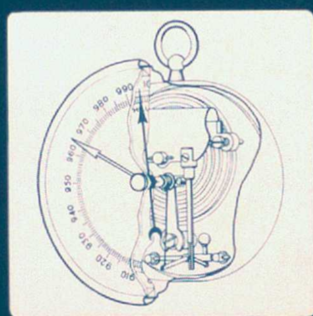
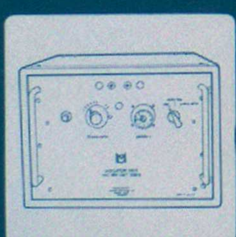
Meteorological Office

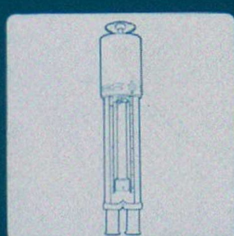
Handbook of Meteorological Instruments

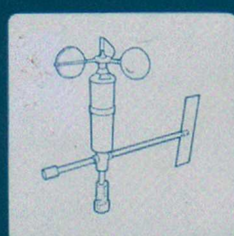
Second Edition

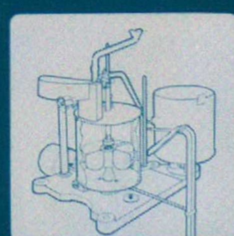
1 Measurement of Atmospheric Pressure

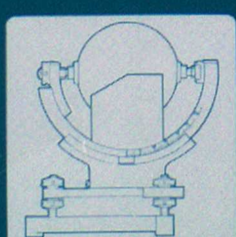


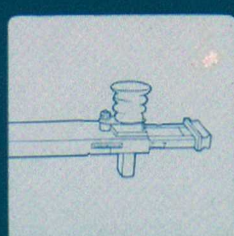


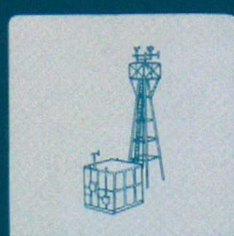












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METEOROLOGICAL OFFICE

HANDBOOK OF METEOROLOGICAL INSTRUMENTS

SECOND EDITION

VOLUME 1

MEASUREMENT OF ATMOSPHERIC PRESSURE

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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 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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1 GENERAL PRINCIPLES

1.1 Introduction and early development

The fact that the atmosphere has weight, and therefore exerts a pressure, was apparently first clearly recognized by Galileo and Torricelli, and in 1643 Torricelli demonstrated this by showing that the atmospheric pressure could support a column of mercury about 760 mm high. A further crucial experiment was performed in 1648, when Pascal and Perrier showed that the height of the mercury column supported was less at the top of a mountain than at its base.

Until the invention of the aneroid barometer by Vidie in about 1843 the column of mercury remained the basis of practically all barometers, and it is still the basis of some standard instruments for the accurate determination of atmospheric pressure. With the introduction of the aneroid barometer the search for new types of mercury barometers largely ceased, and development was concentrated on improving the existing forms of mercury barometer.

1.2 Principles of barometers

Mercury barometers. The principle of mercury barometers is illustrated in Figure 1; if the space above A is completely exhausted of all gases (except, of necessity, the mercury vapour) the simple manometer at (a) becomes the barometer of (b) and (c). If the height of the column AB_1, the density of the mercury, and the value of the acceleration due to gravity are known, the pressure at the base of the column, which is equal to the atmospheric pressure, can be calculated.

Mercury is used as the barometric fluid for the following reasons:

(a) Its large relative density makes the column of convenient length.

(b) Its vapour pressure is so small at ordinary working temperatures that it can be neglected in all but the most precise measurements.

(c) It is easily cleaned and purified.

(d) It does not wet the walls of the tube, so that the meniscus is convex – this makes it easy to measure its position with accuracy.

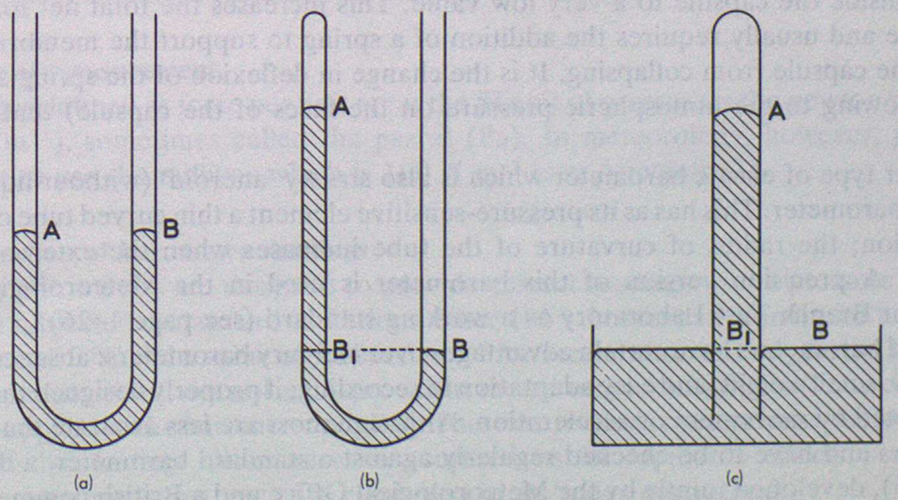


Figure 1. Stages in the development of the mercury barometer.

Reduced to its essentials, a mercury barometer consists of a vertical glass tube in which the barometric column is supported, a cistern to contain the mercury which seals the lower end of the tube, and a scale with which to measure the height of the column. In addition, since the determination of pressure involves a knowledge of the density of the mercury, which is a function of the temperature, an 'attached thermometer' is normally essential.

It is clear that when any change of pressure takes place a re-adjustment of the mercury level occurs not only in the tube but in the cistern. Normally, therefore, a fixed scale graduated in the ordinary units of length will not give the height of the column directly unless either its zero is always adjusted to the level of the mercury in the cistern, or the level of the mercury in the cistern can be adjusted to a fixed datum level. This datum level is the zero of the scale. The principal instrument in the adjustable-cistern class is the Fortin barometer; the lower part of the cistern consists of a flexible leather bag, and a screw jack is provided at the base of the instrument so that the mercury level can be raised or lowered by the required amount.

Alternatively, if the barometer tube and the inside of the cistern have a uniform cross-sectional area, it is possible to set up a contracted scale which will automatically take account of the varying mercury level. Since the volume of the cistern is constant, a rise of the mercury level in the tube will always be associated with a fall of the level in the cistern, and vice versa. A change of pressure of one millimetre will change the mercury level in the tube by an amount less than a millimetre, depending on the relative areas of the tube and the cistern. If a is the area of the tube (at the level of the mercury) and A the area of the cistern (less that of the tailpiece of the tube), a rise of d mm in the tube will be accompanied by a fall of da/A mm in the cistern. The pressure change corresponding to a rise of d mm in the tube is therefore

$$d + da/A = d\,(A + a)/A$$

and a pressure rise of 1 mm will produce a rise in the mercury level of $A/(A + a)$ mm. The contracted scale is therefore graduated in standard units modified by the factor $A/(A + a)$.

The commonest example of the contracted-scale barometer is the Kew-pattern (see page 1–7). One great advantage of this type of barometer is that only one setting operation is required when a reading is taken.

Aneroid barometers. The elastic properties of a thin metal membrane or diaphragm are used in aneroid barometers. If such a membrane is held at the edges it will be deformed if the pressure on one side is greater than on the other. In the aneroid barometer two such membranes form the walls of a capsule; one membrane is usually fixed at its centre while the movement of the other, due to changes in the thickness of the capsule brought about by changes in the atmospheric pressure, is magnified by a system of levers and indicated on a scale. To avoid errors due to temperature changes it is necessary, however, to reduce the air pressure inside the capsule to a very low value. This increases the total net force on the membrane and usually requires the addition of a spring to support the membrane and to prevent the capsule from collapsing. It is the change in deflexion of the spring as the load changes (owing to the atmospheric pressure on the faces of the capsule) that is usually measured.

Another type of elastic barometer which is also strictly 'aneroid' (without liquid) is the Bourdon barometer. This has as its pressure-sensitive element a thin curved tube of elliptical cross-section; the radius of curvature of the tube increases when the external pressure increases. A precision version of this barometer is used in the Meteorological Office Instrument Branch Test Laboratory as a working standard (see page 1–26).

Aneroid barometers have certain advantages over mercury barometers: absence of liquid, portability, small weight, and easy adaptation to recording; if properly designed they are also little affected by movement or acceleration. Although most are less accurate than mercury barometers and have to be checked regularly against a standard barometer, a design (see page 1–15), developed jointly by the Meteorological Office and a British commercial firm, achieves an accuracy comparable with a good mercury barometer. It is thus suitable for synoptic use and has largely replaced mercury barometers aboard ships and at Meteorological Office reporting stations.

1.3 Errors in the measurement of pressure

The following paragraphs deal with errors which occur when measuring the atmospheric pressure with any type of barometer.

Errors due to wind. When air in motion strikes an obstruction it generally causes a change in the total atmospheric pressure at the surface of the obstruction, owing to the change in speed of the air. If the air is brought completely to rest the resultant excess pressure is equal to $\frac{1}{2}\rho v^2$, where v is the speed of the air and ρ its density. This is equal to about 2.5 mb under normal surface conditions, when v is 40 kn.

Except in conditions of calm or light winds therefore, a barometer will not give a true reading of the static pressure, its reading fluctuating with the wind velocity. A similar effect will be observed in a room whose exterior is exposed to the wind; the magnitude and sign of the fluctuations depend on the nature of the openings of the room (doors, windows, chimneys, etc.) and their positions in relation to the direction of the wind. It is often found that a wind from a certain direction will cause violent fluctuations or pumping, while an equally strong wind from another direction causes little. In general the effect cannot be calculated theoretically. At sea the error is nearly always present, owing to the ship's progress.

It is possible to overcome this effect to a very large extent by making the barometer air-tight except for a lead to a special 'head' exposed to the atmosphere and designed to ensure that the pressure inside it is the true static pressure (Kodama 1967) (see page 1–17).

Errors due to variation in the temperature of the instrument. It is usually essential that the barometer should have a uniform temperature, and in many instruments corrections must be applied for the difference between the actual temperature and a certain standard temperature. The barometer should therefore be hung or placed in a room in which the temperature changes only slowly, and in which gradients of temperature do not occur. It should not be exposed to draughts from badly fitting windows or doors or be near heating apparatus, and the sun should not shine on it at any time.

A stratification of temperature is often found in a room which is otherwise suitable; the top of the column in a mercury barometer may then be as much as two or three degrees warmer than the cistern, and it would be difficult to find the true mean temperature to use in correcting the readings.

Errors due to movement. Most barometers are only designed to be used in a position of rest, and if they are subjected to an acceleration in any direction their readings are liable to error. It is possible, however, by careful design or by the addition of a damping mechanism, to reduce such errors in an aneroid barometer to a negligible value (see page 1–17).

1.4 Units of measurement

Pressure is defined as force per unit area; the SI unit of pressure is the newton per square metre (N m^{-2}), sometimes called the pascal (Pa). In meteorology, however, it is more convenient to use the millibar which is 100 N m^{-2} (see Appendix 2).

1.5 Correction of barometer readings

Mercury barometers are designed to provide correct readings of the pressure at cistern level when subjected to standard conditions. Since 1955 the standard conditions have been a temperature of 0 °C and a value of 9.80665 m s^{-2} for acceleration due to gravity. In practice standard conditions will not normally prevail at the barometer location and corrections will have to be applied to the barometer reading. These corrections can amount to as much as 0.5 per cent of the reading. Other necessary corrections for capillarity effects, scale errors, residual vacuum pressures, etc., are combined in an 'index correction'.

Aneroid barometers will normally require only an 'index correction'.

A correction may also be necessary if the pressure is to be related to some reference level other than the cistern or 'station' level.

Correction for index error and standard conditions for the Meteorological Office Mk 2 Kew-pattern station barometer. For the Meteorological Office Mk 2 Kew-pattern station barometer account is taken of index error and local deviations from standard conditions in the formula for fixed cistern barometers recommended by the World Meteorological Organization

$$P = \frac{g}{9.80665}\left\{ B + i - B\left[\frac{(\alpha - \beta)T}{1 + \alpha T}\right] - f\frac{V}{A}(\alpha - 3 \times 10^{-5})T \right\},$$

where P = corrected reading of the barometer
B = the barometer reading
i = the index error
g = the local acceleration due to gravity in m s^{-2}
α = the coefficient of expansion of mercury
β = the coefficient of linear expansion of the scale
T = the temperature of the barometer in degrees Celsius
V = the volume of mercury in cubic millimetres
A = effective area of cistern (i.e. total internal area less the area of the glass tube) in square millimetres
f = the unit conversion factor (e.g. 1.333 for a millibar scale).

The value 10^{-5} °C^{-1} in the equation is a linear expansion coefficient representing chiefly the expansion of the steel cistern and the glass tube.

Correction to reduce the station-level pressure to that at a fixed datum level. The horizontal gradient of pressure is often required between stations at different levels. This cannot be deduced by direct comparison of the 'station' pressures because of the variation in pressure with height. Consequently it is necessary to reduce pressure readings to a common datum level. The WMO recommendation (World Meteorological Organization, 1971) is that the observed atmospheric pressure should be reduced to mean sea level for all stations where this can be done with reasonable accuracy. Where this is not possible, a station should by regional agreement report either the geopotential * of an agreed 'constant pressure level', e.g. 850 mb, or the pressure reduced to an agreed datum level for that station (often 1000, 1500, 2000, etc. geopotential metres above mean sea level).

The reduction consists of adding to the observed pressure the pressure due to the weight of a hypothetical vertical column of air equal in length to the height of the barometer above the datum level. If the barometer is below the datum level the correction is subtracted.

The pressure due to a column of air depends on its temperature, the amount of water vapour in it, the value of gravity and the pressure at the top of the column. In the hypothetical case the first three may be assumed either to be constant or to vary along the column. In the United Kingdom, where reductions are made to mean sea level and where stations are mostly below 300 m above mean sea level, it is customary to neglect the effect of water vapour and assume that the temperature of the air column is constant and equal to the temperature of the outside air at the level of the station. For mercury barometers a correction for the variation of gravity with height is applied separately; such a correction is unnecessary for aneroid barometers.

The reduction formula used by the Meteorological Office is taken from the *International Meteorological Tables* (International Meteorological Committee, 1890), and is

$$M = p\,(10^{m} - 1).$$

*The geopotential (Φ) at a particular height above mean sea level is the work which must be done against gravity in raising unit mass from sea level to that height, i.e. $\Phi = \int_0^z g\,dz$, where g is the local acceleration of gravity at the geometric height z. The practical unit of geopotential adopted by WMO in 1972 is the 'standard geopotential metre' (Z). It is related to z by $Z = g\,z/9.80665$ and thus has a numerical value approximately equal to z.

Table I. *Reduction of pressure in millibars from barometer level to another level*

Pressure at barometer level, 1000 mb*

Values are positive for reduction to a level below that of the barometer

Height	Air temperature (°C) Dry bulb in screen −15	−10	−5	0	5	10	15	20	25	30	35	40
metres	*millibars*											
5	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.5
10	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1
15	2.0	1.9	1.9	1.9	1.8	1.8	1.8	1.7	1.7	1.7	1.7	1.6
20	2.6	2.6	2.5	2.5	2.5	2.4	2.4	2.3	2.3	2.3	2.2	2.2
25	3.3	3.2	3.2	3.1	3.1	3.0	3.0	2.9	2.9	2.8	2.8	2.7
30	4.0	3.9	3.8	3.8	3.7	3.6	3.6	3.5	3.4	3.4	3.3	3.3
35	4.6	4.5	4.5	4.4	4.3	4.2	4.2	4.1	4.0	3.9	3.9	3.8
40	5.3	5.2	5.1	5.0	4.9	4.8	4.7	4.7	4.6	4.5	4.4	4.4
45	6.0	5.9	5.7	5.6	5.5	5.4	5.3	5.3	5.2	5.1	5.0	4.9
50	6.6	6.5	6.4	6.3	6.2	6.0	5.9	5.8	5.7	5.6	5.6	5.5
55	7.3	7.2	7.0	6.9	6.8	6.7	6.5	6.4	6.3	6.2	6.1	6.0
60	8.0	7.8	7.7	7.5	7.4	7.3	7.1	7.0	6.9	6.8	6.7	6.6
65	8.6	8.5	8.3	8.2	8.0	7.9	7.7	7.6	7.5	7.3	7.2	7.1
70	9.3	9.1	8.9	8.8	8.6	8.5	8.3	8.2	8.0	7.9	7.8	7.7
75	10.0	9.8	9.6	9.4	9.2	9.1	8.9	8.8	8.6	8.5	8.3	8.2
80	10.6	10.4	10.2	10.0	9.9	9.7	9.5	9.4	9.2	9.0	8.9	8.8
85	11.3	11.1	10.9	10.7	10.5	10.3	10.1	9.9	9.8	9.6	9.5	9.3
90	12.0	11.7	11.5	11.3	11.1	10.9	10.7	10.5	10.4	10.2	10.0	9.9
95	12.6	12.4	12.2	11.9	11.7	11.5	11.3	11.1	10.9	10.8	10.6	10.4
100	13.3	13.1	12.8	12.6	12.3	12.1	11.9	11.7	11.5	11.3	11.1	11.0
105	14.0	13.7	13.5	13.2	13.0	12.7	12.5	12.3	12.1	11.9	11.7	11.5
110	14.6	14.4	14.1	13.8	13.6	13.3	13.1	12.9	12.7	12.5	12.3	12.1
115	15.3	15.0	14.7	14.5	14.2	14.0	13.7	13.5	13.2	13.0	12.8	12.6
120	16.0	15.7	15.4	15.1	14.8	14.6	14.3	14.1	13.8	13.6	13.4	13.2
125	16.7	16.3	16.0	15.7	15.5	15.2	14.9	14.7	14.4	14.2	13.9	13.7
130	17.3	17.0	16.7	16.4	16.1	15.8	15.5	15.2	15.0	14.7	14.5	14.3
135	18.0	17.7	17.3	17.0	16.7	16.4	16.1	15.8	15.6	15.3	15.1	14.8
140	18.7	18.3	18.0	17.6	17.3	17.0	16.7	16.4	16.2	15.9	15.6	15.4
145	19.4	19.0	18.6	18.3	17.9	17.6	17.3	17.0	16.7	16.5	16.2	15.9
150	20.0	19.6	19.3	18.9	18.6	18.2	17.9	17.6	17.3	17.0	16.7	16.5
155	20.7	20.3	19.9	19.6	19.2	18.9	18.5	18.2	17.9	17.6	17.3	17.0
160	21.4	21.0	20.6	20.2	19.8	19.5	19.1	18.8	18.5	18.2	17.9	17.6
165	22.1	21.6	21.2	20.8	20.5	20.1	19.7	19.4	19.1	18.7	18.4	18.1
170	22.7	22.3	21.9	21.5	21.1	20.7	20.3	20.0	19.6	19.3	19.0	18.7
175	23.4	23.0	22.5	22.1	21.7	21.3	20.9	20.6	20.2	19.9	19.6	19.3
180	24.1	23.6	23.2	22.7	22.3	21.9	21.5	21.2	20.8	20.5	20.1	19.8
185	24.8	24.3	23.8	23.4	23.0	22.5	22.2	21.8	21.4	21.0	20.7	20.4
190	25.4	24.9	24.5	24.0	23.6	23.2	22.8	22.4	22.0	21.6	21.3	20.9
195	26.1	25.6	25.1	24.7	24.2	23.8	23.4	23.0	22.6	22.2	21.8	21.5
200	26.8	26.3	25.8	25.3	24.8	24.4	24.0	23.6	23.2	22.8	22.4	22.0
205	27.5	26.9	26.4	25.9	25.5	25.0	24.6	24.2	23.7	23.3	23.0	22.6
210	28.2	27.6	27.1	26.6	26.1	25.6	25.2	24.7	24.3	23.9	23.5	23.1
215	28.8	28.3	27.7	27.2	26.7	26.3	25.8	25.3	24.9	24.5	24.1	23.7
220	29.5	28.9	28.4	27.9	27.4	26.9	26.4	25.9	25.5	25.1	24.7	24.3
225	30.2	29.6	29.0	28.5	28.0	27.5	27.0	26.5	26.1	25.7	25.2	24.8
230	30.9	30.3	29.7	29.2	28.6	28.1	27.6	27.1	26.7	26.2	25.8	25.4
235	31.6	30.9	30.4	29.8	29.3	28.7	28.2	27.7	27.3	26.8	26.4	25.9
240	32.2	31.6	31.0	30.4	29.9	29.3	28.8	28.3	27.8	27.4	26.9	26.5
245	32.9	32.3	31.7	31.1	30.5	30.0	29.4	28.9	28.4	28.0	27.5	27.1
250	33.6	33.0	32.3	31.7	31.1	30.6	30.0	29.5	29.0	28.5	28.1	27.6

*For other pressures the corrections to be applied are in proportion.

Table I (*continued*)

Pressure at barometer level, 1000 mb*

Values are positive for reduction to a level below that of the barometer

Height	Air temperature (°C) Dry bulb in screen											
	−15	−10	−5	0	5	10	15	20	25	30	35	40
metres	*millibars*											
255	34.3	33.6	33.0	32.4	31.8	31.2	30.7	30.1	29.6	29.1	28.6	28.2
260	35.0	34.3	33.6	33.0	32.4	31.8	31.3	30.7	30.2	29.7	29.2	28.7
265	35.7	35.0	34.3	33.7	33.0	32.5	31.9	31.3	30.8	30.3	29.8	29.3
270	36.3	35.6	35.0	34.3	33.7	33.1	32.5	31.9	31.4	30.9	30.4	29.9
275	37.0	36.3	35.6	35.0	34.3	33.7	33.1	32.5	32.0	31.4	30.9	30.4
280	37.7	37.0	36.3	35.6	34.9	34.3	33.7	33.1	32.6	32.0	31.5	31.0
285	38.4	37.7	36.9	36.2	35.6	34.9	34.3	33.7	33.2	32.6	32.1	31.5
290	39.1	38.3	37.6	36.9	36.2	35.6	34.9	34.3	33.7	33.2	32.6	32.1
295	39.8	39.0	38.3	37.5	36.9	36.2	35.6	34.9	34.3	33.8	33.2	32.7
300	40.5	39.7	38.9	38.2	37.5	36.8	36.2	35.5	34.9	34.3	33.8	33.2
305	41.1	40.3	39.6	38.8	38.1	37.4	36.8	36.1	35.5	34.9	34.4	33.8
310	41.8	41.0	40.2	39.5	38.8	38.1	37.4	36.7	36.1	35.5	34.9	34.4
315	42.5	41.7	40.9	40.1	39.4	38.7	38.0	37.3	36.7	36.1	35.5	34.9
320	43.2	42.4	41.6	40.8	40.0	39.3	38.6	38.0	37.3	36.7	36.1	35.5
325	43.9	43.0	42.2	41.4	40.7	39.9	39.2	38.6	37.9	37.3	36.6	36.0
330	44.6	43.7	42.9	42.1	41.3	40.6	39.9	39.2	38.5	37.8	37.2	36.6
335	45.3	44.4	43.6	42.7	42.0	41.2	40.5	39.8	39.1	38.4	37.8	37.2
340	46.0	45.1	44.2	43.4	42.6	41.8	41.1	40.4	39.7	39.0	38.4	37.7
345	46.7	45.8	44.9	44.0	43.2	42.5	41.7	41.0	40.3	39.6	38.9	38.3
350	47.4	46.4	45.6	44.7	43.9	43.1	42.3	41.6	40.9	40.2	39.5	38.9
355	48.1	47.1	46.2	45.4	44.5	43.7	42.9	42.2	41.5	40.8	40.1	39.4
360	48.7	47.8	46.9	46.0	45.2	44.3	43.6	42.8	42.1	41.4	40.7	40.0
365	49.4	48.5	47.5	46.7	45.8	45.0	44.2	43.4	42.7	41.9	41.2	40.6
370	50.1	49.2	48.2	47.3	46.4	45.6	44.8	44.0	43.3	42.5	41.8	41.1
375	50.8	49.8	48.9	48.0	47.1	46.2	45.4	44.6	43.9	43.1	42.4	41.7
380	51.5	50.5	49.5	48.6	47.7	46.9	46.0	45.2	44.5	43.7	43.0	42.3
385	52.2	51.2	50.2	49.3	48.4	47.5	46.6	45.8	45.0	44.3	43.6	42.8
390	52.9	51.9	50.9	49.9	49.0	48.1	47.3	46.4	45.6	44.9	44.1	43.4
395	53.6	52.6	51.6	50.6	49.7	48.8	47.9	47.1	46.2	45.5	44.7	44.0
400	54.3	53.2	52.2	51.2	50.3	49.4	48.5	47.7	46.8	46.1	45.3	44.5
405	55.0	53.9	52.9	51.9	50.9	50.0	49.1	48.3	47.4	46.6	45.9	45.1
410	55.7	54.6	53.6	52.6	51.6	50.7	49.8	48.9	48.0	47.2	46.4	45.7
415	56.4	55.3	54.2	53.2	52.2	51.3	50.4	49.5	48.6	47.8	47.0	46.3
420	57.1	56.0	54.9	53.9	52.9	51.9	51.0	50.1	49.2	48.4	47.6	46.8
425	57.8	56.7	55.6	54.5	53.5	52.6	51.6	50.7	49.8	49.0	48.2	47.4
430	58.5	57.3	56.2	55.2	54.2	53.2	52.2	51.3	50.4	49.6	48.8	48.0
435	59.2	58.0	56.9	55.9	54.8	53.8	52.9	51.9	51.0	50.2	49.3	48.5
440	59.9	58.7	57.6	56.5	55.5	54.5	53.5	52.6	51.6	50.8	49.9	49.1
445	60.6	59.4	58.3	57.2	56.1	55.1	54.1	53.2	52.2	51.4	50.5	49.7
450	61.3	60.1	58.9	57.8	56.8	55.7	54.7	53.8	52.9	52.0	51.1	50.3
455	62.0	60.8	59.6	58.5	57.4	56.4	55.4	54.4	53.5	52.5	51.7	50.8
460	62.7	61.5	60.3	59.2	58.1	57.0	56.0	55.0	54.1	53.1	52.3	51.4
465	63.4	62.2	61.0	59.8	58.7	57.6	56.6	55.6	54.7	53.7	52.8	52.0
470	64.1	62.8	61.6	60.5	59.4	58.3	57.2	56.2	55.3	54.3	53.4	52.5
475	64.8	63.5	62.3	61.1	60.0	58.9	57.9	56.8	55.9	54.9	54.0	53.1
480	65.5	64.2	63.0	61.8	60.7	59.6	58.5	57.5	56.5	55.5	54.6	53.7
485	66.2	64.9	63.7	62.5	61.3	60.2	59.1	58.1	57.1	56.1	55.2	54.3
490	66.9	65.6	64.3	63.1	62.0	60.8	59.7	58.7	57.7	56.7	55.8	54.8
495	67.6	66.3	65.0	63.8	62.6	61.5	60.4	59.3	58.3	57.3	56.3	55.4
500	68.3	67.0	65.7	64.5	63.3	62.1	61.0	59.9	58.9	57.9	56.9	56.0

*For other pressures the corrections to be applied are in proportion.

where $m = \dfrac{h}{18429.1 + 67.53\,T + 0.003\,h}$

and M = the correction in millibars
p = the observed pressure at the station level in millibars
T = the observed temperature at the station level in degrees Celsius
h = the height of the station above mean sea level in metres.

The value of M is tabulated in Table I for a value of p equal to 1000 mb and for various values of air temperature. The correction for other values of p can be obtained by multiplying the value of M given in the table by the factor $p/1000$.

This method does not give good results for higher–level stations, especially where there is a large diurnal range of temperature, and modified methods are often used (Schüepp *et al.* 1964). Many countries assume that the temperature of the hypothetical column of air increases downwards, from the station-level air temperature at the top, at a rate of 5 °C km^{-1} (approximately half the dry adiabatic lapse rate).

Other countries may take a mean of the current air temperature and either the air temperature 12 hours previously or the air temperatures 6, 12 and 18 hours previously. Account may also be taken of the decrease in gravity with height, and the fact that the density of the air depends on its water vapour content.

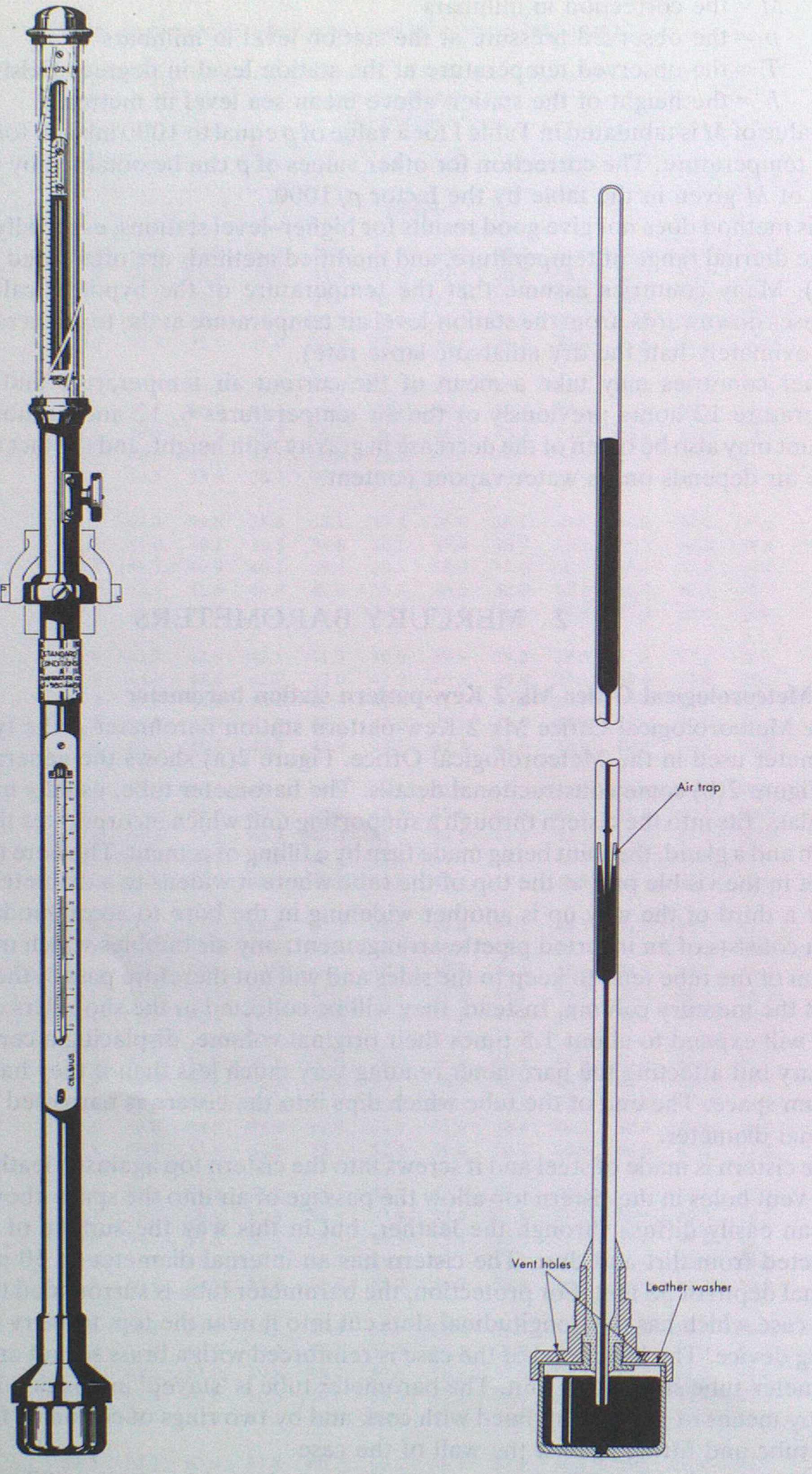
2 MERCURY BAROMETERS

2.1 Meteorological Office Mk 2 Kew-pattern station barometer

The Meteorological Office Mk 2 Kew-pattern station barometer is the type of mercury barometer used in the Meteorological Office. Figure 2(a) shows the general arrangement and Figure 2(b) some constructional details. The barometer tube, usually made of English lead glass, fits into the cistern through a supporting unit which incorporates the cover for the cistern and a gland, the joint being made firm by a filling of cement. The bore is about 1.6 mm except in the visible part at the top of the tube where it widens to a diameter of 8 mm. Just under a third of the way up is another widening in the bore to accommodate the air trap which consists of an inverted pipette arrangement; any air bubbles which may enter at the bottom of the tube tend to keep to the sides and will not therefore pass to the vacuum at the top of the mercury column. Instead, they will be collected in the shoulders of the trap, and there will expand to about 1.5 times their original volume, displacing a certain amount of mercury but affecting the barometer reading very much less than if they had passed to the vacuum space. The end of the tube which dips into the cistern is narrowed to about 6 mm external diameter.

The cistern is made of steel and it screws into the cistern top against a leather washer; two small vent holes in the cistern top allow the passage of air into the space above the mercury. Air can easily diffuse through the leather, but in this way the surface of the mercury is protected from dirt and dust. The cistern has an internal diameter of 50 mm and a clear internal depth of 35 mm. For protection, the barometer tube is surrounded throughout by a brass case which has two longitudinal slots cut into it near the top, to carry the vernier and setting device. The lower end of the case is reinforced with a brass socket and fits on to the barometer-tube supporting unit. The barometer tube is 'stayed' in position inside the brass case by means of a brass cap lined with cork and by two rings of cotton or felt glued to the glass tube and fitting against the wall of the case.

Scales and vernier. The barometer scale is graduated in whole millibars, from 870 to 1100 mb, on the left of the slot in the case. A cylindrical glass shade is provided to protect the scales. The vernier is mounted on a brass cylinder, which is a sliding fit inside the case, with the lower edge of the vernier perpendicular to the axis of the barometer tube. Adjustment of the vernier is by means of a rack-and-pinion movement, the pinion being situated at the side



(a) General arrangement (b) Some constructional details

Figure 2. Meteorological Office Kew-pattern station barometer Mk 2.

of the brass case just below the glass shade. The vernier is graduated on its left side so that 10 vernier divisions exactly cover 39 millibar divisions. It is thus possible to read directly to 0.1 mb and by estimation to 0.05 mb.

Attached thermometer. A mercury-in-glass thermometer is mounted in a metal frame on the front of the barometer to indicate the temperature of the instrument. It has a cylindrical bulb, which is protected from radiation by being mounted behind a metal plate, and is graduated on the stem either in kelvins or in degrees Celsius.

2.2 Meteorological Office Kew-pattern marine barometer

The Kew-pattern marine barometer, now mostly replaced by the Precision Aneroid Barometer (see page 1–15), was specially designed for use at sea. If an ordinary barometer were used at sea the oscillations or pumping of the mercury due to the pitching and rolling motion and vertical accelerations of the ship would often be so great that it would be difficult to obtain accurate readings of the barometer. To reduce this effect, the tube of the marine barometer differs from that of the station instrument in having the middle portion of its length made of capillary bore which offers a resistance to the rapid oscillations of the mercury.

2.3 Sources of error of Kew-pattern barometers

The general errors in the measurement of pressure are discussed on page 1–3. Other sources of error, peculiar to mercury barometers, as applicable to Kew-pattern barometers are discussed below.

Effects of the surface tension of the mercury (capillarity). The amount by which the top of the mercury column is lowered by surface tension is known as the capillary depression. In practice an allowance for capillary depression in the barometer tube is included in the barometer scale graduation. It is, therefore, only the variation in capillary depression which gives rise to errors. The error is usually negligible, its magnitude depending chiefly on the diameter of the barometer tube (the narrower the tube the greater the error).

A second error arises when the surface of the mercury in the cistern becomes flatter than normal resulting in a lowering of the barometer reading. Flattening of the meniscus in the cistern may be caused by (a) contamination of the mercury, and may remain undetected, or (b) an increase in pressure in which case there may be an associated bulge in the meniscus in the tube, and the effect can be minimized by tapping the barometer.

Defective vacuum. A defective vacuum is usually caused by the presence of air or water vapour. The presence of air can be detected by inspecting the closed end of the barometer tube when the tube is inclined so as to be filled with mercury; a little bubble will be seen if air is present.

Alternatively if the mercury is allowed to run slowly against the end of the tube there should be a sharp and metallic sound. If the sound is muffled or cannot be heard at all there is probably air in the tube. This test cannot be applied to marine barometers.

The presence of water vapour in the vacuum space is difficult to determine conclusively, as it condenses to liquid water if the mercury is allowed to fill the barometer tube. Even a very small amount of water vapour will effect the readings; one hundredth of a milligram would cause an error of about 2.3 mb at normal pressures.

Temperature measurement. The magnitude of the error due to the delay of the barometric column in following the temperature indicated by the attached thermometer, when the temperature is changing slowly, has been investigated. It was found that even if the average Kew-pattern barometer were subjected to a steady rise in external temperature of $1\,^{\circ}\mathrm{C\,h^{-1}}$, the error due to this cause would not exceed 0.03 mb. The errors due to the errors of the thermometer itself are usually negligible compared with those due to the uneven temperature of the barometer.

Verticality. The error in the reading of a Kew-pattern barometer for an inclination to the vertical of 5 min of arc is only 0.012 mb, and is thus negligibly small. When the instrument is suspended from a gimbal mounting it should hang very closely to the vertical (probably to within the limit given above) provided it is not disturbed.

Incomplete compensation of the Kew-pattern barometer for capacity. The contraction value of the scale is dependent on the internal diameter of the barometer tube, the internal diameter of the cistern and the external diameter of the tailpiece of the tube (the part which dips into the cistern).

In a new instrument the scale can be divided precisely once the dimensions of the barometer tube and cistern are known. In repaired instruments, however, it is the glass tube which normally requires replacing and this has to be chosen carefully. The effect of variations in the external diameter of the tailpiece is very small – an error of 1 mm causes an error of 0.01 per cent in the contraction value. The effect of changes in the internal diameter of the barometer tube is greater – an error of 0.5 mm causes an error of 0.31 per cent in the contraction value, equivalent to an error of 0.3 mb over 100 mb of the scale. This is the maximum permissible error in the Meteorological Office.

Index error. The index error is that due to any imperfections in the construction and adjustment of the barometer. Included are errors from causes such as residual gas in the vacuum space, refraction errors in the glass tube and excess or insufficient mercury. The index error is determined by comparision of the barometer readings with those of a working standard.

Special errors of Kew-pattern marine barometers. Marine barometers have sources of error additional to those already discussed. These arise from the movement of the barometer, caused by the ship's motion, the presence of the constriction in the barometer tube, and vibration.

(a) *Errors due to the barometer time constant.* When the pressure is changing at a constant rate the barometer reading differs from the true pressure by an amount $\alpha\tau$, where α is the rate of change of pressure and τ is the time-constant, provided the time interval since the change began is large compared with τ, τ varies between 6 and 9 min for the Meteorological Office Kew-pattern marine barometer.

(b) *Errors due to swinging of the barometer on its gimbals.* Two types of error arise owing to:

(1) An increase in the mean length of the mercury column because on average the barometer is inclined to the vertical.

(2) A decrease in the length of the mercury column, because of an apparent increase in the value of the acceleration due to gravity, due to the 'centrifugal force' set up by the swinging of the barometer.

The total error can be significant but will only be recorded in full if the swinging has been going on for some time which is large compared with the time-constant, i.e. 15 to 20 min or more.

(c) *Error due to a change in longitude.* When a ship is proceeding on a course with an east–west component, there is a change in the centrifugal force produced by the earth's rotation acting on the ship. The local acceleration due to gravity is consequently changed by an amount equal to $-2\omega v\cos\phi\sin\theta$, where v is the speed of the ship, ω is the angular velocity of the earth, ϕ is the latitude of the ship and θ is the direction of the ship's course from true north. The barometer indicates too high a pressure when the ship is moving eastward and too low a pressure when moving westward. The error can usually be neglected in comparison with the other errors in measurement of pressure on board ship.

(d) *Effect of motion of the ship in general.* Rolling, pitching, yawing and vibration lead to errors in two ways; they make it difficult to take a reading because of pumping and because of an ill-defined meniscus, and they lead, or may lead, to an incorrect mean pressure.

3 ANEROID BAROMETERS

3.1 General

The mechanism of an aneroid barometer often takes the form shown in Figure 3. When the pressure of the atmosphere on the capsule (1) decreases, the spring (2) relaxes and the capsule expands and moves the arm (3) upwards. This arm, through the connecting link (4) rotates the rocking bar (5). A projecting arm (6) on the rocking bar moves towards the centre allowing the hairspring (7) to contract and wind the arbor chain (8) upon the pulley (9), and thus to move the pointer. A screw in the base plate enables the position of the carriage to be adjusted slightly and thus the zero to be altered. This type of instrument is usually compensated for the effect of temperature changes by inserting a strip of different metal in the arm (3), making it a bimetal.

The same type of movement could be used for a recording barograph, but to overcome the increased friction it is better to have several aneroid capsules in series and to use less magnification in the lever system. This makes an external spring difficult to apply so that internal springs of some sort are used. Flexible capsules are often used nowadays, together

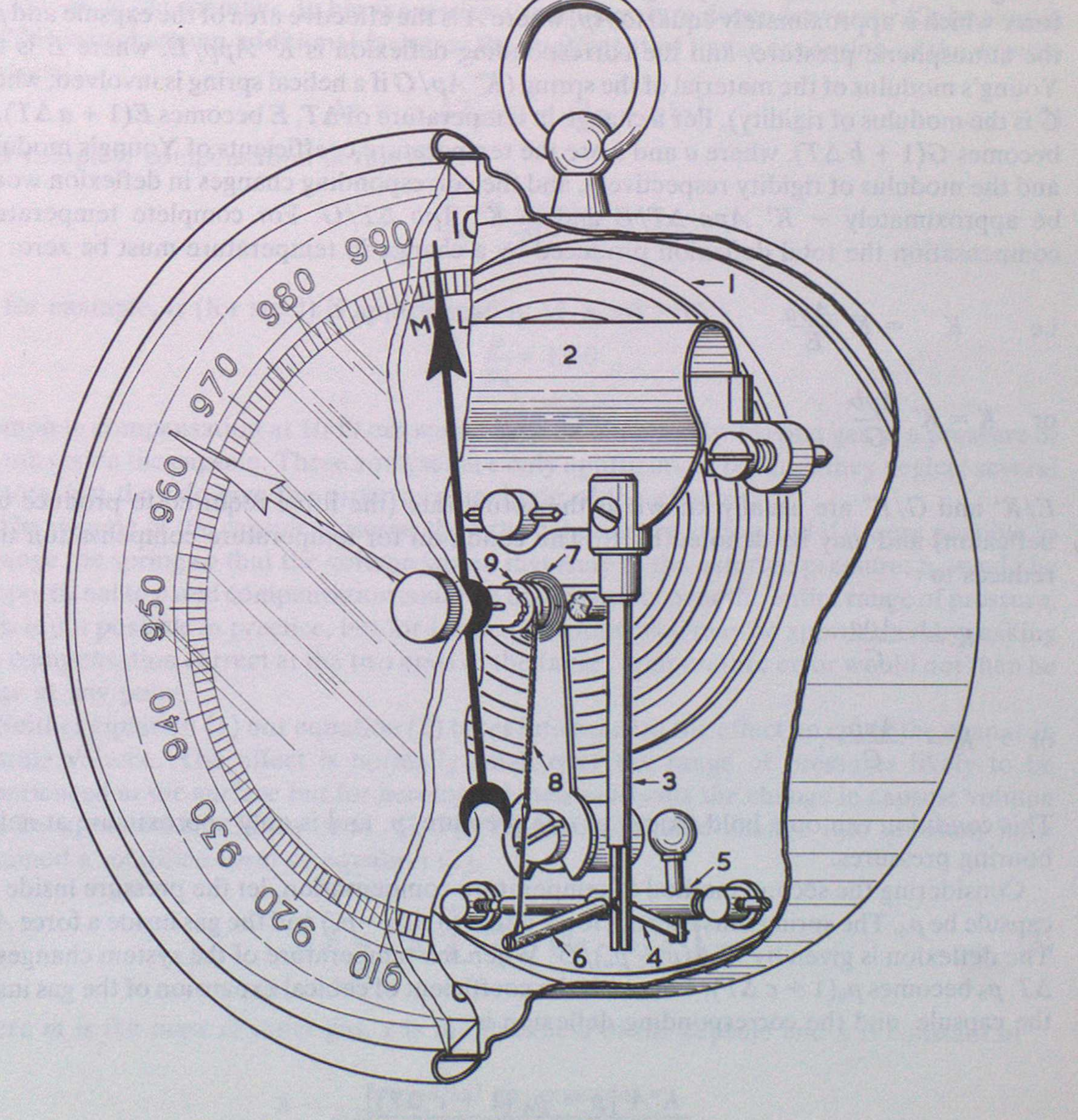


Figure 3. Typical mechanism of an aneroid barometer.

with an internal helical spring; there is the possibility of friction here, as when such a spring is compressed one end tends to rotate relative to the other. Friction errors are much reduced if the capsule is made of tempered steel with welded edges, so that the capsule acts as its own spring.

3.2. Sources of error of aneroid barometers

Temperature dependent errors. The properties of aneroid systems depend on the elastic properties of the capsule itself and the supporting spring (if any). The deflexion of the capsule thus depends on the value of Young's modulus, or the value of the modulus of rigidity, of the material of the spring and the capsule, and both of these vary with temperature. In most metals and alloys the temperature coefficients of the elastic moduli are negative, so that there will be an apparent increase in pressure when the temperature of the barometer rises. There are two methods of compensating for this effect; first by inserting a bimetallic link in the magnification system (as already described) and secondly by leaving a certain amount of gas inside the capsule.

The bimetallic link serves to alter the zero of the instrument by an amount which is proportional to the change in temperature (i.e. $K \Delta T$ where K is a constant and ΔT is the change in temperature). The spring (or the spring plus capsule, or the capsule alone) exerts a force which is approximately equal to Ap, where A is the effective area of the capsule and p is the atmospheric pressure, and the corresponding deflexion is $K' App/E$, where E is the Young's modulus of the material of the spring ($K'' Ap/G$ if a helical spring is involved, where G is the modulus of rigidity). For a change in temperature of ΔT, E becomes $E(1 + a\,\Delta T)$, G becomes $G(1 + b\,\Delta T)$, where a and b are the temperature coefficients of Young's modulus and the modulus of rigidity respectively, and the corresponding changes in deflexion would be approximately $-\ K' Apa\ \Delta T/E$ and $-\ K'' Apb\ \Delta T/G$. For complete temperature compensation the total deflexion produced by a change in temperature must be zero:

i.e $$K = K' \frac{Apa}{E}$$

or $$K = K'' \frac{Apb}{G}\ .$$

E/K' and G/K'' are usually known as the spring rate (the force required to produce unit deflexion) and may be denoted by C. The condition for temperature compensation then reduces to

$$K = \frac{Apa}{C}$$

or $$K = \frac{Apb}{C}\ .$$

This condition can only hold strictly at one pressure, p, and is only approximate at neighbouring pressures.

Considering the second method of temperature compensation, let the pressure inside the capsule be p_o. The spring thus exerts a force equal to $A(p - p_o)$ and the gas inside a force Ap_o. The deflexion is given by $K''A(p - p_o)/G$. When the temperature of the system changes by ΔT, p_o becomes $p_o(1 + c\,\Delta T)$, where c is the coefficient of cubical expansion of the gas inside the capsule, and the corresponding deflexion is

$$\frac{K''A\,[p - p_o\,(1 + c\,\Delta T)]}{G(1 + b\Delta T)}\ .$$

This results in a change in deflexion (ΔD) which is approximately given by

$$\Delta D = -K''A\ \Delta T \frac{cp_o + (p - p_o)b}{G}\ ,$$

and this corresponds to a temperature dependent error (Δp) given by

$$\Delta p = -\Delta T[cp_o + (p - p_o)b] \qquad \text{.....(1)}$$

where Δp is positive when the capsule contracts.

If p_o is known this may be used to give some indication of Δp. For complete compensation

$$\frac{p - p_o}{p_o} = -\frac{c}{b}\ ,$$

$$\frac{p}{p_o} = 1 - \frac{c}{b}\ .$$

This again can be true for only one value of p. If, for example, b (for steel) is -2.6×10^{-4} $°C^{-1}$ and c is 3.67×10^{-3} $°C^{-1}$, then

$$\frac{p}{p_o} = 1 + 14.1 = 15.1\ .$$

Complete compensation at 1000 mb would then be obtained by leaving gas to a pressure of 66 mb inside the chamber. In his expression for temperature dependent error Kleinschmidt (1928) introduces an additional factor α, the coefficient of linear expansion of the capsule material,

$$\Delta p = -\ \Delta T[cp_o - (2\alpha - b)p]\ . \qquad \text{.....(2)}$$

For complete compensation in this case

$$\frac{p}{p_o} = \frac{c}{2\alpha - b}\ .$$

If, for example, α (for steel) is approximately 11×10^{-6} $°C^{-1}$

$$\frac{p}{p_o} = 13.0\ .$$

Complete compensation at 1000 mb would then be obtained by leaving gas to a pressure of 77 mb inside the capsule. These analyses are only approximate because they neglect several factors, but they do give the order of magnitude of the effects.

The volume of the capsule varies as the external pressure varies, and if it were possible to arrange the spring so that the volume varied inversely as the external pressure, p_o would be proportional to p and compensation could be made perfect over the entire range of pressure. This is not possible in practice, but for surface instruments it may be approached by making the compensation correct at the two ends of the range; temperature error would not then be large at any point.

Neither equation (1) nor equation (2) takes into account the effect on cp_o of the change in capsule volume. The effect is normally small over the range of pressures likely to be experienced at the surface but for aerological measurements the change in capsule volume can be appreciable. Okada *et al.* (1976) by taking volume change into account, have obtained a modified form of equation (2),

$$\Delta p = -\Delta T\left[\frac{mk}{x} - (2\alpha - b)\,p\right], \qquad \text{.....(3)}$$

where m is the mass of inner gas, x is the thickness of the capsule and k is constant or

$$k = \frac{\text{universal gas constant}}{\text{molecular weight of gas} \times A}\ .$$

Even equation (3) is considered by Okada to be incomplete for aerological applications as it makes no allowance for the effect on temperature dependent errors of the dimensions and shape of the capsule corrugations.

Elastic errors. When a capsule is exposed to low pressure it expands and the strains in the material, which are greatest at surface pressure, decrease; by lowering the pressure to a value equal to the inner pressure of the capsule the plates of the capsule are fully relaxed. If the pressure is subsequently increased to its original value the capsule deflexion should also return to its original value. Unfortunately this does not always happen with the desired accuracy, the deflexion for a given pressure being different with rising pressure from that with falling pressure. This phenomenon is called hysteresis. If, for a pressure cycle, the pressure is plotted against capsule deflexion, a loop is obtained (see Figure 4 which is exaggerated for illustration). If the cycle is repeated at short intervals each successive loop is narrower until after about four or five cycles a steady state is reached.

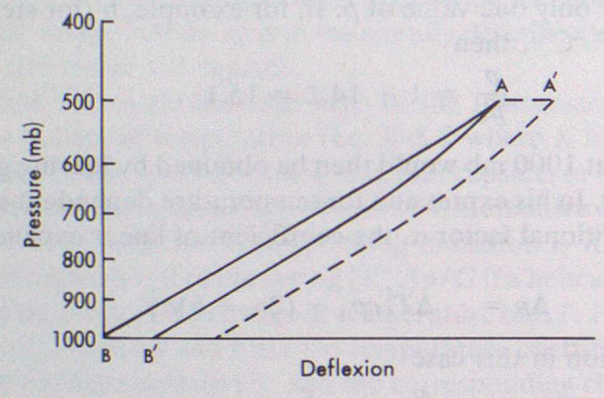


Figure 4. Effect of hysteresis.

According to Fink (1968) hysteresis may be considered as having three contributory factors. In his investigation a collection of capsules was subjected to a series of calibrations under conditions of falling pressure. With a normal period of about 24 hours between calibrations it was found that the capsule deflexion, D, for a given pressure tended to decrease with successive calibrations. This is said to be caused by fatigue, F in Figure 5. By interrupting the spacing between calibrations with an occasional period of 2 or 3 days, the

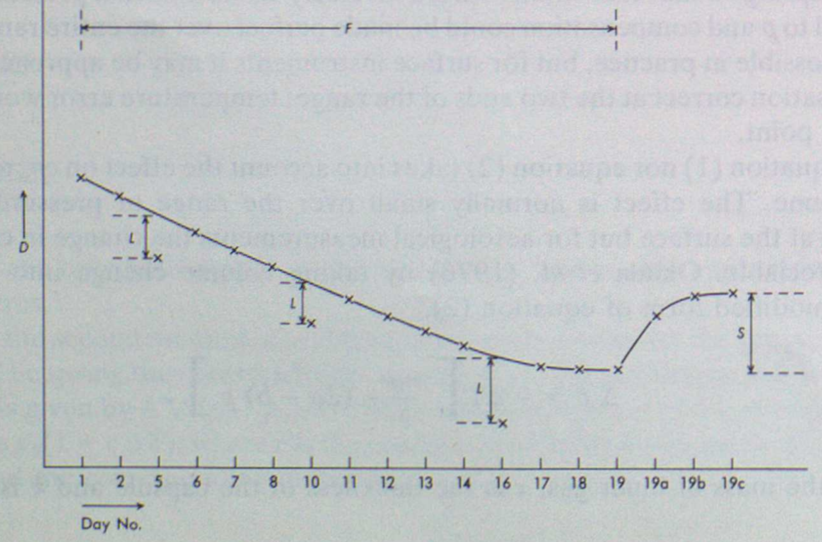


Figure 5. Factors contributing to hysteresis.

next calibration produced a deviation from the curve greater than might be expected from a normal scattering of the points. This was due to the capsule not having recovered from its previous calibration, and was termed 'long-term after-effect', L in Figure 5. Finally the time between calibrations was reduced to only a few hours. This also resulted in a deviation from the curve but with successive calibrations the change in deflexion lessened until a steady value for D was reached. This effect was termed 'short-term after-effect', S in Figure 5, and differed from L in that it disappeared after the capsule had been 'at rest' for about 24 hours.

Summarizing the results of the investigation:

(a) The long-term after-effect occurs in very few capsules and, as its value is small even at surface pressures, may be ignored.
(b) If the period between calibrations is long enough and the rate of change of pressure is not too great, the short-term after-effect can be minimized.
(c) The magnitude of the fatigue effect for any one calibration is usually small but it can be cumulative and after several calibrations may become unacceptably large.

Fink was essentially concerned with the accuracy of capsules for aerological application and, as no calibrations were made under conditions of rising pressure, actual measurements of hysteresis were not achieved. However, the effects observed, particularly fatigue, would seem equally applicable to instruments for measuring surface pressure.

If in the cycle of pressure changes shown in Figure 4 the pressure is held constant at point A′, it is found that the capsule deflexion will slowly change in the direction of A. This process is known as creep and is the reason for calibration drift (see page 1–20).

In general the elastic errors of capsules vary directly with:

(a) the temperature,
(b) the range of pressure, and
(c) the rate of change of pressure.

Because of the limited range of pressure and the small rate of change of pressure, elastic errors in surface station aneroid barometers and barographs are usually unimportant in the short term.

3.3 Meteorological Office aneroid barometers Mk 2 and Mk 3

The Meteorological Office aneroid barometers Mk 2 and Mk 3 were designed to be used as portable station barometers where the use of a mercury barometer is impracticable, but they are hardly accurate enough for synoptic work. The mechanism follows the general design described on page 1–11, being compensated for temperature with a bimetallic link and housed in a cylindrical brass case with a bevelled glass front. The zero adjustment screw can be operated through a hole in the back of the case. The pointer moves over a scale which is graduated in whole millibars from 855 to 1055 mb for the Mk 2 and 875 to 1075 mb for the Mk 3. A movable index fitted to the glass face can be set independently of the pointer and is useful for showing changes in pressure.

3.4 Precision aneroid barometers (PABs)

The practical advantages, ease of reading, convenience of transporting, and reduced physical size of aneroid barometers have long been realized. The disadvantages, which once precluded their use internationally at main reporting stations, lay in the errors introduced mainly by mechanical linkages, magnification movements, and constraining springs within the capsules. A system has been developed whereby the movement of a lightly constrained capsule stack is precisely measured by a manually operated micrometer screw. Contact between capsule and micrometer screw is indicated electrically, and atmospheric pressure is displayed in millibars and tenths of a millibar.

The Meteorological Office uses two versions of the precision aneroid barometer (PAB Mk 1 and PAB Mk 2), both having a range from 1050 mb to 900 mb. The versions differ in physical appearance (see Plates I and II) but not in the principle of operation.

The pressure-sensing element of the PAB is a stack of three disc-type beryllium–copper alloy capsules, (A) in Figure 6, containing a gas with a pressure of 67–69 mb, rigidly fixed on one side to an inside wall of a cast-metal chamber. One end of a counter-balanced (B) jewel-pivoted contact arm (C) is very lightly constrained, by a hair spring (D), on to the centre of the free end (E) of the capsule stack. A contact (F) on the other end of the arm is aligned with another contact (G) at the end of a micrometer screw (H) running through the opposite wall of the chamber. Movement of the free end of the capsule stack is thus conveyed to the micrometer screw where it can be measured. The contacts are a silver palladium disc (F) and a gold-plated ball (G).

Between the two contacts (F) and (G) an electrical circuit is arranged so that contact between the two is shown by a cathode-ray indicator (I); at the same time the measurement made by the micrometer screw is transferred through gearing (J) to a digital counter (K). When contact is made the cathode-ray indicator shows a continuous line of light; at disengagement a broken line of light is shown. The electrical circuit is designed so that the current passing is minimal.

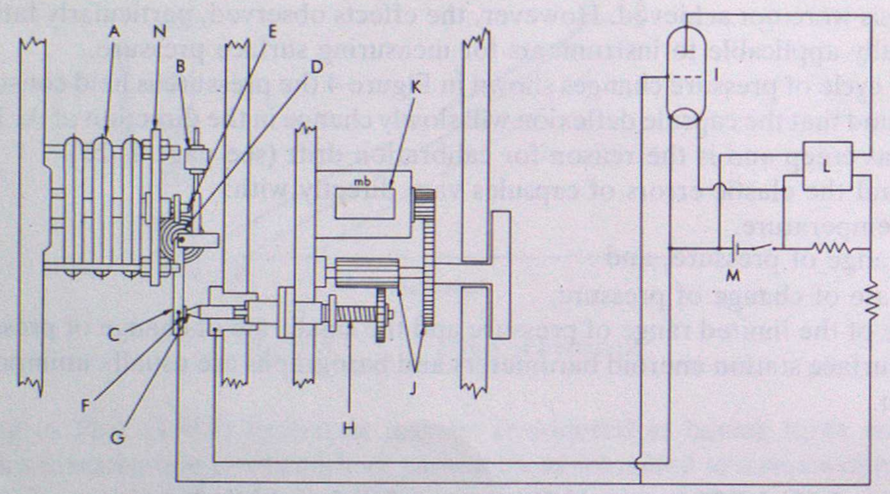


Figure 6. Mechanism of the precision aneroid barometer.

The instrument is designed so that 25.4 μm at the micrometer screw are equivalent to 1 mb, and the contact arm pivot is situated so as to interpose a ratio of approximately 3:1 between the micrometer and the capsule. The deflexion of the capsule over the pressure range 900 to 1050 mb is therefore approximately 1.27 mm.

The metal case has two separate compartments. One compartment houses the d.c.–d.c. converter (L), which boosts the voltage from a standard 1.5 V standard battery (M) to the required operating voltage of 50–100 V d.c., and the other compartment houses the pressure-sensing assembly and forms the pressure chamber (Plate III). An entry tube is fitted to the pressure chamber to allow for control of the pressure during calibration and for attachment of a damping cap (see Plate IV) and an input from a static pressure head (see Figure 7) if required; when the tube is sealed the chamber is airtight.

A 'stop-plate' (N) mounted centrally above the capsule stack prevents expansion at pressures significantly lower than 900 mb thus ensuring that the instrument may safely be transported by aeroplane.

The carrying case for the PAB is designed in a manner that allows the instrument to be operated within it for field-work or similar purposes. The instrument is firmly held within the case by easily detachable retaining rods or screws. The case itself has shock-absorbing feet. The PAB in its carrying case may be safely transported by car over metalled roads or by aircraft without affecting its calibration provided that it is handled without being dropped. For transportation by public carrier the instrument (inside its carrying case) is packed in a shock-absorbing transit package designed to provide protection against physical damage.

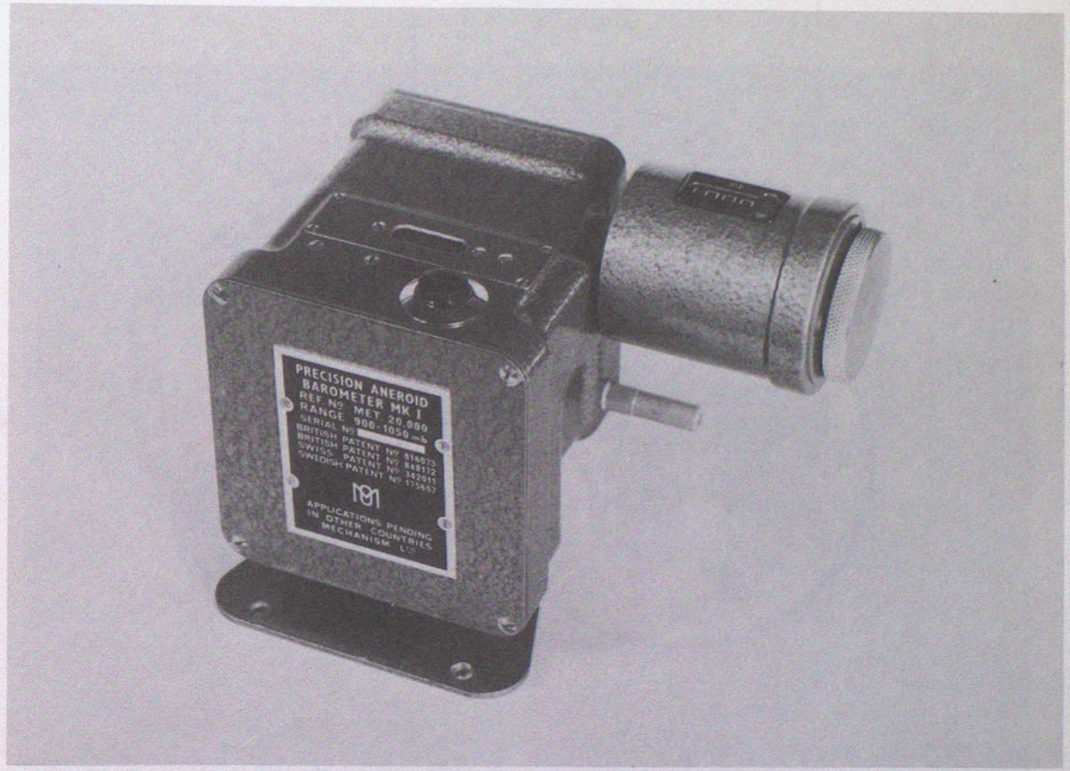


Plate I. Precision aneroid barometer Mk 1.

Plate II. Precision aneroid barometer Mk 2.

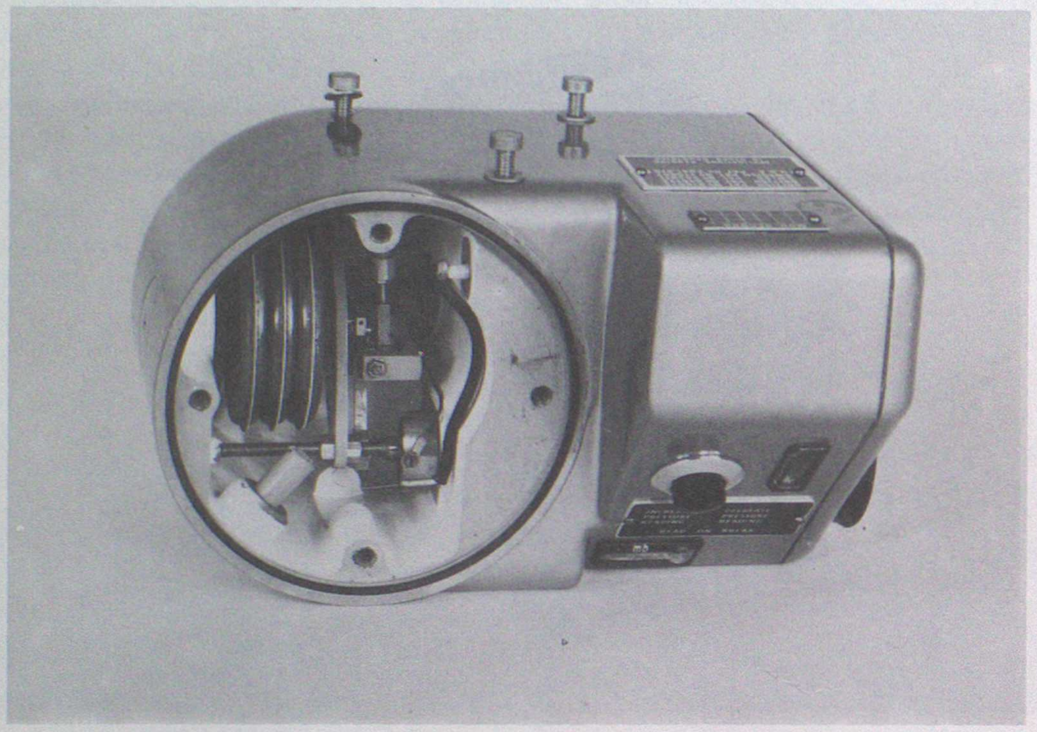


Plate III. Pressure chamber of a precision aneroid barometer Mk 2.

Plate IV. Damping cap for precision aneroid barometer. Illustrated at approximately twice full size.

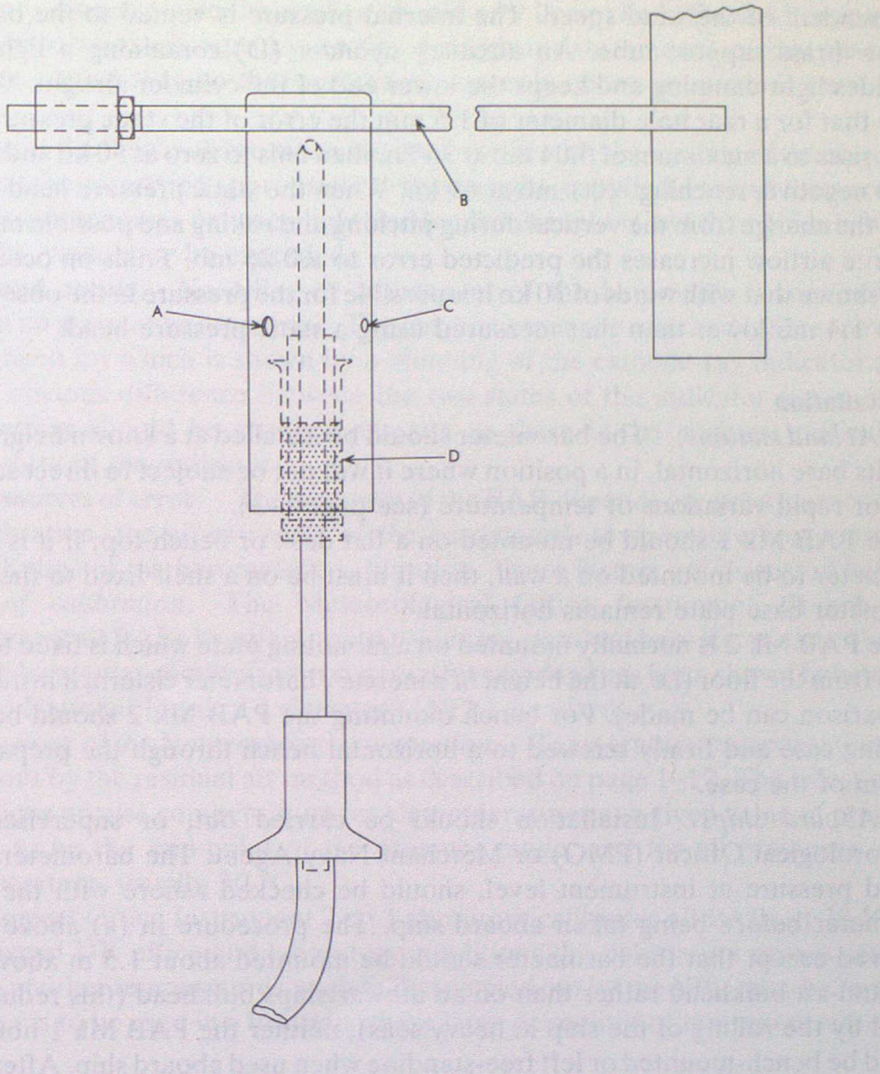


Figure 7. Meteorological Office static pressure head Mk 1.

However, recent experiment and experience have shown that about one PAB in five is delivered with its calibration shifted off limits when use is made of public carriers in the United Kingdom.

Attachments

(a) *Damping cap*. When used at sea the PAB is fitted with a damping cap, the purpose of which is to restrict the response of the instrument to the rapid pressure variations associated with the rise and fall of a ship. It will reduce a pressure-step change of 1 mb over a 12-second period to a change of only 0.12 mb. The cap (Plate IV) is in the form of a tube, about 38 mm long, one end of which fits over the outlet tube of the barometer; the other end, reduced in diameter to 8 mm, contains a material sufficiently permeable to achieve the required damping without entirely blocking the flow of air into and out of the pressure chamber.

(b) *Static pressure head*. A static pressure head can readily be fitted to a PAB, its purpose being to minimize the errors associated with strong and gusty winds (see page 1–3).

The Meteorological Office static pressure head Mk 1 is essentially a cylinder 210 mm long and 63 mm in diameter (Figure 7). There are two 6.35 mm diameter holes (A) approximately 97 mm from the top end, their centres subtending an angle of 78° at the axis of the cylinder. The ends of the cylinder are closed and the cylinder is mounted, with its axis vertical, on a wind vane (B) so that the bisector of the angle subtended by the holes is in line with the wind direction. The holes are on the upwind side. A third small hole (C) is drilled, in the line of the bisector, on the downwind side. The size of this hole has been determined experimentally during wind-tunnel tests so that the internal pressure in the cylinder remains independent of the wind speed. The internal pressure is vented to the barometer via the hollow brass support tube. An auxiliary cylinder (D) containing a light lubricating oil provides light damping and keeps the lower end of the cylinder airtight. Wind-tunnel tests show that for a rear hole diameter of 1.5 mm the error of the static pressure head measurement rises to a maximum of 0.04 mb at 35 kn, then falls to zero at 50 kn and becomes rapidly more negative, reaching −0.1 mb at 60 kn. When the static pressure head is used on board ships the change from the vertical during pitching and rolling and possible misalignment with the true airflow increases the predicted error to ±0.25 mb. Trials on ocean weather ships have shown that with winds of 30 kn it is possible for the pressure in the observing office to be up to 1.4 mb lower than that measured using a static pressure head.

Installation

(a) *At land stations*. The barometer should be installed at a known height (see page 1–4) with its base horizontal, in a position where it will not be subject to direct sunshine, knocks, jolts or rapid variations of temperature (see page 1–3).

The PAB Mk 1 should be mounted on a flat desk or bench top; if it is essential for the barometer to be mounted on a wall, then it must be on a shelf fixed to the wall so that the barometer base plate remains horizontal.

The PAB Mk 2 is normally mounted on a mounting plate which is fixed to a wall at about 1.2 m from the floor (i.e. at the height of a mercury barometer cistern, if installed, so that true comparison can be made). For bench mounting the PAB Mk 2 should be kept within its carrying case and firmly screwed to a horizontal bench through the prepared holes in the bottom of the case.

(b) *Aboard ships*. Installation should be carried out, or supervised, by the Port Meteorological Officer (PMO) or Merchant Navy Agent. The barometer, which is set to record pressure at instrument level, should be checked ashore with the PMO standard barometer before being taken aboard ship. The procedure in (a) above should then be followed except that the barometer should be mounted about 1.5 m above the deck on a fore-and-aft bulkhead rather than on an athwartships bulkhead (this reduces errors introduced by the rolling of the ship in heavy seas); neither the PAB Mk 1 nor the PAB Mk 2 should be bench-mounted or left free-standing when used aboard ship. After installation the damping cap should be fitted as follows:

For PABs Mk 1

The rubber dust-cover, if fitted, should be removed from the outlet tube and replaced by the damping cap which should be firmly pressed home.

For PABs Mk 2

The static vent fitted towards the top of the left-hand side of the instrument should be unscrewed very carefully and taken out. It should then be reversed and screwed back in, finger-tight, making sure that the 'O' ring on the static tube remains in position in the hole. The damping cap should then be pushed over the end of the static vent.

Method of use. Comprehensive 'Observers Instructions' are issued with each barometer; the description of an observation, given below, is an extract from the instructions.

(a) Depress the switch button.

(b) (1) If the thread of light in the cathode-ray indicator is broken turn the knurled knob, so that the pressure reading decreases, until the thread becomes continuous.
(2) If the thread of light in the indicator is continuous, turn the knurled knob, so that the pressure reading increases, until the thread of light just breaks.

(c) The setting should be repeated, i.e. the thread of light should be made to make and break again to avoid any error that could arise from 'over-shooting' the correct setting on the first attempt.

(d) The barometer is reading the correct pressure when the light just breaks and the pressure should then be read from the display window. If parts of two figures show equally in the tenth-of-a-millibar position the odd number should be taken.

(e) The necessary corrections to the reading should now be applied. The PAB is compensated for temperature changes by leaving an appropriate amount of dry air in the capsules (see page 1–12), so that corrections are only necessary for index error and altitude.

On ships, because the height above mean sea level varies with the loading of the ship, care must be taken that the correction appropriate to the draught is applied. In most instances the difference in pressure readings between light and loaded draught is less than 1.5 mb, but on rare occasions this value may be exceeded.

Maintenance and repair. No oiling or adjustment of the barometer is required and repairs should on no account be attempted. The only maintenance required is the renewal of the battery, the need for which is shown by a dimming of the cathode-ray indicator and a lessening of the obvious difference between the two states of the indicator (i.e. made or broken). The battery should be changed as soon as there is the slightest difficulty in recognizing the state of the indicator.

Accuracy and sources of error. The accuracy of the PAB depends on: the accuracy of the barometer's calibration, the effectiveness of the barometer's temperature compensation, and the drift with time of the barometer's calibration. These factors are discussed below.

(a) *Accuracy of calibration*. The Meteorological Office Instrument Branch Test Laboratory calibrates all PABs by reference to a working standard barometer, described on page 1–26, which by regular comparisons via a transfer standard has been shown to be within ±0.05 mb of the National Physical Laboratory (NPL) standards.

(b) *The effectiveness of the temperature compensation*. Temperature compensation with PABs is carried out by the residual air method as described on page 1–12. The effect of this method is to achieve precise compensation for all temperatures at a given value of pressure, which is chosen to be the mid-point of the pressure range, and for all pressures at the calibration temperature, usually 20 °C.

The Meteorological Office Instrument Test Laboratory calibrates all PABs at 20 °C and when used in normal UK office and laboratory conditions this calibration proves satisfactory. Calibration at other temperatures, such as that carried out by the NPL, may be required when a barometer is to be used in a location where large deviations of temperature from 20 °C are likely.

The results of the calibration of 30 PABs Mk 2 by the NPL at temperatures of +5 °C and +35 °C are shown in Table II.

Table II. *Mean temperature corrections — precision aneroid barometers Mk 2*

Temperature	Pressure			
	1050 mb	1000 mb	950 mb	900 mb
		millibars		
5 °C	+0.297	+0.113	−0.040	−0.220
35 °C	−0.208	−0.104	+0.112	+0.280

These represent the mean pressure corrections required after the application of the corrections from each barometer's calibration card for 20 °C; the standard deviation of all the corrections is 0.08 mb.

These results may be expressed in the form of a linear equation $\Delta p = [-2.31 \times 10^{-4} P + 0.233] (T-20)$ where P is the pressure in millibars and T the temperature in degrees Celsius. The correction Δp must be applied in addition to that given for +20 °C operation.

This formula is a means of deriving an occasional correction when extremes of temperature occur but the readings so obtained are not as accurate as those from a barometer specifically calibrated for temperatures other than 20 °C.

(*c*) *Calibration drift in the PAB*. The capsule stack of the PAB is under continuous stress due to its low internal pressure. All metals when in a stressed condition undergo slow changes in their state of strain; this condition is referred to as creep. The effect of creep on the capsule stack is to cause a slow inward deformation which manifests itself as a positive calibration drift.

The average drift determined from 1169 calibrations of Mk 2 PABs over a period of four years was about 0.08 mb in six months. However, the drift is often greater in the earliest years of life and reduces as time passes. Calibration drift limits the accuracy of the PAB in use and in order to maintain an acceptable performance the Meteorological Office checks all PABs at intervals of six months. There is evidence that jumps in calibration may occur because of careless handling in transit despite careful packaging — see page 1–16.

3.5 Checking barometers

It is important to check the accuracy of the station barometer at frequent intervals so that a defective instrument may be detected and replaced as soon as possible.

Six-monthly barometer checking. The robust qualities of the PAB make it ideal for use as a travelling standard for checking station barometers. The PAB is first calibrated by the Meteorological Office Instrument Branch Test Laboratory and then despatched to a meteorological station. At the station, 25 comparison readings of pressure, over a period of 5 days, are made between the travelling standard and the station barometers. The readings are made with all the barometers at the same height, when the wind speed is less than 25 kn and when the pressure is steady, or changing by less than 1 mb h^{-1}. In practice, for convenience, the readings are corrected to mean sea level. It has been found that the standard deviation of the differences obtained when a mercury barometer is checked by this method is 0.14 mb, and when a PAB is similarly checked the standard deviation of the differences is 0.09 mb. The use of this system allows the accuracy of barometers at Meteorological Office stations to be checked every six months with an uncertainty of slightly better than 0.1 mb. It is to be noted that the check does not represent a new calibration of the station barometers. However, any station barometer whose mean difference from the travelling standard barometer exceeds 0.25 mb is regarded as unserviceable and is returned to the Test Laboratory for recalibration.

Daily barometer checking. Each Meteorological Office station has two station barometers which are compared once a day. If any single difference exceeds by more than 0.3 mb the mean difference obtained in the corresponding comparisons made at the beginning of the current six-month period, a travelling standard PAB may be requested so that the offending barometer may be identified. However, when a station has two PABs there is a possibility that both could exhibit relatively large positive calibration drift. Such an occurrence, with both barometers comparing satisfactorily, could produce errors of up to 0.4 mb. This problem is countered by ensuring, at issue, that one of the PABs at each station has a history of low drift. This barometer is called a low-drift barometer and is selected by the Test Laboratory from its previous calibration record. With the arrival of each new barometer at a station six-monthly comparison readings are made and the mean difference between the low-drift and the new barometer is established. Subsequent to this, daily readings of each barometer are made and a running sum of 25 differences calculated. If the new barometer and the low-drift barometer exhibit different rates of drift the sums of the 25 differences will change. If the sum changes by more than 4.0 mb from that established at the six-monthly comparison an emergency check barometer is called for. The use of this checking procedure ensures that unnoticed errors of more than +0.3 mb rarely occur. In the case of a station with one mercury barometer and one PAB, the mercury barometer may be used as the low-drift barometer provided it has shown no marked changes in calibration in previous six-monthly comparisons. A mercury barometer showing charges of more than 0.2 mb between two consecutive barometer checks is unsatisfactory as a low-drift barometer.

4 ANEROID BAROGRAPHS

4.1 General

The principle of the aneroid barograph is similar to that of the aneroid barometer, except that a recording pen is used instead of a pointer; this involves some change in the design of the capsule stack, and usually means a decrease in the overall magnification and an increase in the number and size of the capsules used.

The 'control' of the barograph (see page A–3) may be expressed as the force which is required to move the pointer over one unit of the scale (1 mb), and is thus equal to the force required to prevent the pen from moving when the pressure changes by 1 mb. It is a measure of the effect that friction is likely to have on the details of the record.

The force required to overcome movement of the capsule when the pressure changes by 1 mb is $100A$ newtons, where A is the effective cross-sectional area of the capsule in square metres. If the magnification is X, the force necessary to keep the pen from moving is 100 A/X newtons and varies as A/X. For a given type of capsule and scale value the value of X will be largely independent of A, so that the control of a barograph pen may be considered to vary approximately as the effective cross-sectional area of the capsule.

4.2 Meteorological Office open-scale barograph

The capsule of the open-scale barograph is of the bellows type with an internal spring, Plate V. It is fixed to a brass base plate, and the vertical motion of the top (A) is transmitted to the pen arm through a system of levers (Figure 8). An analysis of the magnification of the lever system is given at the end of this section.

An 'O' type drum (see page A–6) is used together with a weekly clock and the range of pressure covered is from 950 to 1050 mb. The scale value on the barogram is 1.8 mm mb^{-1}. The clock and the brass mounting plate for the capsule and lever mechanism are mounted on a stout metal base and a glass cover with a metal framework is provided to exclude the dust and protect the mechanism. A time-marking device is fitted to the base and consists of a spring-loaded horizontal rod which when pushed in makes contact with a vertical rod supported in a collar on the mounting plate. The vertical rod, in turn, rises against the lever EC (Figure 8).

The setting of the pen can be altered by means of the screw which raises or lowers the pivot E. The range of setting which can be employed is limited by the size of the springs used in the screw mechanism.

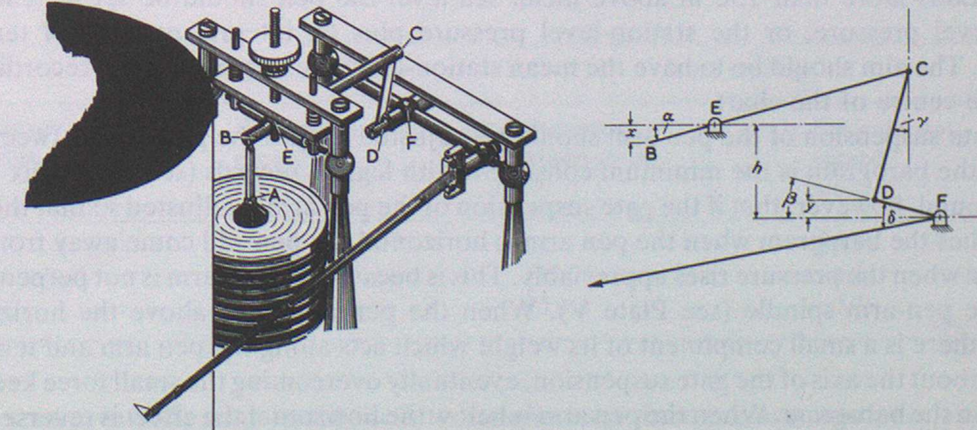


Figure 8. Lever system of open-scale barograph.

The projection of the pen arm on to the vertical plane defined by BECDF (Figure 8) should always coincide with DE; for consider the magnification of the lever system when the arms BEC and DF are inclined to the horizontal at angles α and β respectively. If x is the vertical distance from B to the horizontal plane through E, y is the vertical distance from D to the horizontal plane through F, and h is the vertical distance between E and F, then

$$\text{DF} \sin\beta = y = h + x\,(\text{CE}/\text{EB}) - \text{DC} \cos \gamma$$

where γ is the inclination of the lever CD to the vertical. This angle is always very small and changes only very slowly so that the term DC cos γ may be considered constant. It can then be shown that a change of Δx in x causes a change of $(\text{CE}\Delta x)/(\text{EB.DF} \cos \beta)$ in β. If the length of the projection of the pen arm on to the plane BECDF is l and the angle between the projection of the pen arm and the level DF is δ, then the vertical distance of the pen below the horizontal plane through F is $l \sin(\delta - \beta)$, and the change in this distance due to a change of Δx in x is thus

$$\frac{-l \cos(\delta - \beta)\, \text{CE}\, \Delta x}{\text{EB.DF} \cos \beta}.$$

For a linear scale on the barogram this has to be constant over the whole range of the instrument (as Δx is proportional to the change in pressure). This can be so only when δ is zero. Strictly, l should be constant as well, but the variation in this length, due to the pen arm approaching more closely to the vertical plane BECDF as it rises or falls from its mean position, is so small as to be negligible.

The condition that δ equal zero should always be fulfilled for barographs received direct from the provisioning branch, but in other cases a check should be made, and if the pen arm is not correctly adjusted the screw fixing the pen arm in position relative to the pen-arm spindle should be loosened and the necessary adjustment made.

Installation and adjustment. The barograph should be placed on a rigid shelf or other horizontal support at a convenient height for observation, but where it will not be exposed to sunlight or sources of artificial heat. If the building is subject to vibration it is advisable to mount the barograph on rubber pads, or other suitable packing, taking care that the instrument remains horizontal. The setting of the pen should be adjusted, if necessary, to the correct pressure indication on the barogram.

The barograph actually records the variations in pressure at the station level, but at stations not far above mean sea level it is customary to set the pen so that it indicates the pressure at mean sea level. Once set the barograph will, of course, not read correctly when the outside temperature changes because of the change in the mean-sea-level correction, but for stations up to about 150 m above mean sea level the error introduced is usually small and the barogram may be treated as a record of mean-sea-level pressure.

At stations more than 150 m above mean sea level the pen should be set to read the station-level pressure, or the station-level pressure plus an integral number of tens of millibars. The aim should be to have the mean station-level pressure produce a recording at about the centre of the chart.

The gate suspension of the pen arm should be adjusted so that the pressure between the pen and the barogram is the minimum consistent with legible records (see Appendix 1). It may be found, however, that if the gate suspension of the pen arm is adjusted so that the pen just touches the barogram when the pen arm is horizontal the pen will come away from the barogram when the pressure rises appreciably. This is because the pen arm is not perpendicular to the pen-arm spindle (see Plate V). When the pen arm rises above the horizontal position there is a small component of its weight which acts along the pen arm and tends to rotate it about the axis of the gate suspension, eventually overcoming the small force keeping the pen on the barogram. When the pen arm is below the horizontal the effect is reversed. To obtain the best pressure between the pen and the barogram the gate suspension should therefore be adjusted with the pen arm near the upper limit of pressure which will be encountered.

The adjustment of the position of the pen to the initial correct setting should be made by turning the setting screw; the pen arm itself should not be rotated relative to the pen-arm spindle. Quite a large range of movement is possible in this way, and on most instruments the central pressure can be made at least as low as 880 mb.

As very low values of pressure are outside the normal working range of the capsule, some change in scale value may result at high-level stations. This can be detected by comparing the pressure as recorded by the barograph with the true pressure as obtained from a barometer over a period of about 3 months without altering the setting of the barograph. If the errors are then plotted as a function of pressure any systematic change in the errors with pressure can be seen and corrections made to the observations. Alternatively, it is possible to make a small change in the scale value by altering the position of the lever BEC in the collar at E (Figure 8). This alters the ratio CE/BE.

Method of use. There is little to add to the general instructions for the routine use of recording instruments (see Appendix 1). A time mark should be made at least once a day at about the same hour. The time-marking device should be used carefully and only a very small mark made to avoid straining the capsule. The barogram is usually changed on Monday mornings, and the barograph should be set to read correctly at the same time. The barogram should be written up as detailed in Appendix 1.

Because of friction between the pen and the barogram it is advisable to tap the instrument lightly before a reading is made of the instantaneous atmospheric pressure. The barometric tendency over any period (usually that over the last three hours is required) can be readily obtained from the trace of this instrument because of the large-scale value; it is not, however, advisable to tap the instrument when taking a reading of the tendency.

Maintenance. The instrument should be kept clean, and in particular the pen and pen arm should be kept free of congealed ink. The pivots should be kept clean and free but without any slackness. A little clock oil can be applied at infrequent intervals. It will be found that the time-marking device needs occasional attention to keep it in good order; it is essential that its movement be smooth to avoid straining the capsule by moving the lever BC violently.

Accuracy. The instrument has to pass tests before being accepted by the Meteorological Office (see page 1–29). As the barograph is normally housed indoors the temperature change encountered should not be excessive and errors due to this should be small. Temperature compensation is effected by leaving air (or other gas) in the capsule; the compensation is complete at about 1000 mb but is incomplete at other pressures and at high-level stations appreciable errors may arise.

A representative instrument was tested over a period of 2 months against a mercury barometer without altering the barograph setting. Readings were taken both before and after tapping the instrument gently, with the following results:

Before tapping		After tapping	
Percentage of observations %	Error did not exceed mb	Percentage of observations %	Error did not exceed mb
30.5	±0.15	38	±0.15
68	±0.45	77	±0.45
90	±0.75	93	±0.75

A second investigation was made into the accuracy of the pressure tendency as read from the barograph when compared with that obtained by reading a standard mercury barometer. It was found that 28 per cent of the readings were correct, 73 per cent had an error not exceeding ±0.1 mb and that 92 per cent had an error not exceeding ±0.2 mb. The tendencies ranged from +3.8 to −3.8 mb in three hours. The errors in the tendencies would probably have been larger if more rapid pressure changes had taken place.

The barograph responds to changes in pressure at the station level, so that if it is originally adjusted to record the mean-sea-level pressure it will not continue to do so when the outside temperature changes. For a station at 75 m above sea level a change in outside air temperature of 30 °C means a change in the mean-sea-level correction of 0.9 mb; i.e. if the original adjustment was made at 15 °C the barograph would be about 0.4 mb in error from this cause when the outside temperature was 0 °C or 30 °C. The error would be less if the temperature change were smaller or if the station were lower, and greater if the station were higher.

4.3 Meteorological Office small barograph

The capsule stack of the small barograph usually consists of seven or eight separate capsules fitted with internal springs and connected together in series, the lowest being firmly mounted on a brass plate on the base of the instrument (Plate VI). The movement of the top of the capsule stack is transmitted through a lever system, similar to that of the open-scale barograph, to the pen-arm spindle, and thus to the pen arm itself. The pen records on a barogram placed on a standard 'S' type drum driven by a weekly clock. A scale value of 0.75 mm mb^{-1} is employed and the barogram covers a span of 100 mb (950 to 1050 mb).

The setting of the pen on the barogram can be altered in one of two ways; either the capsule stack is moved bodily up or down by raising or lowering the base, or the fulcrum of the main lever is suspended from a bridge which can be raised or lowered. In either case the adjustment is carried out by simply turning a milled-head screw. The case is hinged to the base on the left-hand side and has glass windows in the front and left-hand end. A handle is fixed to the top for carrying purposes.

Installation and adjustment. The siting, mounting and adjustment of the small barograph should follow the same lines as for the open-scale barograph (see page 1–22).

Method of use. The small barograph should be used in the same way as the open-scale instrument (see page 1–23) but the scale value is too small to enable the pressure tendency to be read from the barogram with sufficient accuracy for synoptic purposes.

Maintenance. The instrument should be kept clean, and in particular the pen and pen arm should be kept free of congealed ink. The pivots of the lever mechanism should be kept clean and free but without any slackness which may lead to lost motion. A little clock oil may be applied at infrequent intervals.

Accuracy. The instrument has to pass tests before it is accepted by the Meteorological Office (see page 1–29).

It has been found that when a barograph of this type is compared with the readings of a mercury barometer over a period of two months without any resetting, 60 per cent of the errors do not exceed 0.75 mb and 73 per cent do not exceed 1.05 mb. Evidence of a gradual change in zero throughout the test suggests better results can be obtained if the barograph is reset regularly. This is about the best that can be hoped for with the compressed scale employed.

4.4 Use of barographs at sea

Barograms obtained from ships at sea are often unsatisfactory because the trace is widened into a ribbon several millibars wide. The broadening is due to four factors:

(a) Vibration due to ship's engines etc.
(b) Angular acceleration of the ship (rolling and pitching).
(c) Transient pressure changes caused by gusts of wind.
(d) Oscillations of pressure due to the rise and fall of the ship.

The relative importance of these causes depends on the size of the ship and the weather conditions.

Meteorological Office marine barograph. The effect of transient pressure changes on the open-scale barograph is reduced by increasing its time-constant. This, however, also reduces the speed at which the instrument responds to true changes of pressure and a compromise

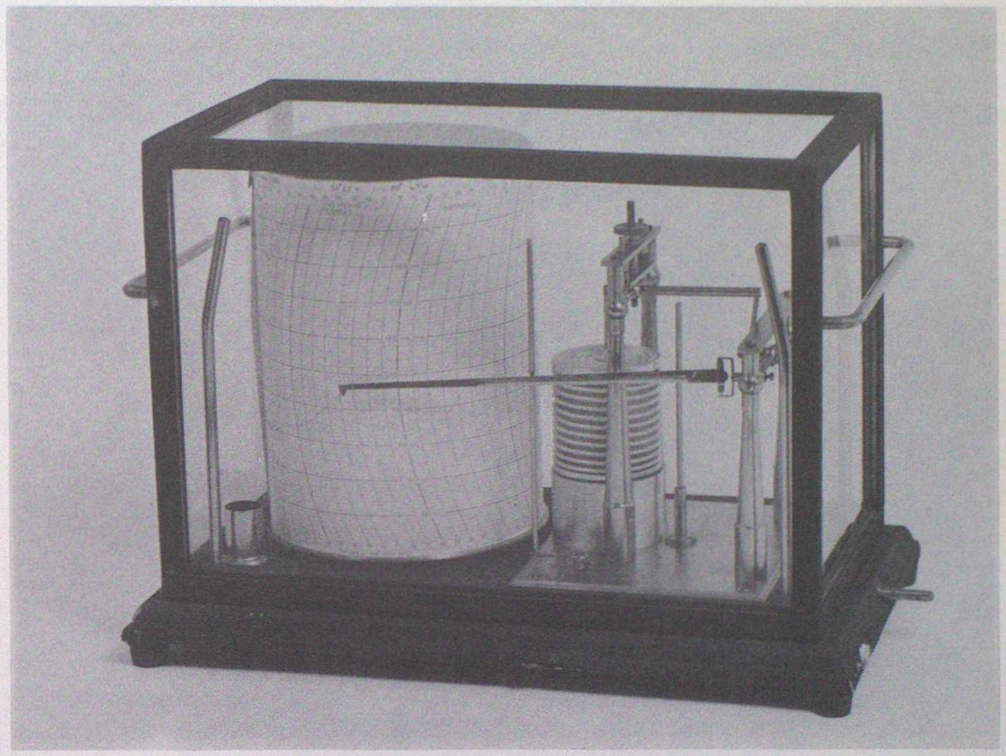


Plate V. Meteorological Office open-scale barograph.

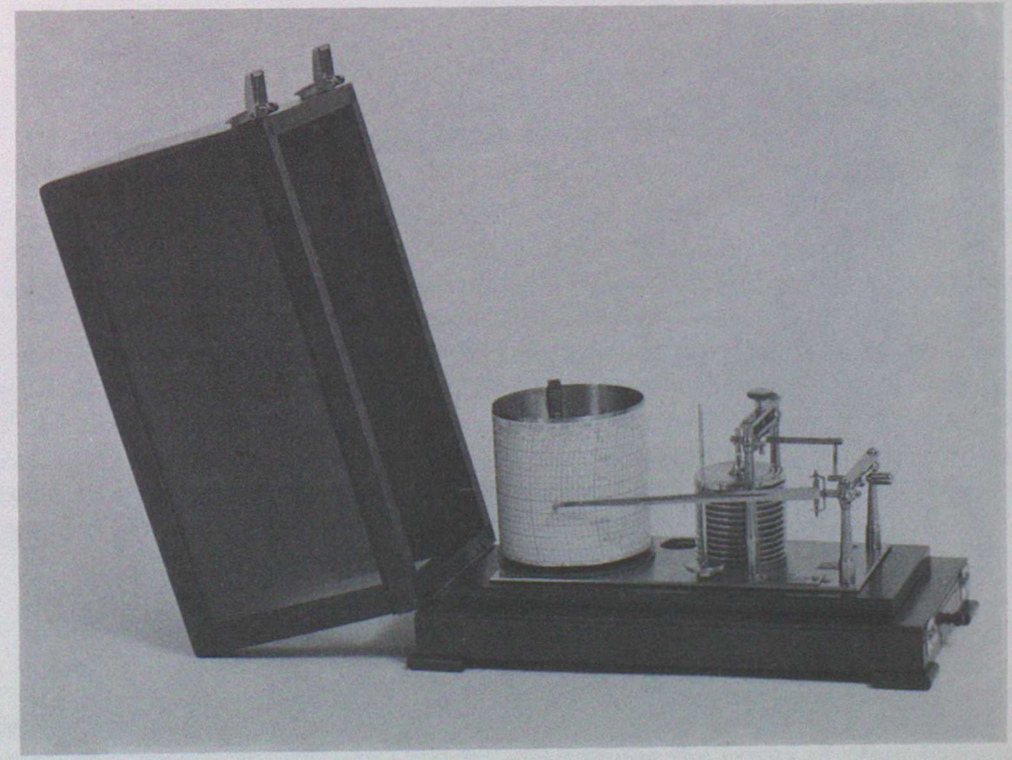


Plate VI. Meteorological Office small-pattern barograph.

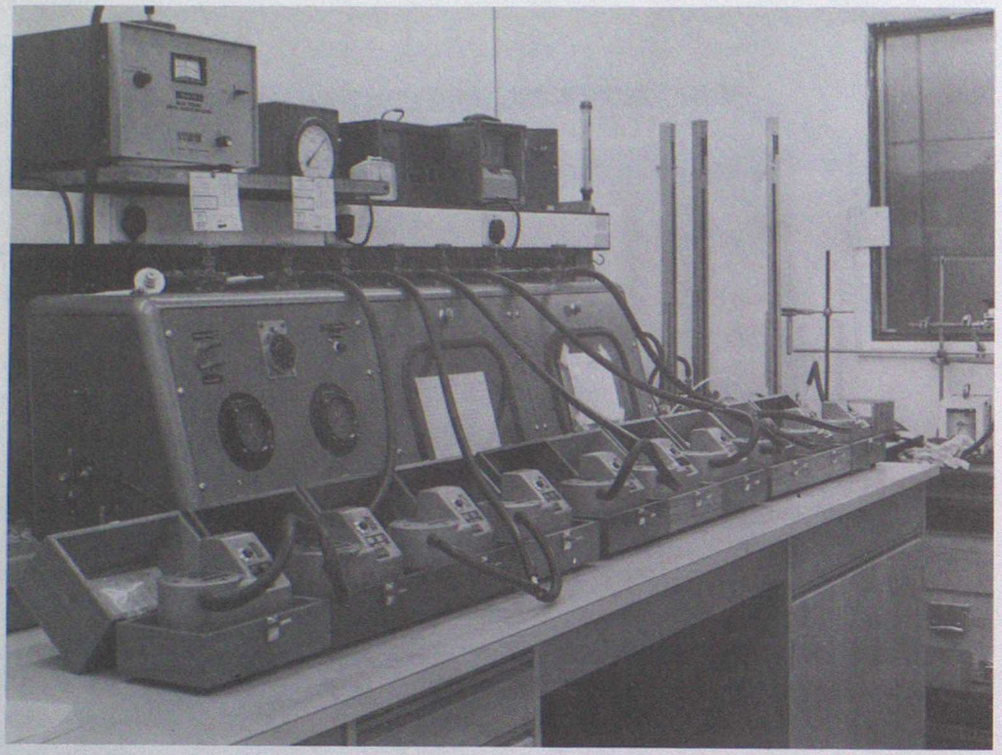


Plate VII. Instrument Branch Test Laboratory precision aneroid barometer calibration unit.

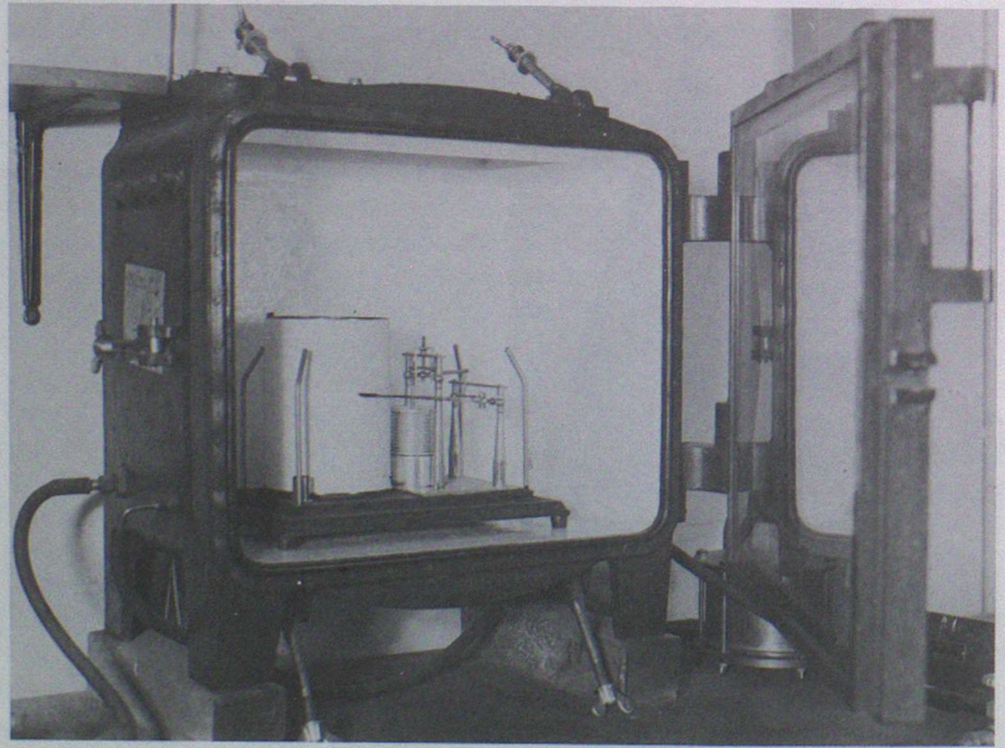


Plate VIII. Instrument Branch Test Laboratory barograph test chamber.

must be reached. Bibby (1948) has shown that by considering three extreme cases of possible variation the desirable time-constant is between about 30 and 120 seconds.

A time-constant of this order has been achieved by immersing the capsule in a brass cylinder filled with oil (Figure 9) so that the capsule can only expand or contract by forcing oil to flow through a narrow annular gap where the rod passes through the hole A in the metal diaphragm. With the open-scale barograph a change in pressure of 1 mb causes about 50 mm^3 to flow through the gap. It has been found that the time-constant of the barograph is approximately proportional to the viscosity of the oil for a given size of the gap, and as the viscosity of most oils varies greatly with temperature a corresponding variation in the time-constant can be obtained.

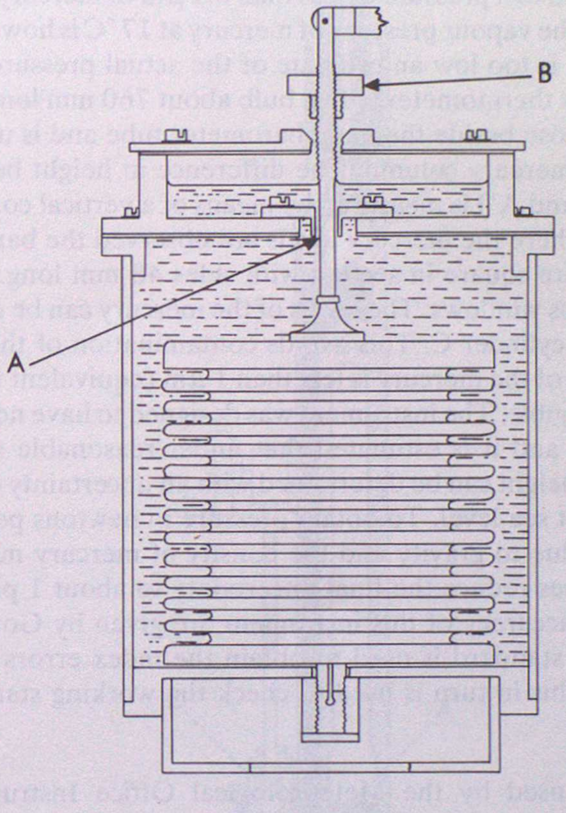


Figure 9. Mechanism of a Meteorological Office marine barograph.

Over the range of temperature normally experienced the viscosity of the silicone oil used by the Meteorological Office changes by 2.5:1. This is found to be acceptable.

Installation. The brass plug B (Figure 9), threaded both internally and externally, should be screwed right down into the lid of the oil cylinder during transit, and at other times when the barograph is likely to be moved appreciably from the upright position, to prevent the loss of the oil. When bringing the instrument into use the plug should be screwed to the top of the vertical screwed rod and left there. No attempt should be made to 'top up' the instrument with other kinds of oil as the variation in viscosity with temperature of ordinary hydrocarbon oils is too great. Apart from these points the barograph is used exactly as a normal open-scale barograph.

5 TEST BAROMETERS

5.1 General

The standard barometers that are used for determining the errors of other barometers may be divided into two classes: first, those whose errors have been reduced to the smallest limits and in which the errors can be determined by separate measurements, and secondly, instruments of high precision whose index errors have been accurately determined by comparison with instruments in the first class. The first class are called the primary standard barometers while the second are called the working standards.

5.2 Primary standard instruments

The ultimate standard of atmospheric pressure measured in the United Kingdom is the primary standard barometer at the National Physical Laboratory. A simplified diagram of its construction is shown in Figure 10. It is essentially a siphon barometer with the barometer tube made of steel and fitted with vacuum pumps so that the space above the mercury can be kept continuously evacuated to a pressure of less than 0.1 μm of mercury (1.3×10^{-4} mb) as read on a McLeod gauge. The vapour pressure of mercury at 17 °C is however 2×10^{-3} mb so that the recorded pressure is too low an estimate of the actual pressure over the mercury surface. A mercury-in-glass thermometer with a bulb about 760 mm long is let into another tube B in the steel block close beside the main barometer tube and is used to measure the mean temperature of the mercury column. The difference in height between the top and bottom mercury levels (A and A′) is measured by means of a vertical comparator and a line standard made of invar. Where the mercury levels are observed the barometer tube opens out into chambers which are square in section with sides 48 mm long. The chambers are fitted with optically flat glass windows. The levels of the mercury can be altered as necessary by raising or lowering the cylinder C. This avoids contamination of the glass windows.

The capillary depression of the mercury is less than 1 μm (equivalent to 13×10^{-4} mb) at each level and is quite negligible. The instrument was designed to have no error from a single source greater than 1 μm and it is estimated that under reasonable steady atmospheric conditions the barometric height can be determined with an uncertainty of 2 μm or approximately 1 part in 400 000 at sea level. To obtain pressure in newtons per square metre the value of the acceleration due to gravity and the density of mercury must also be known. Uncertainties in these values reduce the final uncertainty to about 1 part in 10 000 (0.01 mb). Fuller details of the accuracy of this instrument are given by Gould (1946).

In practice this primary standard is used to obtain the index errors of a semi-portable 'secondary' standard and this in turn is used to check the working standards.

5.3 Working standards

The working standard used by the Meteorological Office Instrument Branch Test Laboratory is a fused-quartz Bourdon-tube pressure gauge with an uncertainty of 0.025 mb.

The method of operation is that the deflexion of a Bourdon tube is detected optically. An optical transducer, A in Figure 11, containing a light source and a pair of matched photocells, is mounted on a gear B that travels concentrically around the Bourdon tube C. The gear is meshed to a worm screw D which actuates a six-digit display E. Light reflected from the tube mirror F on to the photocells is converted to an output signal and fed to a null-reading meter. The null reading, representing the deflexion of the Bourdon tube at any given moment, is obtained by rotating the gear until the reflected light falls equally on the photocells. Changes in deflexion are introduced by varying the input to the pressure inlet G. The physical measurement of the deflexion, displayed by the digital counter, is converted to the equivalent pressure, in millibars, with the use of tables. The tube is temperature controlled at a selected temperature, usually between 35 °C and 50 °C, so that it is unaffected by ambient temperature changes.

The pressure gauge is checked daily against a transfer standard which is a precision aneroid barometer chosen for its low drift. The transfer standard is in turn checked at regular intervals against a working standard at the NPL.

Another instrument, used to check the Bourdon-tube pressure gauge, is a highly accurate pneumatic pressure balance shown in Figure 12. In this a piston B, moving freely in a cylinder C, floats in equilibrium on a volume of gas. The space above the piston–cylinder assembly is enclosed in an airtight transparent dome, and is evacuated by means of a vacuum

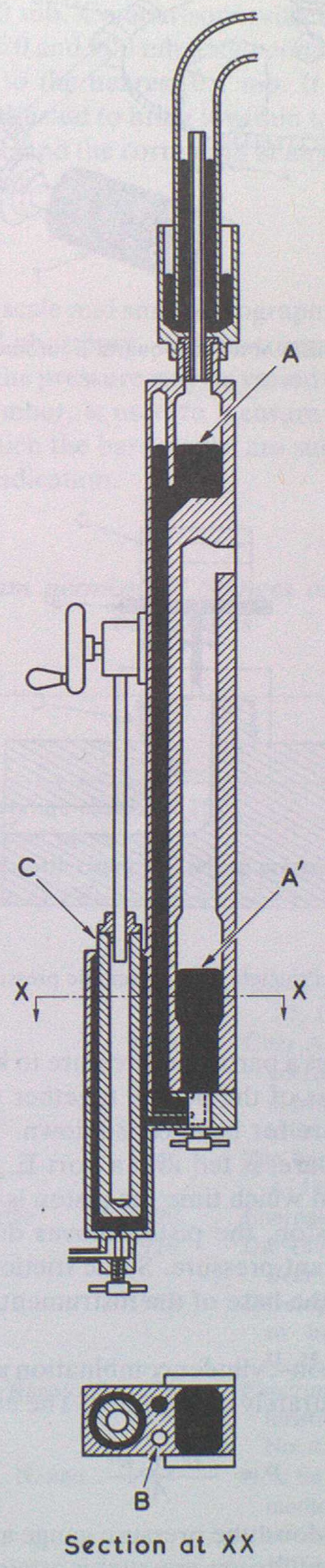


Figure 10. Primary standard barometer at the National Physical Laboratory.

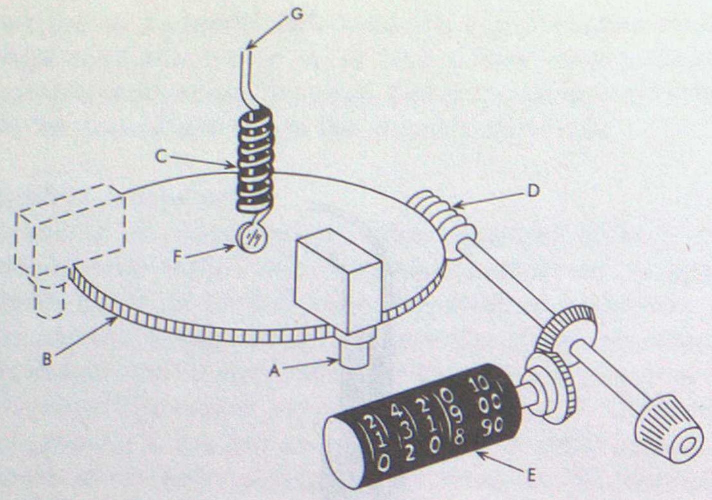


Figure 11. Mechanism of a fused-quartz Bourdon-tube pressure gauge.

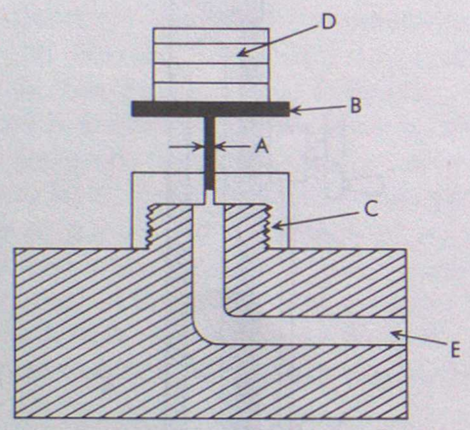


Figure 12. Principle of a pneumatic pressure balance.

pump. The weighted piston requires a particular pressure to keep it suspended so that, given the effective surface area and mass of the piston, together with the mass of the weight D being supported, the exact pressure for balance is known.

An inert gas, of unknown pressure, is fed into a port E. Pressure is increased until the piston and weights are balanced, at which time the piston is floating in equilibrium. As the gas escapes slowly around the piston, the piston moves downwards in the cylinder thus automatically maintaining a constant pressure. Static friction is eliminated by rotating the piston and weights by a motor in the base of the instrument. Equilibrium pressures can be maintained for several minutes.

The effective area, A, of the piston–cylinder combination and the weight of the piston, W, and the added weights, w, are accurately determined. The actual pressure being measured, P, is therefore:

$$P = \frac{W + w}{A}.$$

For checking purposes the Bourdon-tube pressure gauge and pneumatic pressure balance are connected in parallel. Once equilibrium pressure is attained by the pressure balance the gas feed is isolated, the pressure maintained within the system by the pressure balance then being used to check the pressure gauge.

5.4 Determination of barometer errors

The Meteorological Office Instrument Branch Test Laboratory calibrates PABs by comparison with a working standard (Plate VII). The procedure is to submit each PAB to a cycle of pressure changes 1000 – 1050 – 900 – 1000 mb at a controlled temperature of 20 °C. The mean rate of change of pressure during the cycle is 5 mb min^{-1}, excluding intervals of 5 minutes each at 1050 and 900 mb. Comparisons with the working standard are made at 1050, 1020, 1000, 980, 950, 920 and 900 mb under conditions of increasing and decreasing pressure. Readings are made to the nearest 0.1 mb. If the initial correction at 1000 mb exceeds ±0.3 mb the PAB is adjusted to bring it within tolerance. If the difference between the mean correction at 1000 mb and the correction at any other point tested exceeds 0.4 mb the PAB is withdrawn for repair.

5.5 Test of barographs

Meteorological Office open-scale and small barographs are tested, before acceptance, by the Instrument Branch Test Laboratory. The instruments are placed in a glass-fronted chamber (Plate VIII) in which the pressure may be varied over the range 950 mb to 1050 mb. A PAB, connected to the chamber, is used to measure the pressure within the chamber. Table III shows the tests to which the barographs are subjected and the maximum permissible changes of or errors in indication.

Table III. *Tests and maximum permissible changes or errors of Meteorological Office barographs*

Test	Open-scale barograph	Small barograph
Change in reading caused by a temperature change of 15 °C	≤1.0 mb	≤2.0 mb
Errors at 1000, 975 and 950 mb ambient pressure	≤2.0 mb	≤2.0 mb
Difference between errors at 1000 mb with rising and falling pressure	≤1.0 mb	≤2.0 mb

References

Bibby, J. R.	1948	The use of barographs in ships. *Meteorol Mag*, **77**, 176.
Fink, C.	1968	Über Aneroid-Dosen für Radiosonden [On aneroid capsules for radiosondes]. Offenbach a. M., Dtsch Wetterdienst, Instrum.-Amt München, 1–69
Gould, F. A.	1946	The barometric standard. *Proc R Soc, London*, A, **186**, 195.
International Meteorological Committee	1890	International Meteorological Tables. Paris.
Kleinschmidt, E.	1928	Die Temperaturkorrektion von Vidiebarometern. *Beitr Phys frei Atmos*, **14**, 183–190.
Kodama, M., Ishida, Y. and Shimizu, I.	1967	Development of a barometric sensor insensitive to high winds. *J Meteorol Soc Japan*, II, **45**, 191–195.
Okada, Y., Sukamoto, T., Kosha, M., Kaneto, S. and Miura, N.	1976	Experimental study on temperature characteristics of aneroid capsule. *Geophys Mag*, **37**, No. 4, 309–332.
Schüepp, M., Burnett, F. W., Rao, K. N. and Rouaud, A.	1964	Note on the standardization of pressure reduction methods in the international network of synoptic stations. *Tech Note Wld Meteorol Org*, No. 61.
World Meteorological Organization	1971	Guide to meteorological instrument and observing practices. Geneva, WMO Publication No. 8 (TP 3).

APPENDIX 1

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

CONTENTS

LIST OF DIAGRAMS

LIST OF PLATES

APPENDIX 1

A.1 RECORDING METHODS

A.1.1 Introduction

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

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

A.1.2 Recording charts

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

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

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

A.1.3 Pen recorders

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

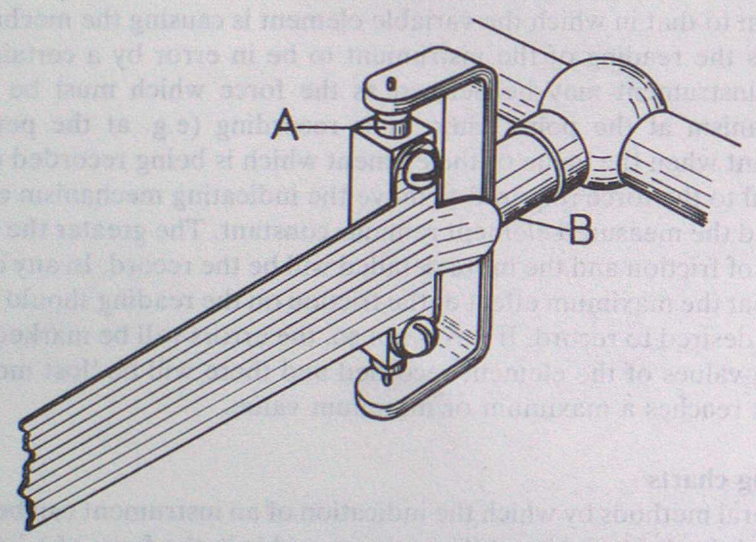


Figure A1. Gate suspension for pen arm.

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

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

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

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

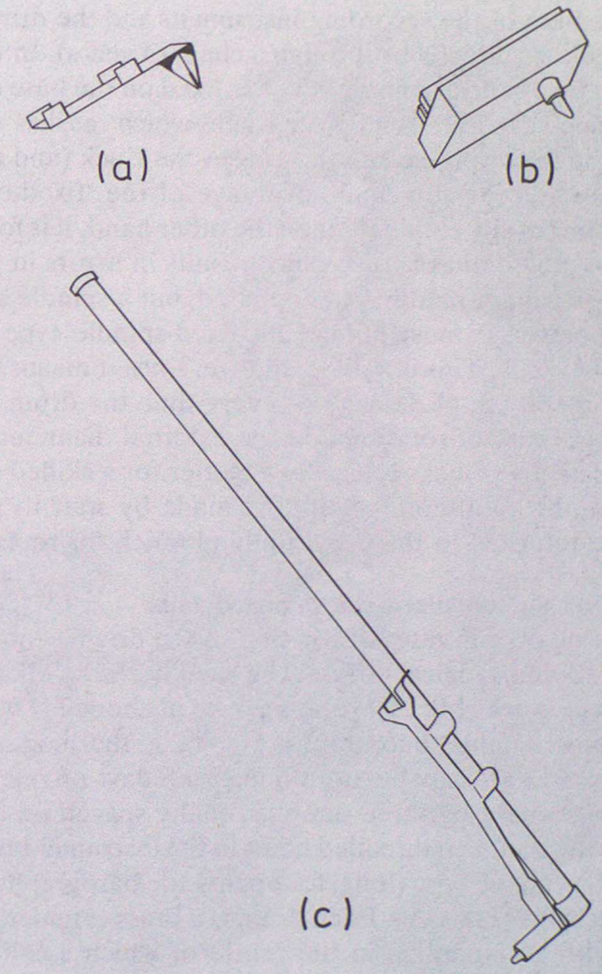


Figure A2. Instrument pens.

A.1.4 Electrosensitive paper

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

A.1.5 Electrical recorders

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

A.1.6 Clocks, drums and time-scales

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

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

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

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

A.1.7 Meteorological Office standardized clocks and drums

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

Plate A. Standard Meteorological Office clocks and drums.

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

A.2 CORRECTION OF RECORDING INSTRUMENTS

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

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

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

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

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

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

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

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

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

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

A.3. OPERATIONAL PROCEDURE

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

A.3.1 Changing the chart

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

(a) The chart should fit tightly round the drum.

(b) The lines of equal scale value should be parallel to the flange at the bottom of the drum, i.e. corresponding lines on the beginning and end of the chart in the overlap portion should coincide.

(c) The bottom of the chart should be as close to the flange as possible and touching it in at least one place (if the chart is not cut quite correctly it may not be possible for it to touch the flange in all places and still comply with the other conditions cited).

(d) The end of the chart should overlap the beginning and not vice versa.

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

A.3.2 Writing up the chart

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

A.3.3 Care at each main observation hour

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

A.3.4 General hints (including cleaning)

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

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

(a) *Plain brass or copper parts.* Unlacquered brass or copper parts may be kept bright by the use of jeweller's rouge applied with an oily rag or by metal polish applied sparingly. The polish should not be allowed to reach any bearing surfaces. The inside of a rain-gauge funnel should however only be rubbed with a dry rag.

(b) *Lacquered brass or copper parts.* These should be cleaned with a soft chamois leather. No polish should be applied, but where there is exposure to damp a little petroleum jelly may be used with advantage.

(c) *Polished woodwork.* This should be cleaned with a soft chamois-leather. A little linseed oil may be rubbed in with a soft cloth if necessary.

(d) *Glass and porcelain.* The dirt should be cleaned off with a moist rag or chamois-leather.

(e) *Bearings, pinions and hinges of instrument cases.* These should be lubricated sparingly with a touch of clock oil. Refer also to the detailed instructions for the instrument.

(f) *Ball races.* These should be treated in accordance with the detailed instructions for each instrument.

(g) *Steel parts.* These should be cleaned with an oily rag and protected from rust with a trace of petroleum jelly. If, in spite of care, rust appears, the part should be carefully cleaned with a fine emery cloth or carborundum cloth.

(h) *Painted woodwork.* In dusty localities woodwork should be brushed periodically, and at stations affected by smoke or soot a thorough cleaning with soap and water should be carried out once a month.

(i) *Painted surfaces liable to inking.* The ink should be removed while wet with a damp cloth. Older stains should be removed by the application of a small quantity of whiting applied with a damp cloth. Methylated spirit may be used with the whiting if there is no risk of this getting on to lacquered brass or polished woodwork.

(j) Naphthalene balls are effective in keeping insects from the interior of instruments exposed out of doors, e.g. recording rain-gauges.

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

APPENDIX 2

The International Systems of units (SI)

The International System (SI) consists of seven 'base units' together with two 'supplementary units'. From these are formed others known as 'derived units'. The base and supplementary units, and some of the derived units, have been given names and symbols. The symbols are printed in lower case except 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	$1\ \text{Hz} = 1\ \text{s}^{-1}$
force	newton	N	$1\ \text{N} = 1\ \text{kg m s}^{-2}$
pressure	pascal	Pa	$1\ \text{Pa} = 1\ \text{N m}^{-2}$
work	joule	J	$1\ \text{J} = 1\ \text{N m}$
power	watt	W	$1\ \text{W} = 1\ \text{J s}^{-1}$

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

Multiplying prefixes

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

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

1 yard = 3 feet = 36 inches,

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

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

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

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

NON-SI UNITS

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

1. **Pressure**

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

2. **Temperature**

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

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

3. **Distance**

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

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

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

4. **Height**

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

5. **Speed**

The derived SI unit is the metre per second (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 °C to +60 °C.

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

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

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

Resolution. See *Discrimination.*

Response. See *Indication.*

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

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

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

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

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

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

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

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

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

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

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*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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