constant varies with the magnitude of the humidity change, the temperature and the humidity. In general, time-constants increase roughly exponentially with decreasing temperatures. Uncertainty, including hysteresis effects, is usually about 5 per cent relative humidity at temperatures above 0 °C but increases at temperatures below 0 °C and may exceed 10 per cent relative humidity at -40 °C.

The detrimental effects of atmospheric contaminants, a problem with many sensors, can be largely overcome by the use of some form of shield or filter though usually at the expense of an increase in the time-constant. Exposure of a sensor to saturated air (e.g. fog) may cause a 'wash-out' of the sensitive surface and a shift in calibration which is often irreversible. A change in calibration, due to progressive changes in the surface characteristics, may also occur as a sensor ages, so regular checking is necessary. The use of alternating current is usually recommended in order to obviate or reduce sensor polarization.

The following are examples of some types of electric hygrometer sensor:

ALUMINIUM OXIDE SENSOR (Jason, 1965). The aluminium oxide sensor consists basically of an anodized aluminium substrate on to which is evaporated a thin metal film, e.g. aluminium or gold, permeable to water. The substrate and metal film act as the sensor electrodes and the aluminium oxide layer as the dielectric. Changes in ambient humidity effect changes in the amount of water adsorbed (or desorbed) by the oxide structure, producing corresponding changes in the dielectric constant, usually sensed by the equivalent change in capacitance.

THIN-FILM CAPACITOR SENSOR (Nelson and Amdur, 1965a). The thin-film capacitor sensor has an insulating substrate on one surface of which is deposited a pair of interleaved gold electrodes. A thin layer of polymer covering the surface and electrodes is, in turn, covered with a protective layer of gold permeable to water. Water is absorbed (or liberated) by the

polymer dielectric causing capacitance changes proportional to the ambient relative humidity.

POLYELECTROLYTE SENSOR (Musa and Schnable, 1965; Folland, 1973). The polyelectrolyte sensor consists of an inert polystyrene substrate, covered on both sides with a thin layer of highly porous ion-exchange resin produced by sulphonation of polystyrene. The ion-exchange resin adsorbs (or desorbs) water in proportion to the ambient relative humidity. Associated with the resin molecules are electrostatically held H⁺ ions which become mobile in the presence of an applied voltage. The mobility of the H⁺ ions, and thus the impedance of the sensor, depends mainly on the amount of adsorbed water. It is the sensor resistance that is usually used to measure the relative humidity. A voltage is applied via a pair of interleaved electrodes attached to each surface, connected electrically in parallel.

CARBON SENSOR (Stine, 1965). In the carbon sensor a flat acrylic plastic strip, with its long edges metallized to form electrodes, is covered with a cellulose coating containing finely divided carbon particles in suspension. The cellulose expands and contracts with increasing and decreasing relative humidity. The function of the carbon, which is relatively inert to water vapour, is to convert the dimensional change into a resistivity change.

ELECTROLYTIC SENSOR (Matthews, 1965). The concentration, and consequently the conductivity, of an aqueous electrolytic solution (e.g. lithium chloride) depends on the ambient relative humidity. If the solution is dispersed in an inert absorbent material mounted on an insulating substrate, the conductivity of the solution can be measured using a pair of electrodes attached to the substrate.

PIEZOELECTRIC SENSOR (King, 1965). The resonant frequency of a piezoelectric quartz crystal in an oscillator circuit is a function of its mass. If the crystal is coated with a hygroscopic material, the mass of the crystal plus coating will depend on the amount of water vapour adsorbed (or absorbed, depending on the coating material) which, in turn, will depend on the ambient humidity.

The performance characteristics of the sensor are decided by the choice of coating material. Molecular sieves, for example, give a high sensitivity. Polar liquids on the other hand are least sensitive but have the fastest response times.

(b) *Mechanical hygrometers*. Certain materials vary dimensionally with humidity and when coupled to a mechanical system can be used to move a pointer over a scale or a pen across a chart. Low cost, unattended operation and simplicity of design and construction are the main virtues of a mechanical hygrometer.

Its principal limitations are instability under normal operating conditions, appreciable hysteresis and a large time-constant; the time-constant increases and the reliability decreases with decreasing temperature. For optimum performance, therefore, regular checking or recalibration is necessary.

The most common sensing material used for this purpose is human hair, its length being independent of all common vapours or gases except water vapour; a change in humidity from 0 to 100 per cent produces a 2½ per cent change in hair length. Pre-treatment of the hair is necessary to remove natural grease. The time-constant can be reduced by flattening the hair between rollers under high pressure, though this reduces the hair's tensile strength. Table I shows the variation in time-constant with temperature for ordinary and rolled hair.

Table I. Variation with temperature of the time-constant of a hair hygograph

	Temperature (°C)					
	20	10	0	-10	-20	-30
	seconds					
Ordinary hair	30	40	55	175	400	800
Hair rolled flat	10	10	12	15	20	30

(3) Condensation methods

Instruments using condensation methods depend on a vapour-solid or vapour-liquid equilibrium being established.

(a) *Dew- and frost-point hygrometer* (Wexler, 1965). With the dew-point (frost-point) hygrometer the dew-point (frost-point) of the air is measured directly. A polished surface is cooled until condensation occurs and the temperature at which a deposit of dew or hoar-frost of defined thickness is unchanging is measured. Formation of the deposit can be detected visually or photoelectrically. The temperature sensor is usually embedded beneath, but as close as possible to, the polished surface. Continuous, automatic, unattended operation for extended periods is possible but difficult; the instrument's ability to operate at very low temperatures makes it suitable, in its most accurate form, for checking or calibrating instruments of lesser accuracy.

Regtien and Makkink (1978) describe a miniature dew-point sensor based on the capacitive detection of dew on a silicon chip. A planar npn transistor is located in the centre of a silicon chip 1.8 mm square. The temperature dependence of the transistor's base-emitter voltage is used to determine the surface temperature of the chip. Around the transistor an interleaved aluminium pattern is deposited forming the capacitor electrodes. If the temperature of the chip falls below the dew-point, water vapour condenses on to the chip, the deposited water forming part of the dielectric. The chip is mounted on a small Peltier* device which, by suitable control, enables the sensor temperature to be alternately decreased to just below the dew-point and raised just above it.

(b) *Vapour equilibrium hygrometer* (Nelson and Amdur, 1965b). The vapour equilibrium hygrometer utilizes the fact that, at any temperature, the equilibrium vapour pressure of a saturated salt solution is less than that of a water surface at the same temperature. This effect is exhibited by all salt solutions but particularly so by lithium chloride solution which has an exceptionally low vapour pressure.

One type of vapour equilibrium hygrometer is the 'dewcel'† in which a layer of glass fibre tape, impregnated with lithium chloride solution, is wound round a metal tube containing a temperature sensor. A pair of parallel overlay wires is wound in a spiral over the outside of the tape; the wires are not in electrical contact, the only conducting path being via the lithium chloride solution. The instrument is operated by passing an alternating current between the windings which causes Joule heating. The element temperature rises until the vapour pressure of the solution exceeds that of the ambient air. At this point evaporation commences and the electrical conductivity of the solution decreases, reducing the heating current. The element will then cool until condensation is sufficient to maintain an equilibrium temperature at which value the solution just maintains saturation. Any change in the ambient relative humidity causes the solution temperature to change in the same sense until a new equilibrium temperature is reached. Response time is of the order of 1 to 3.5 minutes. The equilibrium temperature is related to ambient dew-point temperature by previous calibration.

The dewcel can give continuous indication or recording, but it has to be re-covered periodically with fresh lithium chloride solution, owing to the effects of atmospheric pollution. It is less accurate than a psychrometer at high humidities, especially in fog, but is more reliable at temperatures below 0 °C (Folland, 1975).

Since the dewcel element cannot be cooled below the ambient temperature it will not measure less than the saturation vapour pressure over saturated lithium chloride at the ambient temperature. In terms of relative humidity this corresponds to 11 per cent at 50 °C, 15 per cent at 0 °C and 100 per cent at -45 °C.

*Peltier effect. The phenomenon whereby heat is liberated or absorbed at a junction where an electric current passes from one metal to another.

† The name 'dewcel' was originally a manufacturing firm's trade name for its particular hygrometer. Through common usage the name has now assumed a generic connotation.

2 PSYCHROMETERS

2.1 General

A psychrometer consists essentially of two thermometers exposed side by side, the bulb of one being bare and dry (known as the dry bulb), while the bulb of the other (known as the wet bulb) is covered with a piece of thin wet material or a film of water or ice. The temperature of the wet-bulb thermometer, because of evaporation of water from the bulb, is generally lower than that of the dry bulb; the drier the air is the greater is the evaporation and, in turn, the difference in temperature between the two thermometers.

2.2 Psychrometric formulae

The psychrometric formula for determining the vapour pressure, e , from the readings of the dry- and wet-bulb thermometers is

$$e = e_s - Ap(T - T_w), \quad \dots (2)$$

where T = the dry-bulb temperature

T_w = the wet-bulb temperature

p = the atmospheric pressure

e_s = the saturation vapour pressure at temperature T_w

A = the psychrometer coefficient.

The psychrometer coefficient. Values of the psychrometer coefficient A have been derived both theoretically and experimentally. According to Wylie (1968) the various theoretical estimates of A made so far tend to underestimate its observed value by as much as 9 per cent. Most experiments, in the absence of stem heat conduction, show that the value of A for ordinary thermometers, at ventilation rates in excess of about 3 m s^{-1} , tends to within 2 per cent of $0.667 \times 10^{-3} \text{ K}^{-1}$. However, some of the difference between the theoretical and observed values of A is likely to be due to the fact that the wet bulbs of practical psychrometers are seldom covered with pure water.

An example of the theoretical studies of A is that due to work by Kondo (1967). He considered the heat budget at the wet bulb and obtained a series of formulae for spherical and cylindrical thermometer bulbs at various ventilation rates. These formulae, assuming no short-wave radiation effects, can be expressed in the simplified general form

$$A = B + \frac{a\beta}{u^{\frac{1}{2}} + b\alpha(T - T_w)^{\frac{1}{2}}}$$

where u is the ventilation rate, B , α and β are parameters depending on temperature (B also depends to a small extent on the ventilation rate) and a and b are factors determined by the shape and dimensions of the thermometer bulb.

Basically, as the size of the thermometer bulb decreases or the ventilation rate increases, so the value of A decreases. Variations in the value of relative humidity with changes in the wet-bulb depression and the psychrometer coefficient can be derived as follows:

By definition, $U = e/e_T$,

where U = the relative humidity expressed as a fraction

and e_T = the saturation vapour pressure at temperature T .

Thus, from equation (2),

$$U = \frac{e_s - Ap(T - T_w)}{e_T}$$

If a change of ΔA in A , or ΔT_w in T_w , produces a change of ΔU in derived U , then

$$\Delta U / \frac{\Delta A}{A} = \frac{(e_s - Ue_T)}{e_T}$$

$$\text{and } \Delta U / \Delta T_w = \frac{\beta' + Ap}{e_T},$$

where β' = the change of saturation vapour pressure with temperature at temperature T_w .

Tables II and III show the values of ΔU for a 10 per cent change in the value of A and a change of 1 °C in T_w respectively, for constant atmospheric conditions.

Table II. The change in the relative humidity derived from given wet- and dry-bulb temperatures, for a 10 per cent change in the value used for the psychrometer coefficient

T (°C)	U (per cent)					
	0	20	40	60	80	100
	%	%	%	%	%	%
0	6.4	5.1	3.8	2.5	1.2	0
5	5.8	4.5	3.3	2.2	1.1	0
10	5.2	4.0	2.9	1.9	0.9	0
15	4.6	3.5	2.5	1.6	0.8	0
20	4.0	3.0	2.2	1.4	0.7	0
25	3.5	2.6	1.8	1.2	0.5	0
30	3.0	2.2	1.5	1.0	0.5	0

Table III. The change in the derived relative humidity for a change of 1 °C in the value of the wet-bulb temperature ($A = 0.667 \times 10^{-3} \text{ K}^{-1}$)

T (°C)	U (per cent)					
	0	20	40	60	80	100
	%	%	%	%	%	%
0	15.9	16.3	16.7	17.2	17.7	18.2
5	11.9	12.4	13.0	13.5	14.1	14.6
10	9.2	9.7	10.3	10.9	11.5	12.1
15	7.2	7.7	8.3	9.0	9.7	10.4
20	5.6	6.3	6.9	7.6	8.3	9.1
25	4.5	5.1	5.8	6.6	7.3	8.1
30	3.6	4.3	5.0	5.8	6.5	7.3

2.3 Time-constant of the psychrometer

The behaviour of the dry-bulb thermometer when the temperature changes is discussed in Volume 2. It is shown that the value of the time-constant, τ_d , of the dry-bulb thermometer is given by

$$\frac{1}{\tau_d} = \frac{mc_p}{C},$$

where m = the mass of air flowing past the thermometer bulb in unit time,

c_p = the specific heat of air at constant pressure, and

C = the thermal capacity of the dry bulb.

A similar treatment can be given to the wet-bulb thermometer. Suppose a mass m , of moist air flows past the thermometer bulb in unit time and in so doing has its temperature changed from its normal value, T , to that of the thermometer, T_w . If m_v is the mass of water vapour contained in the mass m , and the heat given up by the air in a short time Δt is Q , then

$$Q = [(m - m_v)c_p + m_v c_p'] (T - T_w) \Delta t \\ = [mc_p + m_v(c_p' - c_p)] (T - T_w) \Delta t,$$

where c_p' = the specific heat of water vapour at constant pressure.

From equation (1), $m_v = q(m_v + m_a) = qm$. The value of q is small (maximum about 0.04 kg kg^{-1}) and $(c_p' - c_p) \approx 0.9c_p$.

Thus $Q \approx mc_p (T - T_w) \Delta t$.

If mass m_s of air becomes saturated and Q' is the heat required for evaporation of water from the wet bulb in time Δt , then

$$Q' = m_s(r_s - r)L\Delta t,$$

where r_s = the saturation mixing ratio,

r = the mixing ratio, and

L = the latent heat of evaporation.

$$\text{But } r_s \approx \frac{0.622e_s}{p} \quad \text{and } r \approx \frac{0.622e}{p},$$

$$\text{thus } Q' \approx \frac{0.622m_s(e_s - e)}{p} L\Delta t.$$

The net quantity of heat absorbed by the wet bulb, of thermal capacity C_w , in changing its temperature by an amount ΔT_w , is given by

$$C_w \Delta T_w = Q - Q',$$

$$\text{i.e. } C_w \Delta T_w = -[mc_p(T_w - T) + \frac{0.622m_s(e_s - e)L}{p}] \Delta t.$$

Therefore

$$\frac{\Delta T_w}{\Delta t} = -\left[\frac{mc_p(T_w - T)}{C_w} + \frac{0.622m_sL(e_s - e)}{C_wp}\right].$$

$$\text{But } \frac{\Delta T_w}{\Delta t} = -\frac{1}{\tau_w}(T_w - T),$$

where τ_w is the time-constant of the wet-bulb thermometer.

Therefore

$$\frac{1}{\tau_w} = \frac{mc_p}{C_w} + \frac{0.622m_sL\beta'}{C_wp},$$

where β' is approximately de_s/dT_w at temperature T_w .

C will be less than C_w because of the covering of material and water on the wet bulb, but the effect of the additional factor in $1/\tau_w$ normally causes τ_w to be less than τ_d for a thermometer of the same size and exposed to the same ventilation.

As with the dry bulb (see Volume 2), the time-constant of the wet bulb varies with the ventilation rate and may be represented by an equation in the form $\tau_w = K(\rho v)^{-n}$, where K is a constant and n is less than unity. Some indications of the values of τ_d for dry-bulb thermometers are given in Table IV together with the value of τ_w for a mercury-in-glass wet bulb. The corresponding values of n are also included.

When the ventilation rate is high it may be assumed that $m = m_s$. The ratio of the time-constants of dry- and wet-bulb thermometers of the same size, at the same ventilation rate and with approximately the same thermal capacity, will then be given by

$$\frac{\tau_w}{\tau_d} = \frac{mc_p C_w}{C} \left[\frac{1}{mc_p + \frac{0.622mL\beta'}{p}} \right] \approx \left[\frac{1}{1 + \frac{0.622L\beta'}{pc_p}} \right] \quad \text{if } C \approx C_w.$$

The values of this ratio, for various wet-bulb temperatures T_w , are given in Table V for a pressure of 1000 mb.

The main trend again in this table is borne out in practice, but the actual values of τ_w/τ_d will be appreciably greater than those given because C_w will be greater than C owing to the film of water on the bulb and the wet-bulb covering. In the United Kingdom values of 0.5 to 0.7 are likely to be typical at temperatures above 0 °C.

Table IV. Time-constants of various thermometers

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

Table V. Ratio of wet-bulb to dry-bulb time-constants

T_w (°C)	30	20	10	0	-10	-20
τ_w/τ_d	0.21	0.31	0.44	0.57	0.71	0.85

2.4 Screen-type psychrometer

The commonest type of psychrometer is a pair of mercury-in-glass thermometers or electrical resistance thermometer elements, one dry-bulb and one wet-bulb, exposed in a screen (either large, ordinary or marine) without further ventilation. Details of these thermometers and thermometer elements, and their general arrangement in the screen can be found in Volume 2; the wet bulb is supported in a similar manner and is of a similar type to the dry bulb. General instructions with regard to the use and care of wet bulbs are given in section 2.8.

2.5 Sources of error in humidity derived from the screen psychrometer

Errors in derived humidity due to use of an incorrect psychrometer coefficient. Errors of this nature are most likely to occur at low ventilation rates since it is under such conditions that the value of A departs most from the constant values usually assumed. Folland (1977) calculated values of A , for thermometers in use in the Meteorological Office, using Kondo's formulae and compared them with values obtained experimentally in the Meteorological Office wind-tunnel. These values, shown in Table VI, illustrate the dependence of A on ventilation rate; the bulb diameters include the thickness of the wet-bulb covering.

The values of A used by the Meteorological Office (see Table VII) depend on the method of ventilation (i.e. natural or forced) and the condition of the wet bulb (i.e. ice- or water-covered). Folland suggests that in a large screen the mean ventilation rate is about 15 per

cent of the mean wind speed at 10 m. For a mean wind speed at 10 m of 5 m s⁻¹ (close to the average yearly mean 10 m wind speed over the British Isles) the corresponding mean ventilation rate is about 0.75 m s⁻¹. A similar investigation by Bultot and Dupriez (1971) showed that in a large screen a ventilation rate of 1 m s⁻¹ was reached only very exceptionally and that more often it was between 0.2 and 0.6 m s⁻¹.

Whatever value is assumed for a mean ventilation rate, however, there will always be a superimposed natural variation, with a corresponding variation in the value of A .

Table VI. Values of the psychrometer coefficient, (a) based on work of Kondo and (b) from Folland

Ventilation rate m s ⁻¹	Spherical bulb, diameter 12 mm		Cylindrical resistance bulb, diameter 8 mm	
	(a)	(b)	(a)	(b)
	$\times 10^{-3} \text{ K}^{-1}$		$\times 10^{-3} \text{ K}^{-1}$	
0	0.90	1.31	0.96	1.01
0.3	0.73	1.10	0.77	0.80
1.0	0.68	0.88	0.71	0.72
2.0	0.66	0.83	0.68	0.67
3.0	0.65	0.81	0.66	0.66
5.0	0.63	0.79	0.65	0.66

Table VII. Values of the psychrometer coefficient used by the Meteorological Office

Ventilation	Wet-bulb temperature	
	0 °C or greater	less than 0 °C
	$\times 10^{-3} \text{ K}^{-1}$	
Natural (1-1.5 m s ⁻¹)	0.799	0.720
Forced ($\geq 3.6 \text{ m s}^{-1}$)	0.666	0.594

Errors in derived humidity due to errors in the wet-bulb temperature. Errors in the wet-bulb thermometer reading are usually due to one or more of the following causes:

- Errors in the thermometer itself (dealt with in Volume 2).
- Too thick a covering of material (or ice) on the wet bulb will increase the thermometer time-constant. Errors in the wet-bulb reading will consequently be greatest during conditions of rapidly changing humidity. However, since the time-constant of a wet-bulb thermometer is normally appreciably less than that of a dry-bulb thermometer (assuming identical thermometers) this effect is not usually significant.
- A contaminated wet-bulb covering or the use of impure water. Either will lower the saturation vapour pressure over the wet bulb and result in an apparent increase in wet-bulb temperature.
- Uncertainty, at wet-bulb temperatures below 0 °C, as to whether the wet bulb is water- or ice-covered or both.
- Stem heat conduction, due to the use of a badly designed wet-bulb covering.
- Insufficient ventilation in the screen.

Errors from (a) are usually small and can, where appropriate, be eliminated by application of the thermometer index correction. Careful maintenance of the wet bulb and the water reservoir will eliminate or minimize errors due to (b), (c) or (d).

Conduction of heat down the stem of the thermometer will cause an apparent increase in

wet-bulb temperature. Unless, therefore, a corresponding increase is made in the value used for A the derived humidity will be in error. In Table VI the differences between theoretical and experimental values for the Meteorological Office spherical bulb illustrate the magnitude of the required adjustment to A to compensate for stem heat conduction when the thermometer is fitted with a fabric cap.

The values of A in Table VII are those adopted by Pernter (1903) and, being based on experiments with glass thermometers, implicitly take stem heat conduction into account. The value of $0.799 \times 10^{-3} \text{ K}^{-1}$ for a naturally ventilated psychrometer, however, differs from the experimental values in Table VI for both spherical and resistance bulbs. The Meteorological Office electrical resistance thermometer element Mk 2, used with its length (100 mm) covered with tubular wick, is known to exhibit negligible stem heat conduction, as shown by the close agreement between theoretical and experimental values for A . Conversely, the mercury-in-glass thermometer fitted with a fabric cap is shown by Folland to exhibit appreciably more stem heat conduction than is implied in Pernter's value of $0.799 \times 10^{-3} \text{ K}^{-1}$ for A . Folland shows, however, that the excess stem heat conduction can be largely eliminated by enclosing the outer sheath of a mercury-in-glass thermometer in tubular wick for a distance of approximately 50 mm above the thermometer neck, and in contact with the fabric cap on the bulb. That part of the stem immediately in contact with the bulb itself is then always at a temperature very close to the bulb temperature no matter how large the wet-bulb depression. Values of A with this arrangement are shown in Figure 1.

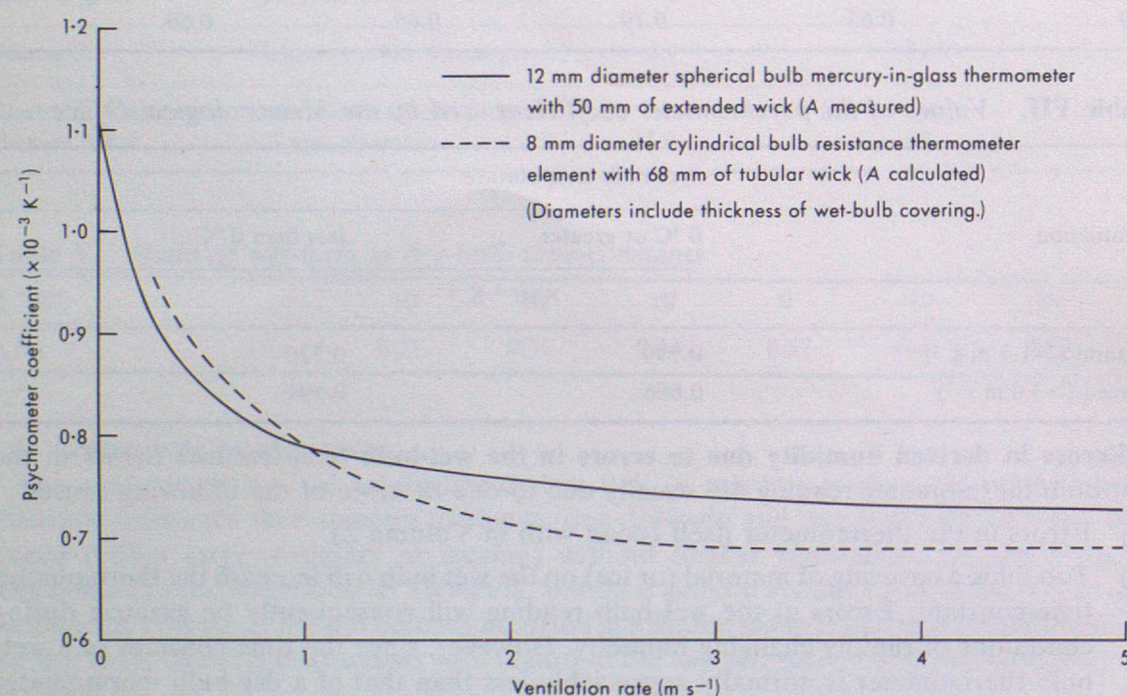


Figure 1. Comparison of psychrometer coefficients

With the electrical resistance thermometer element Mk 2, largely because of its different geometry, it is necessary to introduce stem heat conduction in order to produce a wet bulb similar in performance to the mercury-in-glass thermometer with long wick. This is achieved by reducing the length of stem covered with tubular wick from 100 mm to about 68 mm. From Figure 1 it can be seen that both thermometers now have a value for A , at about 0.9 m s^{-1} , approaching $0.799 \times 10^{-3} \text{ K}^{-1}$, close to the value due to Pernter used in the *Hygrometric tables*.

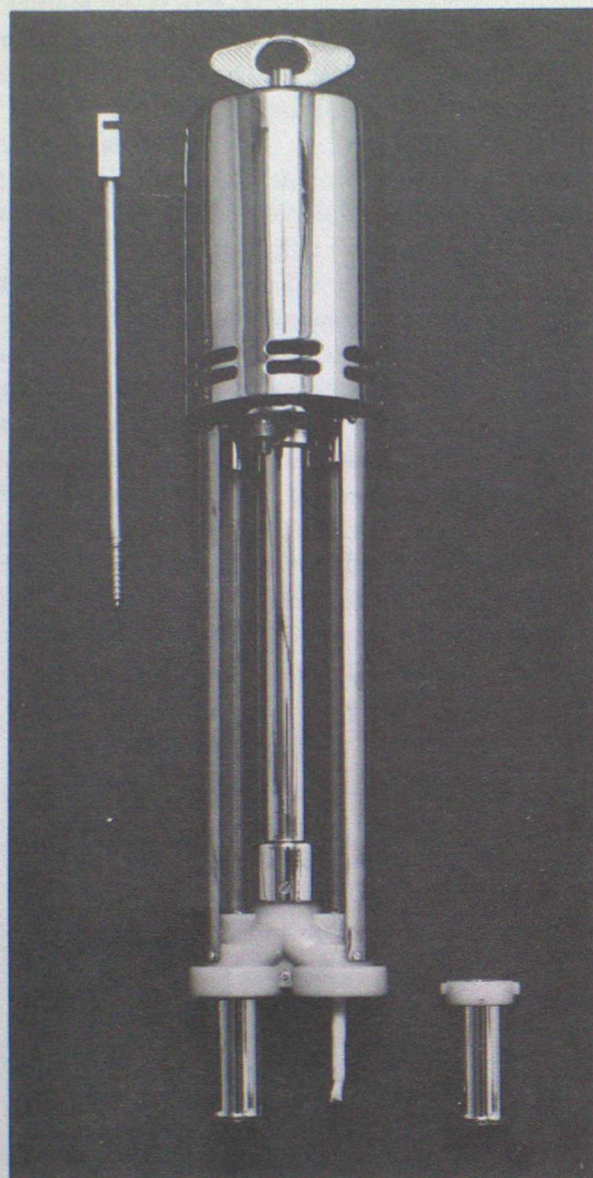


Plate I Clockwork-aspirated psychrometer Mk 3

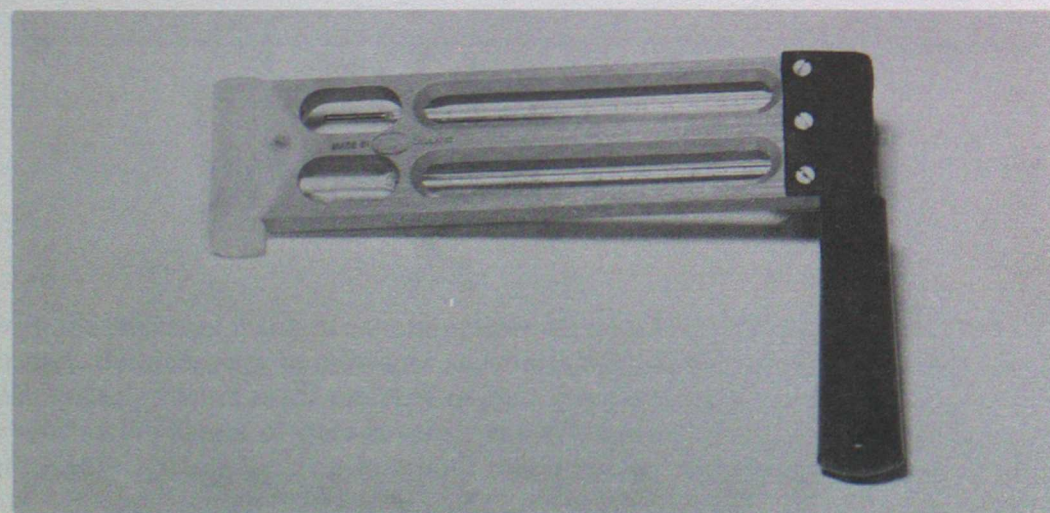


Plate II. Whirling psychrometer

Evaporation of water from the wet-bulb covering produces a layer of moist air around the bulb normally removed by the flow of air past the bulb. In the absence of such a flow, the moist air is removed by the slower process of diffusion, and evaporation at the wet bulb is reduced. Consequently the wet-bulb thermometer will indicate too high a temperature. An investigation by Painter (1973) into the performance of wet-bulb thermometers in a large screen suggests that with light winds a mercury-in-glass thermometer with fabric cap can produce an error as large as $+0.85^{\circ}\text{C}$. Similarly, an electrical resistance thermometer element with tubular sleeve may be in error by $+0.15^{\circ}\text{C}$.

Errors in derived humidity due to errors in the dry-bulb temperature. Errors in dry-bulb readings can arise owing to moisture on the dry-bulb thermometer (George, 1970). The moisture, which may be the result of condensation during water-fog or other cause, may be deposited on the bulb of a thermometer in a screen. This moisture may not evaporate until some hours after fog dispersal or removal of other cause of water deposition. Significant under-reading of the dry-bulb temperature could therefore occur when the relative humidity has fallen below 100 per cent, resulting in erroneous humidity data. If ΔT is the change in dry-bulb temperature, the change, ΔU , in derived humidity is given by

$$\frac{\Delta U}{\Delta T} = -\frac{\beta U + A p}{e_T + \beta \Delta T},$$

where β is the change in saturation vapour pressure with temperature at temperature T .

Table VIII shows the change in derived humidity for a change of 1°C in the dry-bulb temperature.

Table VIII. The change in the derived relative humidity for a change of 1°C in the value of the dry-bulb temperature ($A = 0.667 \times 10^{-3} \text{ K}^{-1}$)

$T (^{\circ}\text{C})$	U (per cent)					
	0	20	40	60	80	100
	%	%	%	%	%	%
0	4.9	3.9	2.9	1.9	0.9	0
5	4.3	3.4	2.5	1.7	0.8	0
10	3.7	2.9	2.2	1.4	0.7	0
15	3.2	2.5	1.9	1.2	0.6	0
20	2.8	2.1	1.6	1.0	0.5	0
25	2.4	1.8	1.3	0.9	0.4	0
30	2.0	1.6	1.1	0.7	0.4	0

Any moisture deposited on the bulb of a (normally dry) thermometer in a screen should be removed using a clean tissue, blotting paper or cloth, taking care not to warm the thermometer. Such cleaning should not be undertaken during the 10 minutes before taking a dry-bulb temperature reading.

Errors in the dry-bulb reading due to insufficient ventilation in the screen are dealt with in Volume 2.

2.6 Aspirated psychrometers with mercury-in-glass thermometers

Clockwork-aspirated psychrometer Mk 3 (Plate I). The clockwork-aspirated psychrometer Mk 3 comprises essentially two parts, a duct assembly and a detachable motor-driven fan. The duct assembly consists of a chromium-plated highly polished frame, with a central (hollow) column joined by a bifurcated nylon duct to two coaxial double-walled radiation shields. Air is drawn through the shields by means of the fan mounted at the top of the central column. The thermometers are mounted in the frame, either side of the central column,

through holes in the top mounting plate and the bifurcated duct so that the thermometer bulbs are surrounded by the radiation shields.

One full winding of the motor will maintain a constant ventilation rate, for at least seven minutes, in the range 3.0 to 4.5 m s⁻¹.

Fitting the thermometers

- (1) Loosen the captive knurled nuts protruding below the mounting plate at the top of the duct assembly. Holding the motor casing, turn the duct assembly a quarter turn to the left and lift off.
- (2) Rotate the knurled thermometer clamping ring on the top of the duct assembly until the two cut-outs coincide with the thermometer holes.
- (3) Check that the thermometers are roughly in agreement and that there are no breaks in the mercury columns. A broken mercury column can usually be rejoined by steadily swinging the thermometer backwards and forwards, or by holding the thermometer in a vertical position and gently tapping the bulb on a slightly resilient pad.
- (4) Insert the thermometers, bulbs downwards, through the holes in the top of the duct assembly and carefully lower so that the bulbs enter the appropriate holes in the bifurcated nylon duct and, at the same time, ensure that the thermometer scales are aligned and facing the same direction for easy and correct reading. The thermometers may now be pressed home by applying a slight pressure to the metal caps. When correctly in position the top of the metal caps will be slightly recessed below the top surface of the duct assembly. Rotate the knurled thermometer clamping ring so that the thermometers are locked in place.
- (5) Replace the motor by engaging the captive knurled nuts in the appropriate holes in the top of the duct assembly, turn the duct assembly to the right and tighten the captive nuts.

Installation and exposure. For normal measurements of wet- and dry-bulb temperatures the psychrometer should be mounted so that the air intakes are 1.25 m above ground level. The support rod provided may be screwed into any convenient object, preferably a thin post in an open situation. If the supporting medium is of any appreciable size, the instrument should be mounted on the windward side. If no convenient support is available the psychrometer may be held in the hand, as far as possible from the body and to the windward. In this case the psychrometer may be tilted slightly so that the air intakes face into the wind, but care should be taken to avoid pointing the psychrometer in the direction of the sun. If the wind speed at the level of the psychrometer is greater than 12 kn and the psychrometer is hanging vertically from the support rod, inaccuracies in the readings may occur; the psychrometer should be hand-held instead, tilted into the wind, as described above.

Method of use

(a) **Fitting the wick.** To prepare the wet bulb it is first necessary to remove one of the radiation shields by giving it a short turn to the left. A piece of tubular wick may then be slipped over the thermometer bulb, the wick being of sufficient length to extend at least 12 mm above the thermometer shoulder. Cotton thread should be used to tie one end of the wick securely around the neck of the thermometer, and the other end immediately below the bottom of the thermometer bulb. There should be as little spare wick as possible below the bottom tie. It may be found that the dimension between the top of the shoulder and the neck of the thermometer is such that the thermometer neck is too far inside the lower nylon assembly to allow the wick to be tied around the neck *in situ*. In this case the thermometer must be removed, the wick fitted, and the thermometer then replaced.

(b) **Moistening the wick.** The wick should be moistened by means of the injector provided, which consists of a tube connected to a water container. The injector is filled with distilled or deionized water and is squeezed to force the water to the top of the tube. The wick-covered thermometer bulb is then introduced into the tube and left there until the wick is completely

saturated. The wick should never be moistened by using the injector as a syringe. If, after saturation, there is a residual drop of water on the bottom of the wick, the drop should be removed by touching it with the end of the injector tube.

(c) **Thermometer readings.** Unless the water used to moisten the wet bulb is already at about the wet-bulb temperature, a period of about 2 minutes may be required for the wet-bulb thermometer reading to stabilize. Wind the clockwork motor fully, taking care not to overwind, and place the instrument in its correct position (see page 3-14). The thermometers should be read at approximately half-minute intervals until, in the usual situation, a steady state is reached, when consecutive readings should agree to within 0.1 °C. If the air temperature and humidity are reasonably constant the steady state will be observed about two minutes after commencement of aspiration. Occasionally, when conditions are more variable, consecutive readings may vary by as much as 0.5 °C, and under these circumstances it is best to take the mean of readings at half-minute intervals from minute two to minute five. The thermometers should be read to the nearest 0.1 °C. Apply any necessary index corrections to the thermometer readings.

The wet bulb should be managed in accordance with the general principles outlined later (page 3-16), especially with regard to treatment when the wet-bulb temperature is below 0 °C, cleanliness of the wick and use of suitable water.

Readings should be taken only when the aspiration fan is rotating at its normal speed; as soon as a slackening of the fan speed becomes noticeable through lowering of the pitch of the note produced, the motor should be rewound before taking any further readings.

The Meteorological Office humidity slide-rule Mk 6 or Mk 6A (see section 2.10) may be used to obtain the value of the dew-point or other humidity parameters from the observations, using either scale 2B or 2C for the wet-bulb depression. Alternatively the Meteorological Office *Hygrometric tables* Part III (°C aspirated) may be used.

Maintenance. The chromium plated parts of the instrument should be rubbed from time to time with a dry clean soft cloth; metal polish should not be used. The bearings of the clockwork motor may be oiled occasionally with a little clock oil. To gain access to the motor, the winding key must be removed by unscrewing anticlockwise, and then the six screws in the casing removed. The casing will then slide off exposing the motor.

If the thermometers fit slackly and, as a result, tend to vibrate round when the motor is running, it is an indication that the 'O' rings require changing. This operation necessitates the complete dismantling of the duct assembly and should only be carried out by trained personnel.

Accuracy and sources of error. Ambient wind can affect the ventilation rate of the psychrometer depending on the position of the psychrometer with relation to the wind direction. Figure 2 shows the three possible positions of the wet-bulb thermometer, X, for a vertically mounted psychrometer.

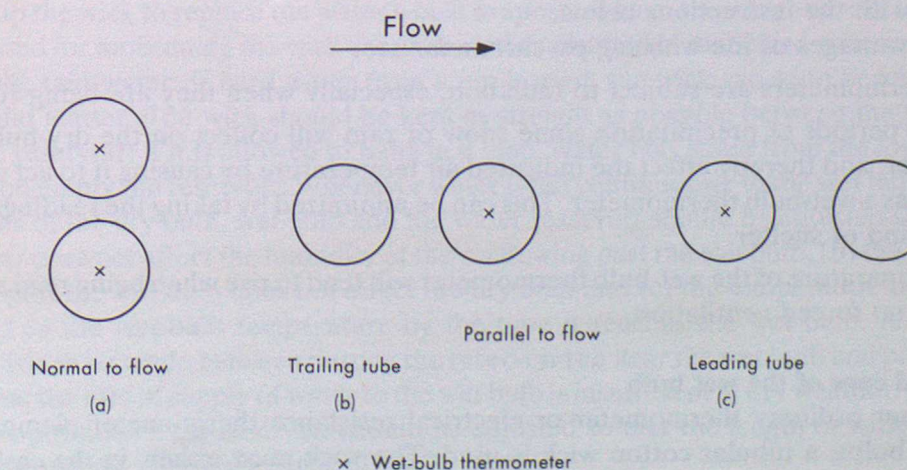


Figure 2. Ventilation of the aspirated psychrometer Mk 3

In Figure 2(a), where the wet-bulb thermometer can be in either tube, the ventilation rate can fall below 3 m s^{-1} with a wind speed of about 16 kn and even reverse in direction above 18 kn; Figure 2(b) is completely different, the ventilation rate continuing to rise as ambient wind speed increases. Figure 2(c) is probably the most severe, the ventilation rate becoming inadequate above 12 kn ambient wind speed. Figure 2(b) and (c) can obviously occur simultaneously. With the psychrometer held at 45° into the wind the ventilation rate increases as the wind speed increases.

Assuming adequate ventilation and provided care is taken over the preparation of the wet bulb and the making of the observations, the average dry- and wet-bulb temperatures of the air should be obtained with an uncertainty of about 0.1°C , except possibly when there are especially large changes in temperature or humidity or in conditions of strong solar radiation.

Electric aspirated psychrometer Mk 3. The general construction of the electric aspirated psychrometer Mk 3 is similar to that of the clockwork-aspirated psychrometer Mk 3, but an electric motor is used to drive the aspirating fan. The ventilation is maintained at a constant rate in the range 4.5 to 9 m s^{-1} .

The general instructions regarding the use and care of the clockwork-aspirated psychrometer Mk 3 apply equally to the electric aspirated psychrometer Mk 3.

2.7 Whirling or sling psychrometers

The small portable type of whirling or sling psychrometer (Plate II) consists of two mercury-in-glass thermometers mounted in a frame which is provided with a handle and spindle, by means of which the frame and thermometers may be rotated quickly about a horizontal axis. The end of the wet-bulb covering dips into a small cylindrical water tank at the end of the frame.

The frame should be rotated rapidly so that the thermometer bulbs pass through the air at a speed of at least 2.5 m s^{-1} . With the psychrometer illustrated the thermometer bulbs are approximately 180 mm from the spindle, so that it should be rotated at a rate of at least three revolutions per second.

The psychrometer should always be rotated in front of and to windward of the observer and in the shade. The effect of radiation on the reading is then not great while the thermometers are being rotated, but when the psychrometer is held steady to be read the effect may be serious. With a little practice a technique can be developed of stopping the instrument smoothly. Several test readings should be taken after the first 30 seconds or so of rotation, until it is observed that consecutive readings of the dry- and wet-bulb temperatures agree to within 0.1°C . This should normally take $1\frac{1}{2}$ –2 minutes, but the time required may be longer in some circumstances. The steady readings should then be noted to the nearest 0.1°C , the wet-bulb temperature being read first. The wet bulb should be managed in accordance with the instructions below.

The disadvantages of the whirling psychrometer are:

- The thermometers are subject to radiation, especially when they are being read.
- During periods of precipitation some snow or rain will collect on the dry-bulb thermometer, and thereby affect the indicated air temperature by causing it to act in some degree as a wet-bulb thermometer. This can be minimized by taking the readings under some kind of shelter.
- The temperature of the wet-bulb thermometer will tend to rise when being read as there is then no forced ventilation.

2.8 Use and care of the wet bulb

When either ordinary thermometer or electrical resistance thermometer elements are used as wet bulbs, a tubular cotton wick is used. The wick must either, in the case of an ordinary thermometer, cover the bulb and extend up the stem, or cover the resistance thermometer element, and in both cases for a specified length (see below). The length of the

wick actually covering the thermometers is important, not only to accord with the physical factors affecting the derivation of humidity, but also to obtain readings which are consistent between each of these two types of thermometer. In both cases the wick should be tied off with cotton thread just below either the bulb of the ordinary thermometer or the tip of the resistance thermometer element and again, for an ordinary thermometer, immediately above the bulb. The wick is continued up the stem for 50 mm for the ordinary thermometer and tied again, and 68 mm for the resistance thermometer element Mk 2, as shown in Figure 3. The object with wet-bulb coverings is to make them stretch smoothly and closely over the thermometer, avoiding creases as far as possible.

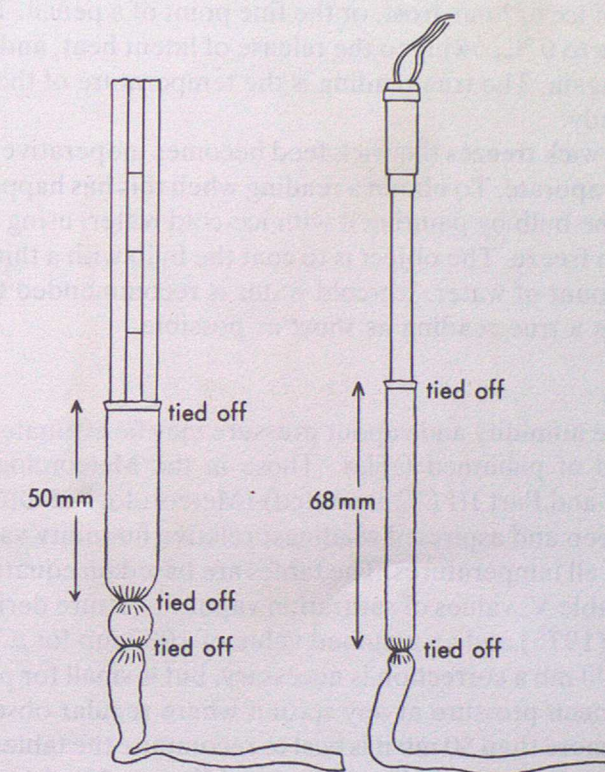


Figure 3. Wet-bulb coverings

The wick is led from the thermometer into a reservoir of water. Capillary action causes water to rise up the wick to replace the water which evaporates from the wick exposed to the air. The water used for moistening the wick should be either distilled or deionized water or, if this is not available, rain-water. If hard water from a tap is used, the wick can soon become encrusted with solid matter. The wick should be kept as straight as possible between the thermometer and the reservoir; if it is allowed to hang in a loop, water may drain from the lowest part and thus soon empty the reservoir. Whenever water is fed continuously to the wet bulb the relative positions of the dry bulb, wet bulb and the water reservoir should be adjusted so that (a) the reservoir does not affect the humidity of the air flowing past the wet bulb, (b) the air which has flowed past the wet bulb does not affect the dry bulb and (c) the temperature of the water is reduced to the wet-bulb temperature by the time it reaches the wet bulb. A compromise usually has to be made between putting the reservoir too near the wet bulb and putting it so far away that the rate of supply of water to the wet bulb is insufficient in dry weather. In the British Isles the position of the reservoir should be adjusted so that the length of wick between the reservoir and the thermometer is 50 to 75 mm.

The wick should always be changed before it gets contaminated. In rural areas once a week may suffice, but at stations near the coast or large industrial areas more frequent changes will

be needed. At coastal stations the water in the reservoir, as well as the wick, should be changed at any time that it is suspected that sea water spray may have entered the screen. This is especially likely to happen during a storm with an onshore wind. An interval of at least 15 minutes should elapse between changing the wick and taking a reading; a longer time will be necessary if the clean water supplied is not approximately at the temperature of the air.

To ensure the best results, lengths of newly received wick should be boiled in water containing a little liquid detergent for an hour and then rinsed thoroughly in distilled or deionized water. It may be convenient to store lengths of prepared wick in a container of distilled or deionized water.

If the wet bulb is covered with supercooled water, this should be induced to freeze by touching it with a piece of ice or hoar-frost, or the fine point of a pencil. The temperature of the wet bulb will then rise to 0 °C, owing to the release of latent heat, and, after all the water has frozen, slowly drop again. The true reading is the temperature of the ice bulb when the reading has become steady.

When the water in the wick freezes the wick feed becomes inoperative, and eventually all the ice on the bulb will evaporate. To obtain a reading when this has happened an ice coating has to be re-formed on the bulb by painting it with ice-cold water, using a camel-hair brush and inducing the water to freeze. The object is to coat the bulb with a thin layer of ice, using the smallest possible amount of water. Ice-cold water is recommended to make the period before the bulb indicates a true reading as short as possible.

2.9 Hygrometric tables

The dew-point, relative humidity and vapour pressure may be evaluated from psychrometer readings with the aid of published tables. Those in the Meteorological Office *Hygrometric tables* Part II (°C) and Part III (°C aspirated) (Meteorological Office, 1961) give the respective values for screen and aspirated readings; relative humidity values are given with respect to liquid water at all temperatures. The tables are based on equation (2), incorporating the values for A in Table V, values of saturation vapour pressure derived from formulae due to Goff and Gratch (1975) and an assumed value of 1000 mb for p . If the atmospheric pressure differs from 1000 mb a correction is necessary, but is small for pressure differences less than 50 mb. If the mean pressure at any station where regular observations are made differs from 1000 mb by more than 50 mb it is best to recompute the tables to allow for this or to use the Meteorological Office humidity slide-rule Mk 6 or Mk 6A.

2.10 Meteorological Office humidity slide-rules Mk 6 and Mk 6A

The Meteorological Office humidity slide-rule Mk 6 (Plate III) is designed to enable the dew-point, frost-point, relative humidity, vapour pressure, mixing ratio, specific humidity and vapour density to be computed quickly and easily from psychrometric observations, either screen or aspirated, and either at ground level or in the upper air, and from radiosonde data and dew-point hygrometer readings. The formulae and coefficients used in its design are the same as those incorporated in the *Hygrometric tables*. It consists of a stock and slide with scales on both sides of each, and a cursor. It is made of rigid PVC which does not warp with changes of humidity and temperature.

Scale 1 on the front of the stock is a scale of temperature with the distance of each graduation from an arbitrary zero proportional to the saturation vapour pressure over water at that temperature. It covers the range -35 °C to 33 °C. Scale 2 on the slide and scale 2B on the reverse of the slide are linear scales of temperature with the spacings between the 1 °C graduations 0.799 and 0.666 respectively of the distance corresponding to 1 mb on scale 1. Thus if the reading of the wet-bulb temperature, T_w , on scale 1 is brought opposite the reading of the wet-bulb depression, $T - T_w$, on scale 2, the zero of scale 2 will indicate on scale 1 a temperature at which the saturation vapour pressure is equal to

$$e_s - 0.799 (T - T_w),$$

i.e. it will indicate the dew-point, if the readings were obtained at a pressure of 1000 mb from a psychrometer exposed in a screen and the wet-bulb temperature was above 0 °C. Similarly



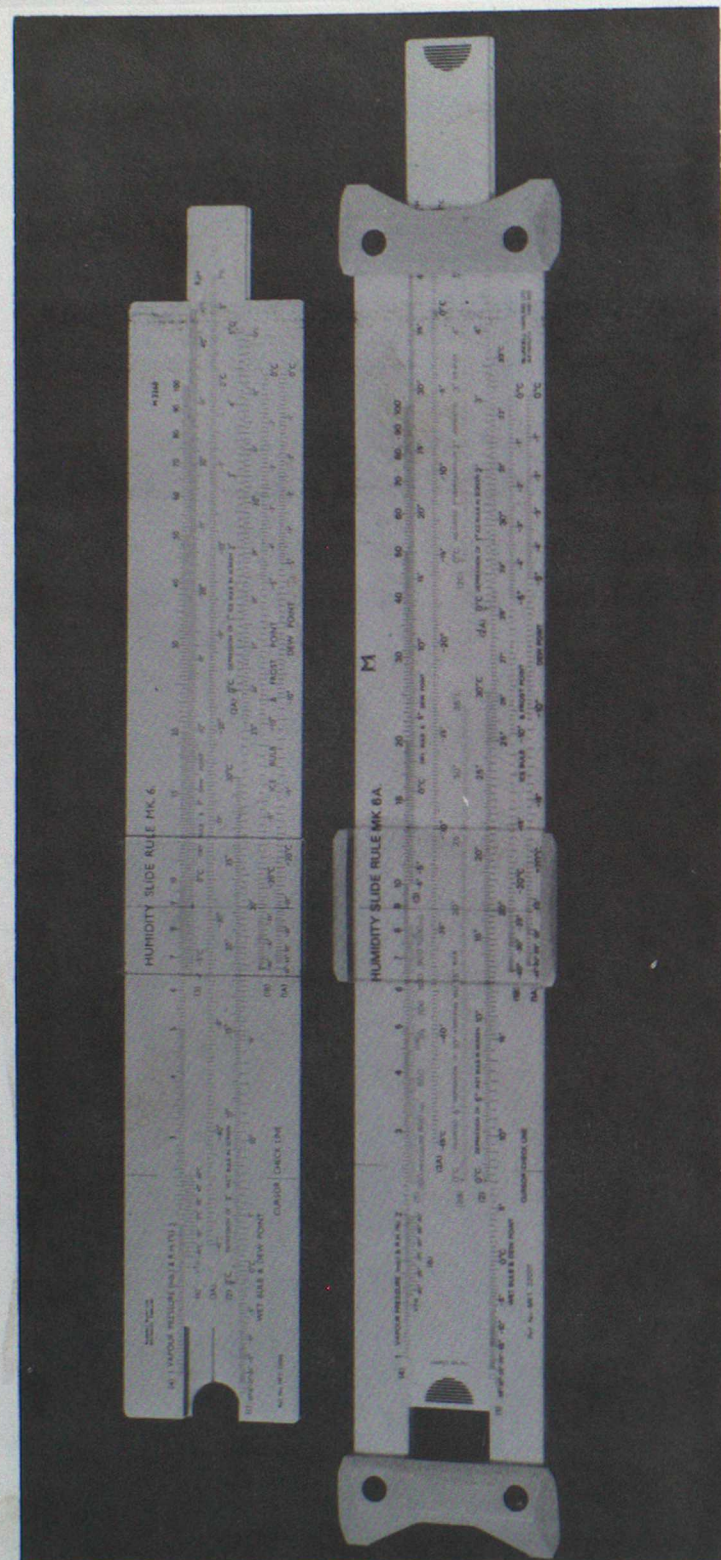


Plate III. Meteorological Office humidity slide-rules Mk 6 and Mk 6A

scale 2B (in red) on the reverse of the slide can be used for aspirated psychrometer readings.

Scale 1A on the front of the stock is a scale of temperature similar to scale 1, but with a greatly increased scale value in terms of millimetres per millibar, so that it can cover the range -45°C to 0°C without the graduations becoming unduly crowded. It has a different arbitrary zero from scale 1. Scale 1B is similar to scale 1A, but is obtained by using the saturation vapour pressure over ice in place of the saturation vapour pressure over water. It covers the range -40°C to 0°C and uses the same zero as scale 1A. Scale 2A on the slide and scale 2C (in red) on the reverse of the slide are linear scales of temperature from 0°C to 5°C with the distances between graduations 1°C apart equal to 0.720 and 0.594 respectively of the distance corresponding to 1 mb on scales 1A and 1B. These four scales can therefore be used in conjunction with each other to evaluate the dew-point when the wet bulb is frozen by setting the ice-bulb temperature on scale 1B and reading the dew-point on scale 1A, after setting the ice-bulb depression on either scale 2A or 2C, according to the type of psychrometer.

Scale 3 is a scale of temperature on the top of the slide ranging from -6°C to 43°C , with the distance of each graduation from an arbitrary zero proportional to the logarithm of the saturation vapour pressure over water at that temperature. Scale 3A is similar to scale 3, but the distance of each graduation from the same zero as used for scale 3 is proportional to the logarithm of ten times the saturation vapour pressure. It ranges from -45°C to $+7^{\circ}\text{C}$. These two scales which occur on both sides of the slide are used in conjunction with scale 4, which is an ordinary logarithmic scale from 1 to 1000 using the same scale value as is used for the logarithms in scales 3 and 3A. The RH (relative humidity) mark at the end of scale 3 is the point corresponding to a vapour pressure of 100 mb; thus if the RH mark on the slide is set opposite the 100 on scale 4 each temperature graduation on scale 3 is opposite the corresponding value of the saturation vapour pressure over water in millibars on scale 4, and each graduation of scale 3A is opposite a figure of ten times this quantity. The relative humidity can be quickly obtained by dividing the actual vapour pressure (found from the dew-point) by the saturation vapour pressure at the dry-bulb temperature.

Scale 5 on the reverse of the slide is a logarithmic scale from 300 to 1050 with the same scale value as scale 4, and is used for applying the pressure correction to the psychrometric readings from aircraft or at high-level stations, and for calculating the mixing ratio and specific humidity. Scale 6 is used to calculate the vapour concentration (vapour density). The distance of each temperature graduation, $T^{\circ}\text{C}$, from the mark VD is proportional to the logarithm of the function $216.7/(273.15 + T)$.

Scale 7 on the back of the stock consists of three parts; the top is a simple logarithmic scale from 0.00009 to 0.500, the centre is a temperature scale from -90°C to -30°C with each graduation opposite the value on the top scale of the saturation vapour pressure over ice at that temperature, and the lowest scale is another temperature scale from -51°C to -32°C with each graduation opposite the value on the top scale of the saturation vapour pressure over water at that temperature. Scale 7 can be used to find the vapour pressure if the frost-point or dew-point is known, and to find the frost-point given the dew-point, and vice versa. There are, as yet, no internationally agreed values of vapour pressure over liquid water at temperatures lower than -50°C .

The Meteorological Office humidity slide-rule Mk 6A differs from the Mk 6 slide-rule as follows:

- It does not have a reversible slide, the aspirated scales (coloured red) being positioned in the centre of the slide.
- It has additional scales on the back of the stock. These are C and D, logarithmic scales from 1 to 10, and TA and TB, tangent scales from 6° to 84° .
- Its scales are compressed by approximately 7 per cent.

Method of use. The following procedures apply to both the Mk 6 and the Mk 6A slide-rules, the numbers in brackets referring to the scales to be used with aspirated observations.

Computation from psychrometric observations (T , T_w). If the pressure at the observation level differs from 1000 mb by 50 mb or more it will be necessary to allow for this by computing an 'adjusted wet-bulb depression', and using this in place of the observed wet-bulb depression.

To compute an 'adjusted wet-bulb depression'

- (1) Set 1000 on scale 5 against $T - T_w$ on scale 4.
- (2) Set the cursor over the value of the air pressure at the observation level on scale 5 and read the 'adjusted wet-bulb depression' on scale 4. If $T - T_w$ is small, multiply it by 10 before the operation and divide the resulting value of adjusted wet-bulb depression by 10.

To compute the dew-point (T_d) and the frost-point (T_f)

- (a) If $T_w > 0^\circ\text{C}$, or $T_w \leq 0^\circ\text{C}$ but the wet bulb is not frozen:

- (1) Set the cursor over T_w on scale 1.
- (2) Bring $T - T_w$ on scale 2(2B) beneath the cursor.
- (3) Read T_d on scale 1 against the zero of scale 2(2B).

- (b) If $T_w \leq 0^\circ\text{C}$ and the wet bulb is frozen:

- (1) Set the cursor over T_w on scale 1B.
- (2) Bring $T - T_w$ on scale 2A(2C) beneath the cursor.
- (3) Set the cursor over the zero of scale 2A(2C) and read T_d from scale 1A, and T_f from scale 1B.

Computation from the dew-point (T_d). To compute the vapour pressure (e) and the relative humidity (U)

- (a) If $T_d \geq -6^\circ\text{C}$

- (1) Set RH on scale 3 against 100 on scale 4.
- (2) Set the cursor over T_d on scale 3.
- (3) Read e on scale 4.
- (4) Bring T on scale 3 beneath the cursor.
- (5) Read U on scale 4 against RH.

- (b) If $T_d < -6^\circ\text{C}$ and $T \leq 7^\circ\text{C}$

- (1) Set RH on scale 3 against 100 on scale 4.
- (2) Set the cursor over T_d on scale 3A.
- (3) Read e on scale 4 and divide the result by 10.
- (4) Bring T on scale 3A beneath the cursor.
- (5) Read U on scale 4 against RH.

- (c) If $T_d < -6^\circ\text{C}$ and $T > 7^\circ\text{C}$

- (1) Set RH on scale 3 against 10 on scale 4.
- (2) Set the cursor over T_d on scale 3A.
- (3) Read e under the cursor from scale 4.
- (4) Bring T on scale 3 beneath the cursor.
- (5) Read U on scale 4 against RH.

Computation from the vapour pressure (e). To compute the vapour concentration (d_v), mixing ratio (r), or specific humidity (q)

In all computations the cursor is set over e or $10e$ on scale 4, dividing the result by 10 when $10e$ is used.

- (a) Vapour concentration (d_v)

- (1) Bring T on scale 6 under the cursor.

- (2) Read d_v on scale 4 against VD on scale 6.

- (b) Mixing ratio (r)

- (1) Bring $p - e$ on scale 5 under the cursor (use $p - e$ not $p - 10e$ even when $10e$ is set on scale 4).

- (2) Read r on scale 4 against MR on scale 5.

- (c) Specific humidity (q)

- (1) Bring p on scale 5 under the cursor.

- (2) Read q on scale 4 against MR on scale 5.

3 HAIR HYGROGRAPH

3.1 Behaviour of the hair

Many hygroscopic organic substances alter their dimensions when their moisture content varies, e.g. hair, gold-beater's skin, and horn. The change in moisture content can be brought about by a change in the relative humidity of the air to which these substances are exposed, and these changes in dimension can be used to obtain an indication of relative humidity.

Human hair is one of the most sensitive of these substances and has been widely used in hygrometers since the eighteenth century, when the first known hair hygrometer was made by de Saussure. The change in length of the hair has been found to be a function primarily of the change in relative humidity with respect to liquid water (both above and below a temperature of 0°C) and not of the actual amount of water vapour in the air.

The length of the hair increases by about 2-2½ per cent when the relative humidity changes from 0 to 100 per cent. Although this overall extension varies from hair to hair, there is a fairly constant relation between the relative humidity and the elongation of the hair expressed as a fraction of the overall change in length, as shown in Table IX.

For relative humidities above 20 per cent the elongation is approximately proportional to the logarithm of the relative humidity.

Table IX. Average elongation of a hair as a percentage of the total elongation for 100 per cent change in relative humidity

Relative humidity (per cent)	0	10	20	30	40	50	60	70	80	90	100
Elongation as percentage of total change	0	21	39	53	64	73	79	85	90	95	100

Time-constant of the hair. The manner in which any given hair responds to fluctuations in humidity is not as simple as that in which a thermometer responds to changes in temperature. It is found that the ratio $(\Delta U / \Delta t) / (U - U_f)$, where U is the instantaneous indicated humidity and U_f the final or true value of the humidity, is not a constant for a given instrument depending only on ventilation, but depends on the actual indicated humidity U , on the temperature, on whether $\Delta U / \Delta t$ is positive or negative, on the tension of the hair, on the previous treatment of the hair, and also, to a limited extent, on the ventilation.

Spilhaus (1935) found that the dependence of $\Delta U / \Delta t$ on U and $(U - U_f)$ could be expressed in the form

$$\left| \frac{1}{U} \frac{\Delta U}{\Delta t} \right| = a \left| (U - U_f) \right|^b,$$

where a and b are factors which vary with the other conditions mentioned above. Thus for a

given value of $(U - U_t)$, $|\Delta U/\Delta t|$ is greater when the indicated humidity is high than when it is low. It is found that b is approximately 1 for increasing humidities, but varies up to 1.5 for decreasing humidities, while a is greater for increasing humidities than for decreasing humidities. The differences in the value of a normally more than counteract the differences in b , so that for values of $|U - U_t|$ up to about 50 per cent, $(1/U)(\Delta U/\Delta t)$ is greater for increasing than for decreasing humidities.

When the tension of the hair is increased it is found that a increases (i.e. the time-constant decreases) while b remains constant. This would seem to show that the maximum tension that does not cause permanent elongation (at 100 per cent relative humidity, which represents the weakest condition) should be used on the hair. Care is needed in applying this result as the permanent elongation may show itself only after some considerable period, causing the zero to shift. The variation in the values of a and b with the time of degreasing treatment of the hair shows that for best results the time of treatment should not exceed one hour. For times of treatment in excess of this the value of a decreases while b remains practically constant.

The time-constant of the hair increases (i.e. a decreases) as the temperature falls, and below temperatures of -29°C a is very close to zero. This places a serious limitation on the usefulness of the hair as an indicator of humidity for upper-air work and at very low temperatures on the ground.

Some numerical values are given in Table I, page 3-5.

Effect of tension on the hair. If a stress is applied to the hair, for an extension of up to 2 per cent the hair behaves like an elastic body with a constant value of Young's modulus (i.e. extension proportional to load), but above the elastic limit the extension increases rapidly (Spilhaus, 1935). The hair breaks at the same extension for all humidities, but the load required is largest for the lowest humidity.

These results were obtained at room temperatures by subjecting the hair to the load for short periods only. There is, however, a gradual 'creep' of the hair over long periods when under tension (even when this tension is less than the elastic limit). This 'creep' is not fully understood and affects the permanence of the zero of an instrument. Most of the creep can be regained by periodically saturating the hair with distilled or deionized water.

3.2 Application to hygrographs

The change of length of a hair or group of hairs with change in relative humidity can be made to move the pen arm of a hygrograph in various ways. Three types of mechanism are illustrated in Figure 4.

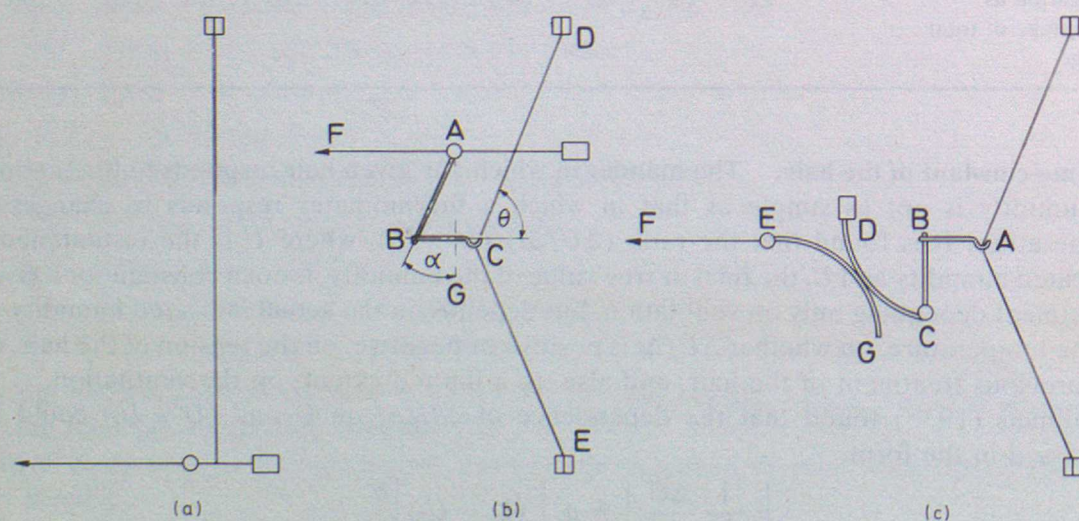


Figure 4. Principles of hygrograph mechanisms

Type (a) is the simplest; it requires only one axis of rotation and any change in zero can be allowed for without change in magnification. Its main disadvantage is that the scale is not linear owing to the non-linear change in length of hair.

In type (b) the hook BC is free to rotate about the axis B and the arm AB can rotate about A. The magnification of this system expressed as the rate of change of the position of the pen with the change in length of the hair DCE, at any given point, is $AF/2AB \cos \alpha \cos \theta$, where α is $\angle BAG$ and θ is $\frac{1}{2} \angle DCE$, AG being parallel to DE. If α is zero at zero humidity then, as $\cos \alpha$ will eventually change faster than $\cos \theta$, the magnification will be greater as the humidity increases. This will tend to counteract the uneven expansion of the hair and result in a more nearly linear scale. Changes in the zero adjustment change the form of the scale somewhat, unless provision is made for making the adjustment by the movement of the jaws D and E, which carry the hair, in a direction perpendicular to the line DE.

Type (c) is more complicated; the change in length of the hair causes the lever system ABC to rotate about a horizontal axis C to which is attached a quadrant CD. The pen arm EF rotates about the horizontal axis E, to which is also attached a quadrant EG. The two quadrants bear upon one another and keep in contact because of the weight D, the weight of the pen arm, and also because of a light spring attached from D to G. The scale reading, indicated by the pen, can be made to be a linear function of the relative humidity by suitable positioning of the quadrants. The friction in this type of movement is greater than in the other systems, and unless the surfaces of the two quadrants are kept very smooth the action of the instrument will be irregular.

3.3 The Meteorological Office hair hygrograph

The mechanism of the Meteorological Office hair hygrograph is type (c) described above; details of the working parts are shown in Figure 5 and Plate IV. A bundle of hairs A is held between the two jaws B and C, and caught up at approximately the centre by a hook D on the lever E, the jaws and lever, together with its spindle, being mounted on the hair-movement plate. The distance apart of the jaws can be adjusted within limits by means of a setting screw F, which is turned by a setting key supplied with the instrument.

It is possible to adjust the position of the hook D on the lever E. The quadrants G and H are attached to the lever E and to the axis of rotation of the pen arm in the hygrograph mechanism type (c). A small spring I helps to keep them in contact. This enables a linear scale to be used on the chart. The small weight J, placed at the upper end of the hair-movement quadrant, is such that the force applied by the hook on the hairs, when the quadrants are in their mean position, is 16 g weight. The normal type of gate suspension is used for the pen arm and one of the normal patterns of clocks is used with a short drum and either a daily or weekly movement.

The pen-arm assembly is mounted on a pedestal on the recording-movement plate, which also carries the clock and drum, and which in turn is carried by the main gunmetal base. The pen arm can be rotated relative to the pen-arm quadrant by loosening the screw K, which fixes the quadrant to the pen-arm spindle.

A hinged copper cover with a glass window is provided for the whole instrument except for the mechanism carried on the hair-movement plate, which is covered with a brass wire cage, so as to leave the hairs freely exposed but at the same time afford some measure of protection.

Installation and method of use. The instrument should be placed on the centre baseboard of a large screen and the general instructions for operating recording instruments (see Appendix 1) should be followed. One particular point to note, however, is that when making a time mark the pen should always be depressed and not moved towards higher humidity; this is necessary because the hairs must not be strained in any way.

Care of the hairs. Careful attention should be paid to the condition of the hairs. They should be kept clean and free from dust by washing with distilled water regularly — about once a week normally but more frequently at stations where the hairs are exposed to salt spray or large concentrations of fumes and dust. The wire cage should be removed and the

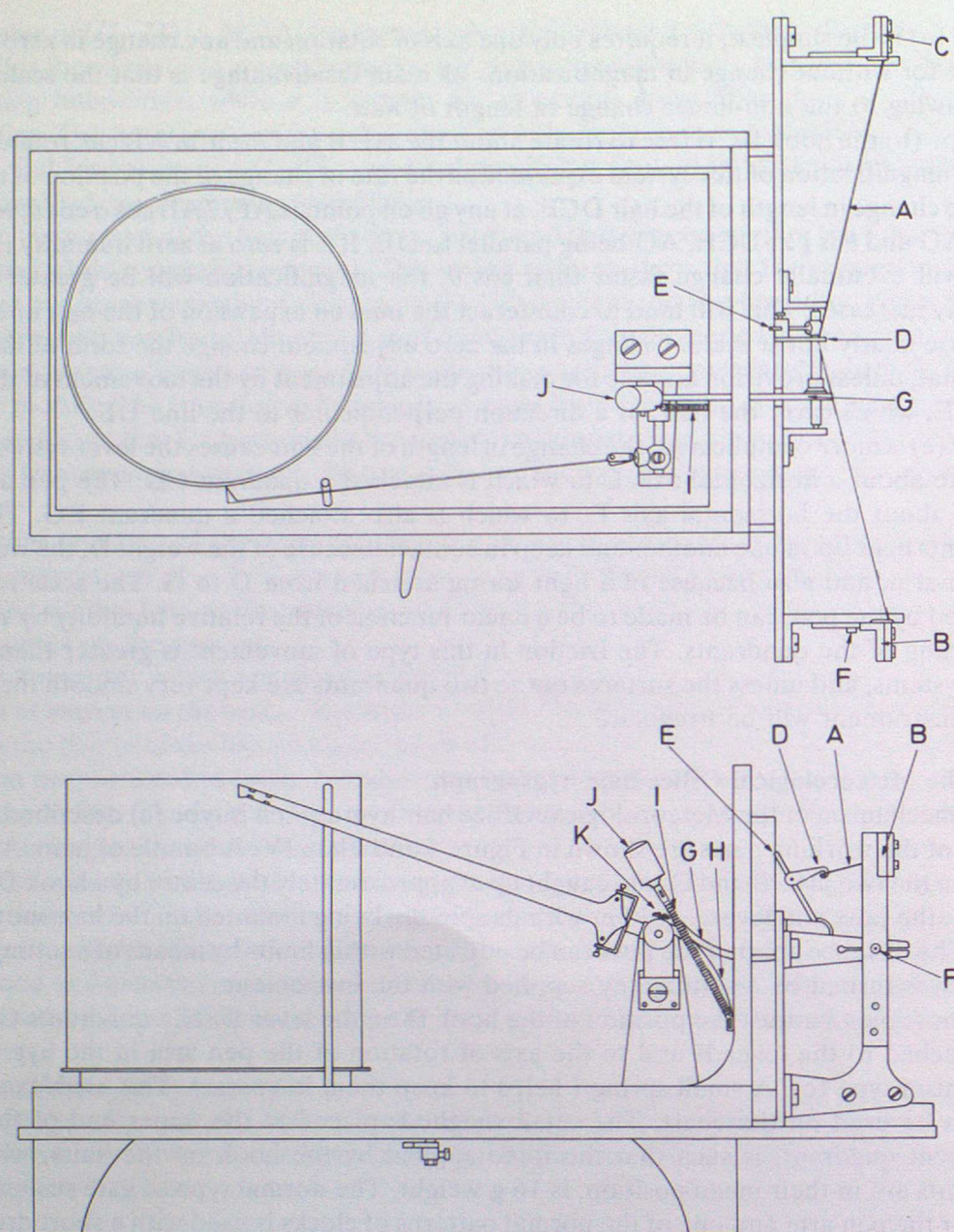


Figure 5. Elevation and plan of Meteorological Office hair hygrometer

water applied with a soft camel-hair brush. Great care should be taken not to handle the hairs with the fingers or any portion of the skin, as the presence of any oil or grease adversely affects the performance of the hairs. The washing of the hairs also helps to minimize the 'creeping' of the zero, especially when the hairs have been exposed to low humidities.

Routine checking. Comparison between the readings of the hygrometer and the hourly readings of a psychrometer are only of limited value, as the difference in the time-constants of the two instruments can cause a difference in the readings of as much as 5 per cent if the humidity is changing. The 100 per cent relative humidity point should be checked periodically by surrounding the instrument with a saturated cloth, and leaving it for about an hour until the hairs are in equilibrium. If this is not possible the hairs should be painted with distilled or deionized water using a camel-hair brush, and the pen adjusted to read 95 per cent when the hairs have reached equilibrium. The reading should not be 100 per cent because some liquid water is retained on the hairs and the weight of the water causes a slight movement of the pen.

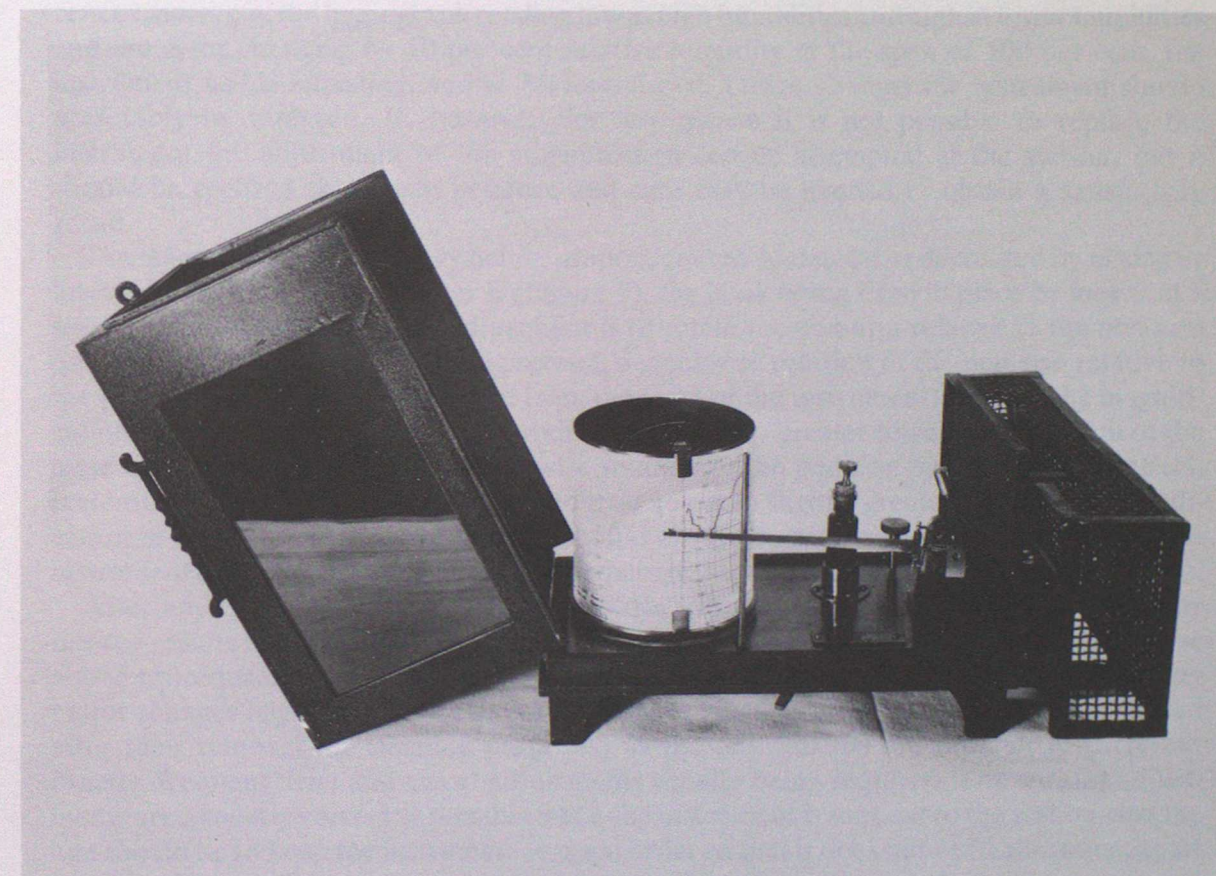


Plate IV. Meteorological Office hair hygrometer

A check at a lower humidity can be made in a room when the room temperature is steady, provided that an aspirated psychrometer is available. When the indication of the hygrograph is steady a series of readings with the psychrometer should be made and the mean relative humidity found. A possible way to keep a routine check on the instrument is to plot the readings of the hygrograph at the main synoptic hours against the relative humidity calculated from the psychrometer readings. A certain amount of scatter may be expected, but the mean line through the points should be a straight line through the origin of slope 45° . If the slope is not 45° the magnification needs adjusting, whilst a purely lateral displacement means a zero error only.

Methods of adjustment. If as a result of the checking carried out as above it is found that there is a zero error, the necessary adjustment should be carried out with the setting key which is used to adjust the setting screw. If there is an error in the magnification of 10 per cent or more, e.g. the hygrograph reading low at high humidities and high at lower humidities and the error changing by 10 per cent relative humidity in the span of 100 per cent, the instrument needs adjusting, and at Meteorological Office stations the instrument should preferably be replaced. If, however, for any reason it is not possible to replace the instrument the adjustment of the magnification can be attempted at the station, but it should be realized that much patience and care may be needed to obtain a satisfactory result.

The magnification can be very nearly proportionately increased or decreased by raising or lowering the hook D on the lever E (Figure 5), the hook being fixed in place by means of a small screw. Another possible adjustment is to rotate the pen arm relative to the pen-arm quadrant (after loosening the fixing screw); a clockwise rotation of the pen arm relative to the pen-arm quadrant (when viewed from the front of the instrument) reduces the magnification over the whole range, but the reduction is slightly greater towards the bottom of the scale than towards the top. Anticlockwise rotation of the pen arm has the contrary effect, increasing the magnification over the whole range with a slightly greater increase in magnification in the lower part of the scale. It should always be remembered when handling this instrument that the hairs are much weaker when the humidity is high than when the air is dry.

After any change in the magnification further tests should be made to check that the desired results have been obtained. It will also be necessary to change the zero setting. The above procedure for altering the magnification should, usually, only be applied when any major changes have taken place in the instrument (such as the replacement of the hairs or after their removal for cleaning purposes) as the adjustments are difficult to carry out exactly, frequent 'trial and error' adjustments usually being required. The various adjustments are as nearly correct as possible when the instrument is sent out to the station, and the aim should be to keep the instrument in good order so that it does not need alteration, apart from occasional slight zero adjustments.

Maintenance. The bearings of the mechanism should be kept clean and a little clock oil occasionally applied. When cleaning the mechanism it is advisable to release the hook from the bundle of hairs to avoid the possibility of any strain. The surface of the quadrants should be kept clean and occasionally polished with a piece of blotting paper rubbed with a lead pencil, to reduce the friction to a minimum. A large part of the total friction in the instrument arises at this point, and an excessive amount seriously reduces the discrimination of the instrument. The remainder of the instrument should be kept clean.

Accuracy and sources of errors. The time-constant of the hairs, their change under tension and the change in zero with time have been described. These factors combine to make a hair hygrograph unsuitable as a standard instrument for measuring humidity, but as a recording instrument it is simple and efficient provided it is regularly checked and kept in good condition. With proper attention the hairs should last for several years in temperate climates, except where there is pollution by acid fumes or ammonia.

3.4 Calibration

Each hygrograph, prior to issue, is calibrated by the Instrument Branch Test Laboratory.

The hair element is first wetted throughout its working length with distilled or deionized water, using a small camel-hair brush, and then, when the hairs have reached equilibrium, the pen arm is adjusted to read approximately 95 per cent. The instrument is then allowed to assume ambient humidity and, under steady conditions, a series of readings as indicated by the pen upon the hygrogram are compared with the relative humidity determined by an aspirated psychrometer. If the readings are in close agreement the hygrograph is then calibrated in an environmental chamber.

The chamber (Plate V) provides stable internal conditions of temperature and humidity, within a specific range, by means of heating and cooling, and humidifying and drying facilities which can be selected separately or together. Heating is provided by electrical elements built into the chamber, and cooling by an evaporation coil and air-cooled refrigeration compressor. Water vapour to raise the humidity level in the chamber is provided by a low-pressure boiler unit.

The hygrograph is calibrated over a range of 20 to 100 per cent relative humidity at intervals of 10 per cent. The permissible error at any point in the range is 5 per cent.

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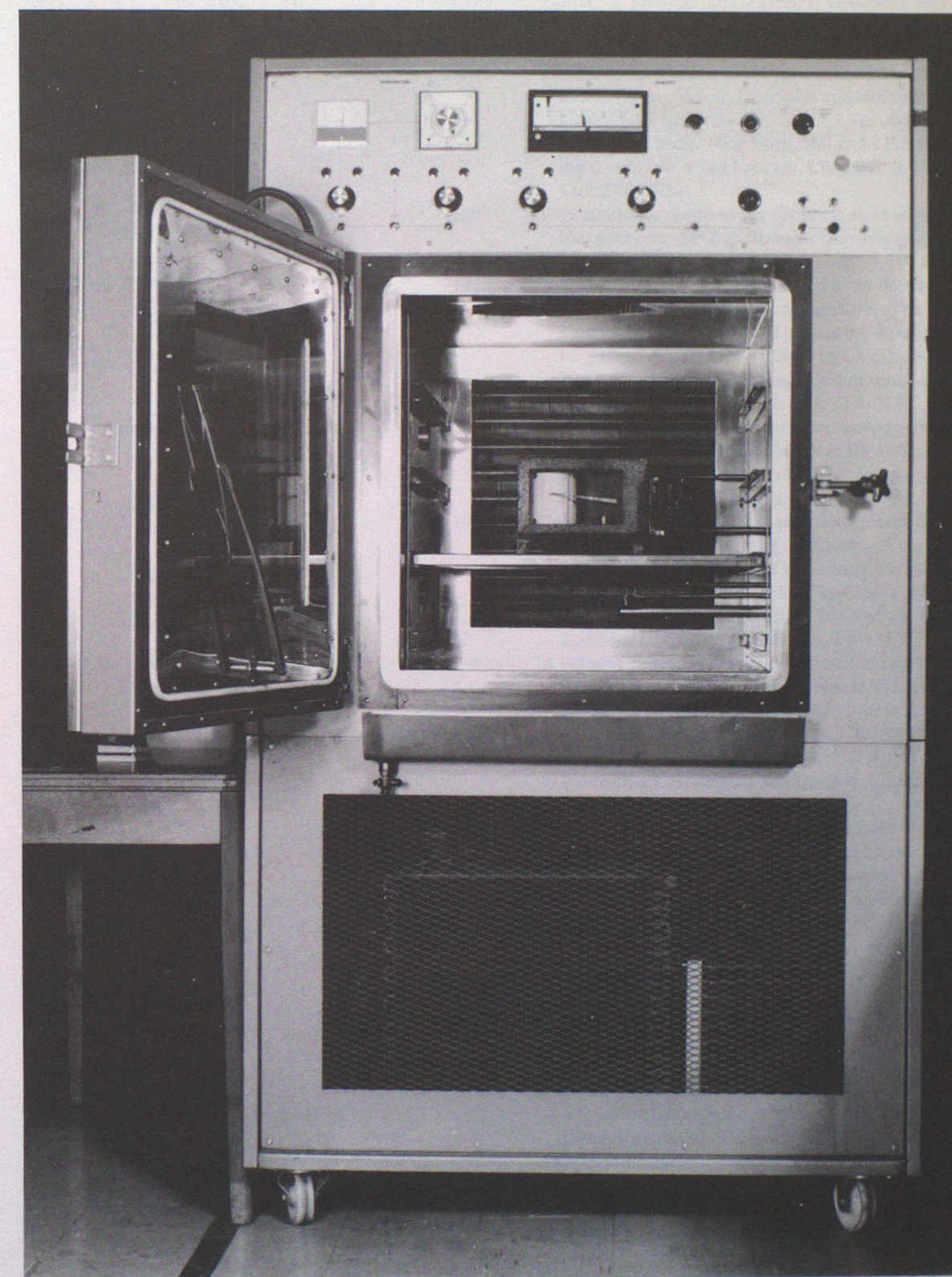


Plate V. Hygrograph calibration chamber

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APPENDIX 1

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

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APPENDIX 1

A.1 RECORDING METHODS

A.1.1 Introduction

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

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

A.1.2 Recording charts

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

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

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

A.1.3 Pen recorders

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

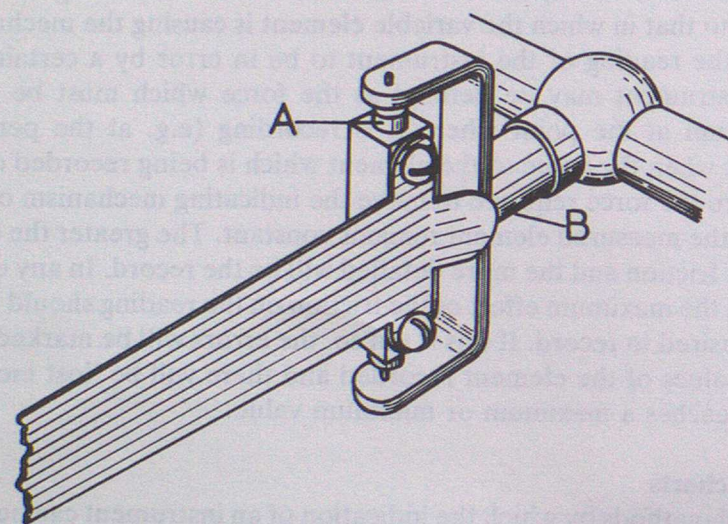


Figure A1. Gate suspension for pen arm.

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

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

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

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

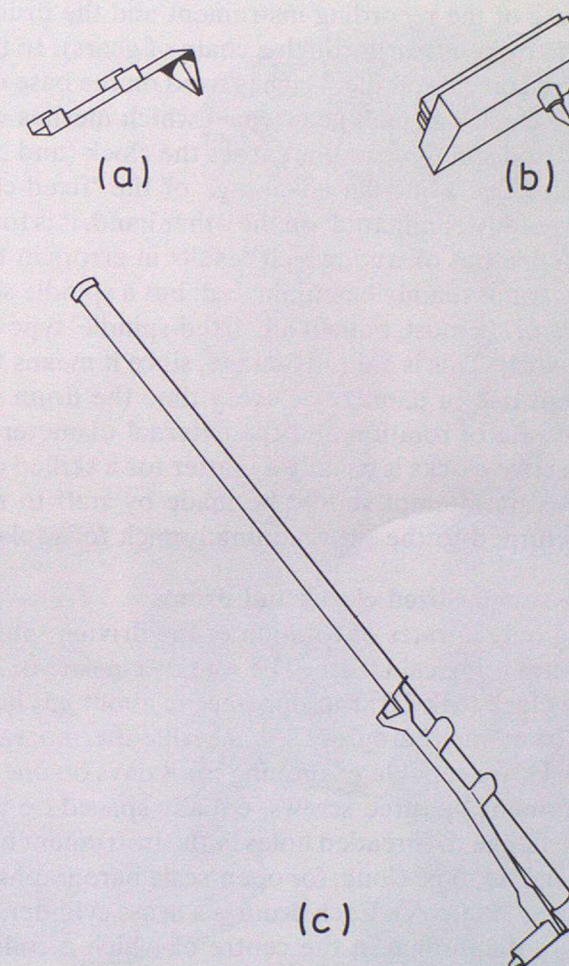


Figure A2. Instrument pens.

A.1.4 Electrosensitive paper

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

A.1.5 Electrical recorders

Devices for balancing potentiometric or bridge recorders have various forms, some manual, some self-balancing. Whatever the method used the principle is the same. A galvanometer, or an electronic circuit, is arranged to detect when the system is out of balance. Where a galvanometer is used, the position of the galvanometer pointer is detected

either manually or electrically, and the slide-wire contact moved to the point of balance. Where an electronic circuit is used to detect the out-of-balance it is usual for the output of the detecting circuit to control the direction of rotation of a reversible motor which moves the slide-wire contact and positions the pen arm or pointer.

A.1.6 Clocks, drums and time-scales

Most meteorological recording instruments are fitted with 'daily' or 'weekly' clocks, i.e. clocks which cause the drum to rotate once in about $25\frac{1}{2}$ hours and once in about $7\frac{1}{2}$ days respectively. The overlap is necessary to allow some margin for the time of changing the chart, and to prevent the trace from crossing the join when the pen is near the top or bottom of the chart (on those instruments in which the hour lines are curved).

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

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

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

A.1.7 Meteorological Office standardized clocks and drums

Two 'fixed' clocks differing only in rates of rotation of the driving spindles, serve as the standardized clocks of the Meteorological Office. The weekly clock (Mk 2A) rotating once in about $7\frac{1}{2}$ days and the daily clock (Mk 2B) rotating once in about $25\frac{1}{2}$ hours are used with the commoner recording instruments (barographs, bimetallic thermographs, hygrographs and rain recorders). Both clocks are capable of running for 8 days on one full winding. The clock is attached to the instrument by three screws, equally spaced on a circle of 89 mm diameter, passing through the flange to threaded holes in the instrument base. Two standardized drums, 'S' type (short) and 'O' type (long, for open-scale barographs), are for use with either of the standardized clocks (Plate A). Each drum is a brass cylinder, of defined height and diameter, provided with a diaphragm in the centre of which a collar is screwed and through which the clock's driving spindle passes. The collar has radial teeth on its underside which engage with similar teeth on a collar attached to a clutch drive on the driving spindle of the clock; a knurled nut secures the drum to the driving spindle of the clock. The object of the clutch drive is to facilitate the setting of the drum to its correct position when fitted to the clock. The drum is flanged around its base and the chart is held in position by two clips. In addition to the chart clips the 'O' type drum has two small pins screwed into its side, lying in the same line as the chart clips. These pins help to keep the chart in position where the two ends overlap. The 'S' type is 93 mm in diameter, so that it gives a time-scale of 11.4 mm h^{-1} with a daily clock. When used with a weekly clock Mk 2A the clock is adjusted to rotate once in 7 days 7.2 hours, giving a time-scale of 1.67 mm h^{-1} . The 'O' type drum is not normally used with a daily clock, but if it were the time-scale would be 17.2 mm h^{-1} . Used with a weekly clock Mk 2A, the clock is adjusted to rotate once in 7 days 8 hours, giving a time-scale of 2.5 mm h^{-1} . (The difference between a time of rotation of 7 days 8 hours and 7 days 7.2 hours is negligible for most purposes.) The standardized clocks and drums are completely



Plate A.

Standard Meteorological Office clocks and drums.

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

A.2 CORRECTION OF RECORDING INSTRUMENTS

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

- (a) Backlash between the drum and the spindle on which it is mounted. This defect is not serious with clocks of the standard Meteorological Office pattern or similar types. It delays the starting of the record and causes a constant error once the record has started.
- (b) An error in the clock rate (or the use of an unsuitable time-scale on the chart). If the difference is small the rate of revolution of the drum can be adjusted to the correct value (given by the time-scale on the chart) by means of the clock regulator. Small errors may occur, however, owing to the variability of the clock rate, e.g. with temperature changes.
- (c) Errors due to the change in length of the chart with humidity variations (see page A-3). These are small in charts which are cut from the paper in the correct direction, but are serious if the chart is cut in the wrong direction.

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

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

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

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

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

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

A.3. OPERATIONAL PROCEDURE

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

A.3.1 Changing the chart

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

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

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

A.3.2 Writing up the chart

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

A.3.3 Care at each main observation hour

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

A.3.4 General hints (including cleaning)

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

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

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

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

APPENDIX 2

The International Systems of units (SI)

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

The *base units* are:

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

The two *supplementary units* are:

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

A few of the *derived units* are:

Quantity	Name of unit	Symbol	Expressed in base units
frequency	hertz	Hz	1 Hz = 1 s ⁻¹
force	newton	N	1 N = 1 kg m s ⁻²
pressure	pascal	Pa	1 Pa = 1 N m ⁻²
work	joule	J	1 J = 1 N m
power	watt	W	1 W = 1 J s ⁻¹

(1 newton = 10⁵ dynes, 1 pascal = 10⁻² millibars, 1 joule = 10⁷ ergs.)

Multiplying prefixes

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

e.g. 1 pound = 16 ounces = 7000 grains

1 yard = 3 feet = 36 inches,

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

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

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

Examples:

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

NON-SI UNITS

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

1. Pressure

The millibar is used as the unit of pressure in meteorology. Despite the recommended abbreviation mbar, the Meteorological Office will continue to use mb (1 mb = 1 hPa, where h = hecto = 10²). The WMO preferred unit is the hPa, though it has yet to be promulgated.

2. Temperature

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

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

3. Distance

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

Because the nautical mile varies with latitude, an internationally agreed International Nautical Mile is preferred. This has been in use in the United Kingdom since 1970.

The International Nautical Mile is defined as 1852 m (6076.12 feet).

4. Height

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

5. Speed

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

6. Time

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

7. Direction

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

8. Cloud amounts

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

APPENDIX 3

Terminology

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Range (of a measuring instrument). The interval between the lower and upper range-limits, e.g. a thermometer may have a range $-40\text{ }^{\circ}\text{C}$ to $+60\text{ }^{\circ}\text{C}$.

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

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

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

Resolution. See *Discrimination*.

Response. See *Indication*.

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

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

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

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

Span. The algebraic difference between the upper and lower values specified as limiting the range of operation of a measuring instrument, e.g. a thermometer intended to measure over the range $-40\text{ }^{\circ}\text{C}$ to $+60\text{ }^{\circ}\text{C}$ has a span of $100\text{ }^{\circ}\text{C}$.

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

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

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

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

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

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

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

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

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

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

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

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