M.O. 577 AIR MINISTRY

METEOROLOGICAL OFFICE

HANDBOOK OF METEOROLOGICAL INSTRUMENTS

PART I

INSTRUMENTS FOR SURFACE OBSERVATIONS

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HANDBOOK OF METEOROLOGICAL INSTRUMENTS

INTRODUCTION

GENERAL instruction in the care and manipulation of instruments at Meteorological Office stations has, until recently, formed part of the scope of the " Meteorological observer's handbook ". In a post-war revision of Meteorological Office publications, however, it was decided to reduce the amount of information on instruments in the " Observer's handbook " to the minimum necessary for their routine operation and day-to-day maintenance. At the same time it was decided to publish a comprehensive handbook of meteorological instruments which would give full information on the design, installation, operation and maintenance of all instruments used at Meteorological Office stations. The task of preparing this Handbook was facilitated by the fact that in the course of the past 35 years the Instruments Division of the Meteorological Office has prepared and issued for official use nearly 250 " Instrument instructions ", giving more detailed and specialized information on numerous instruments than was included in the " Meteorological observer's handbook ". The large majority of these instructions were prepared or revised during and since the Second World War 1939–45.

Although this Handbook is primarily intended to give information to Meteorological Office personnel about the instruments used at official stations, some information about other types of instruments is included in order to illustrate different principles. Where these other types are not described in any great detail the sources of fuller information are given. It is hoped that this Handbook will also prove helpful to users of meteorological instruments outside the Meteorological Office. They will appreciate that certain instructions on procedure in the text are for the guidance of Meteorological Office personnel.

In addition to giving full instructions for the installation, operation and maintenance of Meteorological Office pattern instruments, this Handbook deals with accuracy and sources of error. Such discussion of the limitations of existing instruments may suggest lines for possible improvements. This first part of this Handbook is limited to instruments for surface observations. It is intended that further parts will include instruments for upper air measurements and for some geophysical measurements.

The need for uniformity of practice is, of course, one of the most important requirements for meteorological measurements. The decisions and recommendations of the World Meteorological Organization, so far as they affect instrument practice, have generally been followed in this Handbook.

The preparation of this Handbook has been undertaken in the Instruments Division of the Meteorological Office. Considerable help has been derived from the excellent textbook on " Meteorological instruments " by W. E. Knowles Middleton, whose familiarity with British practice makes his book so useful to instrumental meteorologists in this country. The chapter in this Handbook dealing with the measurement of pressure has been prepared with the assistance of the Metrology Department of the National Physical Laboratory, and makes use of material in the authoritative article on barometry in the " Dictionary of applied physics " and in papers by other members of that Department published in the *Proceedings of the Royal Society*.

Meteorological Office
1953

CHAPTER 1

GENERAL

1.1. GENERAL REQUIREMENTS OF METEOROLOGICAL INSTRUMENTS

1.1.1. Indicating instruments

The requirements of meteorological instruments can be arranged in the following order of importance[1]*

(i) Accuracy
(ii) Reliability
(iii) Simplicity of design
(iv) Ease of reading and manipulation
(v) Robustness and durability
(vi) Low cost of maintenance
(vii) Low initial cost.

These requirements also apply to other scientific instruments, but the order of importance is not always the same. It should be borne in mind that most meteorological instruments have to be maintained in continuous operation and that many are partially or wholly exposed to the weather. In addition, most observers cannot be expected to give the same care and attention to the instruments as a trained physicist or skilled mechanic, and, in any case, many instruments are located away from workshops or facilities for repair. As a consequence, complicated or fragile instruments which can easily get out of adjustment are only suited for use in observatories where the necessary skilled attention can be continuously devoted to them.

1.1.2. Recording instruments

The requirements set out in the previous section apply with equal or even greater force to recording instruments. Many recording instruments have been designed which are far too complicated and fragile to work continuously and reliably at a normal station. The effect of friction on the accuracy of the instrument is also 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, which is being recorded, 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

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* The index numbers refer to the Bibliography on p. 450.

as the force which must be applied to the indicating mechanism at the point where it is recording (e.g. at the pen at the end of the pen arm) 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.

1.2. RECORDING METHODS

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.

When most chart paper is manufactured its fibres are made to 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, however, that the changes in dimensions were very nearly as much when the charts were exposed in a humidity chamber and the relative humidity was altered from about 50 per cent. to as close to 100 per cent. as possible. The change in length " downboard " was 0·1–0·2 per cent., and the change in length in a perpendicular direction was 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 both 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.

1.2.1. 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 (Fig. 1). 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 fall away from it. The pressure between the pen and the paper can thus be adjusted to a suitable value. It 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 than an inclination of the gate axis of about 10° to the vertical is quite sufficient.

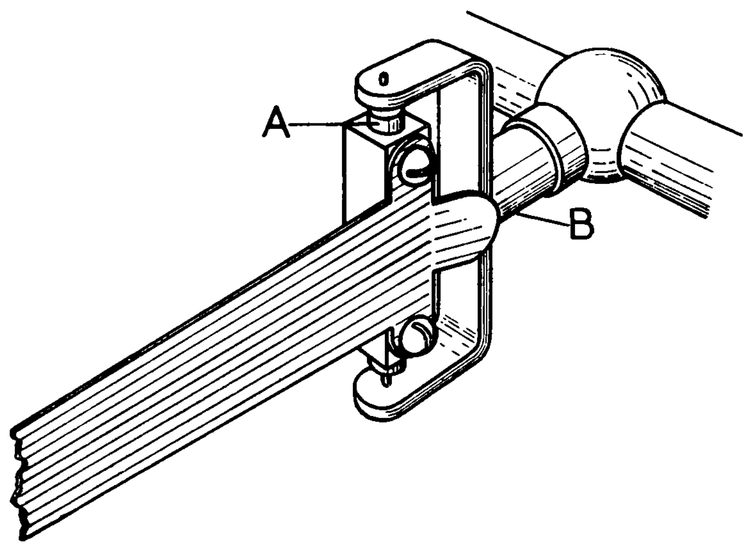


FIG. 1—GATE SUSPENSION FOR PEN ARM

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 radius 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 circular drum 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 not changed. 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 deflection 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.

Another type of pen recorder is typified by the Baxendell wind-direction recorder, in which changes in wind direction are converted into an angular displacement of a cylindrical drum and the record is made by means of a pen driven uniformly by clockwork in a direction parallel to the drum's axis. This principle has certain advantages for recording wind direction, but it is not suitable for general application because of the comparatively large forces required.

Pens and ink.—Various types of pen are used on the standard Meteorological Office instruments ; the chief ones are illustrated in Fig. 2. The type in normal

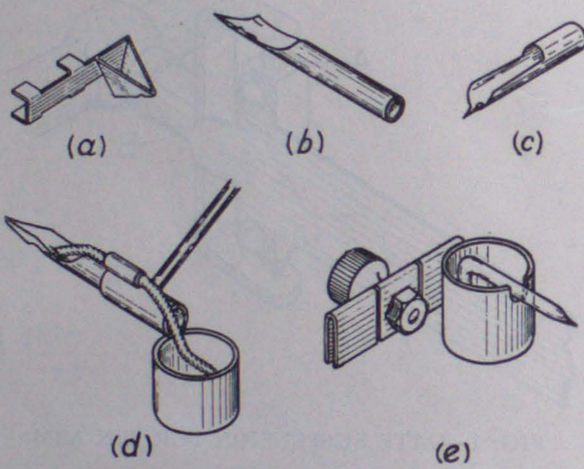


FIG. 2—INSTRUMENT PENS

use on the commoner recording instruments is shown at (*a*) (Stores Ref., Met. 163) ; 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 a normal week's record on any standard-sized drum. Finer pens, of the mapping type, are shown at (*b*) and (*c*). These are called " crow-quill " and " tit-quill " (Stores Ref., Met. 337 and Met. 507), and are used on instruments in which a very fine trace is required (e.g. pressure-tube anemographs). A modified form of pen arrangement for use in pressure-tube anemographs is that shown at (*d*) (Stores Ref., Met. 2777 and Met. 2824). A piece of wet-bulb wick is used to convey ink from a small reservoir to the point of the pen ; this arrangement has been found to give better results than using a pen alone. A different pen altogether is the pressure-tube anemograph pen Mk III (Stores Ref., Met. 829) made from a piece of glass tubing and shown at (*e*). The glass tubing is drawn to a fine point at one end, with the other dipping into the ink reservoir (Stores Ref., Met. 828). The reservoir is clipped to the glass pen by means of an internal spring. This pen does not give such a fine line as the crow-quill or tit-quill pen, but is much more reliable and easier to operate ; in particular it is found that it records the extreme gusts very well. It is however much more expensive than the ordinary pens as it has to be made to very fine limits, if excessive flooding on the one hand or blocking of the tube on the other is to be avoided.

Treatment of pens.—The ideal trace is one which is as thin and fine as possible without becoming illegible, or without the pen scratching the paper. To achieve such a trace it is necessary to treat the pens very carefully. They should be cleaned regularly, using methylated spirit if choked by ink. When pens of the crow-quill or tit-quill type are being used, improved records are often obtained by squaring off the tip of the pen, so that it is perfectly normal to the slit from the eye to the point, and slightly rounding the edges. In addition, as the very light pressures employed in recording instruments are not sufficient to splay the two points of the pen, it has often been found advantageous to draw the temper at the eye by heating for a short time in a very fine pin flame and then to open up at the eye the slit from the eye to the point in such a way that daylight can just be seen at the end, the gap produced tapering away to nothing at the point.

The tip of the ordinary triangular pen can be cleaned by passing a piece of thin strong paper between the points. Thick paper must not be used because of the danger that the point may be permanently opened.

Ink.—Special ink has to be used with pen-recording instruments because normal ink would evaporate too quickly. The evaporation is considerably reduced by the addition of glycerine. The following formula is recommended :

Aniline colour ..	10 gm.	Glycerine ..	125 cm.^{3}
Sugar	10 gm.	Water	250 cm.^{3}

Heat the water and dissolve the sugar in it ; add the glycerine in small quantities and stir the mixture thoroughly until each added portion is dissolved. Beat up the aniline colour in a small quantity of the mixture and stir into the remainder of the mixture. The ink is ready for use when cool. Various dyes can be used, giving different coloured inks.

The normal type of recording ink can be used at ambient temperatures down to about 5° F. in the normal triangular pen, Fig. 2 (*a*), or to about −30° F. in a pen of the crow-quill or tit-quill type, Fig. 2 (*b*) or (*c*). A special ink having the composition, water 50 cm.^{3}, ethylene glycol 50 cm.^{3}, methyl violet 2 cm.^{3}, can be used at temperatures down to about −50° F. with the triangular pen or −75 °F. with the crow-quill or tit-quill pens[2].

1.2.2. Recorders using a stylus

Recorders using a stylus make a record by drawing a line on a specially prepared surface (smoked or silvered surface or paper covered with a thin film of wax) with a sharp point. These recorders can give a very fine trace, and are often used when the scale has to be very compressed (as in some meteorographs). They are not much used for general meteorological instruments at present.

1.2.3. Photographic recorders

The continuous recording of the readings of an indicating instrument by photography has one main advantage in that it imposes no extra load on the instrument by the inertia of moving parts or by friction, and this enables the most sensitive instrument to be used. It also reduces the instrument's lag coefficient (see p. 11) and makes possible the recording of short-period fluctuations which would be smoothed out by instruments with larger lag coefficients.

The disadvantages of photographic recording are that the instrument either has to be totally enclosed or placed in a darkened room, and the photographic paper or film has to be developed before the record is available, i.e. the record cannot be seen while it is being made. In addition, the light sensitive material cannot normally be provided with any graduation marks so that each record has to be measured from calibration points. This procedure makes allowance, however, for possible changes in dimensions of the record during the processing and the drying. Because of these disadvantages the method is not used with normal instruments, but is limited to some instruments at the larger observatories, and to some special research instruments. The Jordan type of sunshine recorder and the night-sky camera are exceptions to this last statement.

1.2.4. Thread recorders

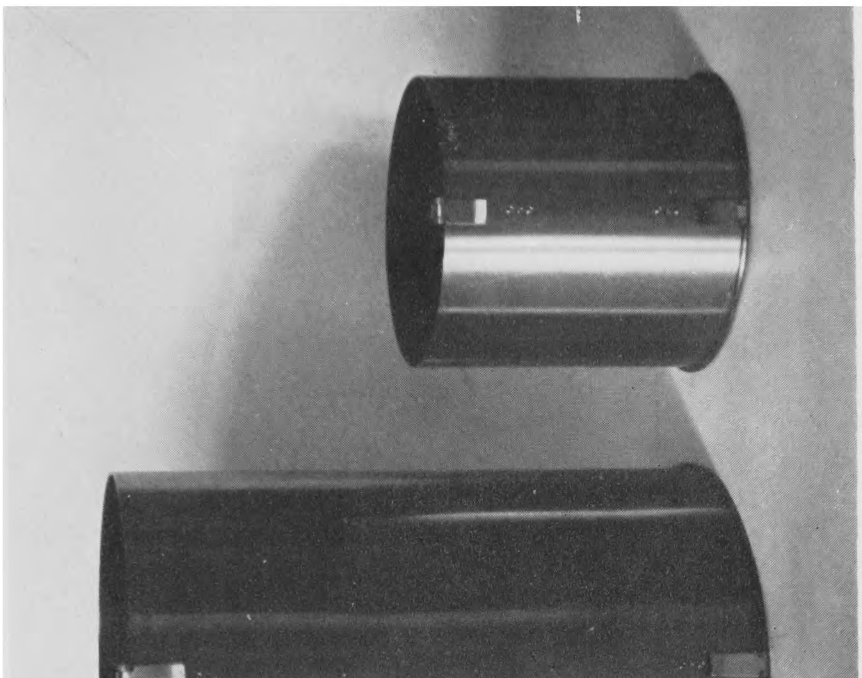
Many sensitive indicating instruments have not enough control to allow direct recording with a pen ; the thread-recorder principle can often be used to provide a record for these. In this device a bar clamps down on the indicating pointer at regular intervals and presses it against an inked thread and thence on to the chart ; the record is therefore obtained as a series of dots. It is mainly used in conjunction with a sensitive galvanometer to record electric currents. With these instruments provision may also be made for obtaining records from two or more circuits, using different coloured threads for each circuit. These recorders are much more complicated than a simple pen recorder and have to be treated with special care. In all cases the maker's instruction booklet should be studied before the instrument is used, and the instructions carefully followed.

1.2.5. Clocks, drums and time scales

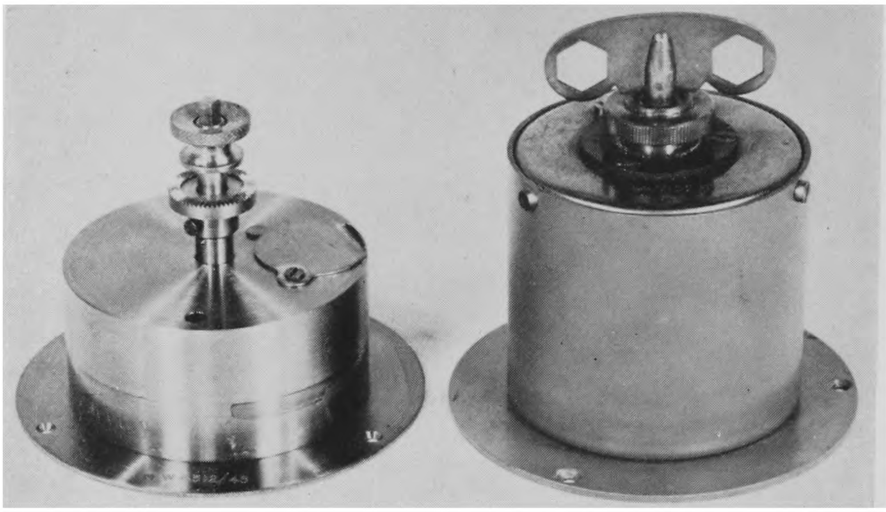
It has long been realized that great advantage could be gained if the number of different types of clocks and drums could be kept to a minimum. Any standardization would reduce the number of spares that would need to be carried in stock, and would reduce the risk of sending the wrong type of clock or drum in replacement for one needing repair.

Most meteorological instruments are fitted with " daily " or " weekly " clocks, i.e. clocks which cause the drum to rotate once in about $25\frac{1}{2}$ hr. and once in about 7 days 8 hr. 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).

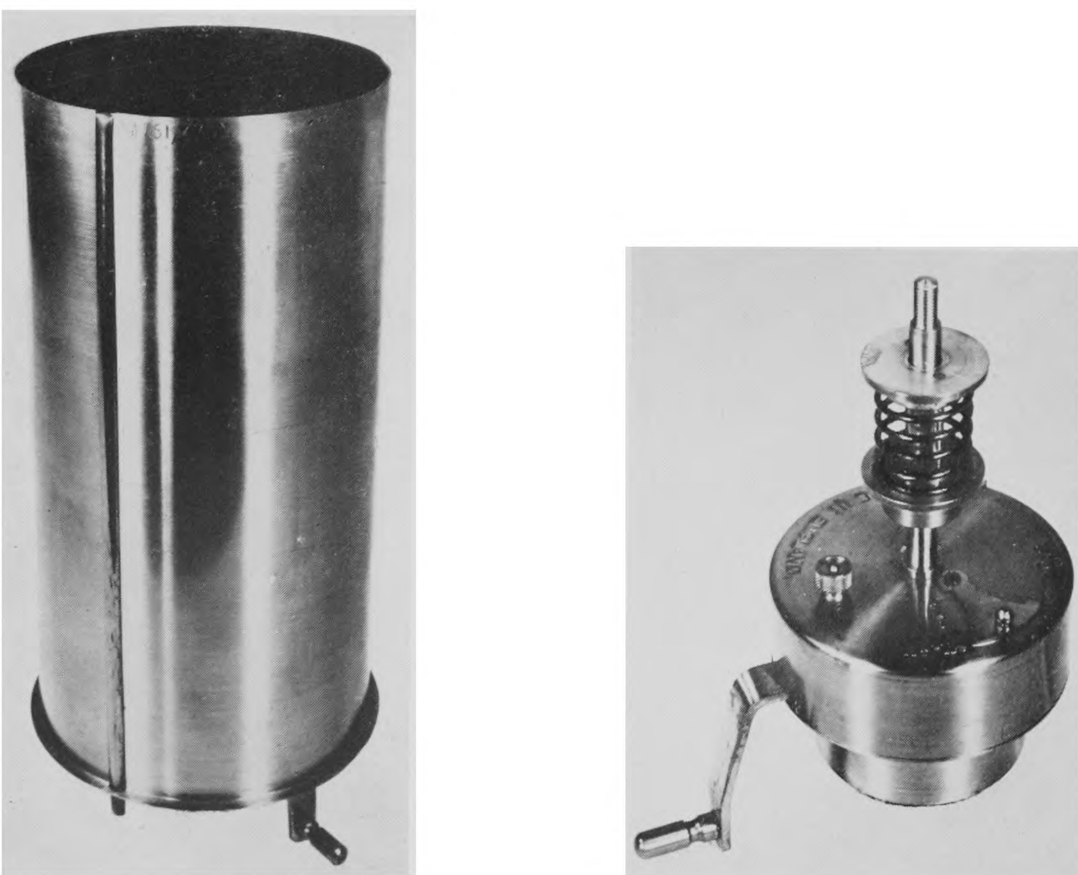
There are two possible ways of using the clock to drive the drum. In the " fixed-clock " type the clock is screwed to the base of the recording instrument and the drum attached to the main spindle of the clock (either directly or through a chain of gears). In the " fixed-spindle " type the clock is supported on a central spindle which is fixed to 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 principle 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



STANDARD METEOROLOGICAL OFFICE CLOCK AND DRUMS



(*a*) (*b*)



(*c*)

OTHER METEOROLOGICAL OFFICE CLOCKS

spindle of the clock can get 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 the staff to repair a defective clock ; the clock should be returned to the Instrument Provisioning Branch and a replacement demanded.

Meteorological Office standard clocks and drums.—In the early 1930's the Meteorological Office standardized its clock requirements for the commoner recording instruments (barographs, bimetallic thermographs, hygrographs and recording rain-gauges) by adopting two " fixed " clocks which were externally similar but with different rates of rotation of the central spindle (Plate I). The daily clock rotates once in 25·6 hr. and the weekly clock once in about 7days 8 hr. They are wound by turning the key permanently fixed to the clock. Both clocks should run for 8 days on one winding.

The drum rests on a fixed collar on the main spindle, which is in the main train of gears ; this collar has radial teeth on its upper surface which fit into similar teeth on a collar on the underneath of the central flange on the drum. A securing nut holds the drum in position. The clock is mounted in position on the instrument by three screws, equally spaced on a circle of 89 mm. diameter, passing through the flange.

For use with either of the standard clocks two different sizes of drum were produced (Plate I) ; these are the " S " type (standard type) (Stores Ref., Met. 557) and the " O " type (Stores Ref., Met. 556) which is used on the open-scale barograph. The drum is a hollow cylinder provided with a diaphragm in the centre of which is a friction collar through which the clock spindle passes. The collar engages with the toothed wheel on the clock spindle and the motion is transmitted to the drum through a spring washer resting on the upper surface of the diaphragm; the washer surrounds the spindle with its upper edge compressed beneath the top of the friction collar, which is rivetted over for this purpose. The object of having a friction drive of the drum is to facilitate the setting of the drum to its correct position after it has been fitted to the clock. The drum is flanged around the base and the chart is held in position by two chart clips. In addition to the chart clips the larger " O " type drum has two small pins screwed into the side of the drum, lying in the same line as the chart clips. These help to keep the chart in position where the two ends overlap.

The " S " type drum is 93 mm. in diameter, so that it gives a time scale of 11·4 mm./hr. with a daily clock. When used with a weekly clock, the clock is adjusted to rotate once in 7 days 7·2 hr., giving a time scale of 1·67 mm./hr. The " O " type drum is not normally used with a daily clock, but if it were the time scale would be 17·2 mm./hr. Used with a weekly clock the clock is adjusted to rotate once in 7 days 8 hr., giving a time scale of 2·5 mm./hr. The difference between a time of rotation of 7 days 8 hr. and 7 days 7·2 hr. is negligible for most purposes.

The standard clocks and drums are completely interchangeable ; i.e. any clock can be used with any drum. The weekly clock can be regulated over a range of 4 hr. in the 7 days, and the daily clock over a range of 30 min. This should provide enough range for the correct adjustment of the clock.

Other types of clocks and drums.—These were introduced at a period when it became impossible to obtain the standard clocks and drums. The rates of rotation, external diameter of the drums, heights of the drums and methods of fixing to the base of the instruments are identical with the standard clocks and drums, so that they can be used in all instruments where the latter are used. The internal dimensions of the clocks (chiefly height and spindle diameter) are however different from the standard, so that the standard drums cannot be used with these clocks.

The spindle of the type of clock shown on Plate II (*b*) (Stores Ref., Met. 120 for a daily clock with an " S " type drum ; Stores Ref., Met. 652 for a weekly clock with an " S " type drum ; Stores Ref., Met. 653 for a weekly clock with an " O " type drum) has a larger diameter than the Meteorological Office standard clock and is less liable to become displaced from its true position. This is even less likely in the weekly clock than the daily clock, because the drum is not driven directly from the main spindle but is supported on a sleeve surrounding the spindle, and this is driven through a train of gears.

The second type of clock is different again in its dimensions (Plate II (*a*)). This type of clock has not been used with an " O " type drum.

Various other types of clock have been used with drums of 93-mm. diameter in Meteorological Office recording instruments from time to time, including some of the spindle type, but these are replaced, if possible, whenever they are worn out by the later types described above.

Special clocks and drums.—Special sizes of clocks and drums have been found necessary for certain instruments which are in less general use. The pressure-tube anemograph drum has a diameter of 127 mm. and a time scale of 15 mm./hr. Several different types of clock have been used with this instrument ; the one in most general use at the present time is shown in Plate II (*c*) (Stores Ref., Met. 519 for Mk IIIA). The clock is fixed to the base of the instrument, and its main distinguishing features are the method of fixing the drum in place and the clock-winding mechanism. The clock is wound by moving to and fro the lever projecting from the base of the drum.

The mercury-in-steel thermograph usually has a weekly clock of the spindle type (Stores Ref., Met. 422). The external diameter, 127 mm., is the same as that of the pressure-tube anemograph drum ; its time scale is 2·17 mm./hr.

1.3. 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.

(i) 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.

(ii) 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.

(iii) Errors due to the change in length of the chart with humidity variations (see p. 4). 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, this 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 pocket register or in a notebook provided for the purpose. 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 $\frac{1}{2}$ hr., but not more than 2 hr., after starting the record, and another after about a further 8–12 hr.

On most instruments a time mark may be made by depressing the pen between $\frac{1}{8}$ in. and $\frac{1}{4}$ in. 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. In photographic recorders a time mark can often be made by switching off the light for a short period ; in a recording galvanometer of the thread-recorder type arrangements could be made to cut the galvanometer out of the circuit (introducing a resistance equal to that in the rest of the circuit, if necessary, to prevent overdamping the instrument).

On some instruments, e.g. barographs, a simple 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 lag coefficients may be expected to cancel out. This last would not be expected to happen if for instance a mercury-in-steel thermograph were being checked against an Assmann psychrometer and a series of readings taken at 0900 each morning but not at other times of the day.

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, presumably the recording instrument. This question is also discussed in later chapters of this Handbook when dealing with specific types of instruments.

1.4. OPERATIONAL PROCEDURE

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

1.4.1. 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 (see p.7) and top up 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).

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

(ii) 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.

(iii) 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).

(iv) 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. In some types of drum a strip of metal is provided to hold the ends of the chart. 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 require re-adjustment not more often than three or four times a year. If careful examination, extending over a period, shows that re-adjustment 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.

1.4.2. 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.

1.4.3. Care at each main observation hour

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

1.4.4. 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 :—

(i) 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.

(ii) 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.

(iii) 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.

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

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

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

(vii) 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.

(viii) 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.

(ix) 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.

(x) 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 (see p. 5).

1.5. TRANSPORT OF INSTRUMENTS

When an instrument has to be sent from one place to another it is very important that it should be properly prepared and packed in a suitable container, so that it can withstand normal transport risks. Most meteorological instruments are delicate, and require more care and attention in this matter than do normal classes of goods.

The instrument should first be prepared for transport. Special instructions are given for some instruments (see appropriate chapters), but the following general rules should be followed in other cases. All clocks and drums should be removed and packed separately. Pen arms should be tied gently with soft cotton to the pen-lifter arms to prevent them being moved violently, but not so tightly as to put a strain on the remainder of the instrument or to bend the pen arm. Other moving parts that may be damaged should be tied or fixed in position. Glass windows in the outer cases should be protected by a sheet of corrugated cardboard or similar material cut to fit the outside of the window exactly and held in place with string. The inside of the cases should be supported as necessary with wads of paper, but great care should be taken in doing this to see that no part of the instrument is damaged or strained by the use of too much paper or too great a force. This applies particularly to pen arms. Ink bottles should be removed. Small items should be wrapped in paper or packed in envelopes. Articles having sharp corners, points or projections, and glassware, such as rain measures, should be wrapped in flexible corrugated paper.

Cup anemometers should be dismantled by removing the rotating head and detaching the cup arms. Wind vanes should be similarly dismantled by removing the vane and direction arms, and the comb should be removed from Besson nephoscopes. Other instruments should be dismantled only in so far as it makes them easier to pack or reduces the risk of damage in transit.

The type of container that should be selected depends on the size of the instrument or part, the distance of the journey, the kind of transportation, and the conditions of handling and storage. Generally speaking it may be said that for all instruments, except small ones being carried personally for short distances (up to 100 miles say) in motor transport or sent by post, some form of wooden crate or packing case should be used. Some instruments are provided with specially shaped packing cases, and these should be used wherever possible. Other instruments should be packed in rectangular containers of a convenient size, and such that the total weight of packing case and contents does not exceed 1 cwt., except for exceptionally bulky and heavy objects. Packing cases exceeding 1 cwt. in weight are very difficult to handle carefully, and these are often subject to harsher treatment than those lighter in weight. The packing cases must be amply strong enough for the journey and handling contemplated.

The case must be so packed that any shock is absorbed by the interior packing and not transmitted to the contents. The container should therefore be of such a size that an adequate amount of cushioning material can be placed between the container and the instruments, and between the instruments themselves. The function of the cushioning material is twofold ; it must be able to absorb shocks to the outer container and prevent them affecting the instruments, and at the same time it should be sufficiently rigid to prevent the instruments moving inside the container and to prevent abrasion by allowing one article to rub against another.

It is not possible to specify exactly the amount of packing required in all instances, but it may be taken that for rail journeys in the British Isles at least one inch of wood-wool or shavings packed moderately tightly should be allowed all round each instrument. In addition, the packing case should be lined throughout with stiff brown paper or other similar material. Enough packing material should be used to keep the instruments firmly in place once the lid is fastened. Subject to these requirements, including the weight limitation mentioned above, as many instruments as can be accommodated should be placed in one packing case. If wood-wool is not available or the instruments are especially sensitive to dust, shredded paper may be used, or alternatively, layers of felt up to the same thickness can be substituted. At Meteorological Office stations suitable cases and packing material may be obtained on demand from the Instruments Provisioning Branch ; it is sufficient to send a list of the instruments to be packed.

When the instruments are finally packed the lid of the case must be firmly fastened. The destination of the case should be clearly stencilled on it, or if this is not possible, it should be written in bold capitals on stout cardboard and this nailed firmly to the case. It is not sufficient to use a stick-on paper label. All crates, except those which contain items which can stand practically unlimited handling e.g. metal stands for thermometer screens, should be labelled " handle with care " and " delicate instruments ", and the correct way up clearly marked. If the crate contains glassware this should also be made quite clear. These notices may be stencilled on the crate, or printed notices may be used.

Any necessary documents and vouchers to be included with the instruments (including packing notes) should be placed in an envelope and inserted between the lid and the packing material, so that they can be easily found.

Whenever possible, any motor transport that may be available should be used for conveying the packing cases, as in this way the handling is reduced to a minimum. If this is not possible, delicate instruments should always be sent by passenger train, not by goods train.

The special precautions necessary for the transport of mercury barometers are fully described in Chapter 2 (p. 56).

CHAPTER 2

MEASUREMENT OF ATMOSPHERIC PRESSURE

2.1. GENERAL PRINCIPLES

2.1.1. Introduction and early development

The fact that the atmosphere has weight, and therefore exerts a pressure, was apparently first clearly recognized by Galileo and Toricelli, and in 1643 Toricelli 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 in 1848 the column of mercury remained the basis of practically all barometers, and it is still the basis of the 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 the instrument.

2.1.2. Principles of barometers

Mercury barometers.—The principle of mercury barometers is illustrated in Fig. 3 ; if the space above A is completely exhausted of all gases (except, of necessity, the vapour of the fluid used) the simple manometer at (*a*) becomes the barometer

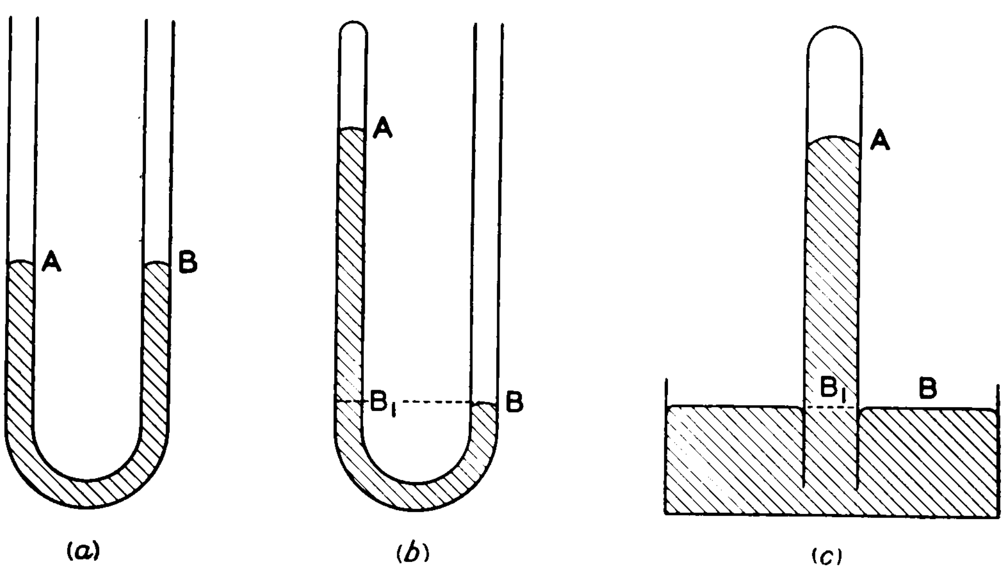


FIG. 3—STAGES IN THE DEVELOPMENT OF THE BAROMETER

of (*b*) and (*c*). If the height of the column AB_1, the density of the fluid, 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 the fluid which is used, almost exclusively, in barometers of this type for the following reasons :—

(i) Its large specific gravity makes the column of convenient length

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

(iii) It is easily cleaned and purified

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

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 barometric fluid, 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 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 its zero is adjusted always to the level of the mercury in the cistern. Alternatively, using a fixed scale the cistern itself can be raised or lowered. Again, if the barometer tube and the inside of the cistern have a uniform cross-sectional area, it is clear that the ratio of the movements in the tube and cistern for a given change in pressure will be a constant. On this basis it is possible to set up a contracted scale which will automatically take account of the varying level. Still another alternative is to detach the scale altogether from the barometer tube and measure the required difference in level directly with a cathetometer.

All four systems of measurement are in use. The cathetometer technique gives the highest precision of measurement, but the arrangement cannot readily be made portable or simple. This system is therefore confined, in practice, to primary standard instruments permanently installed in central institutions.

The adjustable measuring rod system, as on Newman barometers, is still used in barometers which are used as working standards in a number of observatories. The adjustment of the scale, which is mounted on a brass rod and terminates in an ivory pointer, can be made without seriously disturbing the mercury in the cistern, and the instrument is convenient to use.

In the adjustable-cistern barometer the level of the mercury in the cistern is raised or lowered to a certain fixed point (the zero of the scale) before an observation is made. The principal instrument in this class is the Fortin barometer ; the lower part of the cistern consists of a flexible leather bag, and a screw is provided at the base of the instrument so that the mercury can be raised or lowered by the requisite amount. As compared with the Newman barometer it may be noted that the adjustment of level involves the disturbance of the mercury, both in the cistern and the tube. The use of the leather bag to form part of the cistern also introduces a risk of contamination of the mercury. These objections are not serious since all barometers must be tapped before reading, anyway, to ensure that the meniscus has taken up a stable form, and specially treated leather is used. Fortin barometers can be used for routine observations of atmospheric pressure, and instruments with tubes of a wide bore are satisfactory for use as working standards.

The contracted-scale barometer has both a fixed scale and cistern ; the commonest example is the Kew pattern introduced originally for use at sea, but now extensively used at land stations as well. The amount by which the movement of the mercury in the tube differs from the actual change in height of the mercury column can be readily calculated if the internal diameter of the barometer tube, the internal diameter of the cistern, and the external diameter of the tailpiece of the tube dipping into the cistern are all known. One great advantage of this type of barometer is that only one setting operation is required when a reading is taken. The marine type differs from that used on land in that part of the barometer tube is constricted, so that the oscillation of the mercury in the tube or " pumping ", which is otherwise excessive, is greatly reduced.

Instead of measuring the height of the mercury column it is possible to suspend the tube from one end of a balance arm, so that it hangs freely in a fixed cistern of mercury, and then to measure the balancing weight necessary on the other arm of the balance. The magnitude of this weight depends on the atmospheric pressure ; this principle has been used in the construction of an accurate barograph[3].

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 closed chamber ; one membrane is usually fixed at its centre while the movement of the other, due to changes in the thickness of the chamber 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, however, necessary to reduce the air pressure inside the chamber to a very low value. This increases the total net force on the diaphragm and usually necessitates the addition of a spring to support the diaphragm and to prevent the chamber from collapsing. It is the change in deflection of the spring as the load (due to the atmospheric pressure on the faces of the chamber) changes that is 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 curvature of the tube increases when the external pressure increases. It is very little used now for measuring atmospheric pressure.

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. They are not, however, absolute instruments, and have to be regularly checked against a standard barometer ; and, in general, they are not as accurate as mercury barometers.

Hypsometer.—The boiling point of a liquid is the temperature at which the vapour pressure of the liquid equals the pressure above its surface, and once the relation between the vapour pressure and the temperature is known a measurement of the boiling point, with an instrument known as a hypsometer, can be used to determine the atmospheric pressure.

Distilled water is normally used, and a very accurate and sensitive thermometer is required. The thermometer can be directly calibrated in terms of pressure if necessary. This method is especially useful in conditions where a mercury barometer is not available and an aneroid barometer cannot be regularly checked. A very small and portable apparatus can be devised, and a great advantage is that, provided the instrument is carefully designed to avoid any build up of pressure, no corrections, other than those of the thermometer itself, need be applied to the readings.

2.1.3. Units of measurement

Pressure is defined as a force per unit area ; the absolute C.G.S. unit of force is 1 dyne per square centimetre and is sometimes called a " bar ". In meteorology however the word bar is used for a unit of 10^6 dynes/cm.^{2} This unit is rather large for ordinary use, and the practical unit is the millibar, which is equal to 1,000 dynes/cm.^{2} The millibar is almost universally used for meteorology, but barometers calibrated in other units are often encountered.

Since the principal factor in the determination of the atmospheric pressure by means of the mercury barometer is the measurement of the height of the mercury column, the scales of earlier instruments were graduated in length units, such as inches or millimetres.

The length of a mercury column for any given pressure depends upon the density (i.e. temperature) of the mercury and the value of the acceleration due to gravity. Moreover, the indication on a barometer scale set up to measure the length of a column will vary with the temperature of the scale. It is, therefore, necessary to specify " standard conditions "—temperature of mercury and scale, and acceleration due to gravity—and to compute tables whereby corrections may be made for any departure from these conditions. These standard conditions are set out below.

Acceleration due to gravity.—The standard value of gravity, under which a barometer reads correctly without the application of corrections, was changed, with effect from January 1, 1955, from 980·62 cm./sec.^{2} (which is very nearly equal to the gravity at mean sea level in latitude 45°) to 980·665 cm./sec.^{2} (which is a conventional standard). This change was decided upon by the World Meteorological Organization at Geneva in 1953. Meteorological Office barometers are gradually being converted, but it will be many years before the conversion is complete. For this reason it is necessary to have two sets of correction tables available, one for barometers adjusted to 980·62 cm./sec.^{2} and one for barometers adjusted to 980·665 cm./sec.^{2} The standard conditions to which a barometer is adjusted are usually stated on a plate attached to the frame. If standard conditions are not so stated it may be assumed that the barometer, when made, was adjusted to read correctly under gravity of 980·62 cm./sec.^{2} This change of standard gravity has resulted in a consequential change in the definition of an " inch of mercury " and of a " millimetre of mercury " as units of pressure. Before January 1, 1955 these were defined as an inch (millimetre) of mercury at a temperature 0°C. and gravity 980·62 cm./sec.^{2} After that date they were defined as an inch (millimetre) of mercury at a temperature 0°C. and gravity 980·665 cm./sec.^{2}

In order to make a correction to a barometric reading to take account of any variation from standard gravity it is necessary to know the value of the " gravity at the station ". This is sometimes determined from a gravimetric survey ; but more usually it is deduced from an empirical formula.

The empirical formula recommended by the World Meteorological Organization (Geneva, 1953) is

$$g_{\phi,h} = 980\cdot616(1-0\cdot0026373 \cos 2\phi+0\cdot0000059 \cos^2 2\phi) - 0\cdot0000939h, \quad ..(1)$$

where ϕ is the latitude and h is the height of the station above mean sea level in feet ; and correction tables are now based on this formula. Before January 1, 1955 the less accurate formula

$$g_{\phi,h} = 980\cdot62(1-0\cdot00259 \cos 2\phi)\,(1-0\cdot00000006h)$$

was used. This change of formula resulted in a small discontinuity in barometric data, not greater than 0·05 mb. at mean sea level, but amounting to 0·2 mb. or more at stations 3,000 ft. above mean sea level.

Temperature.—The World Meteorological Organization at Geneva in 1953 resolved that, with effect from January 1, 1955, the standard temperature for all mercury barometers should be 0°C. Before that date several standard temperatures were in use :

(i) For Meteorological Office millibar barometers	12°C. for the whole instrument
(ii) For barometers reading in inches..	62°F. for the scale 32°F. for the mercury
(iii) For barometers reading in millimetres	0°C. for the whole instrument.

Meteorological Office millibar barometers are gradually being converted to the new standard temperature as well as to the new standard gravity (see above), but barometers adjusted to the old standard conditions will remain in use for several years. For that reason it is necessary to have two temperature correction tables—one for barometers adjusted to read correctly at 12°C., one for barometers adjusted to read correctly at 0°C.

Temperature corrections must take account of both the variation of temperature, and therefore density, of the mercury and also of the variation of temperature, and therefore the dimensions, of the instrument itself. The density of mercury at 0°C. is 13·5951 gm./cm.^{3}. The density may vary among different samples by $\pm$0·0001 gm./cm.^{3}, but these differences only affect the most precise work. The density, ρ_T, at temperature T°C. is given by

$$\rho_T = 13\cdot5951\,(1 - 0\cdot000182T)\ \text{gm./cm.}^3$$

Corrections to take account of change of temperature of the instrument are complicated and are discussed in detail on p. 38.

2.1.4. 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 a change in the velocity of the air. If the air is completely brought to rest the excess pressure caused 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 mb. under normal surface conditions, when v is 40 kt.

A barometer will not therefore give a true reading of the static pressure if it is exposed to a gusty wind, and its reading will fluctuate 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 position 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. The effect cannot be calculated. At sea the error is nearly always present, owing to the ship's motion.

It is possible to overcome this effect to a very large extent by making the cistern of 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.

Errors due to uncertainty 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 season, or time of day. It is also preferable on this account to hang a mercury barometer on an inside wall if possible.

A stratification of temperature is often found in a room which is otherwise suitable ; the top of the mercury column in the 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. For very accurate work the best position would appear to be in a windowless, unheated basement room with a small electric fan to prevent any stratification of temperature.

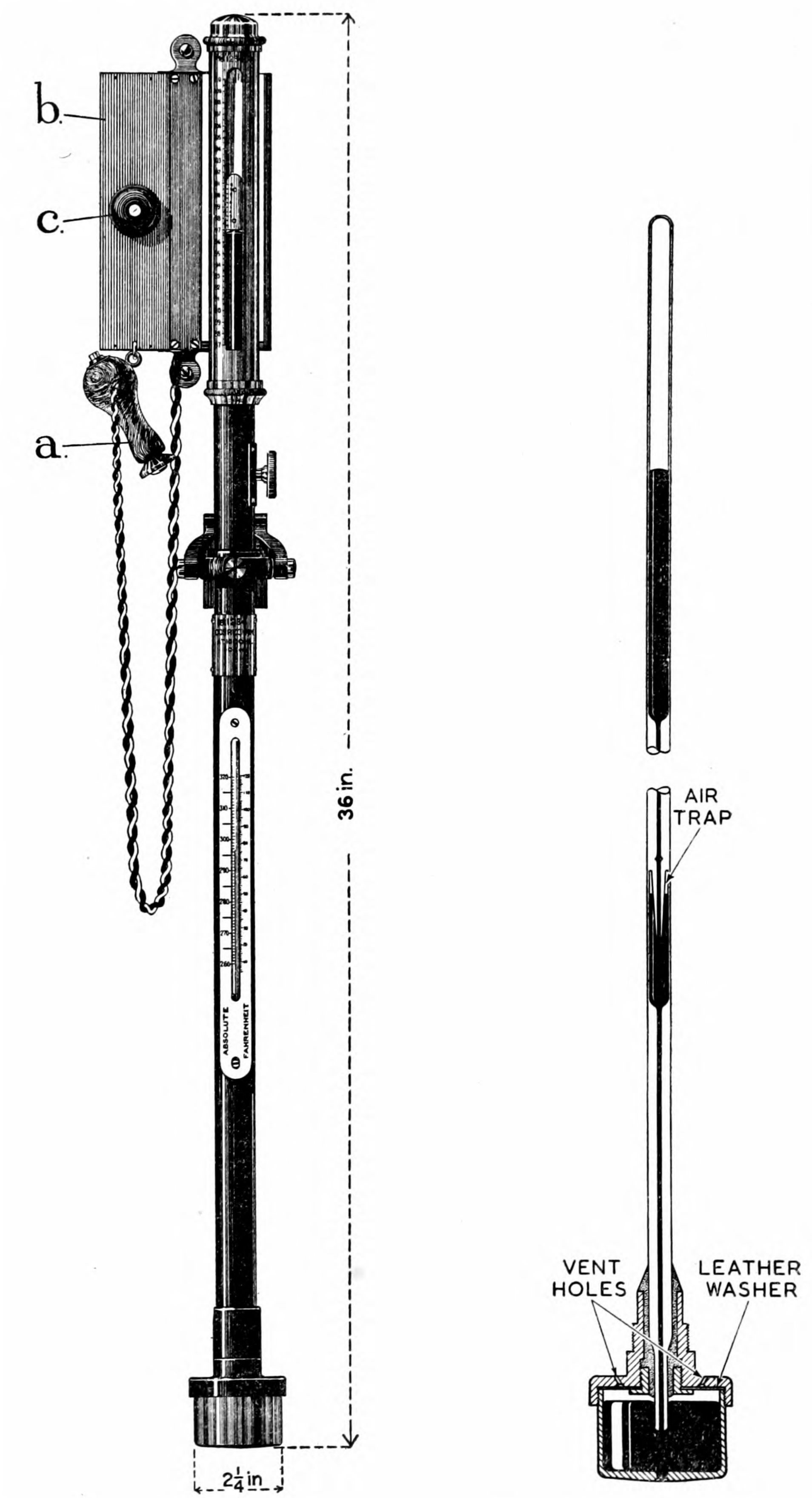
The magnitude of the error in the readings of a mercury barometer, caused by a slow uniform change in temperature because of the thermal lag of the mercury temperature behind that of the attached thermometer, is discussed on p. 52.

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 however possible, by careful design, to produce an aneroid barometer which is so balanced that accelerations, such as are experienced in an aircraft, have negligible effect.

2.2. MERCURY BAROMETERS

2.2.1. Meteorological Office Kew-pattern station barometer

The Meteorological Office Kew-pattern station barometer is the chief type of barometer used in the Meteorological Office ; the main reason for adopting it



with illuminator

section view

FIG. 4—METEOROLOGICAL OFFICE KEW-PATTERN STATION BAROMETER

rather than the Fortin instrument (see p. 33) is that only one setting is required when making an observation. The Mk I instrument (Stores Ref., Met. 70) is adjusted to read correctly when gravity is 980·62 cm./sec.^{2} and the temperature is 12°C. ; the Mk II instrument (Stores Ref., Met. 1543) is adjusted to read correctly when gravity is 980·665 cm./sec.^{2} and the temperature is 0°C. (see p. 19). Fig. 4 shows the general arrangement. 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. for most of the way, but in the visible part at the top of the tube 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 ube 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 itself is made of steel and screws into the cistern top, against a leather washer, two small vent holes in the cistern top allowing 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 is 50 mm. in diameter and has 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, and in some instruments the right-hand side of the slot is also graduated, in units of 0·05 in. from 25·70 to 32·60 in. 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 ; its lower edge is accurately perpendicular to the axis of the barometer tube. It is adjusted by means of a rack and pinion movement, the pinion being situated at the side 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, and, if an inch scale is provided, its right-hand side is graduated so that 25 vernier divisions cover 24 small-scale divisions (1/20 inch). It is thus possible to read directly to 0·1 mb. or 0·002 in., and by estimation to 0·05 mb. and 0·001 in.

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 degrees Absolute or in degrees Centigrade. In addition, if the barometer has an inch scale, the right-hand side of the thermometer frame has the corresponding Fahrenheit graduations marked upon it.

Method of suspension and auxiliary equipment.—The barometer is normally suspended in position by means of a gimbal fitting ; it then hangs freely with its axis vertical. A barometer illuminator (Fig. 4) (Stores Ref., Met. 541) is often used with the barometer to provide a bright and uniformly illuminated background against which to view the top of the mercury meniscus. This consists of a rectangular box, b, with an opal glass plate down one side of the front surface, behind which are mounted two 2·5 V. electric-light bulbs. The battery to supply these bulbs is housed in the box, and they can be switched on by pressing a bell push, c. An additional light, a, on the end of a flexible lead is for use in reading the attached thermometer and in reading the vernier after it has been set. A suitable bell transformer connected to the a-c. mains may be used in place of the batteries.

A stout wooden box is provided in which to keep the barometer when it is not in use or when it has to be moved. The box is fitted with two sets of ring packings and end buffers of soft sponge rubber, to support the barometer when it is placed in position. It should be noted that the barometer should be inserted so that it is supported by the rubber-ring packings just above the cistern and just below the scale (i.e. the cistern is placed at the right-hand end of the box, when it is arranged so that the lid opens away from the packer). If the barometer is inserted the wrong way it is very likely to be damaged when the lid is forced down. The rope handle is arranged so that the cistern end is kept slightly above the top of the barometer when the box is lifted.

Installation.—The mercury barometer is a delicate instrument and should be handled with extreme care at all times. If it has to be moved around the station or on short journeys when it can be carried all the way, it should be first inclined gently so as to allow the mercury to flow slowly to the top of the tube, then placed in its box and transported in a horizontal or inverted position (with the cistern end uppermost). This can be done with safety provided the instrument is not subject to sudden concussions. On no account should it be moved when it is in its normal upright position as the free surface of the mercury may oscillate and break the glass tube, and also air may enter the bottom of the tube as the mercury in the cistern oscillates. The transport of barometers by other means is dealt with later (see p. 57).

The position of the barometer should be selected after carefully considering the principles outlined earlier (p. 21) and taking into account the need for a firm and rigid support. As an ideal situation is rarely possible a compromise has usually to be made ; it should always be possible, however,to prevent the sun from shining on the instrument. The socket into which the hinged tongue of the suspension arm fits can then be screwed firmly into a wooden support and the barometer lifted carefully from its case and fitted into position. Care should be taken to ensure that the screws which secure the instrument in its gimbal mounting are screwed right home or the instrument may slip through and be damaged. When in position the barometer should be hanging freely, and at such a height that the observer can read the scale comfortably while standing upright.

If a barometer illuminator is also to be mounted the distance between the barometer tube and the wall may be found to be insufficient ; in this case a thin piece of wood should be inserted between the socket and the wall, using longer screws if necessary. The illuminator can then be screwed in position behind the top of the barometer tube so that the opal glass plate is immediately behind that part of the tube where the mercury is visible, the bell push being to the left of the barometer. If an illuminator is not being used a white screen or sheet of paper should be fixed to the wall in its place. After installation the instrument should be left at least 2 hr. before any readings are taken, so that it may settle down and reach a temperature equilibrium with the air in the room. In practically all cases the height of the barometer cistern above sea level will have to be found ; this should be determined to the nearest foot from a large-scale Ordnance Survey map or by running a " line of levels " from the nearest bench-mark. A bench-mark is indicated on Ordnance Survey maps by the letters B.M. and its height in feet is given ; the mark itself ⩚ is cut in a wall, a milestone or some other permanent landmark, generally by the roadside. A spirit-level, a straight edge and a graduated staff will be necessary.

On many R.A.F. stations and airports a detailed map of the station with accurate contour lines is available. The local surveyor should be consulted in case of doubt.

Method of use.—When making an observation the routine given below should be followed.

(i) Read and note the temperature of the attached thermometer to the nearest $\frac{1}{2}°$ A. This should be done first, because the changes in temperature caused by the presence of the observer are likely to affect the thermometer more quickly than the remainder of the barometer.

(ii) Tap the instrument gently two or three times with the pads of the fingers on the outer brass case, just beneath the glass shade and also near the cistern. This promotes the formation of mercury menisci of more stable shape, and hence decreases the effect of the direction of change of atmospheric pressure.

(iii) Switch on the barometer illuminator or, if one is not provided and the general level of illumination is not sufficient to enable the barometer to be set with ease, illuminate the white screen or paper behind the instrument. A source of light (such as a hand torch or a lighted match) should not be placed directly behind the barometer as this frequently leads to an inaccurate setting. If a hand torch is used it should be held in front and slightly to the left of the barometer.

(iv) Adjust the vernier and alter the eye level so that the lower edge of the vernier scale and the back lower edge of the brass cylinder on which the vernier is mounted appear in a straight line, and both apparently just touch the highest part of the convex mercury surface. The instrument should be touched as lightly as possible, and it should not be set when displaced from the vertical. When the adjustment has been made no part of the mercury surface should be hidden by the vernier and yet it should be impossible to see any light between the bottom of the vernier and the highest part of the mercury surface. At times, when the atmospheric pressure is falling rapidly and the mercury surface is not quite clean, the mercury meniscus may appear almost flat ; great care is then necessary in setting the vernier. The object in sighting on both the front and back edges of the vernier and mount is to ensure that the observer's eye is at the same level as the top of the mercury column, and thus to avoid errors of parallax (see Fig. 5).

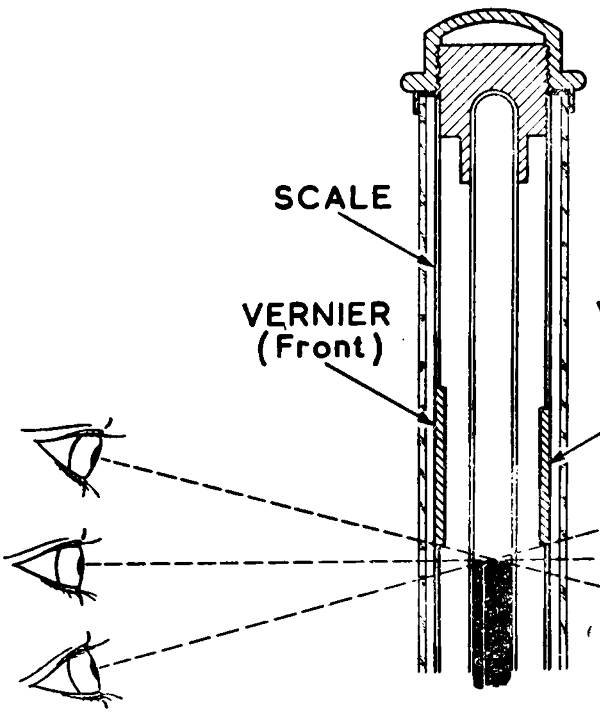


FIG. 5—EFFECT OF INCORRECT EYE LEVEL IN READING THE BAROMETER

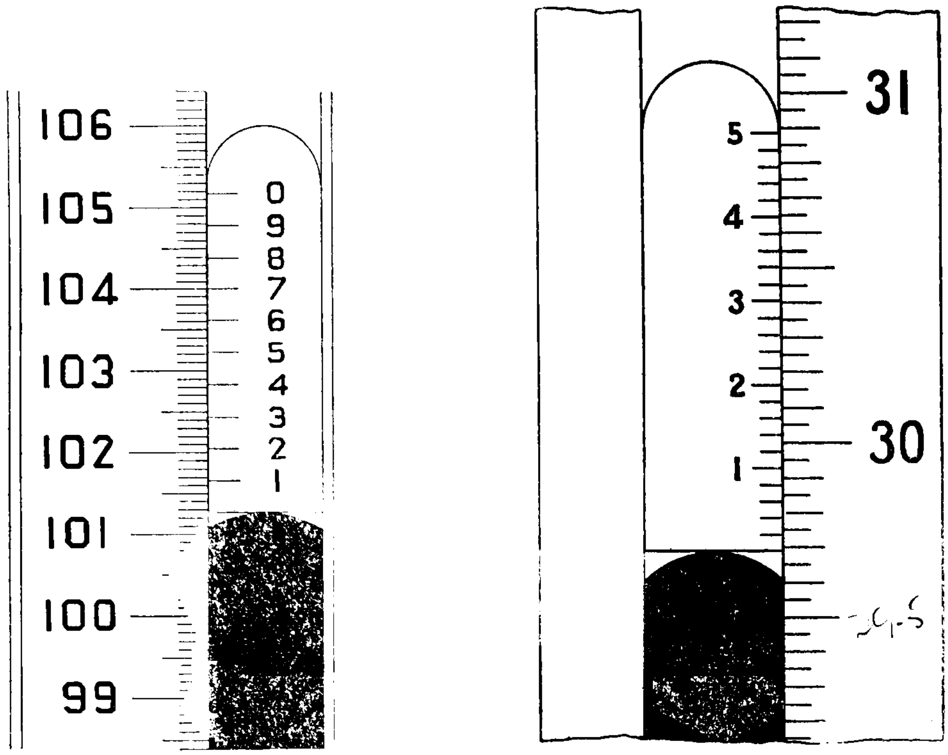
(v) Read the scale using the vernier to read to 0·1 mb. (or 0·002 in.). The use of the vernier is shown in Fig. 6. When reading the millibar scale note the whole millibar graduation mark next below the bottom edge of the vernier, and then look along the vernier until a graduation is found which is in the same horizontal line as one of the graduation marks on the main scale. The value of this vernier graduation (in units of 0·1 mb.) gives the difference in scale reading between the bottom edge of the vernier and the next millibar graduation below it. In Fig. 6 (*a*) for instance : next whole millibar reading below the bottom of the vernier is 1012 mb. Vernier division 7 is exactly opposite a scale reading, so that

reading of barometer = 1012·7 mb.

When reading this type of barometer graduated in inches first note the reading of the graduation mark next below the base of the vernier, and then find, as before, a vernier graduation mark which is in the same horizontal line as a graduation mark on the scale. The main graduations on the vernier (marked 1, 2, 3, etc.) each represent units of 0·010 in. and the smaller graduations, units of 0·002 in. The final scale reading is found by adding the vernier reading to the scale reading. In Fig. 6 (*b*) the value of the graduation mark next below the vernier is 29·65 in. The third small graduation mark above the main vernier division marked 3 coincides with a graduation on the scale. Therefore the reading of the vernier is 0·036 in. so that

reading of barometer = 29·686 in.

After noting the observation in this way a check should be made to ensure that an error of 1, 5, or 10 mb. (or 0·05 or 0·10 in.) has not been made. These errors are very easy to make if the observation is hurried.



(*a*) millibar graduations (*b*) inch graduations

FIG. 6—READING THE BAROMETER SCALE

(vi) Apply the necessary corrections. The reading that has been obtained has to be corrected for the index error of the barometer, its temperature and the value of the acceleration due to gravity at the station. When these corrections have been applied the atmospheric pressure at the level of the cistern will be found. If the corresponding pressure at some other level is required (e.g. at mean sea level) an appropriate reduction has to be made.

Full details of the calculation of these corrections are given later (p. 38), but it may be noted here that for one fixed barometer they will depend on three variable factors, the atmospheric pressure, the temperature of the barometer, and the outside air temperature, so that in general two tables will be required. It has, however, been found possible to take account of the variations in outside air temperature, for stations less than 500 ft. above the datum level, by applying a variable adjustment to the reading of the attached thermometer. It is then possible to obtain the total correction for all factors by using one table in conjunction with the adjusted attached thermometer reading and the uncorrected barometer reading. Separate correction cards would be required if there were more than one level at which the pressure were required, and fresh tables would have to be calculated if the barometer were to be moved.

The most usual type of correction card is Form 1270, a specimen of which is shown in Fig. 7. The following example will show how it is used.

Attached thermometer reading .. .. 287° A.
Barometer reading uncorrected .. .. 1012·3 mb.
Air temperature (dry bulb in the screen) 54° F.

The correction to the attached thermometer for a dry-bulb temperature of 54°F. is +1° A. The adjusted reading of the attached thermometer is therefore 288°A., and the barometer correction corresponding to a barometer reading of 1012 mb. and an adjusted attached thermometer reading of 288°A. is +2·9 mb. The corrected reading of the barometer is thus 1015·2mb. In this example the correction for a barometer reading of 1012 mb. is the same as that given for 1020 mb. and 1000 mb., but if necessary an interpolation would have been made.

A.M. FORM 1270

BAROMETRIC CORRECTION AND REDUCTION TO MEAN SEA LEVEL

Place : South Kensington　　Latitude : 51° 30′ N.

Height above M.S.L. : 66 ft.　　Barometer : No. M.O. 1701

(1) Adjust the reading of the attached thermometer by ADDING the amounts given below:—

Dry Bulb in Screen	Add to Attached Thermometer	Dry Bulb in Screen	Add to Attached Thermometer	Dry Bulb in Screen	Add to Attached Thermometer	Dry Bulb in Screen	Add to Attached Thermometer
Below 24° F.	0° A.	24° — 55° F.	+ 1° A.	56° — 94° F.	+ 2° A.		

(2) Apply to the observed reading of the barometer the correction of the following table corresponding most nearly with the barometer reading and the adjusted reading of the attached thermometer.

Adjusted Reading of Attached Thermometer	Correction to be applied						Adjusted Reading of Attached Thermometer	Correction to be applied					
	940	960	980	1000	1020	1040		940	960	980	1000	1020	1040
°A.	mb.	mb.	mb.	mb.	mb.	mb.	°A.	mb.	mb.	mb.	mb.	mb.	mb.
271	+5·5	+5·6	+5·7	+5·8	+5·8	+5·9	291	+2·3	+2·3	+2·3	+2·3	+2·3	+2·3
272	5·4	5·4	5·5	5·6	5·6	5·7	292	2·1	2·1	2·2	2·2	2·2	2·2
273	5·2	5·3	5·4	5·4	5·5	5·6	293	2·0	2·0	2·0	2·0	2·0	2·0
274	5·0	5·1	5·2	5·3	5·3	5·4	294	1·8	1·8	1·8	1·8	1·8	1·8
275	4·9	5·0	5·0	5·1	5·1	5·2	295	1·7	1·7	1·7	1·7	1·6	1·6
276	4·7	4·8	4·9	4·9	4·9	5·0	296	1·5	1·5	1·5	1·5	1·5	1·5
277	4·6	4·6	4·7	4·7	4·8	4·8	297	1·3	1·3	1·3	1·3	1·3	1·3
278	4·4	4·5	4·5	4·6	4·6	4·7	298	1·2	1·2	1·2	1·2	1·1	1·1
279	4·2	4·3	4·4	4·4	4·4	4·5	299	1·0	1·0	1·0	1·0	0·9	0·9
280	4·1	4·1	4·2	4·2	4·2	4·3	300	0·9	0·8	0·8	0·8	0·8	0·7
281	3·9	4·0	4·0	4·1	4·1	4·1	301	0·7	0·7	0·7	0·6	0·6	0·6
282	3·8	3·8	3·9	3·9	3·9	4·0	302	0·5	0·5	0·5	0·5	0·4	0·4
283	3·6	3·6	3·7	3·7	3·7	3·8	303	0·4	0·3	0·3	0·3	0·2	0·2
284	3·4	3·5	3·5	3·5	3·5	3·6	304	0·2	0·2	0·2	0·1	0·1	0·0
285	3·3	3·3	3·3	3·4	3·4	3·4	305	0·1	0·0	0·0	0·0	−0·1	−0·2
286	3·1	3·1	3·2	3·2	3·2	3·2	306	−0·1	−0·2	−0·2	−0·2	−0·3	−0·3
287	3·0	3·0	3·0	3·0	3·0	3·1	307	−0·3	−0·3	−0·4	−0·4	−0·5	−0·5
288	2·8	2·8	2·8	2·9	2·9	2·9	308	−0·4	−0·5	−0·5	−0·6	−0·6	−0·7
289	2·6	2·6	2·7	2·7	2·7	2·7	309	−0·6	−0·7	−0·7	−0·7	−0·8	−0·9
290	2·5	2·5	2·5	2·5	2·5	2·5	310	−0·8	−0·8	−0·9	−0·9	−1·0	−1·0

Amounts entered in thick type must be added. Amounts entered in thin type must be subtracted.

FIG. 7—SPECIMEN BAROMETER CORRECTION CARD

Checking the barometer.—It is important to check the accuracy of the station barometer at frequent intervals so that a defective instrument may be replaced as soon as possible. At synoptic stations this should be done by regular comparison of the mean-sea-level pressure, as measured by the barometer, with that obtained by reference to a large-scale synoptic chart for the same hour, interpolating between the isobars if necessary. The scale of the chart should be sufficient to allow isobars for every millibar to be drawn. The station observation should not be plotted on the chart until after the isobars are drawn, and occasions of steep pressure gradients or large pressure tendencies should be avoided.

Four to six occasions within a day or so should be used, and the mean difference found between the estimated station pressure from the chart and that measured from the barometer. When this method is used at stations in an area with plenty of observations (so that the isobars can be drawn accurately) the mean difference should not exceed about 0·5 mb.

This method should be used with extreme caution, however, at stations in the neighbourhood of an extensive range of mountains or hills, especially when the wind is at right angles to the range.

A spare barometer complete with correction card should be held at the station, and the two mounted side by side. At regular intervals (about once every three months) a series of readings from both should be made over a period of about three days. The mean difference between the barometer readings corrected for temperature and index error should not exceed $\pm 0 \cdot 2$ mb. if both instruments are in good order, and individual differences should be less than 0·4 mb. If larger differences are found the faulty instrument (as suggested by synoptic-chart comparisons) should be replaced. These comparisons must be made as accurately as possible ; the observations should be made with great care but without undue delay, and corrections to each barometer made, as outlined on p. 27.

Maintenance and repair.—Provided that the instrument is treated carefully little maintenance is required, apart from wiping over occasionally with a soft cloth to remove dust. If an illuminator is in use the battery should be renewed directly it becomes exhausted and any defective light bulbs replaced. The front glass can be slid upwards to replace the bulbs, and the left-hand side of the case can be slid upwards to replace the battery.

If the instrument becomes defective from any cause it will generally be necessary to have it overhauled by a competent instrument maker. To this end Meteorological Office instruments should be returned to the Instrument Provisioning Branch. The accuracy and sources of error of a mercury barometer are considered later (p. 47).

2.2.2. Meteorological Office Kew-pattern long-range barometer

The Meteorological Office Kew-pattern long-range barometer (Mk I (old conventions) Stores Ref., Met. 1736 ; Mk II (new conventions) Stores Ref., Met. 1540 ; see p. 19) is a modification of the standard Kew-pattern station barometer for use at high-level stations where the mean atmospheric pressure is considerably less than at sea level (Plate III). The general construction is similar to the shorter-range barometer, but the slots in the brass case and the upper wide portion of the tube are lengthened, so that the instrument can be used over the range, 700–1100 mb.

As a consequence of the extension of the scale, the gimbal mounting and the attached thermometer are further down the brass case.

The methods of installation and operation are, in general, similar to those of the standard pattern, but different methods of reducing the observations to a given datum level may be employed. If the station is above about 1,600 ft. the observations are not normally reduced to mean sea level, but to some other level depending on regional agreement. Local instructions will be given in each case.

2.2.3. Meteorological Office Kew-pattern marine barometer

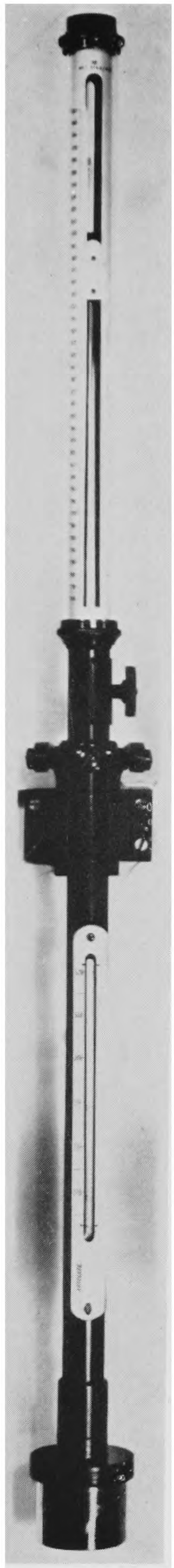
The Kew-pattern marine barometer (Mk I (old conventions) Stores Ref., Met. 69 ; Mk II (new conventions) Stores Ref., Met. 1542 ; see p. 19) is specially designed for use at sea (Fig. 8). If an ordinary barometer were used at sea the oscillations or pumping of the mercury due to the pitching and rolling 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. The constriction thus introduced to the free motion of the mercury in the barometer will also offer a resistance to the natural response of the mercury column to the changes of atmospheric pressure, and this sets a limit to the amount of damping permissible ; the magnitudes of the errors introduced are discussed on p. 55. The amount of constriction employed is a compromise between the error due to the lag of the mercury column and that arising from pumping[4].

The " lagging time " (analogous to the lag coefficient of a thermometer), or the time the barometer takes to indicate 63 per cent. of a sudden change in pressure, is between 6 and 9 min. The barometer therefore responds very little to periodic oscillations of pressure or periodic accelerations of the instrument of a period less than about 12 min. (see p. 89 for the comparable phenomenon in the measurement of temperature).

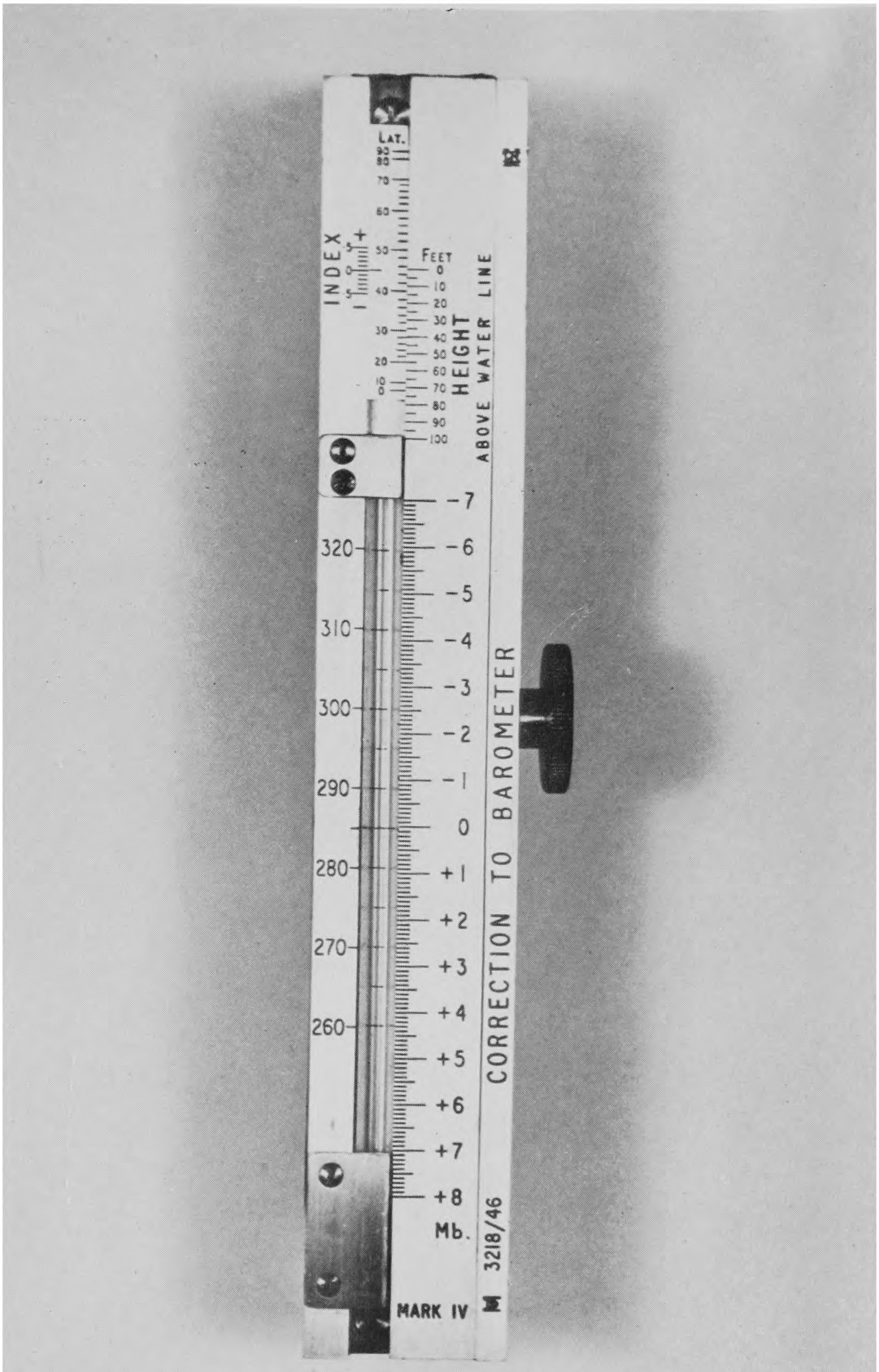
Apart from the constriction in the tube the construction of the barometer is the same as that of the station model. A longer suspension arm is, however, provided to keep the barometer much further away from the wall from which it is suspended (approximately 12 in. compared with 2¼ in. on the station model). This is to prevent the barometer being damaged when it swings on account of the motion of the ship.

The principles governing the choice of site and methods of observation are, in general, similar to those detailed for the station model, but under the conditions experienced at sea they will be more difficult to apply. A position as near the centre of flotation of the ship as possible should be chosen. If the " pumping " is at all serious it is best to make a series of observations of the highest point reached by the mercury meniscus, and a similar number of observations of the lowest point, and to record the mean value.

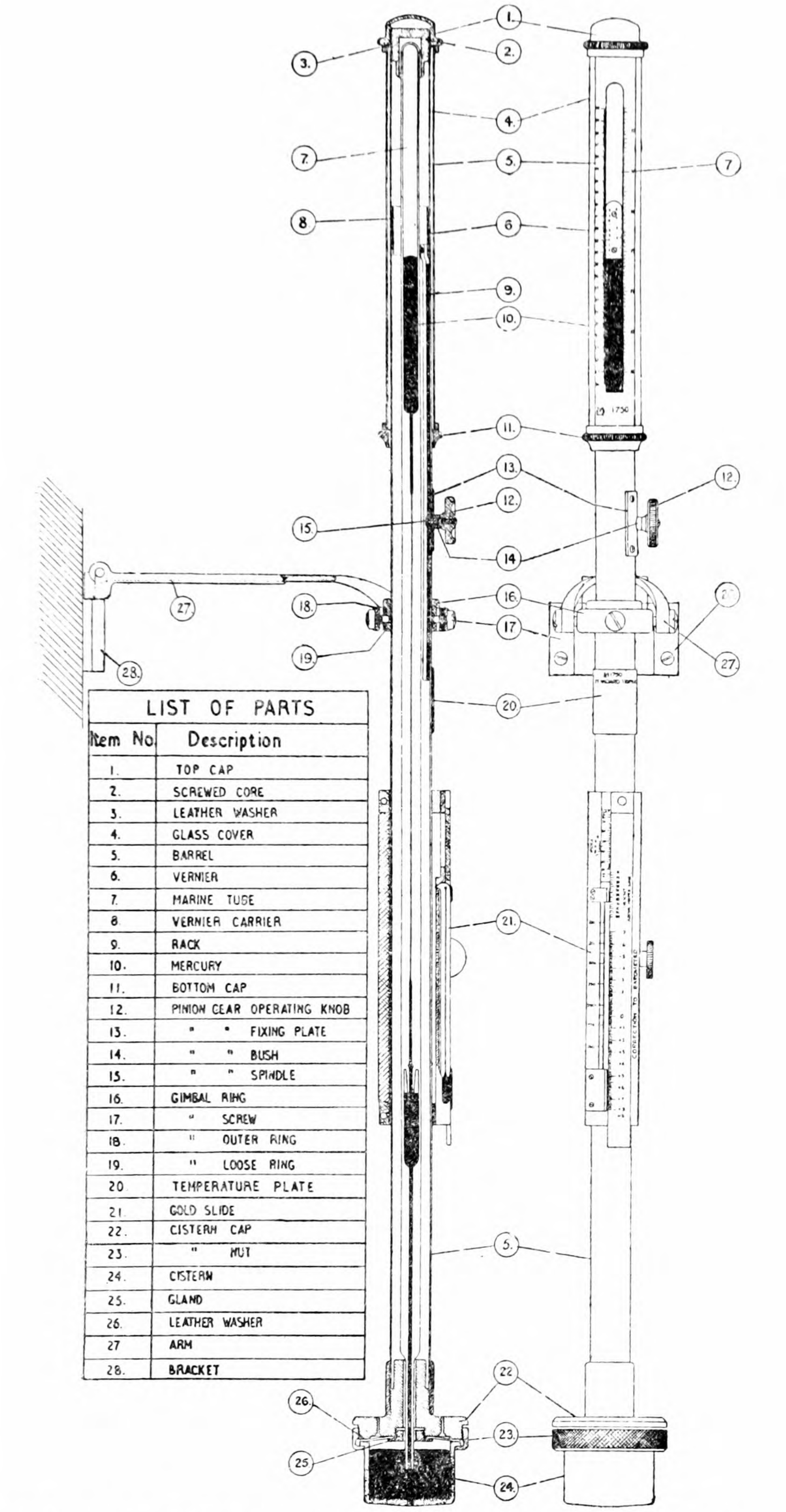
When putting the barometer back into its box it is necessary, as with the station model, to tilt it slightly until the mercury fills the barometer tube before it is finally moved to the horizontal position. This will take a much longer time with the marine barometer because of the constriction in the tube. The barometer box is similar to that of the station model, but it has, in addition, a strong brass clip, lined with felt or leather, which holds the outer case of the barometer when it is



METEOROLOGICAL OFFICE KEW-PATTERN LONG-RANGE BAROMETER



BAROMETER-CORRECTION SLIDE MK IV



LIST OF PARTS

Item No.	Description
1.	TOP CAP
2.	SCREWED CORE
3.	LEATHER WASHER
4.	GLASS COVER
5.	BARREL
6.	VERNIER
7.	MARINE TUBE
8.	VERNIER CARRIER
9.	RACK
10.	MERCURY
11.	BOTTOM CAP
12.	PINION GEAR OPERATING KNOB
13.	" " FIXING PLATE
14.	" " BUSH
15.	" " SPINDLE
16.	GIMBAL RING
17.	" SCREW
18.	" OUTER RING
19.	" LOOSE RING
20.	TEMPERATURE PLATE
21.	GOLD SLIDE
22.	CISTERN CAP
23.	" NUT
24.	CISTERN
25.	GLAND
26.	LEATHER WASHER
27	ARM
28.	BRACKET

FIG. 8—METEOROLOGICAL OFFICE KEW-PATTERN MARINE BAROMETER

with barometer-correction slide Mk IV (Gold slide) placed in the box. The box, with the barometer inside, can therefore be mounted vertically on a wall, when the ship is in port. This is known as " harbour stowage ". It should not be used when the ship is under way.

As the position of the ship varies the correction for gravity will also vary, so that there are four variables which have to be considered when reducing the uncorrected readings to mean sea level. As the barometer is always very close to sea level, the correction for height above mean sea level changes very little with variations in the outside temperature and pressure, and a mean value for each height can be assumed. If, in addition, the variations in the index correction with pressure and the variations in the correction for the barometer temperature with pressure are ignored and mean values assumed, the application of the corrections is much simplified with only a slight loss of accuracy.

Barometer-correction slide.—The barometer-correction slide is a device by which the necessary corrections to the Meteorological Office Kew-pattern marine barometer can be obtained when the assumptions in the last part of the preceding paragraph are made. It consists (see Plate IV) of (i) a solid brass stock carrying a mercury-in-glass thermometer, (ii) a movable slide whose position can be altered by means of a rack and pinion and which carries scales of height above the water-line (0–100 ft.) and corrections to the barometer readings, and (iii) a movable plate, carrying a scale of latitude, which is set in a slot in the stock. Opposite the latitude scale is a scale of index corrections (+0·5 mb. to —0·5 mb.). The thermometer is graduated at every 5°A. ; a temperature scale (every 10°A.) is also engraved and figured on the stock itself. A balance weight is fixed to the rear of the barometer case at the same level as the rest of the slide, so that the barometer will continue to hang vertically when the slide is fitted.

There are two types available—Mk IV (Stores Ref., Met. 235) for use with barometers adjusted to the old standard conditions ; Mk V (Stores Ref., Met. 1553) for use with barometers adjusted to the new standard conditions.

Installation.—Before it can be used with any particular barometer the position of the latitude-scale plate must be adjusted, so that the short red line on the left-hand side of the plate is exactly opposite the value of the index correction of the barometer on the index-correction scale ; the value of the index correction at 1000 mb. should be used for this purpose. Two small screws at the back of the latitude plate will have to be loosened before the adjustment can be made. If the barometer is supplied with the barometer-correction slide fitted in place this adjustment will have already been done and no further attention is necessary.

The barometer-correction slide can now be fitted in the position normally occupied by the attached thermometer, which should be removed if it is still in place ; the thermometer is held in position by two small screws. The long screws passing through the brass strips behind the balance weight should then be unscrewed, the balance weight removed, the brass strips passed around the barometer case and the balance weight replaced in position at the back of the barometer immediately opposite the slide. The whole can then be securely clamped in position by replacing the long screws. It is important that the balance weight should be carefully fitted for otherwise the barometer will not hang vertically.

Method of use.—To obtain the correction to mean sea level the slide is moved until the latitude of the ship (as shown on the latitude scale) is opposite the height of the barometer cistern above the water-line (as shown on the height scale). The required correction is then read from the correction scale on the slide opposite the top of the mercury column on the thermometer. If the correction is shown on the red part of the scale it is negative and should be subtracted from the uncorrected reading, while if it is on the black part of the scale (i.e. below the zero mark) it is positive and should be added to the uncorrected reading. The correction scale is graduated for every tenth of a millibar, and the correction should be read off to this degree of accuracy.

Accuracy.—The basis of this device is the fact that the temperature correction of the barometer is very closely proportional to the difference between the actual temperature and the standard temperature. When the scale value of the attached thermometer is fixed the actual length on the scale of this unit is also fixed. The assumptions which have to be made to reduce the number of variables considered have already been outlined (p. 32). The error introduced in this way can be estimated by calculating the true corrections for various conditions. Consider two extreme cases for a ship whose barometer is 30 ft. above the water-line.

(i) Outside temperature 20° F., pressure 1040 mb., attached thermometer reading 280° A., latitude 80°, index correction 0·0 mb. True correction +4·6 mb., indicated correction by barometer-correction slide +4·4 mb. Error −0·2 mb.

(ii) Outside temperature 100° F., pressure 980 mb., attached thermometer reading 310° A., latitude 0°, index correction 0·0 mb. True correction −5·7 mb., indicated correction by barometer-correction slide −5·8 mb. Error −0·1 mb.

These cases are extreme conditions, and the errors in normal conditions will usually be less than those indicated. These errors may, however, be exceeded if the barometer is more than 30 ft. above the water-line. There may be an additional error due to the change of the barometer index error with pressure, but this does not normally amount to more than 0·1 mb.

The magnitudes of the various corrections and the methods of calculating them are given later.

2.2.4. Patterson barometer

The Patterson barometer[5] (Fig. 9), used in the Meteorological Service of Canada, combines features of both the Kew-pattern and the Fortin barometers. The mercury in the cistern is contained in a leather bag which can be raised so that the mercury nearly fills the barometer when the instrument has to be moved, but in normal use the screw at the bottom is completely removed and the instrument acts as a Kew-pattern barometer.

2.2.5. Fortin barometer

The Fortin barometer (Fig. 10) differs from the Kew-pattern barometer in that the level of the mercury in the cistern is adjusted to a fixed datum level at each observation. This datum level is the zero of the scale. The scale is graduated in true inches or millimetres, if these units are being used. This instrument is no

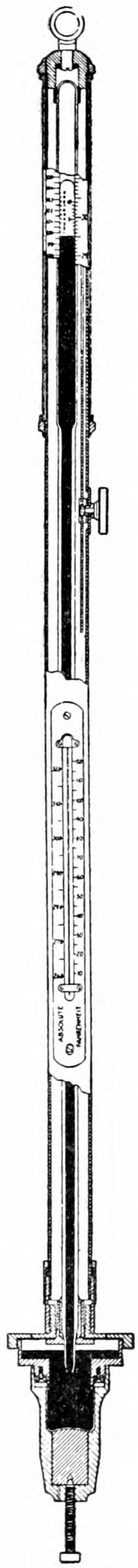


FIG. 9—PATTERSON BAROMETER
partly in section

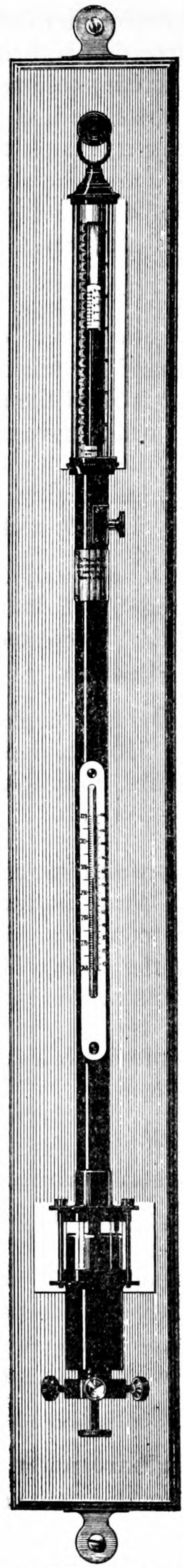


FIG. 10—FORTIN BAROMETER

longer in general use in the Meteorological Office, but is sometimes used for special purposes (e.g. at observatories).

The barometer tube enters the cistern through a boxwood bush, to which it is rigidly attached. The cistern itself (Fig. 11) is made of three main parts: an upper glass cylinder with a brass top to which is fixed the boxwood bush holding the barometer tube, a pliable wash-leather bag which is bound firmly to another boxwood bush and which forms the main mercury container, and a cylindrical brass base which holds the lower bush. Three steel bars hold the cistern base and the glass cylinder firmly to the cistern top. Mounted in the bottom of the cistern base is an adjusting screw, surmounted by a button, by means of which the centre of the wash-leather bag can be raised or lowered. The ivory fiducial pointer is conical in shape and fixed rigidly to the cistern top ; it is usually of such a length that the mercury about three-quarter fills the glass cylinder when an observation is made. An accessory, known as the Simpson dirt trap, is sometimes also fitted inside the upper part of the cistern. This consists of a perforated glass disc, similar to a watch glass but of somewhat greater curvature, whose diameter is equal to the inner diameter of the glass cylinder. The hole in the centre is such that an annular

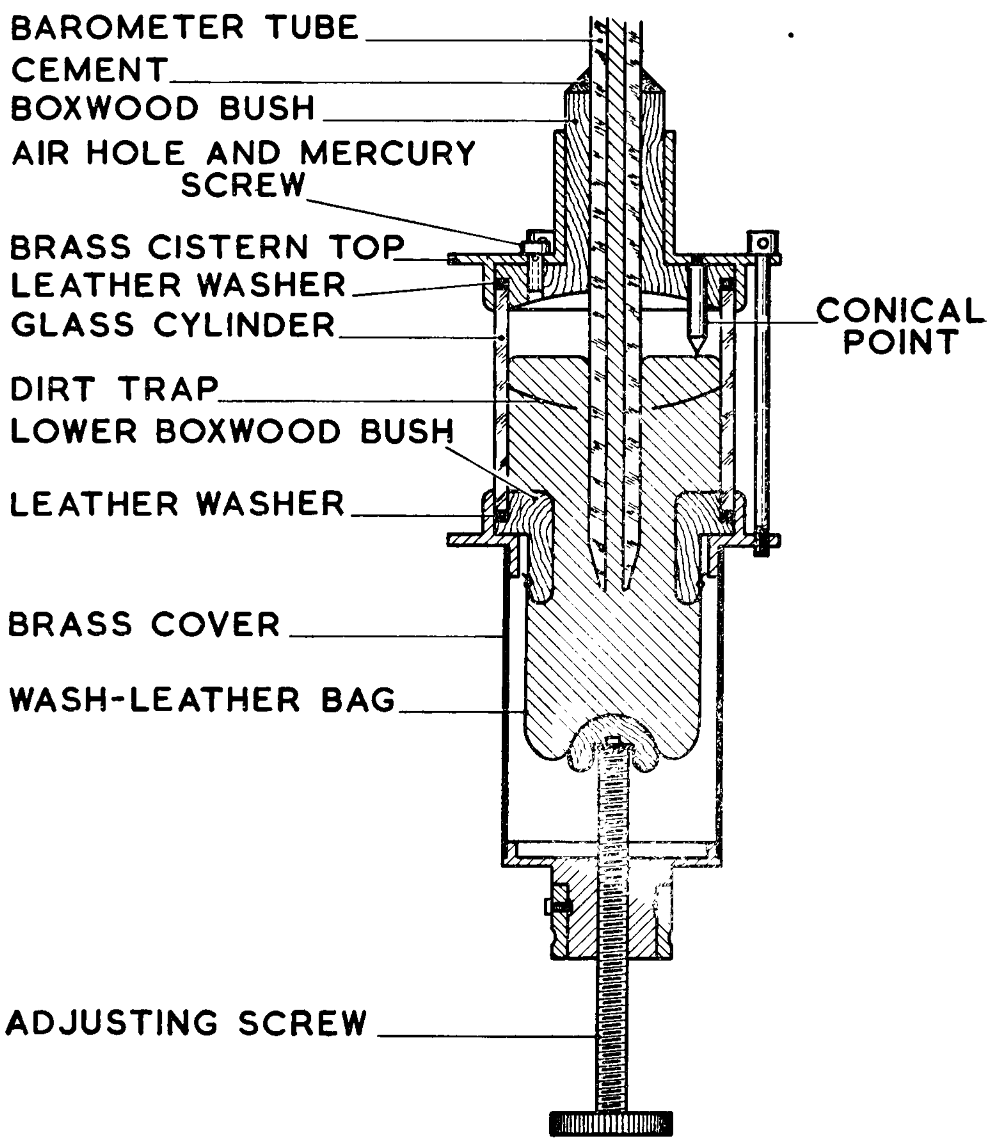


FIG. 11—CISTERN OF A FORTIN BAROMETER

space of about 1/10 in. wide is left around the barometer tube. The trap is positioned so that it is normally completely covered with mercury, but the dimensions of the wash-leather bag are such that the level of the mercury can be made to fall beneath the lowest part of the trap at all pressures in the range covered by unscrewing the screw at the base of the cistern. When the mercury is raised again, after lowering it this far, any dirt on its surface is trapped beneath the glass plate and a fresh clean surface is formed on top.

The remainder of the instrument is, in general, similar to the Kew-pattern instrument except that the bore of the visible part of the tube is slightly larger (0·4 in.) and the system of mounting is different. The barometer is suspended by a stout metal ring at the top of the instrument, which is placed over a metal support near the top of a rectangular board. The board is fixed to a wall, or other similar support, with its long edge vertical. The base of the barometer fits loosely into a screw ring near the bottom of the board, the screw ring containing three screws passing radially through it so that the barometer can be clamped in position. The screws clamp on to a revolving collar so that the barometer can be revolved about a vertical axis even when it is fixed in position.

Installation.—The board is fixed securely, in a position selected according to the principles given on p.21, by means of the two lugs, taking care that the long edge is vertical (this should be checked with a plumb-line). The barometer can then be lifted carefully out of its case and suspended from the hook, the lower end being passed through the ring. The screws on the screw ring should be adjusted until the barometer is fixed firmly in position with the axis of the tube vertical. The criterion for verticality which must be satisfied is that the ivory index, when just in contact with the mercury surface in one position, must remain so in all positions when the barometer is rotated. It will usually be found that the barometer tube is vertical when the barometer is hanging freely, but the criterion given above is more reproducible, and is in fact the criterion used by the National Physical Laboratory when obtaining the certified corrections to the barometer readings.

If the barometer has to be dismounted the screw plunger should first be screwed up until the mercury almost fills the barometer tube ; when this has been done the instrument may be transported in a similar manner to the Kew-pattern instrument.

Method of use.—The routine in making an observation should be as follows :—

(i) Read the attached thermometer.

(ii) Tap the instrument gently on the outer brass case just beneath the glass shade and adjust the level of the mercury in the cistern until it is just in contact with the fiducial point. This is done by watching both the tip of the pointer and its image in the mercury surface and adjusting the screw until they coincide.

(iii) Set and read the vernier in the usual way (as for the Kew-pattern barometer).

The readings are corrected and reduced in the same way as for the Kew-pattern barometer readings, but the magnitudes of some of the corrections are different (see p. 38).

To prevent fouling of the mercury by prolonged contact with the fiducial point the mercury surface should be lowered after each observation.

Maintenance.—The dirt trap should be operated, as described on p. 36, whenever it is necessary to clean the surface of the mercury in the cistern. It is advisable to check the verticality of the barometer from time to time by adjusting the level of the mercury until it just touches the ivory index and then rotating the cistern through 360°. The index should just remain in contact with the mercury throughout. The cistern adjusting screws should be kept clean, and, if necessary, they may be slightly oiled, as it is impossible to adjust them satisfactorily if they are stiff. Apart from these points the only necessary maintenance is to keep the instrument clean.

The accuracy and sources of error of the instrument are discussed under the heading of the accuracy and sources of error of mercury barometers in general (p. 47).

2.2.6. Siphon barometers

The principle of the siphon barometer is illustrated in Fig. 12. It differs from the cistern barometer chiefly in that the areas of the upper and lower mercury surfaces are nearly equal, whereas in cistern barometers the lower mercury surface is much larger than the upper. The distance between the upper and lower mercury

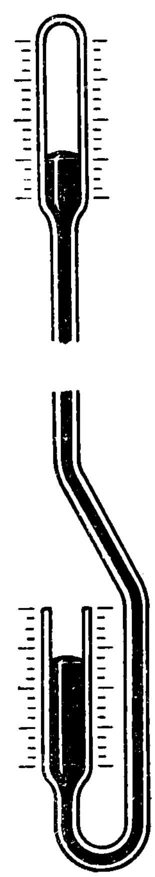


FIG. 12—PRINCIPLE OF
A SIPHON BAROMETER

surfaces can be found by measuring the positions of each surface with reference to a common vertical scale, or, less accurately, by measuring the position of one surface and making allowances (by means of a contracted scale) for changes in the level of the other. Some accurate instruments are provided with means of varying the level of the mercury in the open limb, and thus, by observing the change in the indicated pressure as the volume of the " vacuum space " above the mercury in the closed limb varies, it is possible to make an estimate of the pressure of the gases in the " vacuum space " and apply a correction.

Further details are given by Kleinschmidt[6]. Siphon barometers have no advantages over the cistern type of barometer for routine pressure measurements.

2.2.7. Correction of readings

The pressure exerted by a column of mercury depends, as has been shown, on the density of the mercury and the value of the acceleration due to gravity. In addition the height of the column is measured by a scale whose length depends on the temperature. A correction has therefore to be applied to the observed reading to make it equal to what the reading would be under standard conditions of temperature and gravity.

The discussion which follows relates to the standard conditions in use up to December 31, 1954 and basic correction formulae are obtained. Tables XLVIII–LIII are based on these formulae. Basic correction formulae relating to the new standard conditions are also given and Tables XLVIIIA–LIIIA are based on these.

Corrections for temperature.—*Fortin millibar barometer.*—The Fortin barometer is considered first as it is the simplest to deal with.

Let T = temperature of the barometer

α = mean coefficient of linear expansion of the material of the scale over the range of temperature considered

β = mean cubical coefficient of thermal expansion of mercury over the same range of temperature

H = correct reading of the barometer

H_t = observed reading corrected for index error (see p. 54) and gravity (see p. 42).

The correction, C, which has to be applied to the observed reading is therefore $(H - H_t)$. It can be seen that, if T is in degrees Absolute, then for this type of barometer graduated to read correctly at a temperature of 285° A.,

$$C = - H_t \frac{(\beta - \alpha)(T - 285)}{1 + \beta(T - 285)} \cdot \qquad \ldots\ldots(2)$$

Table LI (p. 436) gives values of this correction for various values of H_t and T, on the assumption of the standard value of β, 0·000182, and that the scale is made of brass for which $\alpha = 0{\cdot}0000184/°$ C. (0·0000102/°F.). When C is negative ($T > 285°$ A.) the correction is subtracted from the observed reading, and when T is less than 285° A. the correction is added.

The corresponding formula under the new conventions is

$$C = - H_t \frac{(\beta - \alpha)(T - 273)}{1 + \beta(T - 273)} \text{ (Table LIA).}$$

Fortin inch barometer.—The correction for this barometer is more complicated because the scale has to be corrected to 62° F. and the mercury to 32° F., C is then given by

$$C = - H_t \frac{(\beta - \alpha)(T - 32) + 30\alpha}{1 + \beta(T - 32)}, \qquad \ldots\ldots(3)$$

where T, α and β refer to degrees Fahrenheit. This correction is tabulated in Table L (p. 433). It is zero at a temperature of about 28·6° F. and is negative above this temperature.

The corresponding formula under the new conventions is

$$C = -H_t \frac{(\beta - \alpha)(T - 32)}{1 + \beta(T - 32)} \text{ (Table LA).}$$

Fortin millimetre barometer.—The correction is given by

$$C = -H_t \frac{(\beta - \alpha)(T - 273)}{1 + \beta(T - 273)}, \qquad \ldots\ldots(4)$$

where T, α and β refer to degrees Absolute as both the scale and the mercury have a standard temperature of 0° C. This formula is also appropriate to the new conventions.

Kew-pattern barometers (general).—Suppose that the temperature of the barometer is above the standard temperature and let A and B (Fig. 13) be the levels of the mercury in the tube and cistern respectively. Suppose now that the temperature

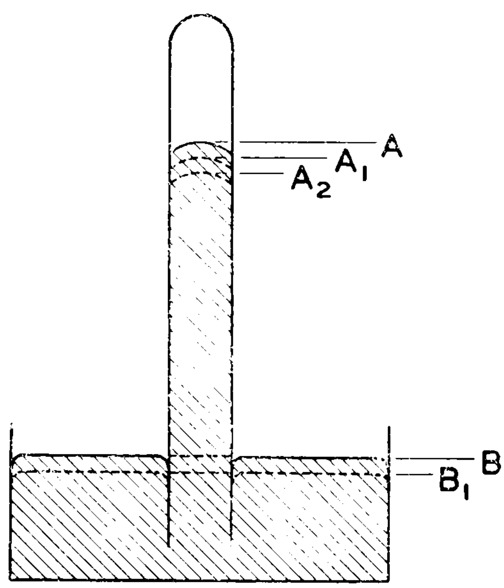


FIG. 13—EFFECT OF A FALL IN TEMPERATURE ON THE LEVELS OF THE MERCURY IN A KEW-PATTERN BAROMETER

of the instrument is lowered to the standard temperature T_0, and suppose that the mercury first decreases in volume without change of density, and then increases in density with no change in volume. If the initial volume of mercury is V, the apparent change in volume will be $V(\beta - 3\eta)(T - T_0)$, where η is a composite coefficient of linear expansion of the glass and steel of which the barometer is made. If the mercury levels are now A_1 and B_1, A_1B_1 must be equal to AB because the density is assumed constant. Thus the fall in mercury level is the same in both tube and cistern, and is

$$\frac{V(\beta - 3\eta)(T - T_0)}{A + A'}$$

where A = effective area of cistern (i.e. total internal area less the area of the glass tube)

A' = area of the top of the mercury column.

Since this is a Kew barometer the distance AA_1 is measured on a scale contracted in the ratio $A/(A + A')$; the apparent fall is therefore

$$\frac{V(\beta - 3\eta)(T - T_0)}{A + A'} \cdot \frac{A + A'}{A} = \frac{V(\beta - 3\eta)(T - T_0)}{A}$$

Now suppose the density of the mercury increases but with no change in volume. The mercury column will shorten by the same amount as in a Fortin barometer. The mercury will fall in the tube to A_2 and rise slightly in the cistern. The change of level in the cistern is taken care of by the contracted scale, and therefore the indicated change will be equal to the true change, i.e. it will be the same as the change in reading of a Fortin barometer for the same temperature change.

It thus follows that the temperature correction of a Kew barometer equals that of a Fortin barometer plus the additional term

$$\frac{V(\beta - 3\eta)(T - T_0)}{A}.$$

The complete correction formulae therefore become as set out in equations (5), (6) and (7).

Kew-pattern millibar barometer.—

$$C = -\left[H_t \frac{(\beta - \alpha)(T - 285)}{1 + \beta(T - 285)} + 1\cdot 33 \frac{V}{A}(\beta - 3\eta)(T - 285)\right]. \quad ..(5)$$

Here the millimetre is the unit of length for V and A and the correction factor of $1\cdot 33$ is inserted to convert the correction into millibars. T, α, β, and η refer to degrees Absolute. The values of this correction for various values of H_t and T are tabulated in Table XLVIII (p. 428).

The corresponding formula under the new conventions is

$$C = -\left[H_t \frac{(\beta - \alpha)(T - 273)}{1 + \beta(T - 273)} + 1\cdot 33 \frac{V}{A}(\beta - 3\eta)(T - 273)\right] \text{(Table XLVIIIA).}$$

Kew-pattern inch barometer.—

$$C = -\left[H_t \frac{(\beta - \alpha)(T - 32) + 30\alpha}{1 + \beta(T - 32)} + \frac{V}{A}(\beta - 3\eta)(T - 62)\right]. \quad ......(6)$$

The inch is here the unit of length for V and A, and T, α, β and η refer to degrees Fahrenheit. The term $(T - 62)$ arises because it has been conventional to make the scales of all inch barometers, whether Kew or Fortin, indicate the correct height of the mercury column when the temperature of the instrument is 62° F. The values of this correction are tabulated in Table XLIX (p. 430).

The corresponding formula under the new conventions is

$$C = -\left[H_t \frac{(\beta - \alpha)(T - 32)}{1 + \beta(T - 32)} + \frac{V}{A}(\beta - 3\eta)(T - 32)\right] \text{(Table XLIXA).}$$

Kew-pattern millimetre barometer.—

$$C = -\left[H_t \frac{(\beta - \alpha)(T - 273)}{1 + \beta(T - 273)} + \frac{V}{A}(\beta - 3\eta)(T - 273)\right]. \quad ......(7)$$

The millimetre is here the unit of length for V and A, and T, α, β and η refer to degrees Absolute.

The corresponding formula under the new conventions is the same, namely

$$C = -\left[H_t \frac{(\beta - \alpha)(T - 273)}{1 + \beta(T - 273)} + \frac{V}{A}(\beta - 3\eta)(T - 273)\right].$$

Numerical values.—The values of V and A have been measured for many barometers of various dimensions and pressure ranges, and it has been found that the ratio V/A varies between 1·0 and 3·5 in. For the Meteorological Office Kew-pattern station and marine barometers the value of V/A is very close to 1·5 in. (38 mm.), and this value is assumed in computing Tables XLVIII and XLIX. These tables can also be used for the Meteorological Office long-range barometer. If, however, for any instrument the value of V/A differs widely from 1·5 in. the correction should be computed afresh using the correct values of V/A. The value of η has been found to be 0·000010/°C.

It may be noted that for the Kew-pattern millibar barometer (inserting numerical values)

$$C = -\left(0{\cdot}000163H_t + 0{\cdot}000202\frac{V}{A}\right)(T - 285) \text{ to a very close approximation}$$

$$= -\,0{\cdot}000163\left[H_t + \frac{202}{163}\frac{V}{A}\right](T - 285). \qquad \ldots\ldots(8)$$

The corresponding formula under the new conventions is

$$C = -0{\cdot}000163\left[H_t + \frac{202}{163}\frac{V}{A}\right](T - 273).$$

This may be compared with the correction for the Fortin millibar barometer :—

$$C = -\,0{\cdot}000163\,H_t\,(T - 285).$$

The corresponding formula under the new conventions is

$$C = -0{\cdot}000163\,H_t\,(T - 273).$$

Thus the tables of correction for the Fortin millibar instrument may be used for the Kew-pattern millibar barometer if the corrections indicated for a pressure (202/163) (V/A) mb. above the actual observed reading are taken, instead of those indicated for the reading itself. For Meteorological Office station, long-range and marine barometers this pressure difference is 47 mb.

Temperature correction of the millibar barometers in the form of a coefficient.—It will be convenient to set out the temperature corrections (for millibar barometers only) in the form of a coefficient.

For the Fortin instruments :

$$C = -\,0{\cdot}000163\,H_t \text{ mb./°A.}$$

$$= -\,0{\cdot}163 \text{ mb./°A. at a pressure of 1000 mb.}$$

For the Meteorological Office Kew-pattern instruments :

$$C = -\,\{0{\cdot}000163\,H_t + 0{\cdot}000202\,(V/A)\} \text{ mb./°A.}$$

$$= -\,H_t(0{\cdot}000163 + 0{\cdot}0077/H_t) \text{ mb./°A.}$$

$$= -\,0{\cdot}171 \text{ mb./°A. at a pressure of 1000 mb.}$$

This last coefficient is not strictly proportional to the observed pressure, but the resulting error in assuming that it is so is very small at all normal pressures.

Correction for gravity.—The empirical formula from which "gravity at the station" may be computed has been given (p. 20). If $g_{\phi,h}$ is the value obtained from this equation, or from a gravimetric survey, then the correction C to the observed reading H is given by

$$C = H \frac{(g_{\phi,h} - g_s)}{g_s}, \qquad \ldots\ldots(9)$$

where g_s is the standard gravity to which the barometer was adjusted. The factor $(g_{\phi,h} - g_s)$ can be regarded as the sum of two terms ; one due to the variation of gravity with latitude and one due to the variation of gravity with height. Tables LII to LIIIA give the latitude correction (Tables LII and LIII relating to a standard gravity of 980·62 cm./sec.^{2} and Tables LIIA and LIIIA relating to a standard gravity of 980·665 cm./sec.^{2}). Table LIV gives the additional correction due to the variation of gravity with height.

Reduction of the station pressure to that at a fixed datum level.—It is often necessary to deduce the horizontal gradient of pressure between two places at different levels. This cannot be done by the direct comparison of the readings of pressure at the stations concerned because of the change in pressure with height. Consequently both the readings are "reduced" to a common datum level (usually mean sea level). This reduction consists in 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 cistern above the datum level. If the barometer cistern 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 constant or may be assumed to vary along the column. In the British Isles, where reductions are made to mean sea level and where stations are mostly below 1,000 ft. above mean sea level, it is customary to neglect the effect of water vapour altogether, 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.

If, in addition, a constant value of g is assumed it may easily be shown that, if the temperature of the air column is T°A., H the height of the column, p_0 the pressure at the base and p the observed pressure at the top of the column, then

$$\log_{10} \frac{p_0}{p} = \frac{0 \cdot 434 Hg}{RT},$$

where R is the gas constant for dry air.

If H is in metres

$$\log_{10} \frac{p_0}{p} = \frac{H}{67 \cdot 4 T}. \qquad \ldots\ldots (10)$$

If H is in feet

$$\log_{10} \frac{p_0}{p} = \frac{H}{221 \cdot 1 T}. \qquad \ldots\ldots (11)$$

The difference, $p_0 - p$, is tabulated in Table LVI (p. 446) in millibars, for a value of p equal to 1000 mb. and for various values of air temperature expressed in degrees Fahrenheit. The correction for other values of p can be obtained by multiplying the correction given in the table by the factor, $p/1000$. This table is taken from the International Meteorological Tables[7] ; allowance is made in these tables for the variation of g with height, but the difference between this table and the corrections calculated from equations (10) and (11) is negligible for heights up to 1,000 ft. A similar table for inch barometers (Table LVII) is given on p. 448.

The correction in millibars for T equal to 260°A. and various values of H has been given to the second decimal place in Table LV, the use of which will become apparent later (p. 47). The heights given in this table are in metres.

International practice in the reduction of barometer readings to a datum level.—The British practice of assuming an isothermal atmosphere, with a temperature equal to that at station level, for reducing barometer readings to sea level is only used for stations up to about 1,000 ft. above mean sea level. This method is not found to give good results for higher-level stations, especially where there is a large diurnal range of temperature, and modified methods are often used. Thus 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 $\frac{1}{2}$° C./100 m. (approximately half the dry adiabatic rate). They may also take account of the fact that the acceleration due to gravity decreases with height, and that the density of the air will depend on its humidity. In North America it is customary to take a mean of the current air temperature and the air temperature twelve hours previously as the air temperature at the top of the hypothetical column. A correction for humidity is made on the basis of a mean dew point over the previous twelve hours. It was decided at the Conference of Directors of the International Meteorological Organization[8] at Washington 1947 that all meteorological services should publish the methods used by their stations in reducing the observed pressure to a given datum level, and reference should be made to these publications (when available) for the details of methods used by any one country. The differences between the various methods are very small for heights of less than 1,000 ft. above mean sea level.

Stations situated in the midst of an appreciable area whose average height above sea level is more than 500 m. (approximately 1,600 ft.) do not usually reduce their station-level pressures to mean sea level, but to some other datum which is the subject of regional agreement. This datum is often 1,000, 1,500, 2,000, etc. geopotential metres above mean sea level (1 geopotential metre = 0·98 of a geodynamic metre and for most purposes can be considered equal to one ordinary metre) but in some areas a round number of geodynamic metres is still in use. The principles used in the computation of the necessary corrections to the station-level pressure in these cases are similar to those used in the reduction to mean sea level.

Isolated stations more than 500 m. above the datum level used in the surrounding area normally do not attempt to reduce their readings and simply report the station-level pressure. A list of stations reporting pressures reduced to a datum other than mean sea level was published by the United States Air Weather Service[9] in 1950.

Preparation of barometer correction cards.—The corrections which have to be applied to the observed reading have been discussed above. There is also the index correction (see p. 54) which is based on the residual error in the readings after all other corrections have been applied. This is determined by the comparison of the instrument with a standard barometer and is detailed at various points of the barometer scale. The aim of a correction card is to enable the total correction to the observed reading to be obtained with the minimum of effort. Since however there are three pertinent factors which vary from day to day (the actual observed pressure, the temperature of the barometer and the temperature of the outside air) two operations at least are necessary, except in the case when the effect of the variations in outside temperature can be neglected. This last is true when the height of the barometer above the datum level is less than 50 ft. The method of preparing barometer correction cards is given here in some detail, but the correction cards for Meteorological Office stations are usually prepared at Headquarters. If this is to be done the following information should be supplied : a copy of the National Physical Laboratory certificate for the barometer, the height of the barometer cistern above mean sea level, and the latitude of the station. The procedure described below applies both to Mk I (old conventions) and to Mk II (new conventions) barometers. Tables XLVIII to LIII should be used for Mk I barometers ; for Mk II barometers the alternative set of tables, suffix A, should be used.

Stations more than 50 *ft. above the datum level.*—The procedure to be followed should be as set out below. Obtain from the National Physical Laboratory certificate the correction for index error at every 20 mb. over a suitable range of pressure (940–1040 mb. for stations near mean sea level, 920–1020 mb. for stations near 500 ft.). These should be interpolated as necessary and given to the nearest 0·02 mb. The best method is to plot the observed corrections as a function of the pressure and draw a smooth curve through the points. In the case of some old Meteorological Office instruments the index correction is not given directly but the " standard temperature " at various pressures is stated (see p. 20). The index corrections can be derived from the standard temperatures by the use of Table XLVIII (or Table LI for a Fortin barometer). Then obtain from Tables LII and LIV the appropriate corrections for gravity to the nearest 0·01 mb., interpolating as necessary, and add them algebraically to the index corrections. The following is an example :—

	Pressure (mb.) 920	940	960	980	1000	1020	1040
				millibars			
Index correction ..	−0·06	−0·08	−0·08	−0·06	−0·02	+0·02	+0·06
Correction for gravity (lat. 52°)	+0·58	+0·59	+0·61	+0·62	+0·63	+0·64	+0·65
Correction for gravity (height 230 ft.) ..	−0·02	−0·02	−0·02	−0·02	−0·02	−0·02	−0·02
Total	+0·50	+0·49	+0·51	+0·54	+0·59	+0·64	+0·69

The final corrections so obtained can now be added to the correction for the temperature of the barometer as given in the appropriate table (Table XLVIII or LI) covering a range of attached thermometer readings from about 270° to 310° A. A table is thus made of the combined corrections for index error, gravity and temperature of the barometer. It gives the corrections to the observed reading to obtain the pressure at station level. The following is an extract from a typical table using the combined corrections for index error and gravity as given above. This is for a Meteorological Office Kew-pattern millibar barometer but a similar method should be used with inch barometers.

Attached thermometer	Pressure (mb.) 920	940	960	980	1000	1020	1040
°A.				*millibars*			
270	+2·87	+2·91	+2·98	+3·06	+3·16	+3·25	+3·35
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
288	+0·03	+0·01	+0·02	+0·04	+0·08	+0·12	+0·16
289	−0·13	−0·15	−0·15	−0·13	−0·09	−0·06	−0·02
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
293	−0·76	−0·80	−0·81	−0·80	−0·78	−0·75	−0·73
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

There are two ways of using this table.

The first method is to round each entry off to the nearest 0·1 mb. and then to construct another table for the reduction to the datum level. Table LVI is used to obtain the correction, for a station pressure of 1000 mb., over a suitable range of dry-bulb temperatures, interpolating as necessary. The columns for 920 and 960 mb. can be completed by subtracting 8 per cent. and 4 per cent. respectively from the values for 1000 mb., and the column for 1040 mb. by adding 4 per cent. The intermediate columns can be derived by interpolation between those already entered. A similar method is used for inch barometers using Table LVII instead of Table LVI. The total correction for any barometer reading can then be found by adding algebraically the corrections found in each table for the appropriate conditions. This method should be used whenever the height of the station is more than 500 ft. above the datum level.

It is however possible to devise a quicker method for stations below 500 ft. above the datum level. Suppose the correction to the datum level for one temperature and a pressure of 1000 mb. is added to each of the combined corrections for barometer temperature, index error and gravity for 1000 mb. When the outside air temperature differs from that assumed an allowance can be made for the change in the datum-level correction by applying a correction to the temperature indicated by the attached thermometer, and because the temperature correction of the barometer changes uniformly with temperature at any given pressure (to a close approximation) a given correction to the attached thermometer will cause the same allowance to be made at all temperatures of the barometer. In addition, both the temperature correction of the barometer and the datum-level corrections are (also to a good approximation) proportional to the pressure, so that if the datum-level correction for the assumed air temperature is added to the whole of the combined table, taking due account of changes with pressure, the correction that has to be applied to the attached thermometer to allow for a given change in outside air temperature will be the same for all pressures, as well as for all barometer temperatures.

A suitable outside air temperature to assume is 260° A. (8·6° F.). This makes practically all the corrections to the attached thermometer positive for stations in the British Isles. Fig. 14 has been constructed for the Meteorological Office Kew-pattern millibar barometers. The curves show the relation between the temperature of the outside air which necessitates a correction to the attached thermometer of 0·5°, 1·5°, 2·5° A., etc., and the height of the barometer cistern above the datum level once the datum-level correction for 260° A. has been applied. The correction to the attached thermometer is normally given in whole degrees Absolute, so that these curves can be used to obtain the limits of air temperature, for which a given correction of a whole number of degrees Absolute has to be made, by drawing a line parallel to the temperature axis through the reading of the height of the cistern on the height scale and noting the values of the air temperature at which it cuts the curves marked 0·5°, 1·5°, 2·5°A., etc.

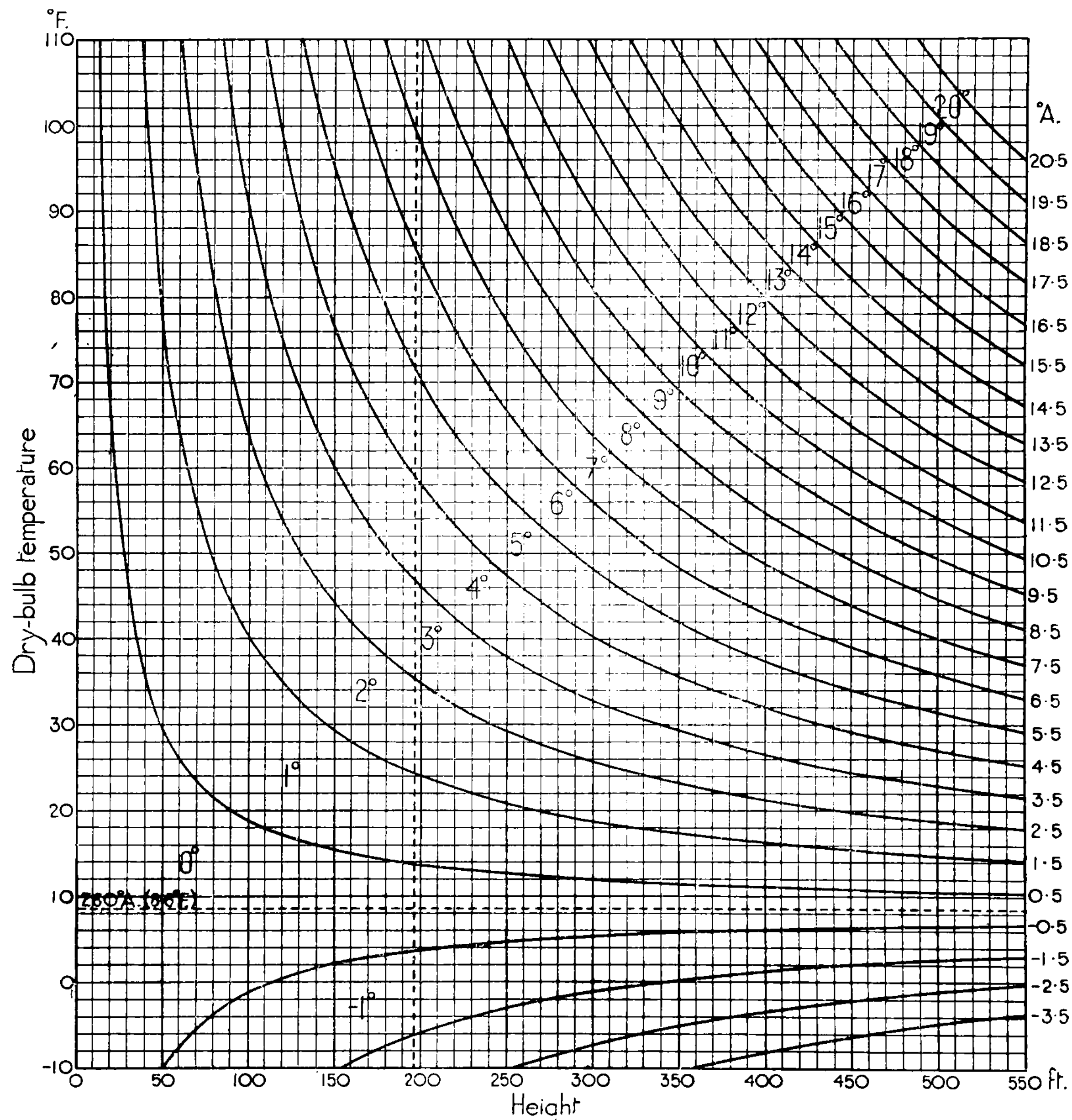


FIG. 14—ADJUSTMENTS TO THE ATTACHED THERMOMETER OF A METEOROLOGICAL OFFICE KEW-PATTERN BAROMETER

Diagram showing the correction to be applied to readings of the attached thermometer on account of altitude and difference of dry-bulb temperature from 260°A. (8·6°F.).

This procedure may be summarized as follows :

(i) Obtain the index error from the National Physical Laboratory certificate, to the nearest 0·02 mb., for every 20 mb. over a suitable range of pressure.

(ii) Obtain corrections for gravity, to the nearest 0·01 mb., for the same pressure range from Tables LII and LIV.

(iii) Obtain corrections to datum level (mean sea level) from Table LV for an outside air temperature of 260°A.—1000 mb. first, then 920, 960 and 1040 mb., and then the intermediate ones.

(iv) Add algebraically the corrections obtained in (i), (ii) and (iii) for corresponding pressures.

(v) Obtain the temperature corrections for the barometer over the same range of pressure, and for a range of temperatures from the attached thermometer from 270° to 310°A., or higher if the maximum barometer temperature plus the maximum correction to the attached thermometer is likely to exceed this.

(vi) Add the corrections obtained under (iv) to each of the corrections in (v) for the same pressure, and then round off to the nearest 0·1 mb.

(vii) From Fig. 14 read off the ranges of air temperature for which corrections of 0°, 1°, 2° A., etc. have to be applied to the attached thermometer.

A specimen correction card (Form 1270) is shown on p. 28.

Stations less than 50 ft. above the datum level.—The above procedure can be simplified for stations less than 50 ft. above the datum level. In place of the height correction for a temperature of 260° A. the correction for an average outside temperature should be used (50° F. is suitable in most parts of the British Isles) and no correction made to the reading of the attached thermometer. Apart from this the procedure is unchanged.

2.2.8. Sources of error of mercury barometers

Most of the errors detailed in this section are common to all types of mercury barometers.

Effects of the surface tension of the mercury (capillarity).—The surface of the mercury in the top of the barometer tube is normally as shown in Fig. 15.

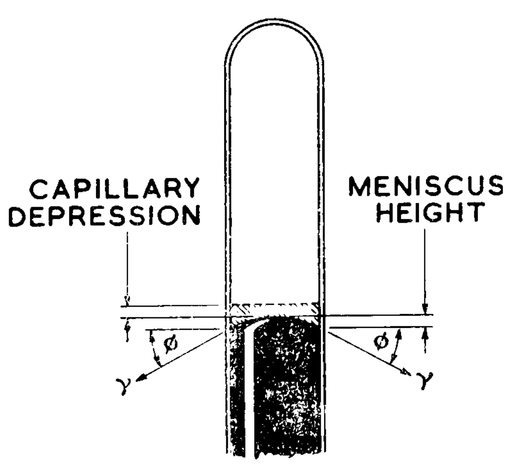


FIG. 15—SURFACE TENSION AND THE FORM OF THE MERCURY MENISCUS IN THE BAROMETER TUBE

The surface tension, γ, acting everywhere in the surface layer of the liquid is equivalent to a resultant force perpendicular to each element of the ring of contact of the mercury with the glass tube, acting downward in a direction at an angle, ϕ, to the horizontal ; ϕ is known as the angle of contact. The actual position of the summit of the mercury column is determined by the fact that the vertically downward component of the force of surface tension on the barometric column is equal to the weight of mercury which would otherwise occupy the position that is shaded in Fig. 15. The amount by which the summit of the mercury column is lowered by surface tension is known as the capillary depression. It depends on the diameter of the tube, the angle of contact, and the value of the surface tension ; in tubes which have a diameter exceeding 1 in. it is negligible. The angle of contact cannot easily be measured directly, but can be deduced from a measurement of the meniscus height (the height of the top of the meniscus above the ring of contact).

In practice the scale of the mercury barometer is graduated so as to make an allowance for the capillary depression in the tube, and it is only the variation in the capillary depression which gives rise to errors. Investigations at the National Physical Laboratory have shown that the average angle of contact is about 35°, and also that in a given barometer tube the average range of variation of the angle of contact is about 8° ; the latter does not include variation with age, but represents variations dependent on the position and cleanliness of the mercury in the tube and also to some extent on whether the pressure is rising or falling. The corresponding errors in terms of pressure measurements are given in Table I.

TABLE I—VALUE OF THE CAPILLARY DEPRESSION

Internal diameter of barometer tube		Estimated absolute value of the capillary depression correspondong to average angle of contact (35°)		Estimated average range of variation in capillary depression from its mean value	
in.	mm.	in.	mb.	in.	mb.
0·20	5·1	0·046	1·56	0·008	0·27
0·25	6·5	0·032	1·08	0·006	0·20
0·30	7·7	0·023	0·78	0·004	0·14
0·40	10·3	0·011	0·37	0·002	0·07
0·50	12·9	0·006	0·20	0·001	0·03
0·60	15·5	0·003	0·10	0·001	0·03
0·75	19·3	0·001	0·05	0·0005	0·02

Tapping the barometer facilitates but by no means ensures a consistent angle of contact. The figures given in Table I are to be regarded as approximate values only, but they probably give a fair average for barometer tubes. This table is based on Glazebrook[1].

It can be seen that the magnitude of the errors due to a change in capillary depression depends chiefly on the diameter of the barometer tube ; the smaller the tube the larger the error. Surface tension also affects the shape of the mercury meniscus in the cistern. In Fortin barometers the errors resulting from changes in the shape are small, except in the case of instruments with very small dimensions, as, provided the fiducial point is situated about midway between the glass tailpiece and the wall of the cistern, the level of the top of the mercury meniscus is used in making the zero setting, and the only error arises from changes in the capillary depression. If the internal diameter of the cistern is 1·1 in. the capillary depression is about 0·008 in., and variations of the order of 0·002 in. (0·07 mb.) or more may be expected. For larger cisterns the error will however be less.

In a Kew-pattern barometer two distinct errors result. The first is due to variations in the capillary depression, and, as in the case of the Fortin, is generally negligible except in the case of a cistern with very small dimensions, but the second is more complicated. In Fig. 16 ABCC′B′A′ represents the position of the mercury surface in an average barometer whose cistern is clean ; the corresponding level of the mercury in the tube is S. If now, the pressure and temperature remaining constant, the mercury in the cistern becomes dirty so that the mercury surface becomes plane, the level of the mercury will fall to DD′ and this in turn will cause the level of the mercury in the tube to fall from S to S′ (equal approximately to the vertical distance between BB′ and DD′). The amount of the fall will be governed by the condition that the total volume of the mercury in the instrument remains constant. The sign of this error is opposite to that due to the corresponding variations in capillary depression, and, as the latter is considerably the smaller of the two in the sizes of the barometer used in practice, the combined effect of the twofold error is a lower barometer reading when the meniscus in the cistern is flatter than normal. The resultant error in the reading of the barometer for cisterns of different sizes and angles of contact has been calculated on the assumption that, with average conditions in an iron cistern to which moist air has access, the angle of contact is 40°. These resultant errors are given in Table II.

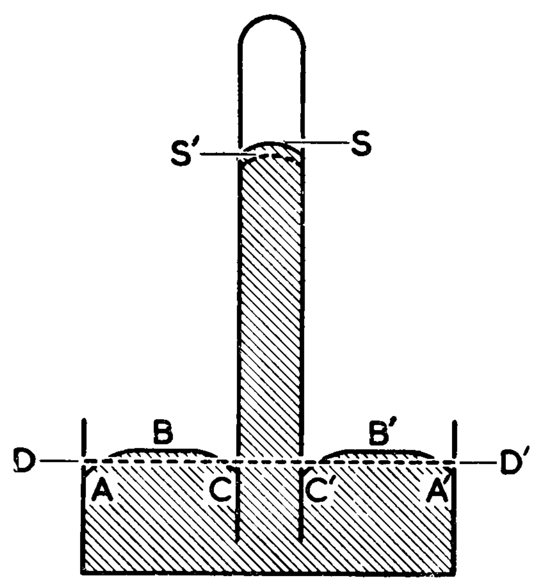


FIG. 16—EFFECT OF VARIATIONS IN THE ANGLE OF CONTACT OF THE MERCURY IN THE CISTERN OF A KEW-PATTERN BAROMETER

There is some evidence to show that the limiting values of the angle of contact (0° and 90°) may both be approached in conditions which obtain in practice. Changes in the angle of contact may also be brought about by the accommodation of the shape of the meniscus to slightly altered pressure conditions ; when the pressure increases, the meniscus in the tube tends to bulge while the meniscus in the cistern tends to flatten, the ring of contact between the mercury and the wall not moving until the meniscus becomes unstable. This effect is minimized by tapping the barometer. During an increase in pressure the changes in the cistern and tube both tend to make the barometer read low, so that without tapping an appreciable difference would be found between the readings for rising and falling pressure. These changes would be more marked in the case of the marine barometer

TABLE II—CISTERN ERROR IN KEW-PATTERN BAROMETERS[1]

Contact angle of mercury in cistern	Corresponding meniscus height		Resultant error of reading Kew-pattern barometer relative to assumed average conditions. For cisterns of internal diameter 1·0 in.		1·5 in.		2·0 in.		4·0 in.		6·0 in.	
°	mm.	in.	in.	mb.	in.	mb.	in.	mb.	in.	mb.	in.	mb.
90	2·6	0·10	+0·009	+0·31	+0·005	+0·18	+0·004	+0·14	+0·002	+0·07	+0·001	+0·05
67	2·0	0·08	+0·007	+0·25	+0·004	+0·15	+0·003	+0·11	+0·001	+0·05	+0·001	+0·04
49	1·5	0·06	+0·003	+0·10	+0·002	+0·06	+0·001	+0·04	+0·001	+0·02	0·000	+0·01
40	1·25	0·05	0·000	0·00	0·000	0·00	0·000	0·00	0·000	0·00	0·000	0·00
32	1·0	0·04	−0·003	−0·10	−0·002	−0·06	−0·001	−0·04	−0·001	−0·02	−0·000	−0·01
16	0·5	0·02	−0·009	−0·31	−0·005	−0·19	−0·004	−0·14	−0·002	−0·07	−0·001	−0·04
0	0·0	0·00	−0·015	−0·53	−0·010	−0·34	−0·007	−0·24	−0·003	−0·12	−0·002	−0·08

because of the constriction in the tube. To obtain the full benefit of tapping in this case it would be necessary to keep it up for several minutes. It is found that the falling and rising indications of a marine barometer may differ by as much as 0·3 mb. for ordinary changes in pressure.

Defective vacuum.—In a good barometer the residual pressure in the vacuum space above the mercury column should not exceed the amount corresponding to the error of reading the instrument under the best conditions. A defective vacuum is usually caused by the presence of air or water vapour. The presence of air in a portable barometer 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. This defect should not be tolerated unless the bubble is very small ; a hard and fast rule cannot be laid down, but as an approximate guide it may be stated that in a barometer tube of 6-mm. bore a bubble of 1-mm. diameter when the tube is laid flat may be tolerated. For wider tubes a slightly larger bubble may be allowed, but even in a tube of 12-mm. diameter a bubble exceeding 2-mm. diameter would be considered excessive.

It is also possible to make an estimate of the air content of the vacuum space by means of the sound or " clang " which occurs when the mercury is run slowly against the end of the tube. The sound should be sharp and metallic ; if it is muffled or cannot be heard at all there is probably air in the tube. This test cannot be applied to marine barometers because of the constriction in the tube.

The deterioration of the vacuum space can be due to several causes ; glass, like many other substances, absorbs gases to a considerable extent, and it is difficult to expel them completely when filling the tube, even with thorough heat treatment. In the course of time some of the remaining gas is liberated into the vacuum space. In addition, there is also the risk that a small amount of air may enter the base of the tube when the barometer is inverted, in spite of the fact that the tailpiece should be sealed with mercury in all positions. This has been shown to happen with the Meteorological Office Kew-pattern station barometer. Most of the air entering the bottom will however be caught in the air trap if one is present and will not enter the vacuum space. This air will cause an error of the opposite sign to that of the defective vacuum, as it acts in the same way as an increase in volume of the mercury ; 100 $mm.^3$ of air entering the trap causes the barometer reading to be increased by about 0·12 mb. The Fortin barometer is not usually provided with an air trap, but when it is prepared for transportation by screwing up the plunger almost all the air is excluded from the cistern, so that the risk of air entering the tube is much reduced.

Water vapour may also be present in the vacuum space. Its presence 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 affects the readings, one hundredth of a milligram would cause an error of about 2·3 mb. at normal pressures with a normal Meteorological Office station barometer. The presence of air or water vapour can be shown by comparing, at a fixed temperature, the actual reading of the barometer with a standard over a range of pressures. The errors will increase as the vacuum space decreases in accordance with Boyle's law, and a correction curve of the form (AB Fig. 17) will be obtained. In a very bad instrument there may even be enough water vapour present to saturate the vacuum space at high pressures. The correction curves at pressures above this would then be as the line CD in Fig. 17 (with no air present in addition to the water). These correction curves would vary with temperature ; in particular the pressure at which the change-over from the hyperbola to a straight line occurs would change rapidly, so that no adequate correction could be applied in this case.

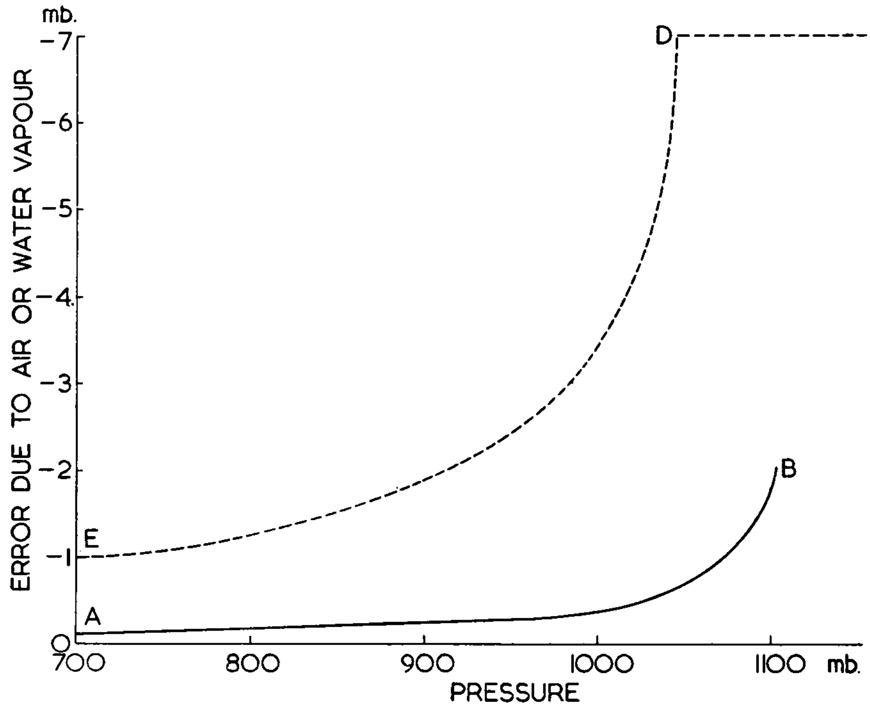


FIG. 17—EFFECT OF AIR AND WATER VAPOUR IN THE TUBE ON THE INDEX ERROR OF A BAROMETER

Temperature measurement.—The general causes of rapid change in temperature of the barometer and the steps that should be taken to eliminate them have already been discussed (p. 21). The magnitude of the error due to the lag of the barometric column in following the temperature indicated by the attached thermometer, when the temperature is changing slowly, has been investigated at the National Physical Laboratory, and it was found that, even if the average Fortin or Kew-pattern barometer were subjected to a steady rise in the external temperature of 2° F./hr., the error due to this cause would not exceed 0·001 in. (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 of barometers.—The errors due to lack of verticality are usually small but by no means always negligible. In the Fortin instrument the fiducial point does not lie on the axis of the instrument, so that the error caused by inclining the barometer tube to the vertical will vary according to the direction in which the inclination takes place ; its magnitude varies between $(H/\cos\theta) + d\tan\theta - H$ and $(H/\cos\theta) - d\tan\theta - H$, where θ is the inclination to the vertical, H is the true height of the mercury column and d is the distance of the fiducial point from the axis of the tube, see Fig. 18. If θ is 5 min. of arc and d is $\frac{1}{2}$ in. the maximum error is about 0·026 mb. for a pressure of 1000 mb. To keep within this limit the lowest part of the barometer must be set correctly to within about 0·06 in. (1·5 mm.) ; the procedure outlined for installing the Fortin barometer (p. 36) should therefore be carefully followed.

The error in the reading of a Kew-pattern barometer for the same inclination to the vertical (5 min. of arc) is only 0·0012 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.

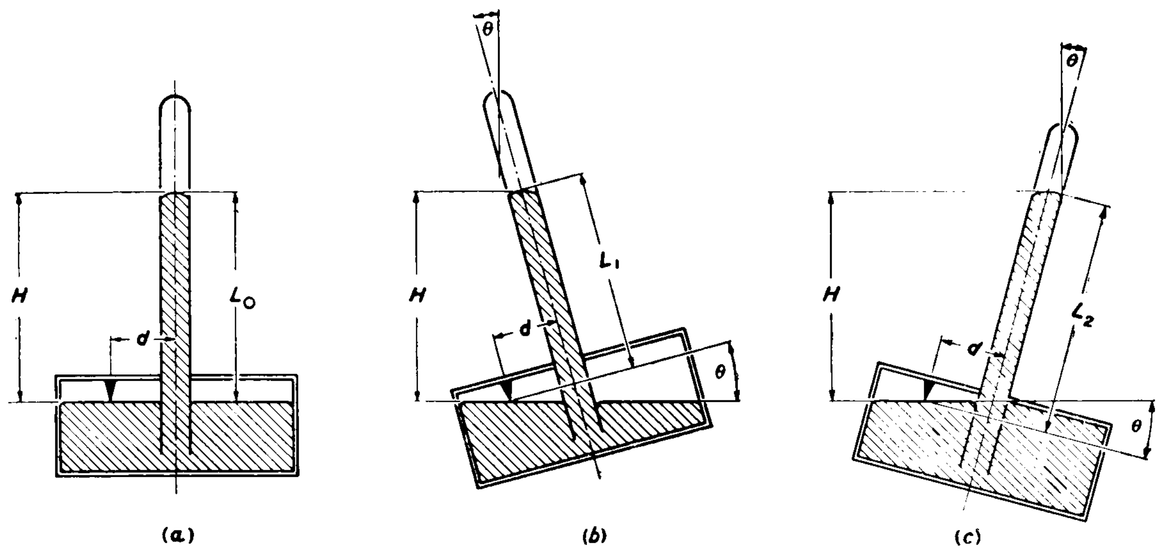


FIG. 18—EFFECT OF TILT ON A FORTIN BAROMETER

Siphon barometers need careful adjustment for verticality, especially if the horizontal distance between the limbs is relatively large.

Incomplete compensation of the Kew-pattern barometer for capacity.—If C is the contraction value of the scale, i.e. C is the ratio of the actual length between two millibar divisions to the length between two millibar divisions on a Fortin instrument, d the internal diameter of the upper portion of the barometer tube, D the internal diameter of the cistern and d_e the external diameter of the tailpiece of the tube (the part which dips into the cistern) then it can be shown that

$$C = \frac{D^2 - d_e^2}{D^2 + d^2 - d_e^2} . \qquad \ldots\ldots (12)$$

In a new instrument the scale can be divided correctly with good precision 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 so that the above relation is satisfied. The effect of variations in the value of d_e is very small indeed—an error of 1 mm. in the Meteorological Office station instrument causes an error of only 0·01 per cent. in C. The effect of changes in d is greater—an error of 0·5 mm. causes an error in C of 0·31 per cent. An error in C of 0·3 per cent. causes an error of 0·3 mb./100 mb. of the scale to develop. This is the maximum rate of change of error that is allowed in the Meteorological Office specification for station and marine barometers. The value of C in the Meteorological Office Kew-pattern barometers is about 0·976.

There is also the possibility that the capacity error is not uniform over the working range of the instrument. This may be due to

(i) lack of uniformity of the bore of tube or cistern

(ii) the mercury level in the cistern taking up a position beyond the uniform cylindrical portion.

Most barometer tubes and cisterns have sufficiently uniform bores to reduce (i) to a negligible amount. The error (ii) may occur in two ways : the mercury may reach the cistern top before the lower working limit is reached or else it may reach a flange or shoulder in the middle of the cistern before the upper working limit is reached. There is no flange in the present Meteorological Office barometers, but they are found in some old instruments. When such a barometer is compared with a standard barometer the effect can be traced by a sharp change in the rate at which the correction changes along the scale. With careful design and manufacture these defects can be avoided, and they are rarely met in modern instruments.

Index error.—The index error is the error due to any imperfections in the construction and adjustment of the barometer. It includes errors from such causes as residual gas in the vacuum space, refraction errors in the glass tube and excess or deficiency in the quantity of mercury in a Kew-pattern barometer. To determine this error it is necessary to compare the readings of the barometer with those of a working standard whose index errors are known accurately. In addition to the errors already discussed there are personal errors in sighting on the top of the mercury meniscus. These are nearly always present in some degree depending on the design and fitting of the setting slide, and are liable to vary with the position of the setting slide on the scale by an amount of the order of 0·002 in. (0·07 mb.) in an average barometer.

The index errors of all Meteorological Office mercury barometers are determined by the National Physical Laboratory. These are given on a certificate which is supplied with the instrument in the form of index corrections ; the certificate is normally fixed inside the barometer box. The corrections are given to the nearest 0·1 mb., with an accuracy of ±0·2 mb., at several points in the range. In addition the " standard temperature " at 1000 mb. (the temperature at which the barometer reads correctly without the application of any corrections, when the pressure is 1000 mb. and the barometer is in latitude 45° at mean sea level) is sometimes determined and engraved on the index plate on the outside of the barometer. The Meteorological Office specifications for new Kew-pattern barometers place certain restrictions on the magnitude of the index error which can be accepted. At 1000 mb. the index error of the station and long-range barometers must not exceed ±0·3 mb., and at other pressures the index error must not exceed ±0·5 mb., with the extra proviso that the error must not change by more than 0·3 mb. in any interval of 100 mb. or less. The conditions for the marine barometer are that the error at any point should not exceed ±0·5 mb., and the difference in error between any two points tested should not exceed 0·5 mb.

Before 1924 a different method was used to specify the index corrections of the Meteorological Office Kew-pattern millibar barometers. Instead of the index correction itself being stated the standard temperature (see previous paragraph), at various pressures was given. A knowledge of the temperature correction of the barometer enables the difference between actual standard temperature at any pressure and the nominal standard temperature (285° A.) to be converted into the corresponding index error in millibars.

General accuracy.—By comparing the readings of several pairs of barometers it was found that the mean probable error of a single observation of pressure with a Kew-pattern station barometer after applying all corrections was about 0·12 mb.

The actual values of the probable error ranged from about 0·08 to 0·32 mb. This is about what would be expected from considerations of the magnitude of the various errors and uncertainties that can arise.

Special errors of marine barometers.—Marine barometers have several special sources of error in addition to those discussed in the previous sections. These arise from the movement of the barometer, because of the motion of the ship, the presence of the constriction in the barometer tube, and vibration.

Errors due to lag.—The equation governing the response of the barometer to pressure changes is

$$\frac{dh}{dt} + \frac{1}{L}(h - h_0) = 0, \qquad \ldots\ldots (13)$$

where h is the height of the mercury above the cistern level, t is the time, L is the lagging time and is a constant for a given barometer, and h_0 is the correct height of the mercury above the cistern. This equation is similar to that governing the response of a thermometer to changes in temperature and may be developed in a similar way (see p. 89). When the pressure is changing at a constant rate the barometer reading lags behind the true reading by an amount equal to αL, where α is the rate of change of pressure, provided the time interval since the change began is large compared with L. L varies between 6 and 9 min. for the Meteorological Office marine barometers so that when the pressure is changing at a rate of 1 mb./hr. the error at any time is about 0·15 mb. (the barometer reading high if the pressure is falling and low if it is rising). If the rate of change of pressure were uniform it would be possible to eliminate this error by reading the barometer at a time L min. later than that for which the pressure is required.

Errors due to swinging of the barometer on its gimbals.—Two types of error arise, owing to

(i) an increase in the mean length of the mercury column because on the average the barometer is inclined to the vertical

(ii) a decrease in the length of the column because of an apparent increase in the value of the acceleration due to gravity because of the " centrifugal force " set up by the swinging of the barometer.

Stokes[10] showed that the two errors could be combined in the correction term

$$\tfrac{1}{4}H\theta^2\left(1 - \frac{4\pi^2 (h_1 - h_2)}{gt^2}\right),$$

where θ is the angle which the barometer makes with the vertical at the extremity of the swing, H is the barometer height, t is the time of oscillation of the barometer, and h_1 and h_2 are respectively the distances below and above the axis of swing of the surfaces of the mercury in the cistern and the tube. For a given value of t it is possible to find a value of $(h_1 - h_2)$ which makes the total error zero ; if however the axis is fixed so that $(h_1 - h_2)$ has this value at one particular pressure it will not be exactly correct at other pressures. In addition forced oscillations can be set up with different periods to the natural period of swing. The error can be minimized, however, if the natural period of swing and the mean barometric height are assumed and the axis adjusted accordingly.

An idea of the magnitude of the error involved can be seen from the following example :—

If $h_1 = 53$ cm., $h_2 = 23$ cm., $t = 1\frac{1}{2}$ sec., $p = 1013$ mb. and $\theta = 5°$ (0·087 radians), then the total error is $+ 0{\cdot}90$ mb. The barometer would be reading too high in this case. The error will only be recorded in full if the swinging has been going on for a time which is large compared with the lagging time, i.e. 15–20 min. or more. It should be noted that this discussion refers to oscillations about the vertical and not an axis fixed relative to the ship.

Errors due to east–west movement of the ship.—Because of the increase or diminution of the centrifugal force produced by the earth's rotation acting on a ship as she proceeds on a course with an east-west component the acceleration due to gravity is changed by an amount equal to $- 2\omega v \cos \phi \sin \theta$, where v is the velocity 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 reckoned from true north. If v is 10 kt., ϕ is 50° and θ is 90° the correction is 0·048 cm./sec.^{2} The corresponding correction to the barometer reading at 1000 mb. is 0·05 mb. The barometer indicates too high a pressure when the ship is moving eastward and too low when it is moving westward. The error can usually be neglected in comparison with the other errors in measuring the pressure on board ship.

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 ; they lead, or may lead, to an incorrect mean pressure (see Giblett[11]). In addition, wind usually has a more marked effect on ships than on land because of the higher wind speeds encountered, the speed of the ship itself, and because of the more exposed position in which the barometer has generally to be set up.

Errors in the mean pressure due to the swinging of the barometer in its gimbals, due to the variable acceleration and due to the wind, may all be either positive or negative. It is therefore impossible to give any precise estimate of the errors ; but it is probably true that in moderate winds errors in the mean pressure of up to 1 mb. are likely, and in severe conditions the errors may be much greater than this. In addition, the difficulty of reading a swinging, pumping barometer, subject also to vibration, introduces a further source of error whose magnitude can hardly be estimated.

2.2.9. Transport of mercury barometers

The transport of mercury barometers from one station to another by train or motor transport is a matter to which much care and consideration needs to be given. If possible, the barometer in its box should be carried personally by a responsible person ; this is the best and most reliable method. The box should be held horizontally, or with the cistern end uppermost, and care should be taken to avoid jars and concussions. If this cannot be arranged, one of the Meteorological Office barometer transit crates, known as barcrates, should be used. An alternative is the older apparatus known as the doolie ; this apparatus is however larger and more cumbersome.

A very convenient carrier for personal transit is the barometer carrying case used in the Canadian Meteorological Service[5]. This is made of cardboard cylinders and wood and has strong cords for carrying over the shoulder.

Barcrate.—The barcrate (Stores Ref., Met. 2838) consists of a galvanized-metal framework from which two pans are suspended by means of stout springs (Fig. 19). The base of the barometer box is placed in the lower pan and the upper pan is fitted over the top of the box. In this way the barometer box can move relative to the frame, but the springs retard the motion sufficiently to prevent the box striking against the floor on which the framework is placed or against the sides of the framework itself. The barcrate should always be placed in an upright position with the wider end acting as the base. In most crates a shield attachment has been fitted to the top of the framework, which makes it impossible for them to be balanced if stood the wrong way up. The crate can be folded flat when empty or not in use.

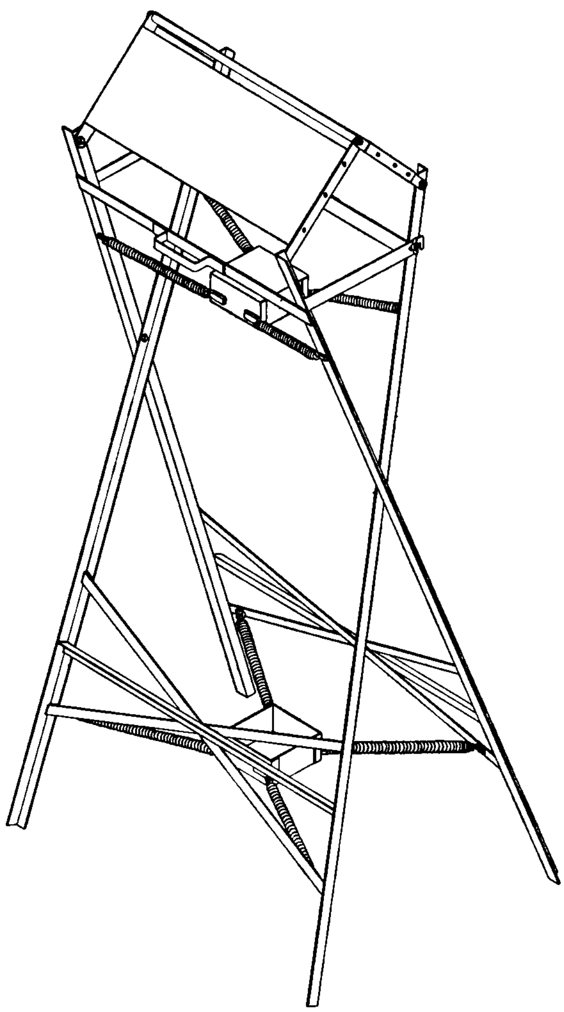


FIG. 19—BARCRATE

Method of use.—The frame should be unfastened by undoing the locking screws and nuts, which are fastened to the frame by means of chains, and then opened. The folding cross-pieces, which are attached to the angle iron with knurled nuts, can then be unfastened and the free ends attached to the frame by means of the wing nuts provided. To fit the barometer box into the barcrate, the box should be carefully turned into a vertical position with the cistern end uppermost and then raised through two of the upper springs so that its bottom end can be placed in the bottom pan. Then, grasping the upper pan in one hand and the barometer box in the other, two of the bottom springs should be depressed with the foot and the upper pan lifted as much as possible so that the top end of the box can be placed under the top pan. The top pan can now be allowed to spring back gently to hold the barometer box in position.

A reverse procedure should be used for removing the barometer from the barcrate. The upper pan should be held with one hand and the barometer box with the other, and two of the bottom springs should be depressed with the foot. The upper pan can then be lifted from the top of the box and the box lifted out, between two of the upper springs. If difficulty is found in depressing the springs with the foot the top pan may be lifted by putting a lever through the ring on top of the top pan.

To close the barcrate the two wing nuts holding the free ends of the two folding cross-pieces at each side of the frame should be loosened and the cross-pieces secured to the angle iron with the locking screws and nuts. When a barcrate containing a barometer has to be sent by rail it should be consigned by passenger train and not by goods train. Its transport should be supervised as far as possible, and the importance of keeping it the correct way up should be stressed to all concerned.

Doolie.—In the doolie (Stores Ref., Met. 181) the barometer box is carried inside a canvas pocket which is suspended by webbing inside a stout wooden framework (Plate V). This framework has a large rectangular base and a narrow top with a lid ; its sides are covered with canvas and it is provided with a set of carrying handles.

Some doolies have several pockets, arranged side by side with a wooden partition between. The doolie should always be kept upright and carried only by the handles. The barometer box should be surrounded by packing material after it has been inserted in the canvas pocket. The disadvantages of the doolie compared with a barcrate lie in its size and weight, and the fact that it deteriorates with use more quickly and is more easily damaged.

2.3. ANEROID BAROMETERS

The basic principles of the aneroid barometer were described on p. 18. In Fig. 20, the walls of the element are attached to the spring by means of two metal posts, A and A′, which pass through holes in the spring B and are locked in position by two small bars. As the atmospheric pressure varies the force on the spring changes and consequently its deflection alters. A lever attached to the top leaf

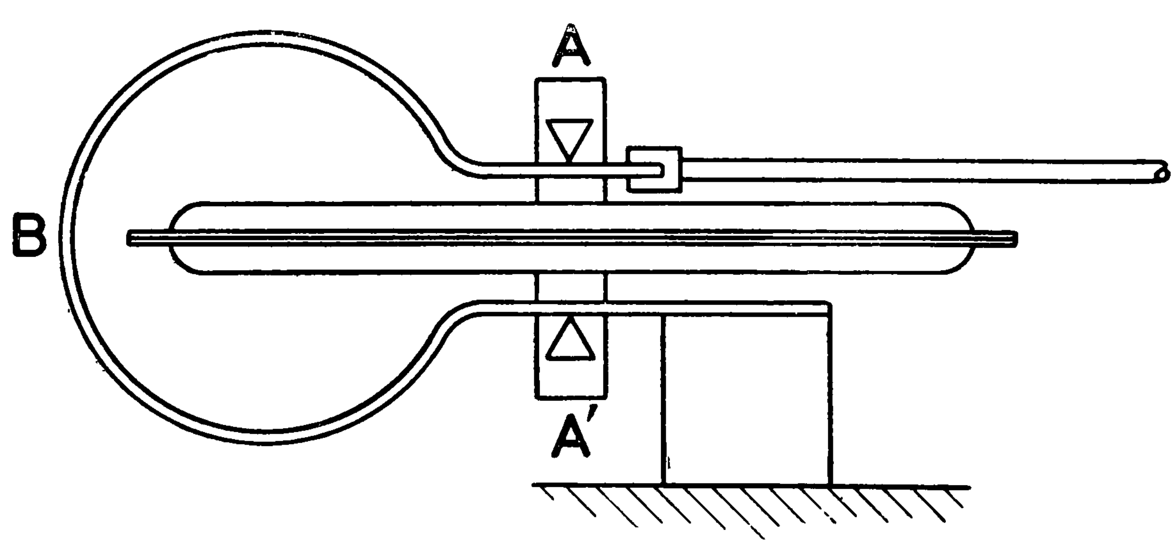
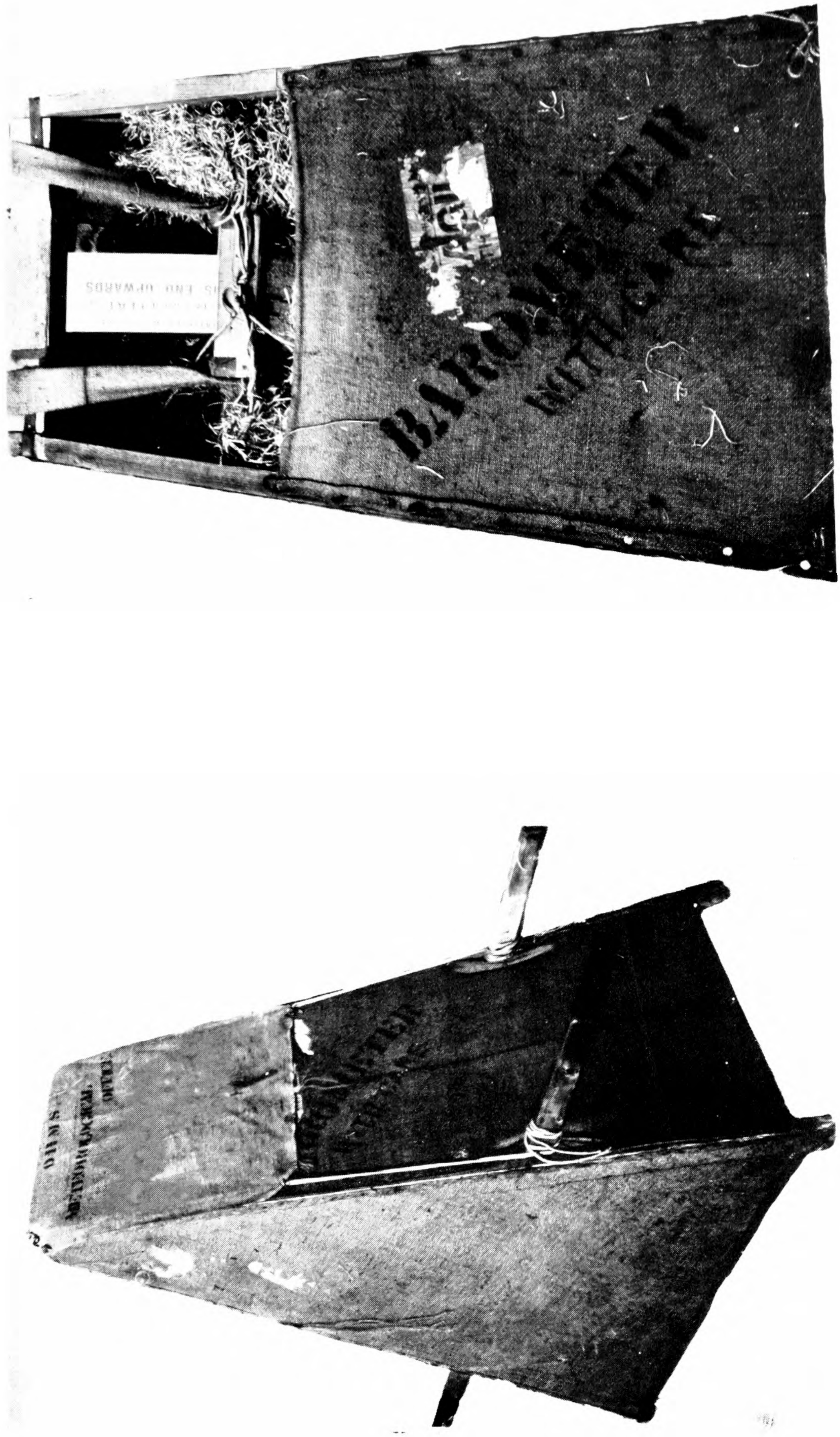


FIG. 20—PRINCIPLE OF AN ANEROID BAROMETER



DOOLIE

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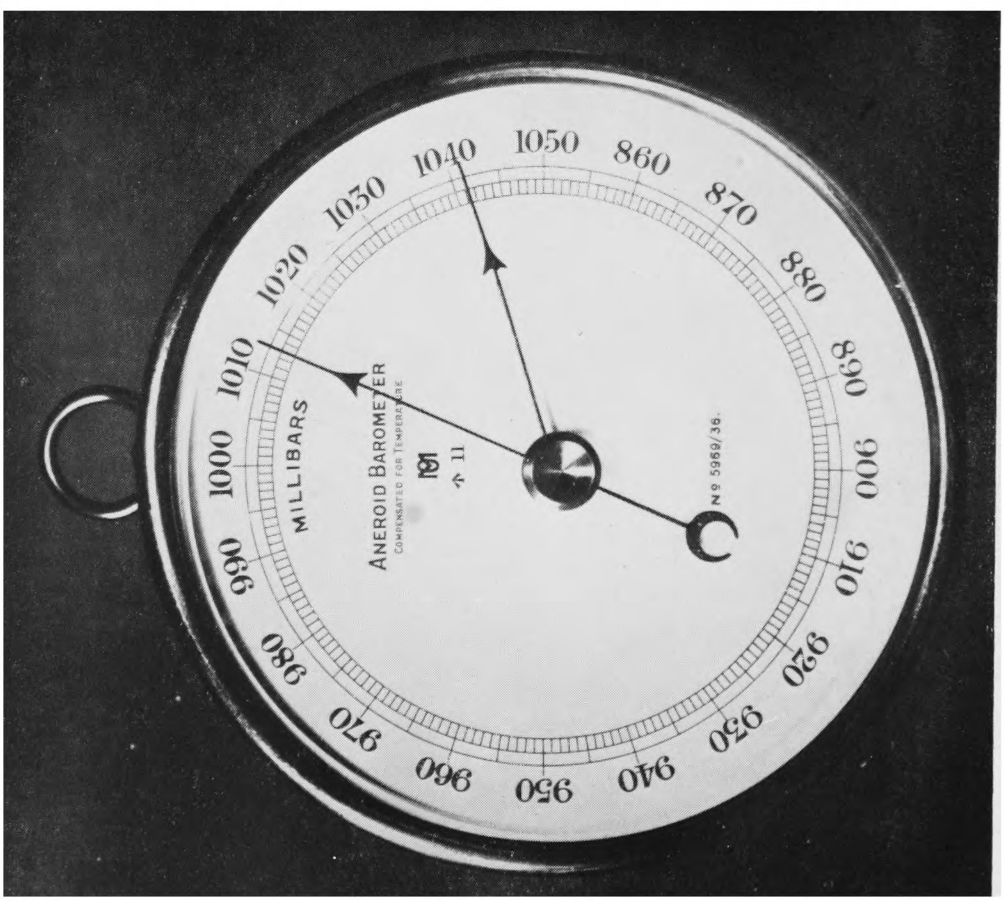
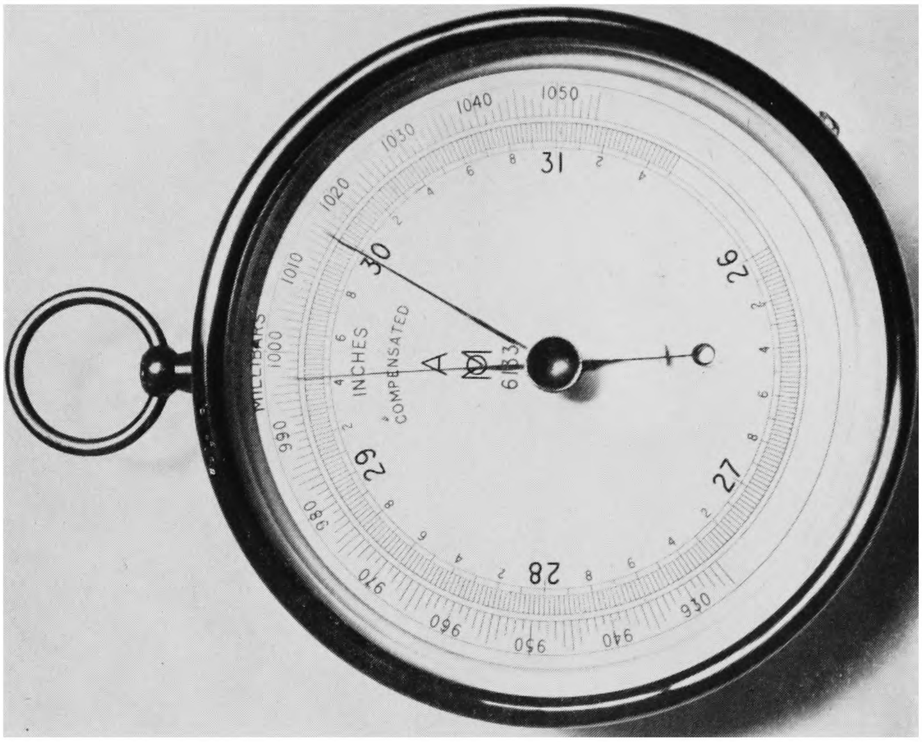


Mk II



Mk I

METEOROLOGICAL OFFICE ANEROID BAROMETERS of the spring moves up or down and forms the first link in the magnifying system. In many aneroid systems practically all the restoring force is concentrated in the spring leaving very little for the element itself.

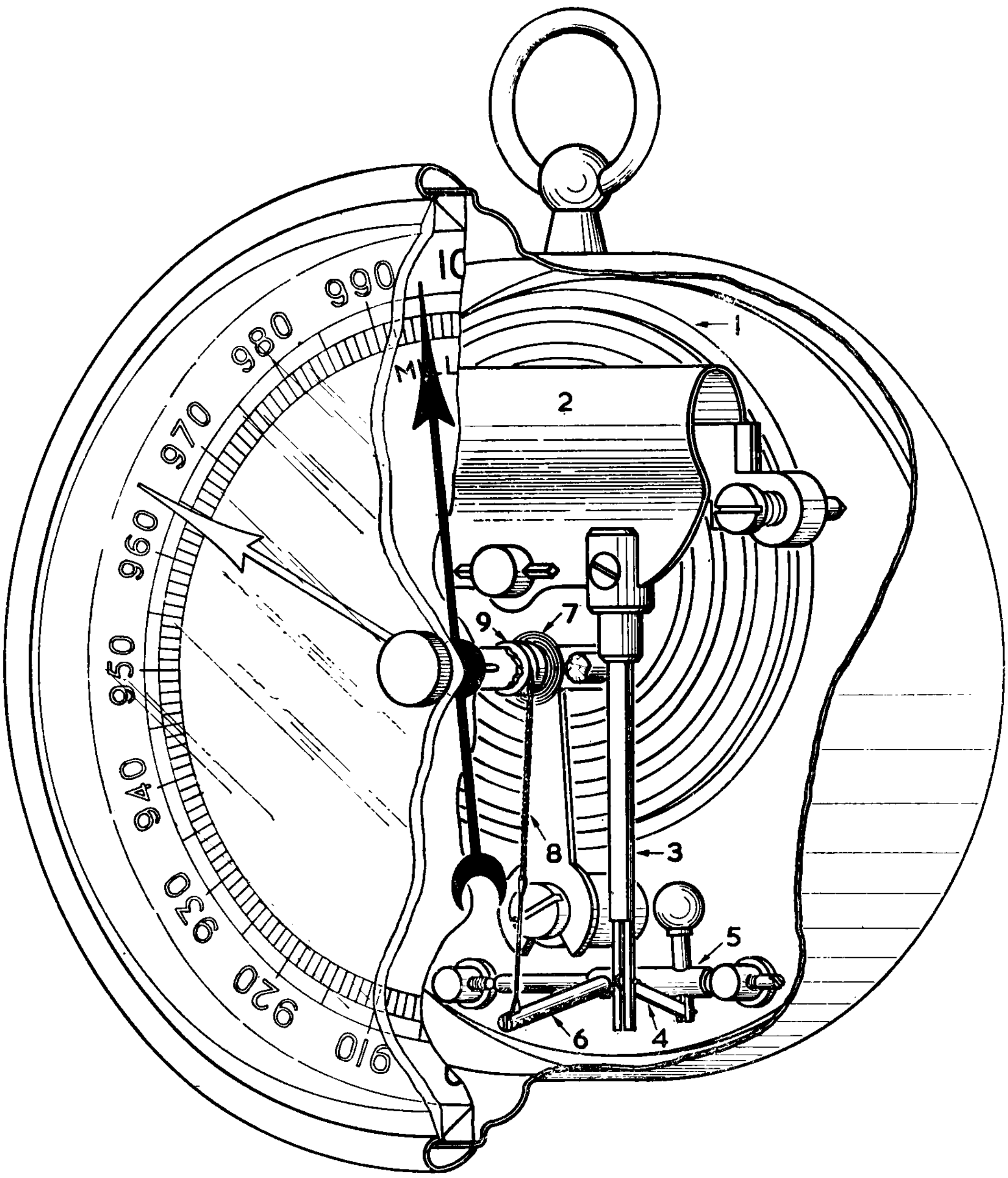
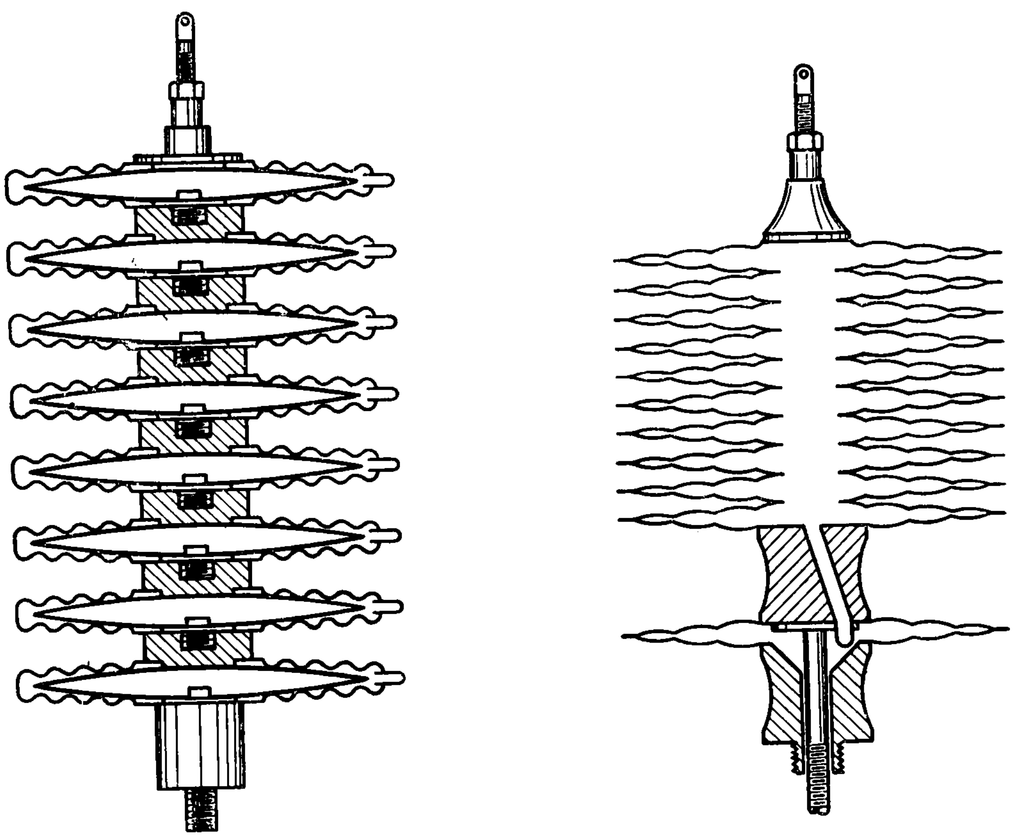


FIG. 21—TYPICAL MECHANISM OF AN ANEROID BAROMETER

The mechanism of an aneroid barometer often takes the form shown in Fig. 21. When the pressure of the atmosphere on the vacuum chamber (1) decreases, the spring (2) relaxes and the vacuum chamber expands and moves the arm (3) upward. This arm, through the connecting link (4) rotates the rocking bar (5). A projecting arm (6) on the rocking bar moving towards the centre allows the hairspring (7) to contract and wind the arbor chain (8) upon the pulley (9), and thus to move the pointer. The 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 effect of this is discussed later (p. 62).

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 cells 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. An old arrangement of a set of cells with internal springs is shown in Fig 22 (*a*). The main disadvantage is that a serious amount of friction may result where the springs touch each other. Flexible metal bellows are often used nowadays, together with an internal helical spring ; there is also 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 aneroid chamber is made of tempered steel with welded edges, so that the chamber itself acts as its own spring, Fig. 22 (b).



(a) (b)

FIG. 22—ANEROID CELLS FOR BAROGRAPHS

2.3.1. Meteorological Office aneroid barometer Mk II

The Meteorological Office aneroid barometer Mk II (Stores Ref., Met. 67) is designed to be used as a portable station barometer where the use of a mercury barometer is impracticable, but it is hardly accurate enough for synoptic work. It is used in preference to the Mk I aneroid barometer except when the pressure is required in inches of mercury. The mechanism follows the general design described on p. 59, being compensated for temperature with a bimetallic link and housed in a cylindrical brass case with a bevelled glass front, Plate VI. The zero adjusting screw can be operated through a hole in the base of the case. The pointer moves over a scale which is graduated in whole millibars from 855 to 1055 mb., and a movable index is fitted to the glass face ; this can be set independently of the aneroid pointer and is useful in showing changes in pressure.

Installation.—The barometer can be hung from the eyebolt fitted to the case so that its face is vertical or it can be laid in any convenient position with its face horizontal. Whichever position is chosen it should, however, be adhered to, and the barometer always read in that position. A special support of simple design has also been made for use, especially on ships, where the barometer must be suspended clear of the bulkhead.

Method of use.—The barometer should be checked as often as possible against a mercury barometer ; any necessary adjustments can be made by turning the zero-adjusting screw in the back of the case. This should be done at least once a month and preferably once a fortnight, if reliable results are required. When reading the instrument the barometer face should first be tapped gently once or twice and then the position of the eye adjusted so that the line joining it and the end of the pointer is perpendicular to the face of the instrument. Readings are only made to the nearest whole millibar, unless the change in pressure over a short period is required.

Maintenance and repair.—Provided the instrument is treated gently at all times and is suitably protected from excessive vibration or shock there is little that can go wrong. If the mechanism does break down, however, the instrument should be overhauled by a competent instrument maker. The brass case and the front glass should be kept clean.

Accuracy and sources of error.—The general sources of error of aneroid barometers are discussed later (p. 62). The Mk II barometer has to pass the following tests before being accepted. It is first tested at room temperature and then at room temperature plus 18° F. ; the difference in the readings should not exceed 1·7 mb. The reading is then taken with the face vertical and with the face horizontal ; the difference should not exceed 1·7 mb. It is then tested at 1000, 950, and 900 mb. and rejected if the errors at these points differ by more than 2·3 mb. The final test is to compare the readings at atmospheric pressure before and after the low-pressure test ; these should not differ by more than 1·7 mb., after allowing for any real change in atmospheric pressure in the interval. No test is made of the stability over a period of time.

From these limits it can be seen that a reading of the barometer, even after it has been correctly set at one pressure, may be up to 2–3 mb. in error if conditions are changing rapidly. Most instruments however keep well within the specified limits. It has been found that if errors due to creep and secular change (see p. 64) are to be kept within 1 mb. the instrument has to be checked against a mercury barometer at least once every fortnight. If this is done the readings can normally be relied on to be within $1\frac{1}{2}$–2 mb. of the correct value.

A series of tests was made with 20 Mk II barometers. They were adjusted to read correctly at a pressure of 1000 mb., and then they were read at 950, 900, 860, and then again at 1000 mb. The statistical probable error* of the reading at each of

* The statistical probable error, r, used here is such that the error of a single observation is just as likely to be within the limits $\pm r$ as it is to be outside these limits.

these pressures is given in Table III together with the temperature-compensation error. Similar results for 20 Mk I aneroid barometers (see next section) are also included.

TABLE III—STATISTICAL PROBABLE ERRORS IN THE READINGS OF THE MK II AND MK I ANEROID BAROMETERS AS DEDUCED FROM SCALE TESTS OVER A SHORT PERIOD OF TIME

	Tolerance in specification	Probable error in aneroid barometer Mk II	Mk I
	millibars		
Scale error at 1000 mb.	adjusted to be correct	adjusted to be correct	
Scale error at 950 mb.	2·3	0·4	0·5
Scale error at 900 mb.	2·3	1·0	0·9
Scale error at 860 mb.	2·3	1·1	1·2
Difference on return to 1000 mb.	1·7	0·4	0·4
Temperature compensation error	1·7	0·4	0·2

2.3.2. Meteorological Office aneroid barometer Mk I

The aneroid barometer Mk I (Stores Ref., Met. 66) differs from the Mk II only in that it has a better quality brass case and dial, and that the dial is graduated in inches as well as millibars, Plate VI. The scale ranges from 26·0 to 31·6 in. (every 1/50th of an inch being marked) and from 880 to 1070 mb. The installation, method of use and maintenance should follow that described for the Mk II. Its performance is similar to the Mk II (see Table III) and it has to undergo similar tests.

2.3.3. Precision aneroid barometers

Because they are less bulky, more convenient to transport and easier to read than a mercury barometer, attempts are being made to produce a precision type of aneroid barometer with a performance about equal to the Kew-pattern station barometer. It could then be used on board ship and at mobile field stations.

2.3.4. Sources of error of aneroid barometers

Errors due to changes in temperature.—The properties of aneroid systems depend on the elastic properties of the chamber itself and the supporting spring (if any). The deflection of the pointer 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 chamber, and both these vary with temperature. In most metals and alloys the temperature coefficient 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 chamber. The first method is usually employed in barometers and the second mainly in barographs.

The bimetallic link serves to alter the indication of the instrument by an amount which is proportional to the change in temperature (i.e. KT_1 where K is a constant and T_1 is the change in temperature). The spring (or the spring plus chamber, or the chamber alone) exerts a force which is approximately equal to Ap, where A is the effective area of the chamber and p is the atmospheric pressure, and the corresponding deflection is $K'Ap/E$, where E is the Young's modulus of the material of the spring ($K''Ap/N$ if a helical spring is involved, where N is the modulus of rigidity). For a change in temperature of T_1, E becomes $E(1 + aT_1)$, N becomes $N(1 + bT_1)$, and the corresponding changes in deflection would be approximately $-K'ApaT_1/E$ and $-K''ApbT_1/N$. For complete temperature compensation the total deflection produced by a change in temperature must be zero;

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

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

E/K' and N/K'' are usually known as the spring rate (the force required to produce unit deflection) 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 chamber be p_0. The spring thus exerts a force equal to $A(p - p_0)$ and the gas inside a force Ap_0. The deflection is given by $K''A(p - p_0)/N$. When the temperature of the system rises by T_1, p_0 becomes $p_0(1 + a_0T_1)$, where a_0 is approximately 1/273, and the corresponding deflection is

$$\frac{K''A\,[p - p_0(1 + a_0T_1)]}{N(1 + bT_1)}.$$

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

$$\Delta D = -K''AT_1\frac{p_0a_0 + (p - p_0)b}{N} \qquad \ldots\ldots (14)$$

and this corresponds to a change in pressure indication (Δp) given by

$$\Delta p = T_1\,[p_0a_0 + (p - p_0)b]. \qquad \ldots\ldots (15)$$

If p_0 is known this may be used to give some indication of Δp. For complete compensation

$$\left.\begin{aligned} \frac{p - p_0}{p_0} &= -\frac{a_0}{b} \\ \frac{p}{p_0} &= 1 - \frac{a_0}{b} \end{aligned}\right\} \qquad \ldots\ldots (16)$$

This again can be true for one value of p only. If for example b (for steel) is $-0{\cdot}0\dot{0}026$

$$\frac{p}{p_0} = 1 + 14{\cdot}1$$
$$= 15{\cdot}1.$$

Complete compensation at 1000 mb. would then be obtained by leaving gas to a pressure of 66 mb. inside the chamber. This analysis is only approximate because it neglects several factors, but it does give the order of magnitude of the effects. In any practical case the aneroid would have to be compensated by trial as the value of b depends a great deal on the treatment of the material.

The volume of the chamber varies appreciably in some instruments as the pressure varies, and if it were possible to arrange the spring so that the volume varied inversely as the outside pressure, p_0 would be proportional to p and the compensation could be made perfect over the entire range of pressure. This is not possible in practice, but it may be approached by making the compensation correct at two ends of the range ; the temperature error would not then be large at any point.

Hysteresis errors and secular change.—If an aneroid is subjected to a cyclic variation in pressure (say 1000 mb. down to 300 mb. and back to 1000 mb.) it is found that the aneroid deflection for a given pressure is different when the pressure is rising to what it was when the pressure was falling. If the pressure change is plotted against the aneroid deflection a loop similar in appearance to a magnetic hysteresis loop is obtained (see Fig. 23 which is exaggerated for illustration, errors as large as shown here do not occur). If the cycle is repeated at short intervals it is found that the width of the loop decreases at first, but eventually after four or five cycles a steady state is reached, and the width of the loop remains constant. This phenomenon is known under the general heading of hysteresis.

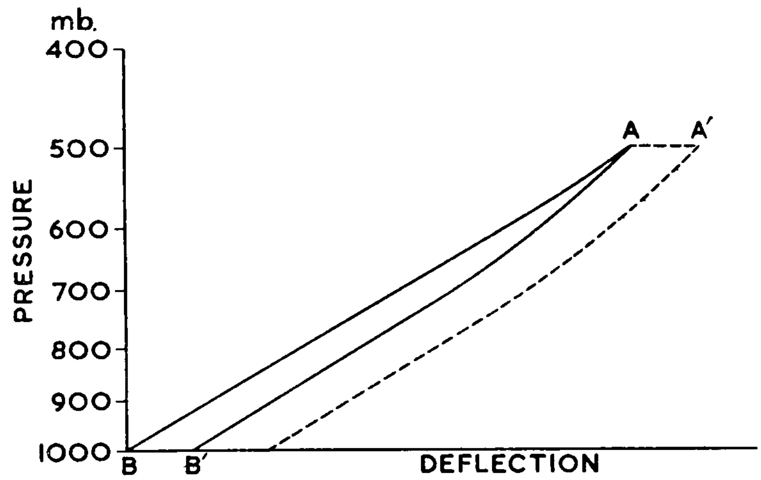


FIG. 23—EFFECT OF HYSTERESIS

If in the cycle of pressure changes referred to above the pressure were held constant at the point denoted by A in Fig. 23 it would be found that the aneroid deflection would slowly increase in the direction of A′, and if at the end of a cycle the deflection were B′ and the pressure was again held constant the aneroid deflection would change slowly in the direction of B. This process is known as creep. It becomes less important after several cycles.

Secular change of an aneroid is the gradual change in the error which goes on constantly, irrespective of the current changes due to its immediate pressure and temperature history. Probably it is mostly due to small changes of structure. It can be minimized by careful treatment of the materials used.

The elastic errors of aneroids, in general, increase

(i) when the temperature increases

(ii) when the range of pressure variation increases

(iii) when the rate of pressure change increases.

They are less important in station aneroid barometers than in aircraft instruments.

2.4. MERCURY BAROGRAPHS

2.4.1. Dines float barograph

The Dines float barograph (Stores Ref., Met. 769) is a sensitive barograph based on the principle of recording the changes in the mercury level of one arm of the siphon mercury barometer, Fig. 24. The barometer tube has an upper and lower reservoir of the same diameter, the upper reservoir being sealed by the mercury in the U-tube attached to it (shown on the extreme left of Fig. 24). The lower reservoir is open to the atmosphere, and on the surface of the mercury rests, mouth downward, a small glass float which is kept co-axial with the reservoir by means of a ring of steel balls floating on the mercury surface between the float and the reservoir walls. A certain fixed amount of air is left beneath the float, and the variations in volume of this air with variations in the temperature of the instrument provide a practically complete compensation for the effect of the temperature variations on the remainder of the instrument.

The float is surmounted by a glass stem which fits inside a steel tube surmounted by a counterweight, which is, in turn, suspended by platinum wire and a steel rod from one of a pair of co-axial pulleys. The recording pen, fixed to a glass rod, is suspended by a pair of platinum wires from the other pulley and rests lightly against a chart on a revolving drum. By means of the bifilar suspension the pressure of the pen on the chart can be made small but definite. The pulley carrying the recording pen is about 4 times the diameter of the other pulley so that the scale value of the record on the chart is just over twice that of the scale on a Fortin barometer (the effect of the air beneath the float is to increase the scale value slightly as well as to compensate for temperature changes). Two fixed pens record datum lines on the chart so that changes in chart size with temperature and humidity can be allowed for. Further details can be found in a paper by L. H. G. Dines[12].

Installation and adjustment.—It is impossible to transport the instrument with mercury in it so it has to be filled on the spot. This is however easier to perform than filling an ordinary mercury barometer. Further details of this and other necessary adjustments can be found in the article cited above.

Accuracy.—The compensation for temperature is strictly correct only at one atmospheric pressure, but it has been shown that for the temperature and pressure changes normally encountered the errors introduced are practically negligible. The diameter of the upper and lower reservoirs is usually about 43 mm. so that the capillary depression and errors due to the variation in capillary depression are also negligible.

The records produced are very clear and detailed and are of an accuracy comparable to that obtained by means of the ordinary station mercury barometer.

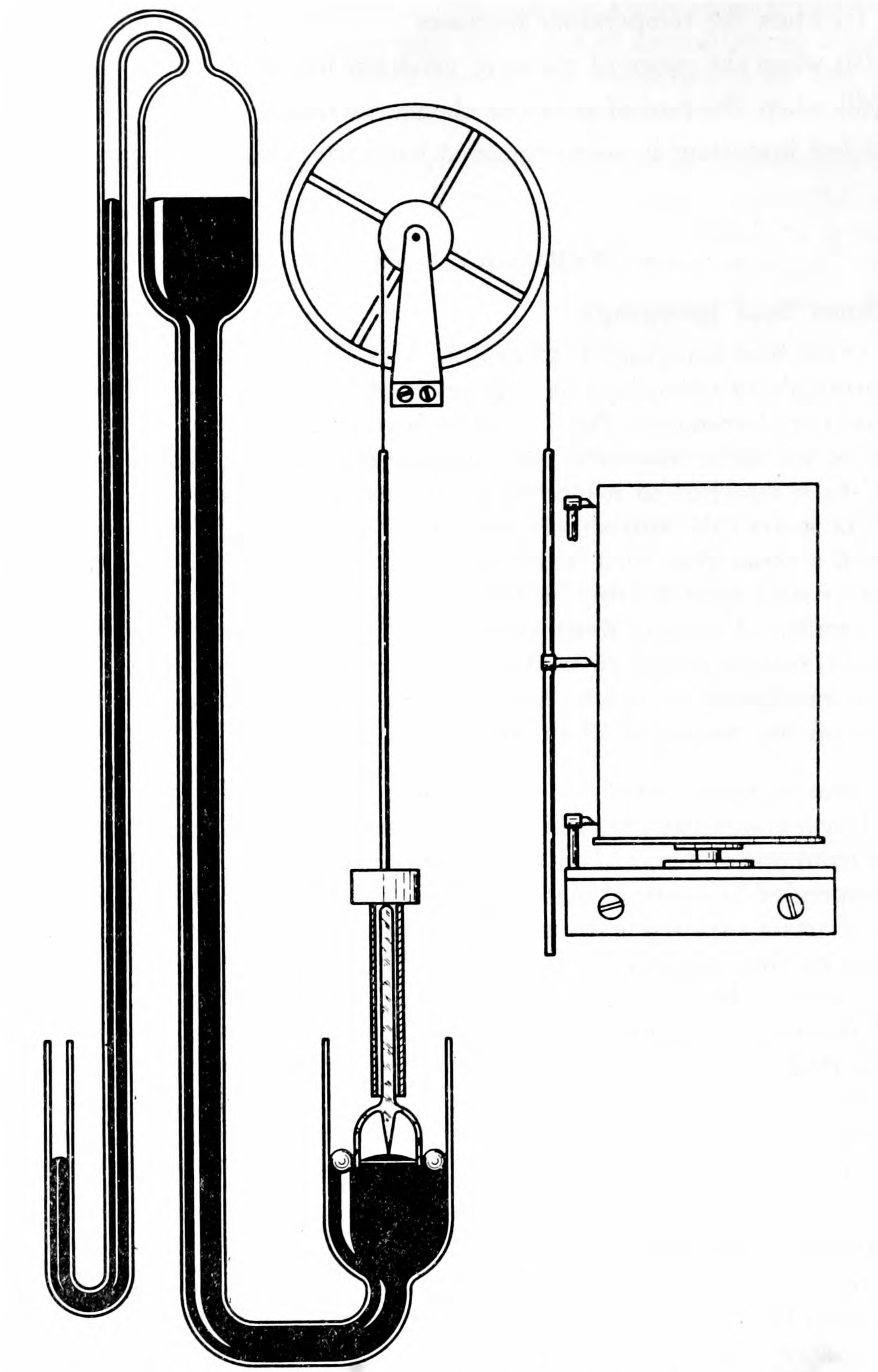


FIG. 24—DINES FLOAT BAROGRAPH

2.4.2. Photographic barograph

The photographic barograph records photographically the height of the mercury column in a large Kew-pattern barometer. A narrow slit behind the top of the barometer tube is illuminated by a light source and a condenser lens, and an image of the slit is thrown on to a piece of sensitized paper wrapped around a revolving drum. The image of the slit is bounded on its upper edge by the image of the mercury in the tube and at its lower by a metal stop which is connected by means of a lever system to two metal rods placed on either side of the barometer tube. These metal rods effect the temperature compensation ; when the temperature of the barometer (and thus that of the metal rods) increases, the stop moves downwards, while at the same time the image of the top of the mercury in the barometer also moves downwards (corresponding to an expansion of the mercury) provided that the pressure does not change. By a suitable adjustment of the lever system connecting the stop to the metal rods it is possible to make these two movements equal, as they are both very nearly proportional to the temperature change. The pressure can thus be deduced from the length of the black image of the developed paper.

The temperature compensation can only be made strictly correct at one pressure, but the errors will not be large at other atmospheric pressures. The records are compared with readings taken from a standard barometer at certain fixed hours, so that the scale value of the instrument and the pressure corresponding to any given width of trace can be determined. This automatically corrects the reading to a standard value of gravity and eliminates index error.

Accuracy.—The record can be measured with a scale and vernier to the nearest 0·001 in., and the pressures obtained from the standard barometer to about the same order of accuracy (equivalent to 0·03 mb.). The uncertainty in the measurements will depend on the accuracy of the instrument as a mercury barometer ; it will be liable to the same sources of error (see p. 47), but by careful filling and the use of a suitably large-bore barometer tube and cistern it has been possible to keep these small. It is probable that the greater part of the uncertainty in the final tabulated measurements lies in the hygrometric properties of the sensitive paper used and in the errors in the temperature compensation, but normally the total error should not exceed about 0·1 mb.

2.5. ANEROID BAROGRAPHS

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 aneroid unit, and usually means a decrease in the overall magnification and an increase in the number and size of the chambers used.

The control of the instrument (see p. 4) is equal to 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 which is required to prevent the aneroid unit itself from moving when the pressure changes by 1 mb. is $1000A$ dynes, where A is the effective cross-sectional area of the aneroid chamber in square centimetres. Therefore the control is approximately $1000A/M$ where M is the magnification, and is thus proportional to A for a given value of M. For a given type of aneroid chamber the value of M which is required for a given scale value will be roughly independent of A, so that it is advantageous to have as large a value of A as possible. Clearer and more detailed records will be obtained if A is increased.

2.5.1. Meteorological Office open-scale barograph

The aneroid unit of the open-scale barograph (Stores Ref., Met. 521) is of the bellows type with an internal spring, Plate VII. 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 (Fig. 25). An analysis of the magnification of the lever system is given at the end of this section.

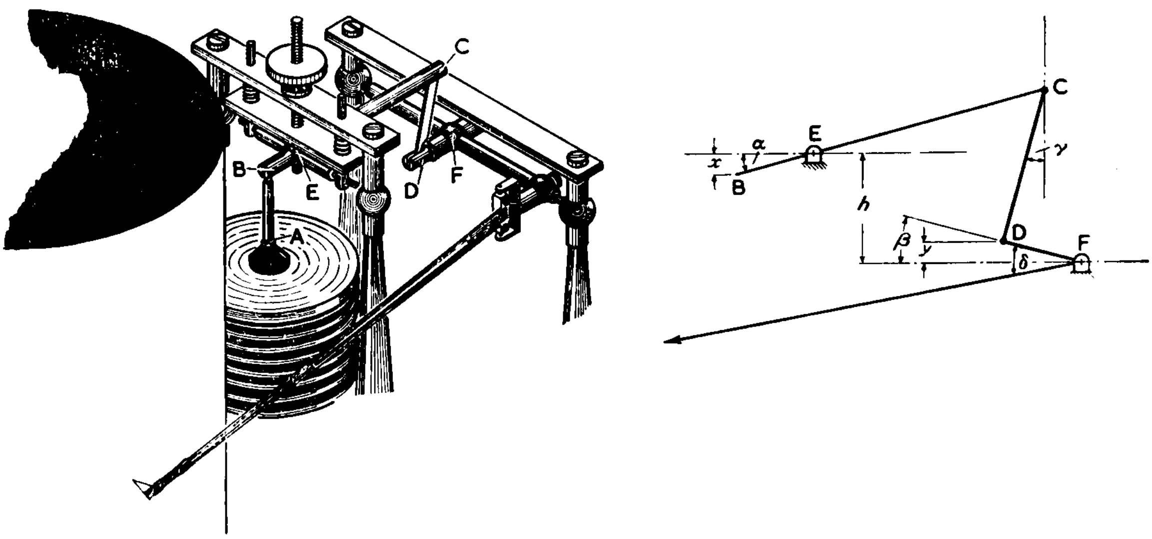


FIG. 25—LEVER SYSTEM OF OPEN-SCALE BAROGRAPH

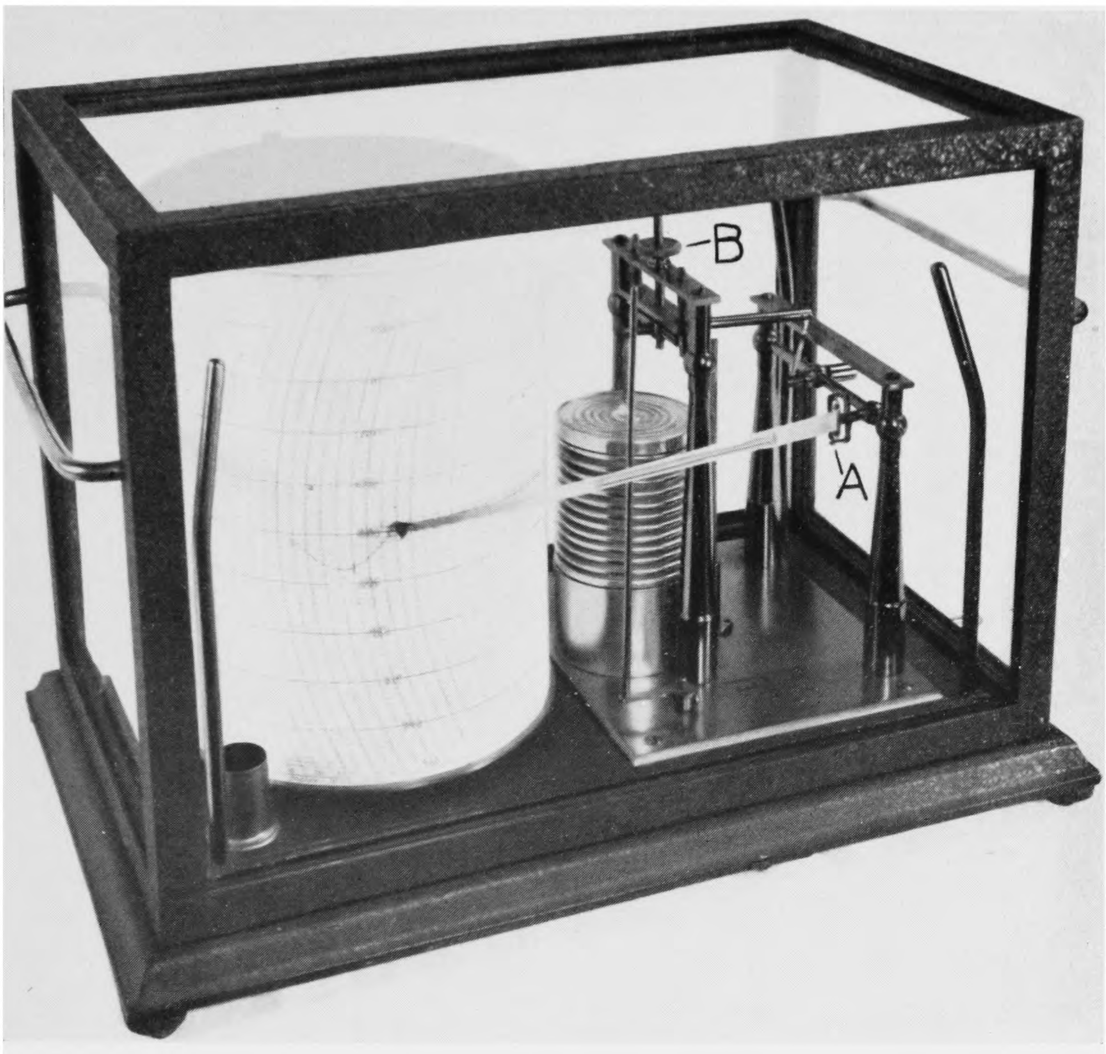
An " O " type drum is used together with a weekly clock and the range of pressure covered is from 950 to 1050 mb. The scale value on the chart is 1·8 mm./mb. The clock and the brass mounting plate for the aneroid unit and lever mechanism are mounted on a stout metal base and a glass cover with a metal framework is provided to keep out the dust and protect the mechanism. A time-marking device is fitted to the base ; this consists of a vertical rod, supported in a collar on the mounting plate, which can be moved up against the lever EC (Fig. 25) when a horizontal rod fitted to the main base is pushed in. An end face, inclined at 45° to the vertical, is fitted to the end of the horizontal rod and this comes into contact with the end of the vertical rod. The horizontal rod is returned to its original position by means of a spring when it is released.

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 screw mechanism.

The projection of the pen arm on to the vertical plane defined by BECDF (Fig. 25) should always coincide with DF ; 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 if the vertical distance between E and F, then

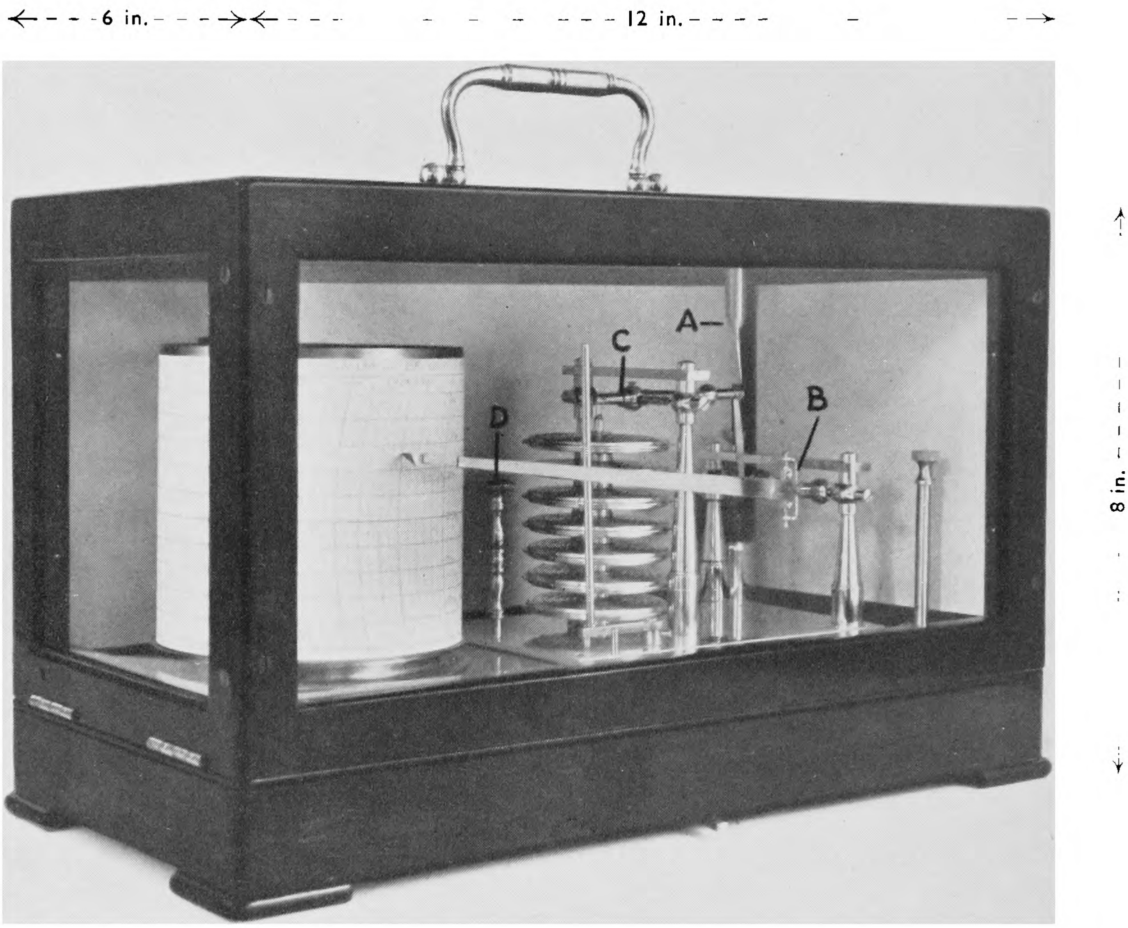
$$\begin{aligned} \mathrm{DF} \sin \beta &= y \\ &= h + x\,(\mathrm{CE}/\mathrm{EB}) - \mathrm{DC} \cos \gamma, \qquad \ldots\ldots(17) \end{aligned}$$

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



METEOROLOGICAL OFFICE OPEN-SCALE BAROGRAPH

A. Gate suspension B. Milled-head adjusting screw



METEOROLOGICAL OFFICE SMALL-PATTERN BAROGRAPH

A. Time marker
B. Gate suspension
C. Principal lever
D. Milled-head adjusting screw

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 lever 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 chart 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 discussed above should always be fulfilled for barographs received direct from the Instrument 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. 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. It should not be exposed to sunshine or placed close to sources of artificial heat. Having fitted a chart to the drum, taking the usual precautions (see p. 12), the setting of the pen on the chart should be adjusted.

The instrument 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. Having once been set it 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 250 ft. above mean sea level the error introduced is usually small and the barograph record may be treated as a record of mean-sea-level pressure. When computing the mean-sea-level pressure in the first instance for the initial setting of the barograph a mean outside air temperature for the month should be assumed, which may not be quite the same as the current outside air temperature. Reference should be made to station records or a standard climatological reference book (e.g. the " Climatological atlas of the British Isles "[13]) for the appropriate temperature to use. The setting of the barograph should therefore be checked at least once a month.

At stations more than 250 ft. above mean sea level the pen should be set to read the station pressure, or the station pressure plus an integral number of tens of millibars. The aim should be to have the mean station pressure at about the centre of the chart.

The gate suspension of the pen arm should be so adjusted that the pressure between the pen and the chart is the minimum consistent with legible records (see p. 5). It may be found, however, that if the gate suspension of the pen arm is adjusted so that the pen just touches the chart when the pen arm is horizontal the pen will come away from the chart when the pressure rises appreciably. This is because the pen arm is not perpendicular to the pen-arm spindle (see Plate VII) ; 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. This will eventually overcome the small force keeping the pen on the chart. When the pen arm is below the horizontal the pen presses harder on the chart. To get the best pressure between the pen and the chart the gate suspension should therefore be adjusted with the pen arm near the upper limit of pressure which will be encountered.

The effect can be overcome by mounting a small counterweight on the pen arm so that the centre of gravity of the combination is brought into the vertical plane through the point of rotation of the pen arm, perpendicular to the pen-arm spindle (as for instance in Fig. 26). The pressure of the pen on the chart will then be uniform throughout the pressure range.

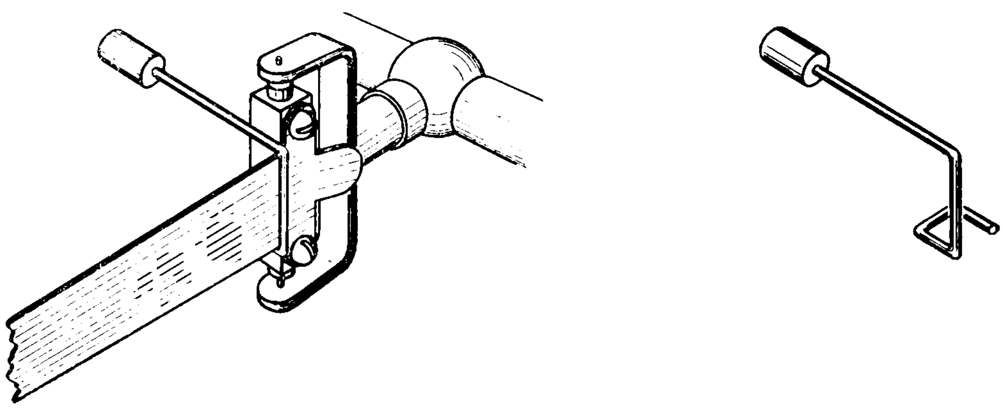


FIG. 26—COUNTERWEIGHT FOR OPEN-SCALE BAROGRAPH

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 aneroid unit, 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 mercury 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 could 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 (Fig. 25). This alters the ratio CE/BE. A modification of the instrument has been designed for occasions when the instrument has to be used at high-level stations, when the range of the adjustment provided by the setting screw is not sufficient to bring the pen on the chart. The column AB is shortened, and is fitted inside a sleeve which is pegged on to the main lever BEC at B ; a screw fixes the column in position. When the pressure is reduced the screw is loosened and the vertical movement of the top of the aneroid is taken up by the movement of the column inside the sleeve. The screw can then be tightened and the instrument is ready to be adjusted in the normal way.

Method of use.—There is little to add to the general instructions for the routine use of recording instruments (p. 4). 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 aneroid unit. The chart is usually changed on Monday mornings, and the barograph should be set to read correctly at the same time. The record should be written up as detailed on p. 12.

Because of friction between the pen and the chart 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. Great care should be taken when replacing the clock drum to prevent the edge of the drum striking the aneroid unit.

Maintenance and repair.—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 good 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 aneroid unit by moving the lever BC violently.

Accuracy.—The instrument has to pass the following tests before being accepted by the Meteorological Office. The change in reading caused by a temperature change of 30° F. must not exceed 1·0 mb. ; the errors at 1000, 975, and 950 mb. must not differ from the error at atmospheric pressure by more than 2·0 mb. ; and the difference between the errors at these points with rising and falling pressures respectively must not exceed 1·0 mb. As the barograph is normally housed indoors the temperature change encountered should not be excessive and errors due to this cause should be small. Temperature compensation is effected by leaving air (or other gas) in the aneroid unit ; 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 setting. Readings were taken both before and after tapping the instrument gently with the following results.

Percentage of observations %	Error did not exceed mb.	Percentage of observations %	Error did not exceed mb.
Before tapping		After tapping	
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 had an error of 0·0 mb., 73 per cent. had an error not exceeding ±0·1 mb. and that 92 per cent. had an error not exceeding $\pm 0\cdot 2$ mb. The tendencies ranged from $+3\cdot 8$ to $-3\cdot 8$ 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 250 ft. above sea level a change in outside air temperature of 50° F. means a change in the mean-sea-level correction of 0·9 mb. ; i.e. if the original adjustment was made at 55° F. the barograph would be about 0·4 mb. in error from this cause when the outside temperature was 30° or 80° F. The error would be less if the temperature change were smaller or if the station were lower, and greater if the station were higher.

2.5.2. Meteorological Office small-pattern barograph

The aneroid unit of the small-pattern barograph (Stores Ref., Met. 520, Met. 2845, or Met. 2846 according to the maker) usually consists of seven or eight separate chambers 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 VIII). The movement of the top of the aneroid unit 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 chart placed on a standard " S " type drum (or one of the equivalent types) driven by a weekly clock. A scale value of 10 mb. to 7·5 mm. is employed and the chart covers a range of 100 mb. (950 to 1050 mb.).

The setting of the pen on the chart can be altered in one of two ways ; either the aneroid unit 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. A time-marking device is fitted. This consists of a spring-loaded lever, mounted in the top of the case, which can be depressed so that it comes into contact with the main lever and thus causes the pen arm to move downward.

The base of the instrument and the case is made of good quality, polished hard wood (usually mahogany). The case itself 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, and a drawer is fitted in the base for carrying a spare pen arm and pens.

Installation and adjustment.—The siting, mounting and adjustment of the small barograph should follow the same lines as for the open-scale barograph (see p. 69).

Method of use.—The small barograph should be used in the same way as the open-scale instrument (see p. 71) but the scale value is not sufficiently great to enable the pressure tendency to be read from the chart with sufficient accuracy for synoptic purposes.

Maintenance and repair.—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 good clock oil may be applied at infrequent intervals.

Accuracy.—The instrument has to pass the following tests before it is accepted by the Meteorological Office. The errors at 1000, 975 and 950 mb. must not differ from that at atmospheric pressure by more than 2 mb., and the change in error at atmospheric pressure 10 min. after leaving 950 mb. must not exceed 2 mb. The change in reading caused by a change in temperature of 30° F. must not exceed 1·5 mb.

It was found that when a barograph of this type was compared with the readings of a mercury barometer over a period of two months without any resetting 60 per cent. of the errors did not exceed 0·75 mb. and 73 per cent. did not exceed 1·05 mb. As there was some evidence of a gradual change in zero throughout the test better results would have been obtained if the barograph had been reset regularly. This is about the best that could be hoped for with the compressed scale employed.

2.5.3. Use of barographs at sea

Barograph records obtained from ships at sea are often unsatisfactory because the trace is widened into a ribbon several millibars wide. For this reason small barographs have been mostly used, and consequently ships have not been able to report barometric tendencies with the accuracy achieved by land stations. The broadening is due to four factors :

(i) Vibration due to ship's engines, etc.
(ii) Angular acceleration of the ship (rolling and pitching)
(iii) Transient pressure changes caused by gusts of wind
(iv) 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. The effects can however be largely overcome by two devices.

Meteorological Office anti-vibration mounting for the open-scale barograph.—This is illustrated in Plate IX, and consists of a metal tray to hold the barograph suspended from fixed brackets by a number of elastic cords. The tray can swivel about an axis parallel to its longer edge ; this prevents the ship's motion from throwing the pen off the chart. A compromise had to be found in deciding the stiffness of the support, the weaker the elastics the greater the freedom from vibration but the greater the displacement of the instrument. The stiffness is therefore determined by the upper limit to the displacement that can be allowed. The period of oscillation of the support when the barograph is in position is about 0·5 sec.

Meteorological Office marine barograph.—The response of the open-scale barograph to transient pressure changes was reduced by increasing its lag coefficient (as in the marine barometer). This, however, also reduces the speed of response of the instrument to true changes of pressure and a compromise must be reached. Bibby[14] has shown that by considering three extreme cases of possible variation the desirable lag coefficient is between about 30 and 120 sec.

A lag coefficient of this order was achieved by immersing the bellows in a brass cylinder filled with oil (Fig. 27) so that the bellows could 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 was found that the lag coefficient of the barograph was 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 lag coefficient was obtained. It was assumed that, in wide-scale use, a temperature range of 30° to 110° F. would be encountered ; the range in viscosity of the oil should therefore be only 4 : 1 (or less) over this range of temperature. A type of silicone fluid was finally adopted ; the lag coefficient of the barograph was then : 100 sec. at 30° F., 70 sec. at 70° F. and 40 sec. at 110° F. The range was thus only 2·5 : 1.

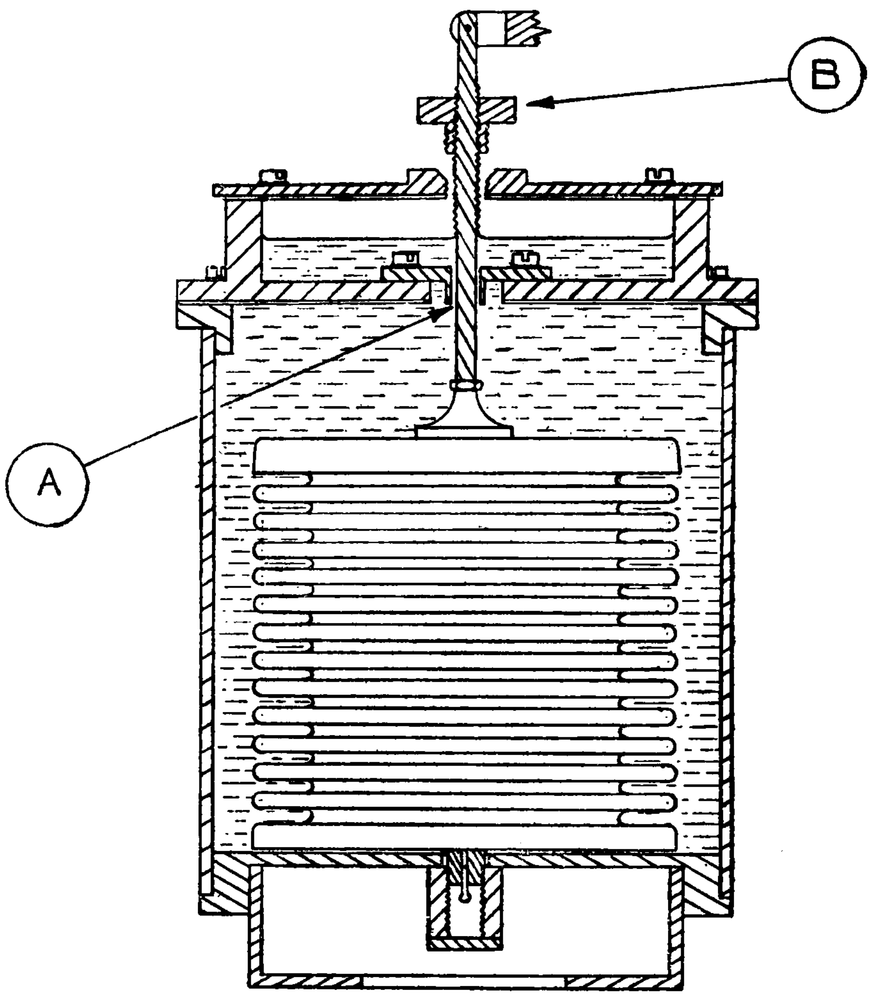
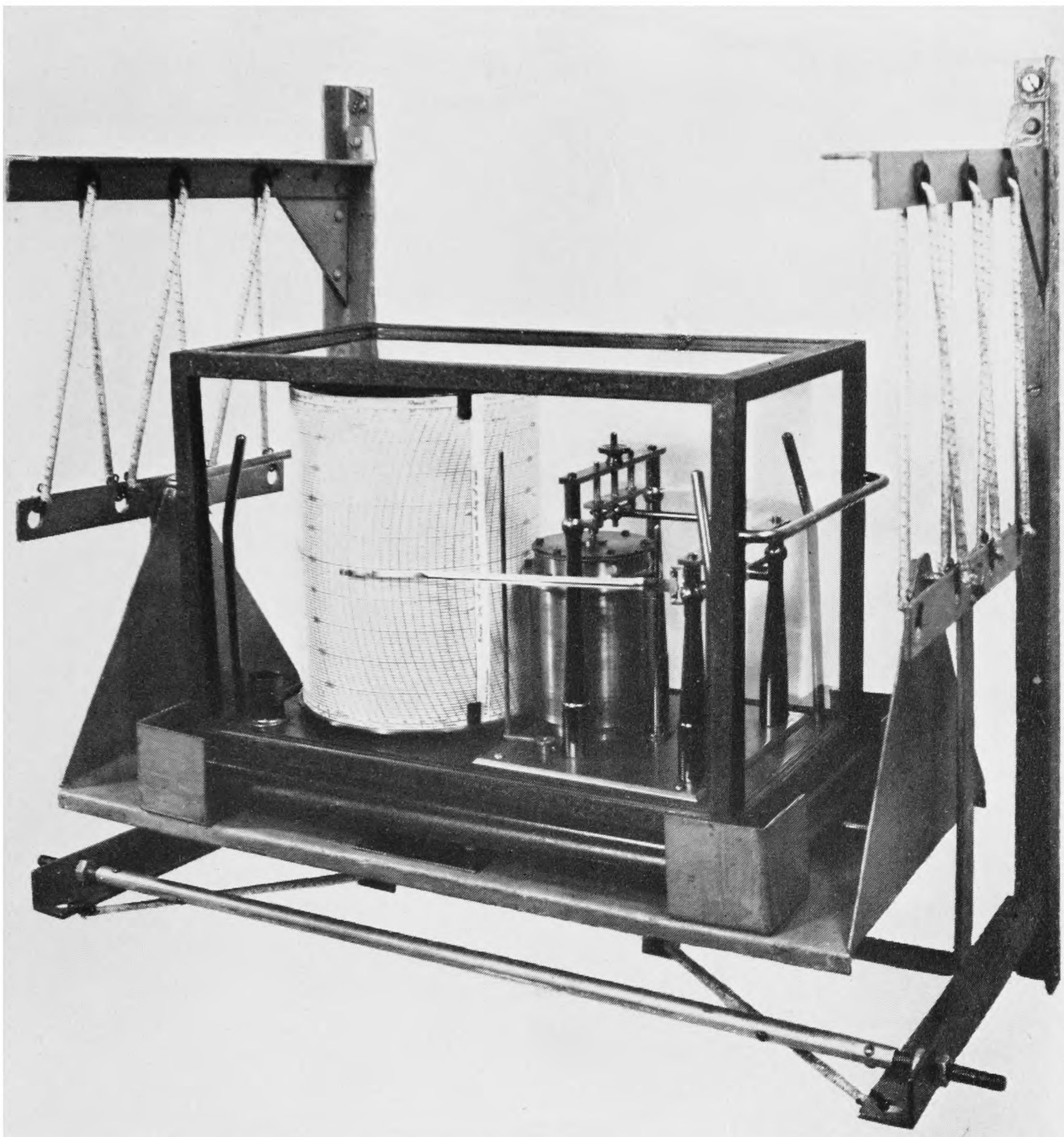


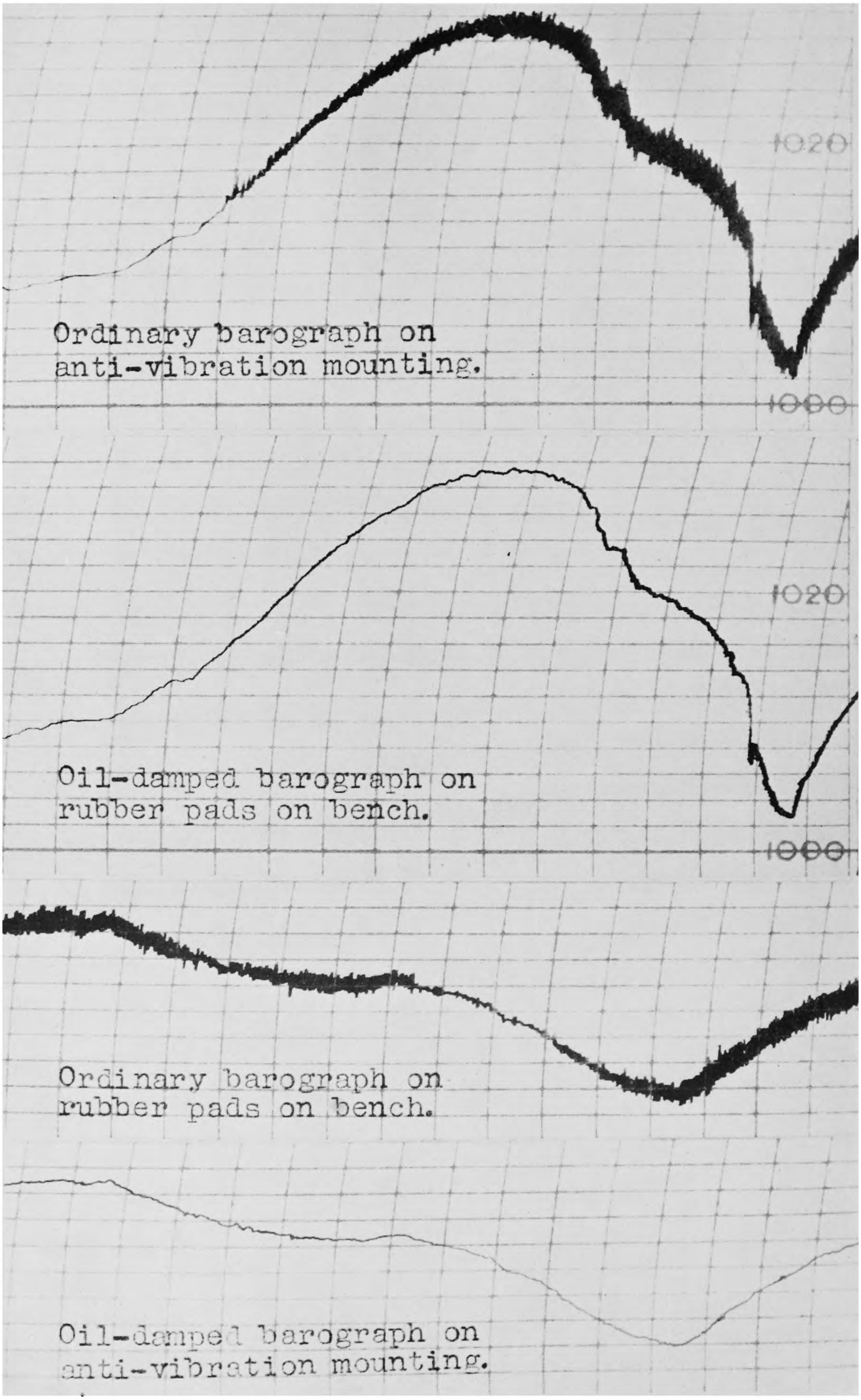
FIG. 27—MECHANISM OF A METEOROLOGICAL OFFICE MARINE BAROGRAPH

Installation.—The brass plug B (Fig. 27), 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 (the silicone fluid being very expensive). 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 hydro-carbon oils is too great. Apart from these points the barograph is used exactly as a normal open-scale barograph. Traces recorded by an oil-damped

* On later models the plug is not threaded internally. After being unscrewed from the lid it can be pushed up to the top of the rod.



METEOROLOGICAL OFFICE MARINE BAROGRAPH ON ANTI-VIBRATION MOUNTING



SPECIMEN BAROGRAMS TRACED ON BOARD THE *WEATHER OBSERVER* barograph and an ordinary barograph placed side by side in an ocean weather ship are shown in Plate X, the two instruments being placed alternately in an anti-vibration mounting and on rubber pads on a bench. It will be seen that the oil-damped barograph gives a much improved trace whether it is placed on the bench or in an anti-vibration mounting, but that for the best results in small ships a combination of both devices should be used.

2.6. INSTRUMENTS FOR RECORDING VERY SMALL PRESSURE CHANGES

Besides the major atmospheric pressure changes which are recorded on normal barographs there are numerous smaller oscillations and changes which are more difficult to record. If the magnification and sensitivity of a normal type of instrument were increased it would require much too long a chart to cover a useful range of pressure. Special instruments have therefore been designed to record these minor fluctuations. These fall into two main categories :

(i) Instruments which record the pressure directly ; these have increased magnification and time scales and some mechanism by which the zero is periodically altered to keep the record on the chart.

(ii) Instruments which do not record the pressure directly but some function of it, such as its rate of change.

An instrument in the second class is the Shaw-Dines microbarograph.

2.6.1. Shaw-Dines microbarograph

The Shaw-Dines microbarograph (Stores Ref., Met. 2080) has a large reservoir, well lagged so that its temperature only changes slowly, connected to the outside atmosphere through the bore of a piece of fine capillary tubing (the leak) ; the difference in pressure between the air in the container and the outside atmosphere is measured by means of a bell-shaped float in a bath of mercury (Fig. 28). An outlet tube from the container rises up through the mercury inside the float. The movement of the float is recorded on a chart by a pen arm connected to the float by a simple link. The reservoir can also be connected directly to the atmosphere, bypassing the leak, by a screw valve.

If an artificial pressure difference is suddenly introduced in the container, e.g. by blowing into it through the large opening, it is found that the pressure difference decreases with time in an exponential manner. The size of the leak can thus be characterized by its time constant (analagous to lagging time or lag coefficient) which is the time taken for the pressure difference to fall to 37 per cent. ($1/e$) of its original value. This time varies from instrument to instrument ; it may be as short as $1\frac{1}{2}$ min. or as long as 1 hr.

A description of the original instrument is given by Shaw and Dines[15].

Theory of the instrument.—The deflection of the instrument is always proportional to the difference in pressure between the outside and the inside of the float. If λ is the time constant of the instrument, p the external atmospheric pressure and p' the pressure inside the container then, if the temperature of the air in the container is not changing,

$$\frac{dp'}{dt} = \frac{1}{\lambda}(p - p'). \qquad \ldots\ldots(18)$$

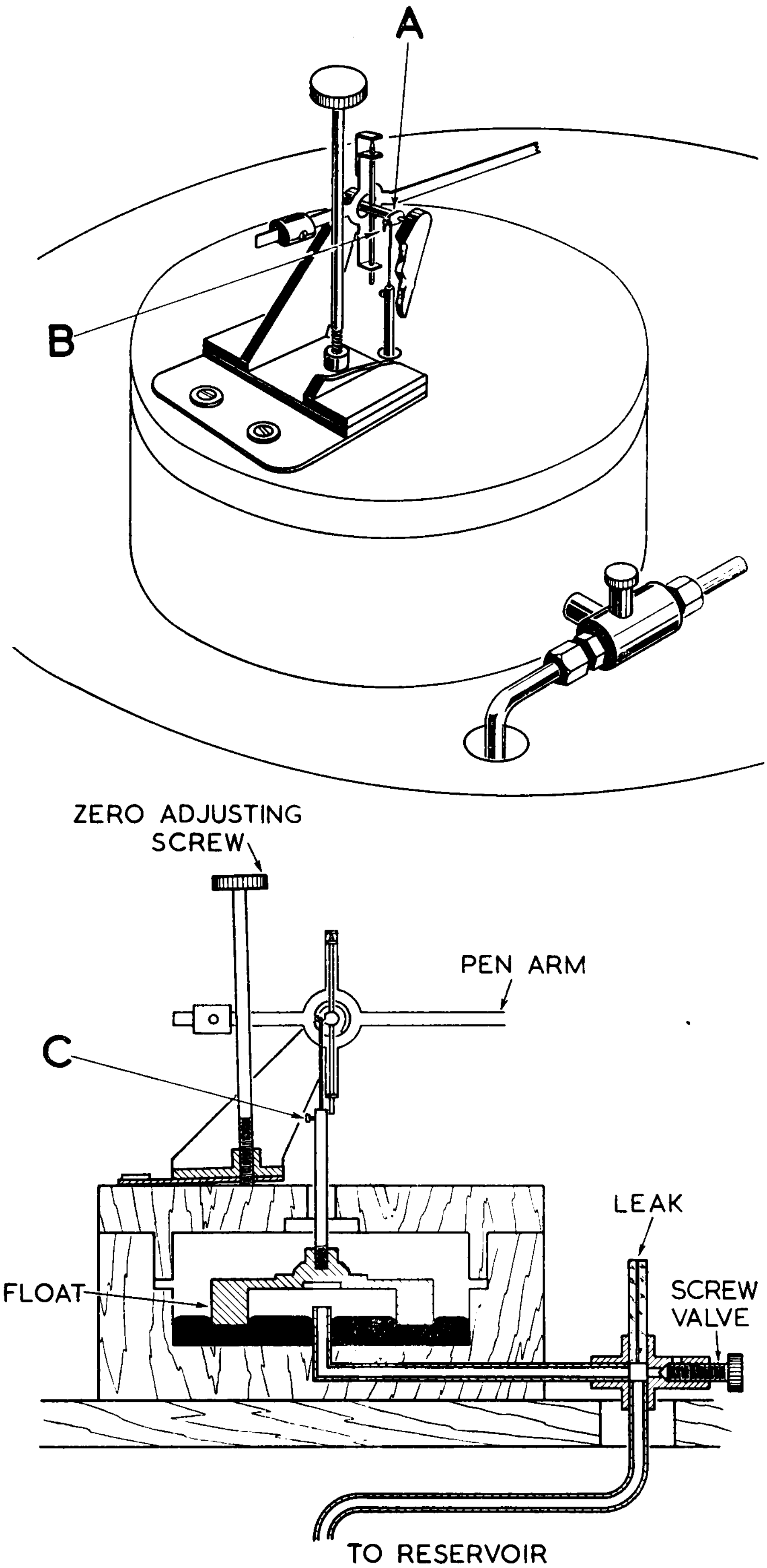


FIG. 28—DETAILS OF THE MICROBAROGRAPH

This expresses the fact that the decay curve is exponential when p is constant. If however p is changing at a steady rate, i.e.

$$p = p_0 + at,$$

then
$$p' = p - a\lambda\,(1 - e^{-t/\lambda}). \qquad \ldots\ldots(19)$$

After a time t which is large compared with λ

$$p - p' = a\lambda, \qquad \ldots\ldots(20)$$

i.e. the deflection of the instrument, when the pressure of the atmosphere is changing steadily, is constant and is proportional to the rate of change of pressure multiplied by the time constant.

The response of the instrument to periodic oscillations depends on their period. If p varies so that the oscillations are of a sine-wave form of amplitude C and of period T,

i.e.
$$p = p_0 + C \sin (2\pi t/T)$$

then the solution of equation (18) is

$$p - p' = Ae^{-t/\lambda} - \frac{C \sin\left(\dfrac{2\pi t}{T} + \tan^{-1}\dfrac{T}{2\pi\lambda}\right)}{\left(1 + \dfrac{T^2}{4\pi^2\lambda^2}\right)^{\frac{1}{2}}}. \qquad \ldots\ldots(21)$$

When t is large compared with λ the first term may be neglected. The second term is periodic with an amplitude less than the actual pressure change and out of phase by an angle $\tan^{-1}T/2\pi\lambda$. The variation in the ratio of the recorded amplitude to the true amplitude, and the variation in the phase change, for different values of (T/λ) are given in Table IV.

TABLE IV—RESPONSE OF THE MICROBAROGRAPH TO SIMPLE HARMONIC VARIATIONS IN ATMOSPHERIC PRESSURE

Ratio of period of oscillations to the time constant ..	0·1	0·5	1·0	2·0	3·0	5·0	10	30
Ratio of recorded amplitude to true amplitude ..	0·999	0·997	0·988	0·952	0·903	0·782	0·532	0·205
				degrees				
Phase difference ..	1	5	9	18	25	38	58	78

Table IV shows that short-period waves, up to a period of about 3λ, are recorded fully and promptly, but that the amplitude of the record of long-period waves is very much less than the true amplitude. The effect of the surface tension of the mercury acting on the float modifies the actual record produced. The contact angle of the mercury at the surface of the float tends to accommodate itself to small movements of the float with the result that the scale value of the record for small oscillations may be only 75 per cent. of that for large oscillations of the same period. The scale value for large oscillations will be nearer the correct value. The scale value of the instrument is determined roughly before the instrument is issued ; it depends on the magnification of the lever system, and for a magnification of about 40 (i.e. ratio of movement of the pen on the chart to the movement of the float is 40) it should be about 15mm./mb.

Installation.—The instrument is usually supplied dismantled ; it consists of a main container, clock and drum unit, float, mercury, a pen arm which is mounted on a support on the float-chamber lid, and pens. It should be installed as follows:—

(i) Fix the clock and drum unit on its support.

(ii) Put a very loose plug of cotton wool into the end of the pipe projecting into the float chamber, and then pour clean mercury into the chamber until its surface reaches about half way up the projecting piece of pipe (i.e. to a depth of about 6 mm.).

(iii) Place the float on the mercury and then fit the float-chamber cover carefully over the stem of the float and screw it down firmly.

(iv) Open the screw valve so that the container is put into immediate equilibrium with the outside air, and then set the counterweight so that the pen arm is roughly balanced without the addition of the pen.

(v) Attach the pen, making sure that its point is at the correct distance from the pen-arm axis (127 mm.). See that the pen is inclined slightly downwards from the horizontal, but that it also lies in a perpendicular plane which passes through the axis of the drum and the point of contact of the pen and the chart.

(vi) Hook the free end of the float stem on to the short lever, A, on the pen-arm spindle. The length of the stem can be varied by movement of the hook, B, in the float stem proper, a small set screw, C, normally holding the hook firm. It should be possible now to raise the pen from the bottom to the top of the chart by means of the zero-adjusting screw, but the length of hook in the float stem proper may have to be further adjusted to ensure this. If there is not enough movement of the hook in the float stem to enable this to be done mercury will have to be added to or taken from the float chamber.

(vii) Level the instrument, if necessary, by inserting packing under the feet so that the float stem is clear of the edges of the central hole in the float-chamber lid.

(viii) Check the balance of the pen arm. If the pen arm is raised by means of the zero-adjusting screw it should just come away from the chart of its own accord when it approaches the top, assuming that the chart was positioned so that the pen was near the centre when the pen arm was horizontal. When this is so the pressure of the pen on the chart when in the normal position is about the minimum consistent with a clear record. The counterweight can be finally fixed when this adjustment and that in (iv) are satisfied.

(ix) The screw valve should now be firmly closed, and the instrument is ready for use. It may however be found that the trace shows a progressive rise or fall for a few hours, probable due to surface-tension effects. The zero can be readjusted when the trace becomes steady.

If the instrument has to be transported to a new position the mercury must be removed and the instrument adjusted again at the new site.

Routine use.—Many of the microbarographs which have been reconditioned have been fitted with pressure-tube anemograph clocks Mk IIIB (Stores Ref., Met. 679). The drums are longer than the standard charts, and in most cases it will be necessary to fit the chart on the drum some distance above the flange. When the chart is in position the pen-arm axis should be 68 mm. above the base of the chart; the position of the chart can be checked by turning the zero-adjusting screw until the pen arm comes to rest, first on one of the horizontal lines and then on another, and checking that the pen cuts both horizontal lines at the same hour mark. Having once found the correct position a mark can be made on the drum. Two or more days' record can then be made on one chart by moving the zero adjustment.

Maintenance.—The value of the time constant should be checked regularly (about once a week) as this is a ready means of detecting any changes in the instrument's performance. This may be done by removing the screw valve, slipping over its socket a length of close-fitting rubber tubing and blowing into it until the pen is deflected from its original position by a convenient amount (x mm. say) and then closing the tube so that it is air-tight. The time can then be taken for the deflection to fall from x mm. to $x/2$ mm. This is actually $0 \cdot 69\lambda$ (see p. 89), but it will serve for comparison purposes. It may be called the half-time constant. This time is generally about 1–3 min. in the reconditioned instruments, but in some older ones it is much more (of the order of 15–40 min.).

If the half-time constant of the system increases markedly it is probable that the capillary tube is blocked; if the tube is removed from its seating after undoing the hexagonal nut it may be cleared with a fine wire. A decrease in the time constant indicates that there is a leak in the system. If necessary the reservoir should be removed from the lagged container and tested by immersing in water.

A straight trace may also be given if mercury from the float chamber gets into the tube between the float chamber and the main container; if this is suspected, expert advice should be obtained.

2.7. TEST BAROMETERS

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 the working standards.

2.7.1. Primary standard instruments

The ultimate standard of atmospheric pressure measurement in Great Britain is the primary standard barometer at the National Physical Laboratory. A simplified diagram of its construction is shown in Fig. 29. 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 $0 \cdot 1\mu$ of mercury ($1 \cdot 3 \times 10^{-4}$ mb.) as read on a McLeod gauge. The vapour pressure of mercury at 64° F. is however $0 \cdot 002$ 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 30 in. 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 4·8 cm. long and 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.

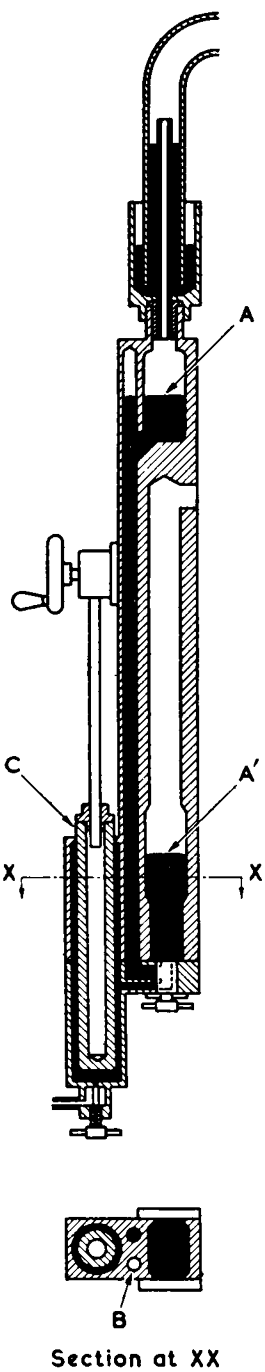


FIG. 29—PRIMARY STANDARD BAROMETER AT THE NATIONAL PHYSICAL LABORATORY

The capillary depression of the mercury is less than 0·0001 cm. (equivalent to 0·00013 mb.) at each level and is quite negligible. The instrument was designed to have no error from any single source greater than 1μ, and it is estimated that under reasonably steady atmospheric conditions the barometric height can be determined to an accuracy of $\pm 0 \cdot 002$ mm. or approximately ± 1 part in 400,000 at sea level. To obtain pressure in dynes per square centimetre the value of the acceleration due to gravity and the density of mercury must also be known. Uncertainties in these values reduce the final accuracy to about ± 1 part in 100,000 ($\pm 0 \cdot 01$ mb.). Fuller details of the accuracy of this instrument are given by Gould[16].

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.

2.7.2. Working standards

Both the Kew and the Fortin types of instrument are suitable for use as working standards provided attention is given to certain conditions which enable the accuracy to be kept within about $\pm(0 \cdot 05$ to $0 \cdot 07)$ mb. Great care has to be taken with the filling and cleaning of the tube and its internal diameter should not be less than 15 mm. The vernier should read directly to $0 \cdot 001$ in. or $0 \cdot 05$ mb. It is especially necessary to observe the precautions outlined on p. 21 when choosing the position in which the barometer is to be mounted ; it is advisable to surround the instrument with a glass case. Its corrections should be redetermined at intervals by comparison with a primary standard. The Newman type of barometer can also be used as a working standard provided similar requirements to those indicated above are fulfilled. A similar accuracy can be maintained.

2.7.3. Determination of barometer errors

The comparison of the readings of a barometer with those of a working standard is usually carried out at several pressures in the range covered by the instrument, while the barometers are in a special chamber designed for the purpose. The accuracy of measurements at the National Physical Laboratory of the index error of the barometer under test is stated to be $\pm 0 \cdot 2$ mb. This possible variation is an extreme upper limit ; the errors in the index errors determined are normally less than this.

Details of the tests that aneroid barometers have to undergo have already been given.

CHAPTER 3

MEASUREMENT OF TEMPERATURE

3.1. GENERAL

There are usually two distinct processes involved in measuring the temperature of an object : (i) a thermometer is brought to the same temperature as the object, i.e. into thermodynamical equilibrium with it, and then (ii) the temperature of the thermometer is measured.

Meteorological work requires the measurement, and often the continuous recording, of the temperature of

(i) the air near the surface

(ii) the upper air

(iii) the soil at various depths

(iv) the surface levels of the sea and lakes.

This chapter deals with (i) and (iii) ; (iv) is dealt with in Chapter XI ; and (ii) will be dealt with in Part II of this Handbook.

3.1.1. Historical

The first application of an instrument to determine relative temperature dates from the time of Galileo (1564–1642) and consisted of a simple air thermometer. Spirits of wine was later used as the thermometric substance, but other liquids, such as linseed oil, were also used. Mercury did not come into general use until it was adopted by Fahrenheit in 1721–24. The method of making the expansion of the thermometric substance apparent was altered from the movement of the water column in the air thermometer to the movement of the liquid in a vertical tube attached to the bulb, whose upper end was open to the atmosphere, and later to the modern form of liquid-in-glass thermometer with a bulb full of liquid which expands into a sealed tube which is normally as nearly as possible exhausted of air and all gases except that of the vapour of the contained liquid. Certain exceptions to this are given on p. 107.

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

Réaumur formed the basis of his scale in 1730 when he used an alcohol thermometer, and observed that a volume of 1,000 units at the freezing point became 1,080 units at the temperature of boiling water. He marked his scale 0 at the freezing point and 80 at the boiling point.

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

3.1.2. Scales of temperature

The basic or thermodynamical scale of temperature is based on the fundamental laws of thermodynamics, and on the numbering of the temperature of equilibrium between ice and water 0° and the temperature of equilibrium between liquid water and its vapour under a pressure of one standard atmosphere (1013·25 mb.) 100°. The scale of temperature generally in use is, however, the international scale of temperature which is based on a number of fixed points (primary and secondary) with approved methods of interpolating between them. These fixed points agree as closely as possible with the thermodynamical scale of temperature so that, in practice, there is negligible difference between them. The four points which cover temperatures of meteorological interest are :

(i) Temperature of equilibrium (T_p) between solid carbon dioxide and gaseous carbon dioxide at atmospheric pressure (p) measured in millimetres of mercury

$$T_p = -78{\cdot}5°\text{ C.} + 0{\cdot}01595\,(p - 760) - 0{\cdot}0000111\,(p - 760)^2.$$

(ii) Temperature of equilibrium between ice and air-saturated water at normal atmospheric pressure ; 0° C., ice point.

(iii) Temperature of transition of sodium sulphate ; 32·38° C.

(iv) Temperature of equilibrium between liquid water and its vapour at atmospheric pressure (p) ; steam point

$$T_e = 100{\cdot}000°\text{ C.} + 0{\cdot}0367\,(p - 760) - 0{\cdot}000023\,(p - 760)^2.$$

The standard method of interpolating over the range of temperature of meteorological interest above 0° C. is by the use of a platinum resistance thermometer whose resistance is assumed to vary in the form

$$R_T = R_0\,(1 + AT + BT^2)\,,$$

where R_0 is the resistance at the ice point and R_T is the resistance at temperature T° C. The constants A and B are determined by calibration at the ice point, the steam point and the sulphur point (the sulphur point is the temperature of equilibrium between liquid sulphur and its vapour at atmospheric pressure). Between 0° and −182° C. the same means are employed, but R_T is assumed to be given by

$$R_T = R_0\,\{1 + AT + BT^2 + C(T - 100)T^2\},$$

where A and B are determined as above and the additional constant C is found by calibration at the oxygen point (the temperature of equilibrium between liquid oxygen and its vapour at atmospheric pressure).

The scale outlined above is usually known as the Centigrade or Celsius scale of temperature. On this scale the pressure of a perfect gas would be zero at a temperature of —273·16° ; this is called the absolute zero and a new scale can be formed by adding 273·16° to each Centigrade temperature. This scale is known as the Absolute or Kelvin scale (°K.) ; the melting point of ice is 273·16°K. and the boiling point of water at a pressure of 1013·25 mb., 373·16°K. Each scale division is equal to one division on the Centigrade scale. There has been in meteorological use the approximate Absolute scale (°A.) made by calling the freezing point of water 273°A., and the steam point 373°A. This was near enough to the true Absolute scale for most purposes and avoided fractions of a degree for the ice and steam points. It has been officially recommended by the International Meteorological Organization (Conference of Directors[8], Resolution 164, p.206) that the use of this scale be discontinued and that the true Absolute or Kelvin scale be used in its place.

On the Fahrenheit scale (°F.) the ice point is numbered 32° and the steam point (at standard pressure) 212°. Each degree on this scale is thus 5/9 of a degree on the international scale or Centigrade scale. The absolute zero is — 459·7°F.

An old scale of temperature which was once used in Europe but whose use has now been largely discontinued is the Réaumur scale. The steam point was numbered 80° and the ice point 0°.

English-speaking countries, in general, use the Fahrenheit scale for all surface meteorological observations, and in some cases for upper air work as well, but international upper air records and most observations in other than English-speaking countries are on the Centigrade scale. Table V summarizes the relations between the various scales.

TABLE V—RELATION BETWEEN THE VARIOUS TEMPERATURE SCALES

Scale	Ice point	Steam point	Relative size of degrees
Fahrenheit (°F.) ..	32	212	9
Centigrade (°C.) ..	0	100	5
Kelvin (°K.)	273·16	373·16	5
Absolute (°A.)	273	373	5
Réaumur (°R.) ..	0	80	4

The Absolute scale is most useful for theoretical work and its use avoids negative temperatures ; for practical work the Centigrade scale is most used by scientists. The Fahrenheit degree is, however, a very convenient size for use in meteorology ; air temperature can be conveniently specified to the nearest degree (see p. 85), whereas to get a similar precision with the Centigrade scale an extra figure would be required. In addition, almost all surface air temperatures in this country lie in the range 0–100°F., which is convenient for tabular work.

3.1.3. Desirable accuracy of temperature measurements in meteorology

Measurement of air temperature near the surface.—The accuracy with which an average value of the air temperature, representative of any appreciable area around the thermometer, can be determined (assuming perfect instruments) is limited by the variations of the air temperature over short distances and short intervals of time. Fig. 30 shows a record of the temperature recorded by a fine thermo-couple exposed 4 ft. 6 in. above the ground, shielded from direct radiation and strongly aspirated by means of a fan. A period of 10 min. shows variations in the temperature of the air of nearly 4°F. Variations in temperature over small areas show similar and, occasionally, even more striking variations, especially in

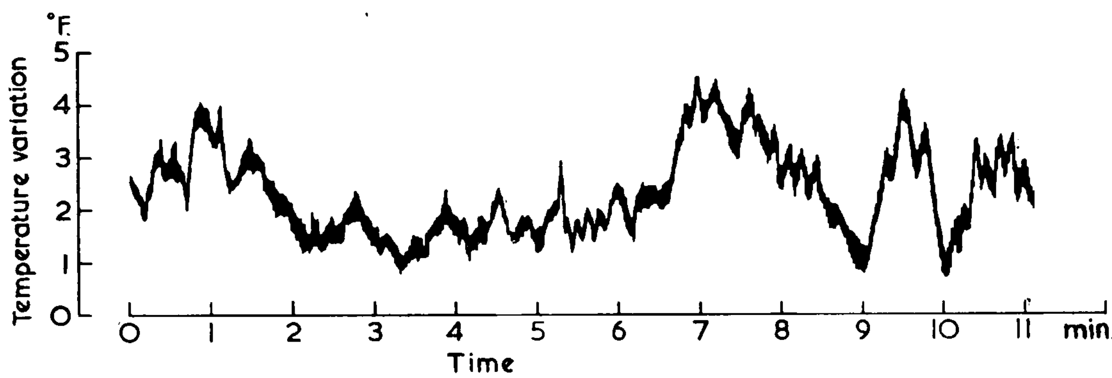


FIG. 30—RAPID TEMPERATURE FLUCTUATIONS

calm conditions at night. This suggests that except when dealing specifically with fine structure it is misleading to state the temperature of the air to a greater degree of accuracy than the nearest one degree Fahrenheit ; when the thermometers are used in a psychrometer the difference between the dry- and wet-bulb temperatures is required to a greater accuracy however, and the temperatures should then be read to the nearest tenth of a degree Fahrenheit.

Measurement of soil temperature.—As the temperature of the soil varies much more slowly than the air temperature, its mean value can be obtained with a higher degree of accuracy. In the surface layers, however, variations of appreciable magnitude may occur within small horizontal areas due to differences in the soil covering, but at lower depths the temperatures over a horizontal area are probably more homogeneous. Readings should be made to the nearest tenth of a degree Fahrenheit. The temperature variations are so slow below about 4 ft. that measurements to an even greater accuracy would be practicable (to the nearest 0·02°F. for instance).

3.1.4. General principles of thermometers

Any physical property of a substance which is a function of temperature can theoretically be used as the basis of a thermometer. The properties most widely used in meteorological thermometers are thermal expansion and the change in electrical resistance with temperature, but thermo-couples are used in special investigations. Thermo-couples are of more limited application because they can only indicate temperature differences.

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

Ordinary liquid-in-glass thermometers.—Liquid-in-glass thermometers make use of the differential expansion of a liquid with respect to its glass container. A tube with a fine bore (called the stem) is attached to the main bulb holding the liquid, and the mass of liquid in the thermometer is adjusted so that the bulb is filled completely but the stem is only partially filled at all temperatures which it is wished to measure. The changes in volume of the liquid with respect to its container are then shown by changes in position of the end of the liquid in the bore of the stem, and, by calibration with respect to a standard thermometer, a scale of temperature can be marked on the stem itself. The liquid used depends on the required temperature range ; for temperatures above its freezing point (−37·9°F.) mercury is generally used ; for lower temperatures ethyl alcohol or other organic liquids are used. The glass should be one of the " normal " or " borosilicate " glasses approved for thermometers. The glass bulb is made as thin as is consistent with reasonable strength to facilitate the conduction of heat to and from the bulb. It can be seen that the narrower the bore the greater will be the change of indication for a given change in temperature and the smaller the range of temperature covered.

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

Minimum thermometers.—The most usual device for indicating the minimum temperature is a glass thermometer filled with colourless organic liquid with a small index placed in the bore below the liquid surface. If the thermometer is tilted so that the bulb is higher than the stem the glass index will fall until its lower end reaches the end of the spirit column ; surface tension does not allow the index to break through the surface. In use, the thermometer is mounted approximately horizontally, and as the temperature falls the index is dragged back along the bore by the contracting spirit, owing to the effect of surface tension at the air-liquid interface. If, however, the temperature rises and the spirit expands the index remains stationary ; the end of the index furthest from the bulb thus indicates the lowest temperature recorded since the instrument was last set. The thermometer can be reset by tilting the instrument so that the index moves to the end of the spirit column.

Mercury-in-steel thermometers.—In the mercury-in-steel thermometer, which is used for remotely indicating and recording the temperature, a hollow flexible metal coil (a form of Bourdon tube) is attached to a steel bulb by means of a thin metal capillary tubing, and the whole is filled with mercury under high pressure. Changes in volume of the mercury in the thermometer bulb cause the coil to expand and contract (i.e. unroll, or roll up more tightly), and these angular movements can be transformed into a movement of a pointer or pen arm.

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

Bourdon-tube thermometers.—Closely allied to mercury-in-steel and bimetallic thermometers in its principle and method of operation is the Bourdon-tube thermometer. A curved metal tube of elliptical cross-section is completely filled with some organic liquid, one end of the tube being fixed and the other end free to move. The volume of the tube depends on its radius of curvature, increasing as the radius of curvature increases so that, as the cubical coefficient of expansion of the liquid is larger than that of the metal, there must be an increase in volume when the temperature of the tube rises. This means that the radius of curvature of the tube increases as the temperature increases, and there is a movement of the free end which can be translated into a movement of a pointer or a pen arm. This type of instrument is not used in the Meteorological Office.

Electrical resistance thermometers.—A measurement of the electrical resistance of a mass of metal or other material whose resistance varies in a known manner with the temperature can be converted into temperature. The resistance of the element and its leads is usually measured by connecting it into a Wheatstone Bridge circuit. It is preferable to use a balanced-bridge circuit, i.e. to adjust one of the remaining resistances in the bridge until there is zero current through the galvanometer, and then calculate the resistance of the element from knowledge of the other resistances. An alternative method is to ensure that the electromotive force applied to the bridge is stabilized by some means and then measure the out-of-balance current in the galvanometer. Changes in the resistance of the element will produce changes in the out-of-balance current in the galvanometer, and, if necessary, the galvanometer can be calibrated directly in terms of temperature. A special form of galvanometer known as a " ratiometer " or cross-coil galvanometer can also be used.

Thermo-couples.—In a thermo-couple two different metals are joined together to make a continuous circuit ; if one junction has a different temperature from the other, an electromotive force is set up in the circuit and a current flows ; the magnitude of this force varies with the temperature difference between the junctions. Thus if one junction is kept at a fixed or reference temperature and the other junction is allowed to take up the temperature it is required to measure, the electromotive force developed in the circuit gives a measure of the difference in temperature between the hot and the cold junctions, and the required temperature can be found. The electromotive force may be measured by connecting a galvanometer in the circuit, or in more accurate work a potentiometer may be used. In the second method no electric current flows through the thermo-couple. There are various combinations of metals which can be used in making a thermo-couple, and the choice depends on the temperature range over which it is to be employed and the accuracy and sensitivity required.

3.1.5. Brief comparison of the different types of thermometers

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

The mercury-in-glass thermometers are the standard instruments for determining the surface air, sea, and earth temperature. Their advantages lie in the simplicity of operation and the freedom from ancillary apparatus. They can usually be read to 0·1°F., and, after applying any necessary corrections, the reading should be accurate to this amount over most of the scale, although it does not follow that the temperature of the bulb will be the required temperature to within the same accuracy. Their main sources of error are from secular changes in the glass of the bulb and parallax errors in reading the instrument. The range of temperature which can be covered is from near the freezing point of mercury to above the highest meteorological temperature likely to be encountered, i.e. from −38°F. upwards.

Spirit-in-glass thermometers are used as minimum thermometers and whenever the temperature is likely to fall below −38°F. Although the coefficient of expansion of the spirit used, with respect to glass, is very much larger than that of mercury, the attainable accuracy is inferior to that obtained by a mercury thermometer of similar cost. They are subject to the following errors in addition to those of mercury thermometers :

(i) Secular changes in the liquid especially with exposure to light

(ii) Adhesion of the spirit to the glass causing the thermometer to read low if the temperature falls rapidly

(iii) Breaking of the liquid column by jolting or by a process of slow distillation into the upper part of the stem.

The lag of the spirit thermometer is usually greater than that of a mercury thermometer of similar dimensions.

Mercury-in-steel thermometers are mainly used for indicating or recording at a distance, although the longest practical length for the capillary connecting tube is about 150 ft. They have the advantage, when used as recording instruments, of having great control over the pen resulting in a clear and detailed record of the changes in temperature of the bulb. Their chief disadvantages are the restriction in length of the capillary tube, some restriction on the relative levels of the thermometer bulb and recording apparatus, and the large lag coefficient of the thermometer bulb so that when the temperature is changing rapidly the error in the temperature recorded by the thermometer is likely to be quite large. The restriction in the relative levels of the thermometer bulb and recorder can be overcome by having the instrument calibrated with the bulb and recorder in the relative levels at which they are going to be used. These thermometers cannot be used at temperatures below −38°F.

The bimetallic principle is used in thermographs and in the temperature element of some radio-sondes. Its advantages lie in its robustness and simplicity. Secular changes take place in the bimetal strip, but these can be reduced by suitable treatment beforehand and any residual effect taken care of by the periodic checking of the zero. A thermograph of this type can be made to record all temperatures of meteorological interest, and its lag coefficient can be made less than that of a mercury-in-glass thermometer. The Bourdon-tube thermometer is not used in this country ; generally speaking the bimetallic principle is quite as accurate and more convenient.

Electrical resistance thermometers can be made to a high degree of accuracy, considerably higher, in fact, than is normally required, or usable, in meteorological work. They are very suitable for remote reading and recording instruments. Their main disadvantage is that ancillary apparatus is required besides the thermometer element and its leads. The Meteorological Office balanced-bridge thermometer indicator for use on aircraft has a scale graduated in whole degrees Fahrenheit and can usually be read to $\pm\frac{1}{4}$°F. This thermometer covers nearly all meteorological temperatures. A lower degree of accuracy and reliability is obtained with arrangements which measure the out-of-balance current through the galvanometer. The lag of these thermometers depends on the ventilation but is generally low. Errors may be caused by the self heating of the element by the electric current, if the ventilation air speed is low and the instrument is used for continuous recording.

Thermo-couples are mostly used when a thermometer of very small lag and capable of remote reading and recording is required. A disadvantage is that they require a constant-temperature enclosure for the cold junction and an ancillary circuit for the measurement of the electromotive force set up. The accuracy obtainable is usually about equal to that of the resistance thermometers in common use, although it can be made very high with suitably sensitive apparatus.

3.1.6. Lag of thermometers

When a thermometer at a certain temperature is suddenly surrounded by a medium at a different temperature its temperature does not change instantaneously to the new value but approaches it gradually. The rate at which the temperature of the thermometer approaches the true temperature varies greatly with the materials of construction, the dimensions of the thermometer, and the different conditions of the surrounding medium ; an understanding of this phenomenon is necessary for an understanding of the limitations of a thermometer in measuring temperature. It is found experimentally that under most conditions, provided the differences in temperature are not too great, the rate of loss of heat or of gain of heat from a body is proportional to the difference in temperature between the body and the surrounding medium (Newton's law of cooling). This leads to the expression for the rate of change of temperature, T, of a thermometer with time, t, when surrounded by a medium at temperature T_1,

$$\frac{dT}{dt} = -\frac{1}{\lambda}(T - T_1). \qquad \ldots\ldots(22)$$

λ is then known as the " lag coefficient " of the thermometer. If T_1 remains constant the equation can be integrated, and becomes

$$(T - T_1) = (T_0 - T_1)\, e^{-t/\lambda}, \qquad \ldots\ldots(23)$$

where T_0 is the value of T when $t = 0$.

This shows that the temperature of the thermometer approaches that of its surroundings in an exponential manner. λ may be evaluated if observations of the value of $(T - T_1)$ are taken at various values of t.

By putting $t = \lambda$ in equation (23) it is seen that λ sec. is the time required for the difference in temperature between the thermometer and its surroundings to fall to $1/e$ (i.e. $1/2{\cdot}718$) of its initial value. The temperature difference will fall to half its original value in $0{\cdot}69\lambda$ sec. and to $1/10$ in $2{\cdot}3\lambda$ sec. A simplified theoretical treatment of the mechanism by which the temperature of the thermometer changes can be given as follows :—

Suppose a mass, m, of the surrounding medium, air for example, flows past the thermometer bulb in unit time and in doing so has its temperature changed from its normal temperature, T_1, to that of the thermometer, T. Actually a larger mass of air than m will be affected by the thermometer, but the temperature changes will not equal $(T_1 - T)$ for the whole of that mass. Then the heat given up by the air in a short time, Δt, will be $c_p m \Delta t (T_1 - T)$. This is the amount of heat absorbed by the thermometer bulb, of thermal capacity C, in changing its temperature by an amount ΔT. Since c_p is the specific heat at constant pressure

$$C\Delta T = - c_p m (T - T_1) \Delta t$$

i.e.

$$\frac{dT}{dt} = \frac{c_p m}{C} (T - T_1), \qquad \ldots\ldots(24)$$

and by comparison with equation (22)

$$\lambda = \frac{C}{c_p m}. \qquad \ldots\ldots(25)$$

The value of λ with the thermometer in air varies with the ventilation as would be expected from equation (25) ; m is in fact a function of ρv where ρ is the density of the air and v is the speed of the air stream. It is found experimentally that λ can be represented by the form $\lambda = K/(\rho v)^n$ where K is a constant and n is less than unity. Table VI gives experimental values of λ in seconds for several different kinds of thermometers, some of the results being given by Middleton[5], together with the appropriate value of n and with some values for the same thermometers when used as a wet bulb. (For further discussion of the lag of wet-bulb thermometers see Chapter 4.) The values have been reduced in many instances to a common ventilation speed of 15 ft./sec.

TABLE VI—LAG COEFFICIENTS OF VARIOUS THERMOMETERS

Thermometer	Bulb dimension	Ventilation	Lag coefficient	n
		ft./sec.	sec.	
Mercury-in-glass	Spherical 1·12 cm. diameter	15	56	0·48
Mercury-in-glass as wet bulb	Spherical 1·12 cm. diameter	15	52	0·36
Mercury-in-glass	Spherical 1·065 cm. diameter	15	50	0·43
Spirit-in-glass	Spherical 1·44 cm. diameter	15	85	0·41
Mercury-in-steel	Cylindrical 14·5 cm. long 1·90 cm. diameter	15	280	0·54
Mercury-in-steel as wet bulb	Cylindrical 14·5 cm. long 1·90 cm. diameter	15	120	0·56
Bimetallic	Helical (station thermograph)	15	21	0·64
Aircraft spirit, Strut Mk 2 and 3	Oval 3·5 cm. long by 1·2 cm. by 0·5 cm.	15	85	0·6
Strut Mk 6	Oval 2·4 cm. long by 0·6 cm. by 0·4 cm.	15	32	0·7
Mercury-in-steel (aircraft)	Cylindrical 30 cm. long 0·6 cm. diameter	15	60	0·7
Electrical resistance, coiled element	Cylindrical former 3·5 cm. long 3·8 cm. diameter	15	8	0·7
Meteorological Office balanced-bridge indicator	Knife-type bulb 9 cm. by 1·9 cm.	35	21 (variable)	0·7
Aspirated thermo-couple	4 thermo-couple junctions	35	1·8	..
Aspirated thermo-couple as wet bulb	4 thermo-couple junctions	35	2·7	..

The simple theory given above does not take into account the differences of temperature inside the bulb itself. The lag coefficient will depend on the conductivity of the various materials, and also on the transfer of heat through the bulb by internal convection (if possible). In general the lag for any given ventilation is greater the smaller the ratio of the exposed surface to the total thermal capacity of the bulb. The type of surface and shape of the bulb also affects the effective value of m in equation (25).

Response of thermometers when the temperature of the medium is changing at a constant rate.—If the temperature of the surrounding medium is changing steadily at a rate of β degrees per second, equation (22) becomes :—

$$\frac{dT}{dt} = -\frac{1}{\lambda}\left\{T - (T_1 + \beta t)\right\}, \qquad \ldots\ldots(26)$$

where T_1 is the value of the temperature of the surrounding medium at a time $t = 0$. If the temperature of the thermometer at $t = 0$ is T_0 then equation (26) gives :—

$$T - (T_1 + \beta t) = (T_0 - T_1)\, e^{-t/\lambda} - \beta\lambda\,(1 - e^{-t/\lambda}). \qquad \ldots\ldots(27)$$

The first term on the right gives the exponentially decreasing amount by which the indicated temperature is influenced by the initial temperature difference $(T_0 - T_1)$; the second term has two parts, one decreases exponentially and the other is a constant. After an interval of time t, which is large compared with λ, both exponential terms may be neglected, and equation (27) reduces to

$$T - (T_1 + \beta t) = -\beta\lambda. \qquad \ldots\ldots(28)$$

This result shows that the reading of the thermometer will lag behind the true temperature by an amount $\beta\lambda$, i.e. the thermometer will indicate what the actual temperature was at a time λ sec. previously.

Response of thermometers to fluctuating temperature.—If the temperature of the medium undergoes a simple harmonic variation about a mean temperature T_1, with a period S sec. and an amplitude a, equation (22) then becomes

$$\frac{dT}{dt} = -\frac{1}{\lambda}\left\{T - \left(T_1 + a\sin\frac{2\pi t}{S}\right)\right\}$$

or

$$\lambda\frac{dT}{dt} + \mathrm{T} = T_1 + a\sin\frac{2\pi t}{S}, \qquad \ldots\ldots(29)$$

and the solution is

$$T - T_1 = C_1 e^{-t/\lambda} + \frac{a}{\sqrt{\left(1 + \frac{4\pi^2\lambda^2}{S^2}\right)}}\sin\left(\frac{2\pi t}{S} - \gamma\right) \ldots(30)$$

where

$$\tan\gamma = \frac{2\pi\lambda}{S}.$$

The value of C_1 depends on the initial conditions but after a time t large compared with λ the term containing C_1 becomes negligible, and the response of the thermometer is a simple harmonic variation of the same period, but with reduced amplitude and lagging behind in phase when compared with the variation in temperature of the medium.

TABLE VII—RESPONSE OF THERMOMETERS TO FLUCTUATING TEMPERATURES

Ratio of period to lag coefficient (S/λ)	0·2	0·4	0·6	0·8	1·0	2·0	4·0	6·0	10·0
Ratio of response to true amplitude	0·04	0·06	0·09	0·13	0·16	0·31	0·54	0·69	0·85
					degrees				
Phase lag (γ)	88	86	85	83	81	72	58	46	32

Table VII gives the ratio of the amplitude of the thermometer response to the amplitude of the temperature variation of the medium and the phase angle by which the thermometer response lags behind the true variation for various values of S/λ.

Temperature fluctuations of period less than the lag coefficient are hardly indicated at all, and it is not until the period equals almost four times the lag coefficient that the response rises to half the true amplitude. The response of the thermometer lags behind the true variation by almost a quarter of a complete period for very short periods. It can be seen also from this table how differently two thermometers with different lag coefficients would respond to the same temperature variations in the medium, if the period of the variation were at all comparable with the value of either lag coefficient.

The fluctuations in temperature which actually occur in the atmosphere are not in fact pure simple harmonic variations but consist of changes of temperature of irregular amplitude and period. Such changes cannot be treated theoretically, but the rather more simple case of periodic fluctuations consisting of an abrupt change of temperature, then steady temperature for a period, followed by a sudden change back to the original temperature, and so on, has been treated[17], and it can be shown that for a period λ sec. the amplitude of the thermometer's response is 0·23 of the actual amplitude (as compared with 0·16 for simple harmonic fluctuations) ; the general features of Table VII are not changed however.

Fig. 30 shows how the temperature of the air can fluctuate when the sun is shining and the wind speed is moderate. The question then arises as to what is required when measuring the air temperature at any instant ; usually it is the average temperature over a period of about 5–10 min., in which case the lag coefficient of the thermometer should not be less than about 30-60 sec., as otherwise it will be unduly influenced by any short-period fluctuations about the average, and several readings would be required to obtain the mean. This applies especially to maximum thermometers, for the fluctuations are often most marked at the time of maximum temperature. The same considerations apply to minimum thermometers, although the fluctuations in temperature are neither so large or rapid at the time of minimum temperature, because of the increased stability at this time.

3.1.7. Exposure of thermometers for measuring air temperature

Radiation from the sun, the clouds, the ground and the surrounding objects passes through the air without appreciably affecting the air temperature in the lower layers, but a thermometer element, exposed freely in the open, usually absorbs the radiation to a considerable extent, and, as a consequence, its temperature may differ from the true air temperature, such difference depending on the nature and finish of the material of the thermometer element, the intensity of the various kinds of radiation, the speed of the air flow past the thermometer, and other factors. With some thermometer elements, such as a very fine wire used as a resistance thermometer, the difference may be very small or even negligible, but with the more usual thermometers the difference may be as much as 50°F. It is usual therefore to provide some form of screen or shield which will serve to support the thermometer, shield it from direct radiation from outside sources while allowing the free circulation of air around it, shield it from precipitation, and prevent accidental damage.

Ideal screen or shield.—The conditions which an ideal screen should satisfy can be set out in the following form[1]:

(i) Screen should be a " uniform temperature enclosure "

(ii) Temperature of the inner walls of the enclosure should be the same as that of the external air whose temperature is required

(iii) Enclosure should completely surround the thermometer

(iv) Enclosure should be impervious to radiation.

Conditions (iii) and (iv) are easy of attainment, but conditions (i) and (ii) are generally difficult ; they are approximated in the screens and shields used by providing them with double walls or louvers with ample air circulation and painting the screens white, or polishing the outer surface of the shields so as to reflect the maximum amount of radiation. When double walls are provided, although the outer wall may be heated to a higher temperature than the air by strong sunshine, the layer of air between the two walls will reduce the amount of heat conducted to the inner enclosure. When the wind is appreciable or when artificial aspiration is provided the air between the two walls is constantly changed, and thus the conduction of heat from the outer walls is further decreased.

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

The air that circulates through the screen or shield will, however, spend a certain time in contact with the outer walls and may have its temperature altered by conduction; this effect is usually negligible when the wind or ventilation is strong, but may become appreciable when the wind is light and the temperature of the outer wall is markedly different from the air temperature. Thus the temperature of the air in a Stevenson screen may be expected to be slightly higher than the true air temperature on a day of strong sunshine and calm wind and slightly lower on a clear calm night. These errors may be of the order of +2°F. and −1°F. in the two extreme cases (see also p. 100).

Location of the screen or shield.—For general meteorological work the temperature required is that which is representative of the free air conditions over as large an area as possible surrounding the station, at a height of 4 ft. above ground level. The height above ground level must be specified, as on many occasions large temperature gradients exist in the lowest layers of the atmosphere. The best site for the screen, or shield, and thermometers is therefore over level ground, freely exposed to sun and wind and not shielded by, or close to, trees and buildings. The most unrestricted exposure available should be used. A site on a steep slope or in a hollow is subject to exceptional conditions and should be avoided. In towns and cities local peculiarities will be more marked than in rural districts, but the best site is an open situation with the screen at the normal height. Observations of temperature on the top of buildings are of doubtful significance and use, owing to the rapid variation of temperature in the vertical and the effect of the building itself on the temperature distribution.

For air temperature at other levels and for other purposes the exposure would have to be modified accordingly.

Effect of speed of ventilation.—When a thermometer is exposed in an air stream of high speed some of the kinetic energy of the moving air is destroyed and converted into heat, leading to a purely local rise in temperature and consequent error in the air temperature recorded. This error is negligible for observations on the surface.

Standard thermometer screens.—The standard types of screen in use in this country for exposing liquid-in-glass thermometers to measure the air temperature are the Stevenson thermometer screen, the large thermometer screen and the small thermometer screen.

Stevenson thermometer screen.—The Stevenson thermometer screen (Stores Ref., Met. 228) is a rectangular wooden box provided with doors at the back and front ; the sides, back and front are double louvered, as shown in Fig. 31, the roof is double and the base consists of overlapping boards separated vertically by an air space. A series of holes, of 1-in. diameter with brass liners, in the inner roof helps the air circulation between the inner and outer roofs. The two sides of the louvers act in a similar manner to double walls, and at the same time allow the air to circulate freely. The screen is painted white and the top of the screen is covered with sheet zinc, which is turned down at the edges. The front door is hinged at the bottom and may be fastened by a brass turn, hasp and staple at the centre top. A suitable length of brass chain is fixed between the side posts and the door, so that the door comes to rest in an approximately horizontal position when opened to its fullest extent. The rear door is identical with the front door, except that the brass turn, hasp and staple are replaced by brass securing plates. These plates can be unscrewed when necessary if access to the rear of the screen is required. On the centre base board is mounted a short mahogany cylinder which is used as a support for the water reservoir, which feeds the wet bulb. The dimensions of the clear rectangular space inside the screen are 17½ in. (wide) by 11½ in. (deep) by 16½ in. (high).

The screen itself is supported on a stand (Stores Ref., Met. 229) consisting of four uprights of angle iron, with angle-iron cross-pieces and diagonal ties of mild-steel strip. Foot plates, 5 in. square, are provided at the base of each upright. The two end sets of angle-iron cross-pieces are riveted to the uprights to form two complete units, while the other members are supplied drilled, ready for assembly, together with the necessary nuts and bolts. The stand should be erected in the following manner.

Place the two end units at about the right distance apart, and attach the four cross-pieces of angle iron, the horizontal surfaces being in each case uppermost and inside ; bolt holes for the attachment of these members will be seen near the top and bottom of each end. Place the diagonal strips in position and secure them by means of a bolt at each end and one passing through both diagonal pieces where they overlap. The ends of the diagonal strips should be inside the uprights and not

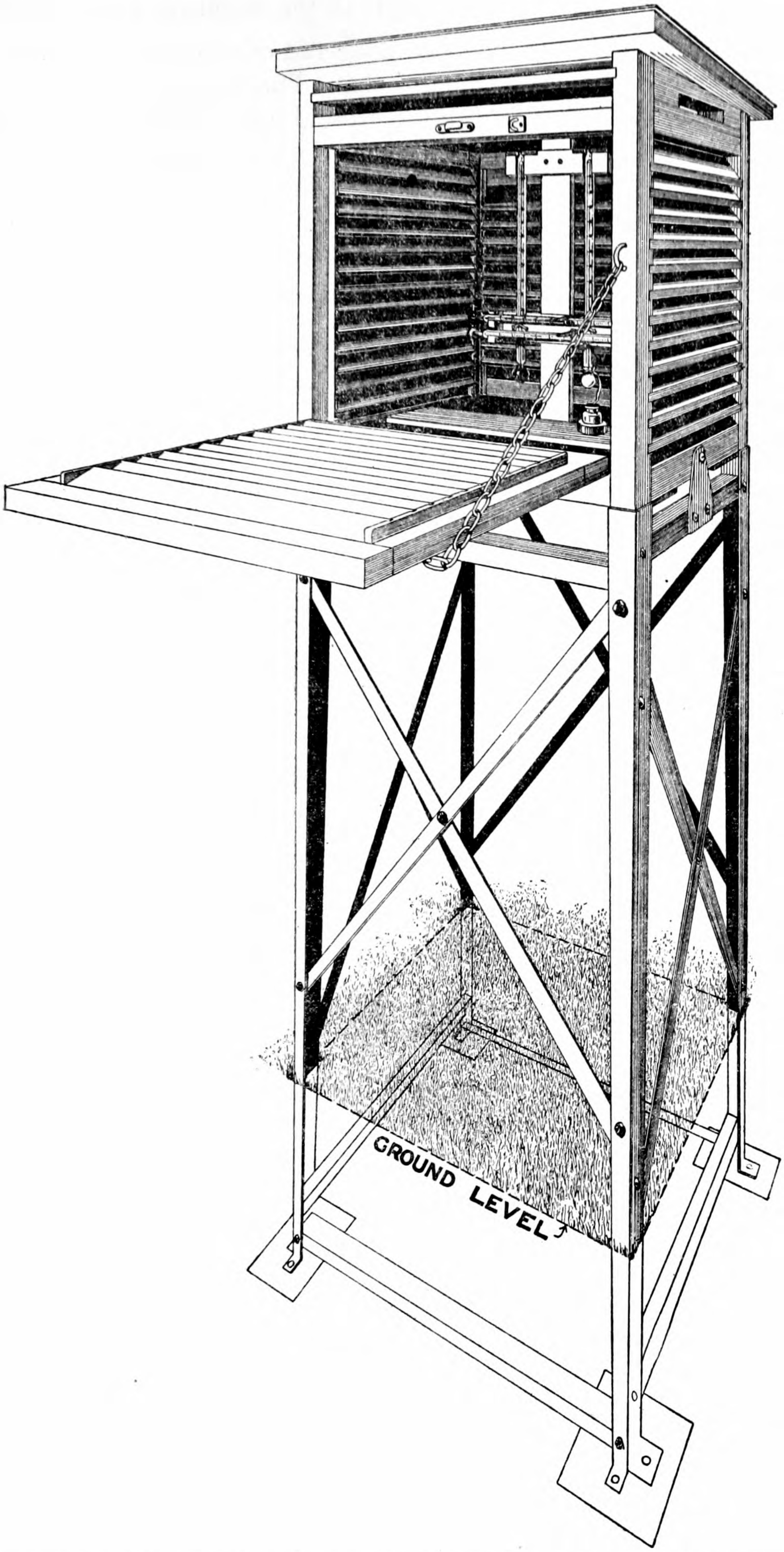


FIG. 31—STEVENSON SCREEN WITH SHEATHED THERMOMETERS AND STEEL STAND

outside. During the process of assembly the nuts should only be put on hand tight, the whole being firmly tightened up when all the members are in position.

A hole should then be dug, one foot deep and of sufficient length and breadth to take the flat ends of the feet of the uprights. This depth should ensure that the base of the screen is 3 ft. 6 in. above the ground level, and thus that the bulbs of the dry- and wet-bulb thermometers are 4 ft. above the ground. The front of the screen should face true north in the northern hemisphere (south in the southern hemisphere) to reduce to a minimum the risk of sunlight reaching the thermometer bulbs when the door is opened. The stand should be placed in the hole, the top checked for levelling, and then the earth filled in and trodden down. The legs should be sufficiently rigid when in position to prevent shaking during gales ; in very exposed situations, however, it is advisable to have the feet set in a layer of concrete. There should be no boarding beneath the base of the screen, and the earth should be compacted to bring it to the level of the surrounding ground. If grass is allowed to grow on the surrounding plot it should be kept cut short. The stand should be given two coats of white paint ; this causes it to reflect a a large fraction of the solar radiation falling on it, and reduces the disturbance to the temperature distribution caused by its presence.

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

The mounting for the thermometers (Fig. 32) consists of a wooden framework firmly fixed in position inside the screen. The dry- and wet-bulb thermometers are suspended in a vertical position, $5\frac{1}{2}$ in. apart, with the button at the top of the thermometer resting in the supports on the upper T-piece of the mounting and being fixed in grooves in the lower T-piece by means of small brass clips. The grooves are sufficiently deep to take the sheathed thermometers but not deep enough to allow any movement, once the thermometers are in position. Details of the arrangement of the wet-bulb reservoir and the covering of the wet bulb will be found in Chapter 4. When in position the bulbs of the two thermometers are about 3 in. above the centre base board of the screen.

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

This arrangement, with the thermometers grouped closely together, reduces to a minimum the obscuring of one thermometer scale by other thermometers, and places the maximum and minimum thermometers in a readily available position for removal for the purpose of resetting. The wet bulb is also well away from the other three bulbs, and there is a space of at least 3 in. between each bulb and the walls of the screen. The firm fixing of the maximum and minimum thermometers is important, as any jolting in strong winds, or when the door of the screen is opened, might otherwise lead to a displacement of the index or mercury column. The reason for the slope of the maximum thermometer is to prevent the mercury column from slipping forward when it is replaced after setting ; if this were unnoticed it might give rise to a serious error in the reading. Too great a slope of the

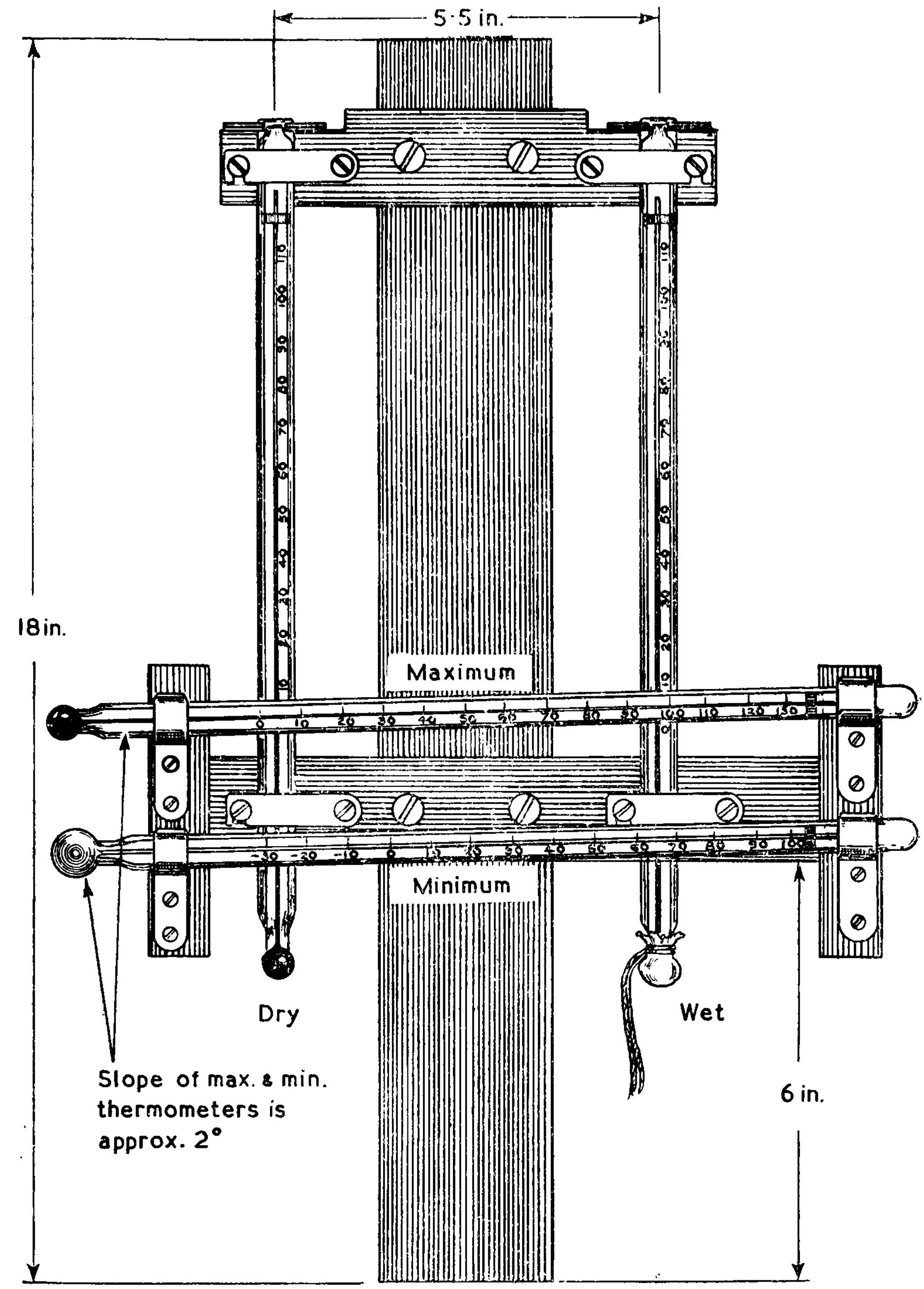


FIG. 32—DETAILS OF THE THERMOMETER MOUNT IN A STEVENSON SCREEN

thermometer might, however, give rise to errors in the other direction, by allowing the mercury to pass back through the constriction when the temperature falls.

The paint on the screen should be kept in good condition and renewed regularly (at least once every two years). A grey screen absorbs much more radiation than a white screen, and thus the errors introduced by the heating of the screen are larger. It is advisable to wash the screen with soap and water regularly in the intervals between painting. This screen is not now in widespread use at Meteorological Office stations. It has been replaced by either the large thermometer screen or the small thermometer screen.

Large thermometer screen.—The large thermometer screen (Stores Ref., Met. 226) is similar to the Stevenson thermometer screen except that it has a clear inside width of 39 in. instead of 17½ in. (Fig. 33). Because of the extra width the door louvers are made in two sections with a supporting post in the centre. The stand (Stores Ref., Met. 227) is similar in design to that of the Stevenson screen. The extra space available is normally used to house a bimetallic thermograph and a hair hygrograph, resting on the centre board, one on each side of the thermometers. Instructions for the assembly and maintenance of the stand are similar to those for the standard screen.

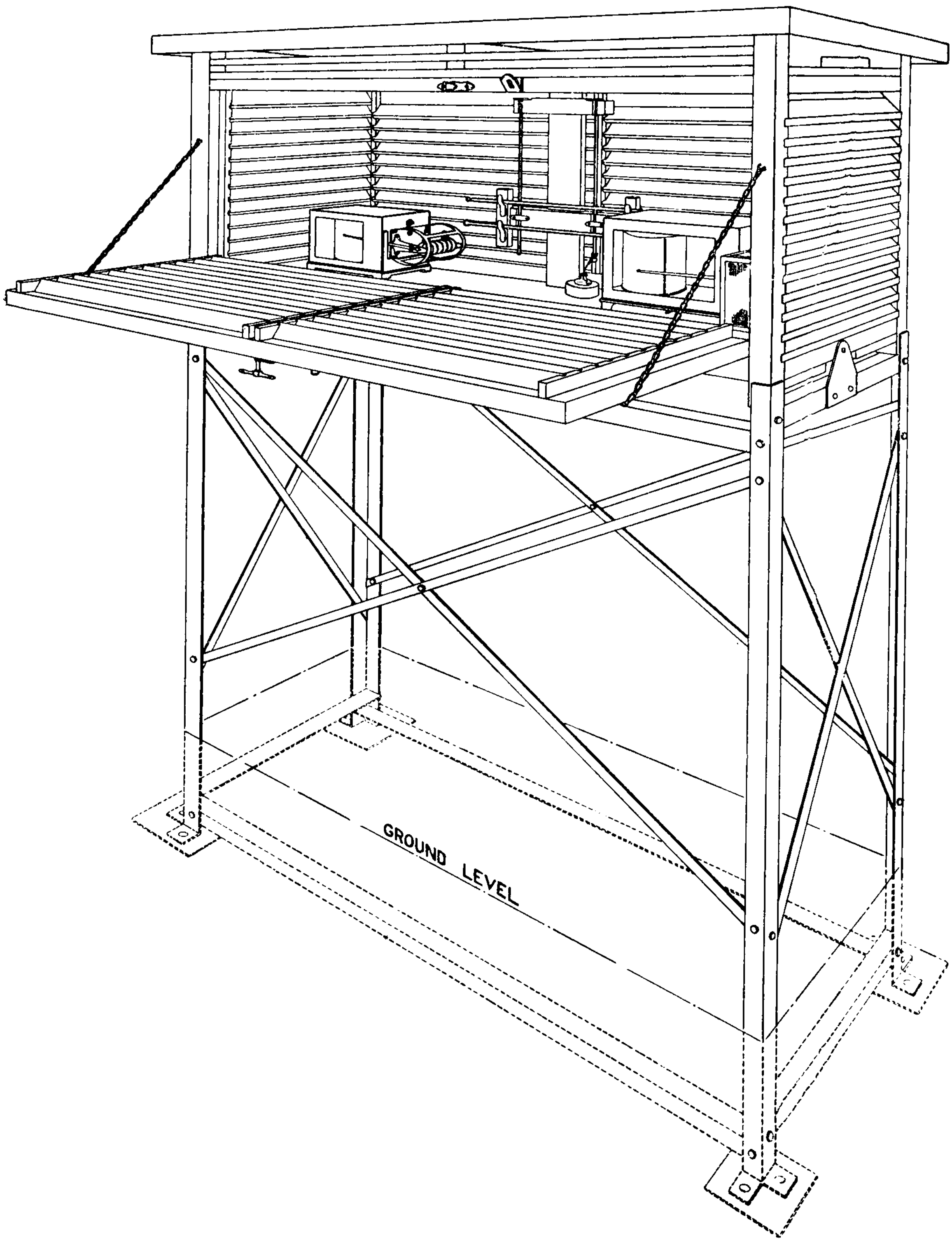


FIG. 33—LARGE THERMOMETER SCREEN

Small thermometer screen.—The small thermometer screen (Stores Ref., Met. 578) is of the same general type as the Stevenson thermometer screen and houses the normal set of four sheathed thermometers (Fig. 34). It is rectangular in plan, but with the outer wall of the double roof sloping up from the back and front towards the centre line, and over-hanging at each end by about 1½ in. Air can enter into the space between the two roofs only from the sides or through the three ventilation holes in the inner roof. Both sides, the back, and the door are double louvered in a similar manner to the Stevenson screen, and the base of the screen is also arranged in a similar way. There is no rear door to the small thermometer screen.

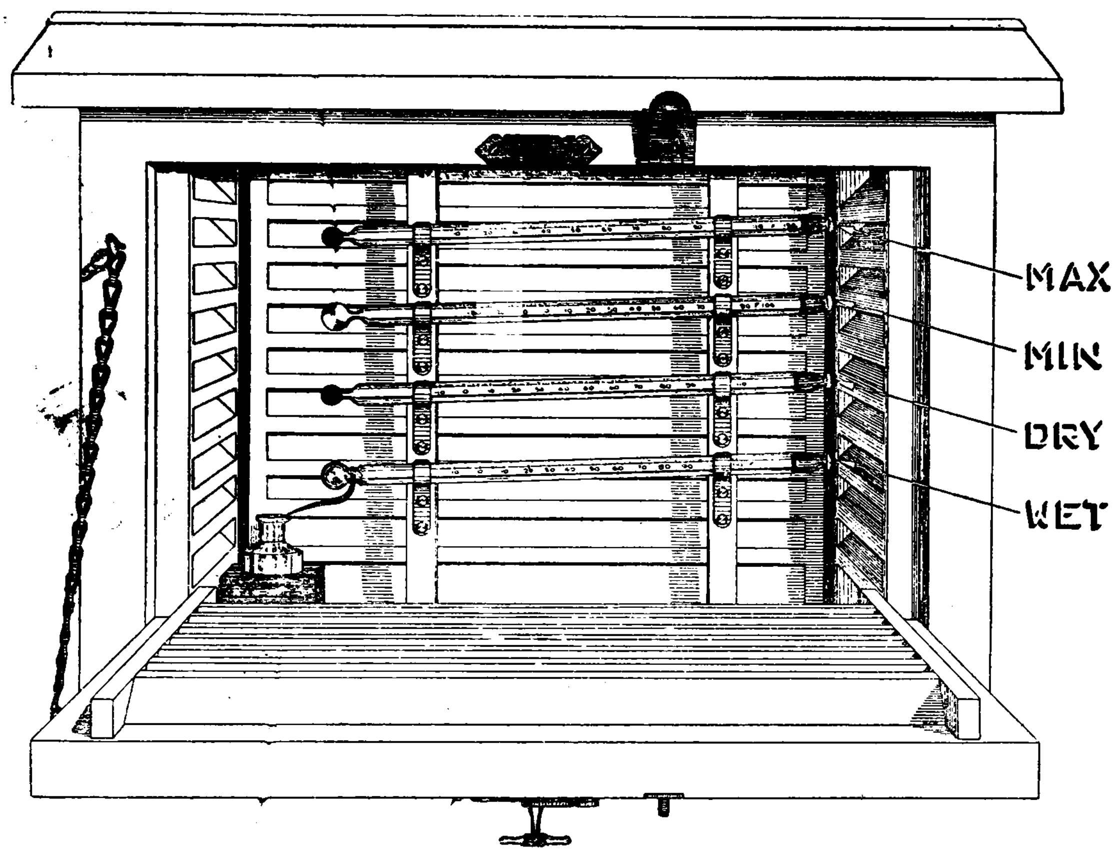


FIG. 34—SMALL THERMOMETER SCREEN

The thermometers are supported on brackets made of brass strip, fastened on two wooden uprights, and when in position they lie at an angle of about 2° to the horizontal with their bulbs at the lower end (the bulbs are on the left-hand side when facing the front of the screen). The wet-bulb thermometer is placed in the lowest position, followed by the dry bulb, minimum and maximum. The inner dimensions of the small screen are 16½ in. (wide) by 6¼ in. (deep) by 12 in. (high) ; the bulbs of the thermometers can therefore be spaced at least 3 in. from the surrounding walls and the vertical separation of each bulb from the adjoining ones is 2 in. The screen is painted white, and this paint should be renewed whenever necessary (preferably at least once every two years). It should be washed at regular intervals between the paintings.

The iron stand (Stores Ref., Met. 579) is of the same general design as that of the Stevenson and large thermometer screens, and similar methods of assembly and installation should be followed. The small screen should not, however, be installed so that it faces due north (true) (or south in the southern hemisphere), because the thermometer bulbs are all to one side of the screen and radiation in the summer could fall on them (when the door is opened) for a longer period in the evening than in the morning, or *vice versa* in the southern hemisphere. The screen should therefore be installed with the door facing north-north-east (true) in the northern hemisphere or south-south-west (true) in the southern hemisphere.

Errors caused by the standard thermometer screens.—The general causes of errors in the temperature measurements made by thermometers exposed in screens of the Stevenson type have already been discussed. A series of comparisons at Potsdam, over a period of about two years[18], between the readings of a thermometer exposed in a screen of the Stevenson type and the readings, at the same time and place, of the dry bulb in an aspirated psychrometer, whose systematic errors can be assumed to be much smaller than those caused by the screen, gave the mean values of the difference (screen temperature — aspirated-thermometer temperature) shown in Table VIII. The observations are divided into two groups, one containing all the observations and the other containing only those made on days when the sun was shining brightly.

These figures give some idea of the order of magnitude of the systematic errors in the Stevenson-screen observations, but their absolute values do not necessarily apply to this country or to screens as manufactured at present. The increased error at 1400 on days of bright sunshine would be expected. The variation in the error throughout the year was very irregular, except at 1400 when there was a maximum about September and a minimum in the period March to April.

TABLE VIII—MEAN VALUES OF DIFFERENCE BETWEEN SCREEN TEMPERATURE AND ASPIRATED-THERMOMETER TEMPERATURE

	Time of observation		
	0700	1400	2100
	degrees Fahrenheit		
Screen temperature — aspirated-thermometer temperature			
Using all observations	−0·05	+0·38	+0·07
Using only days with bright sunshine	−0·14	+0·72	+0·05

Screen for mercury-in-steel thermograph (wet and dry bulb).—This is a small wooden screen (Stores Ref., Met. 552) with single louvers in the walls and only a single roof (Fig. 35). The floor is constructed of three overlapping boards with an air space between. Its internal dimensions are 19 in. (wide) by 10 in. (deep) and a height which varies from 9½ in. at the front door to 9 in. at the rear (heights being measured, as always, above the centre board). Holes are bored in the base of the side walls to permit the exit of the capillary tubing and lead sheath which connect the thermometer bulbs with the recording mechanism.

An iron stand (Stores Ref., Met. 644) is normally provided for supporting the screen ; it is of the same general design as the stand for the Stevenson screens, and similar methods should be used for the assembly and installation. The white paint on the screen should be renewed whenever necessary.

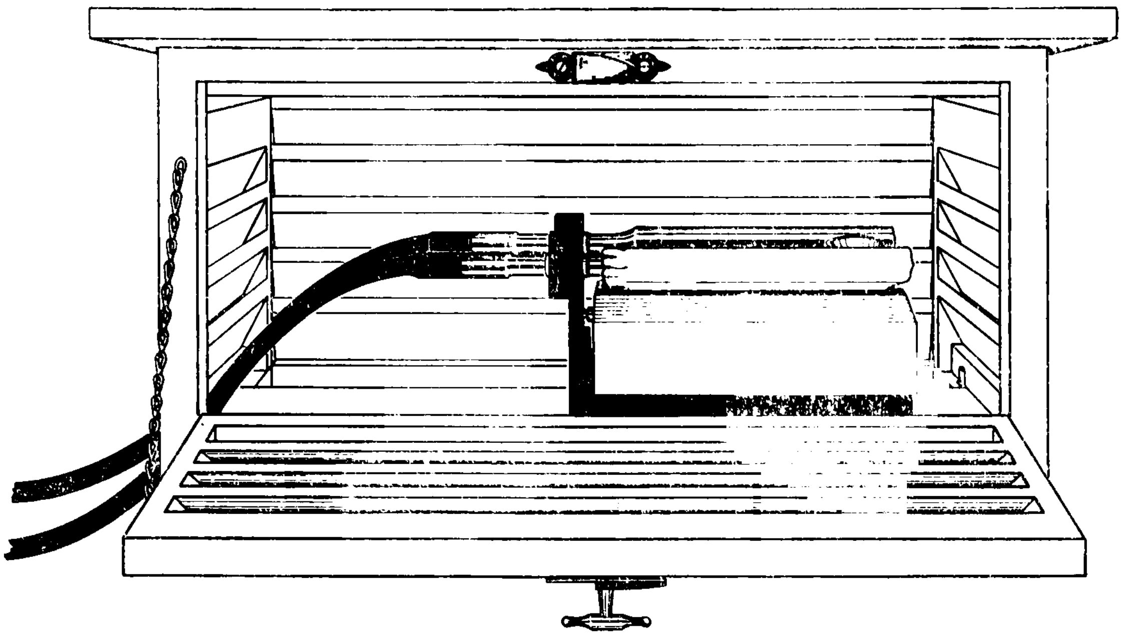


FIG. 35—MERCURY-IN-STEEL THERMOGRAPH SCREEN

Other methods of exposure for measuring air temperature.—The main alternative method of exposing thermometers consists of shielding the thermometer element from direct radiation by placing it on the axis of two cylindrical concentric shields and drawing a current of air between the shields and past the thermometer element. The shields are normally of metal and are kept highly polished to reduce their absorption of radiation. As the inner shield is kept in contact with a moving stream of air on both sides, its temperature, and consequently that of the thermometer element, should approximate very closely to that of the air. The shields are usually mounted with their axes vertical (for an exception see the hand-aspirated psychrometer p. 175) ; direct radiation from the ground can then enter through the base, but the amount of this is small and can be further reduced by making the shields appreciably longer than the thermometer elements. This type of exposure is used in the clockwork-aspirated pyschometer Mk II and the thermo-couple balloon pyschometer (described in Chapter 4).

In the whirling or sling psychrometer (Stores Ref., Met. 560) there is no direct protection from radiation. The thermometer is mounted on a light frame, attached to a handle, so that it can be rapidly whirled by the observer. The details of this method and the main sources of error are given in Chapter 4.

Measuring the grass minimum temperature.—The grass minimum temperature is the lowest temperature recorded by a minimum thermometer, exposed just above ground covered with short grass ; the thermometer should be touching the grass tips and not be shielded at all. Two Y-shaped wooden forks are suitable as supports for the thermometer, and these should be placed in level ground so that the base of the fork is just above the grass tips. The situation chosen should be the most open available ; the temperature recorded is affected even by an open metal framework placed over the thermometer as a guard[19].

3.1.8. Methods of exposure for measuring earth temperature

Earth temperature is usually measured at one or more of certain standard depths ; these are 2 in., 4 in., 8 in., 1 ft., 2 ft., and 4 ft. in this country.

Exceptionally, the temperature at other depths can be measured. The Conference of Directors at Washington in 1947 has, however, recommended that the standard depths be 10, 20, 50 and 100 cm.

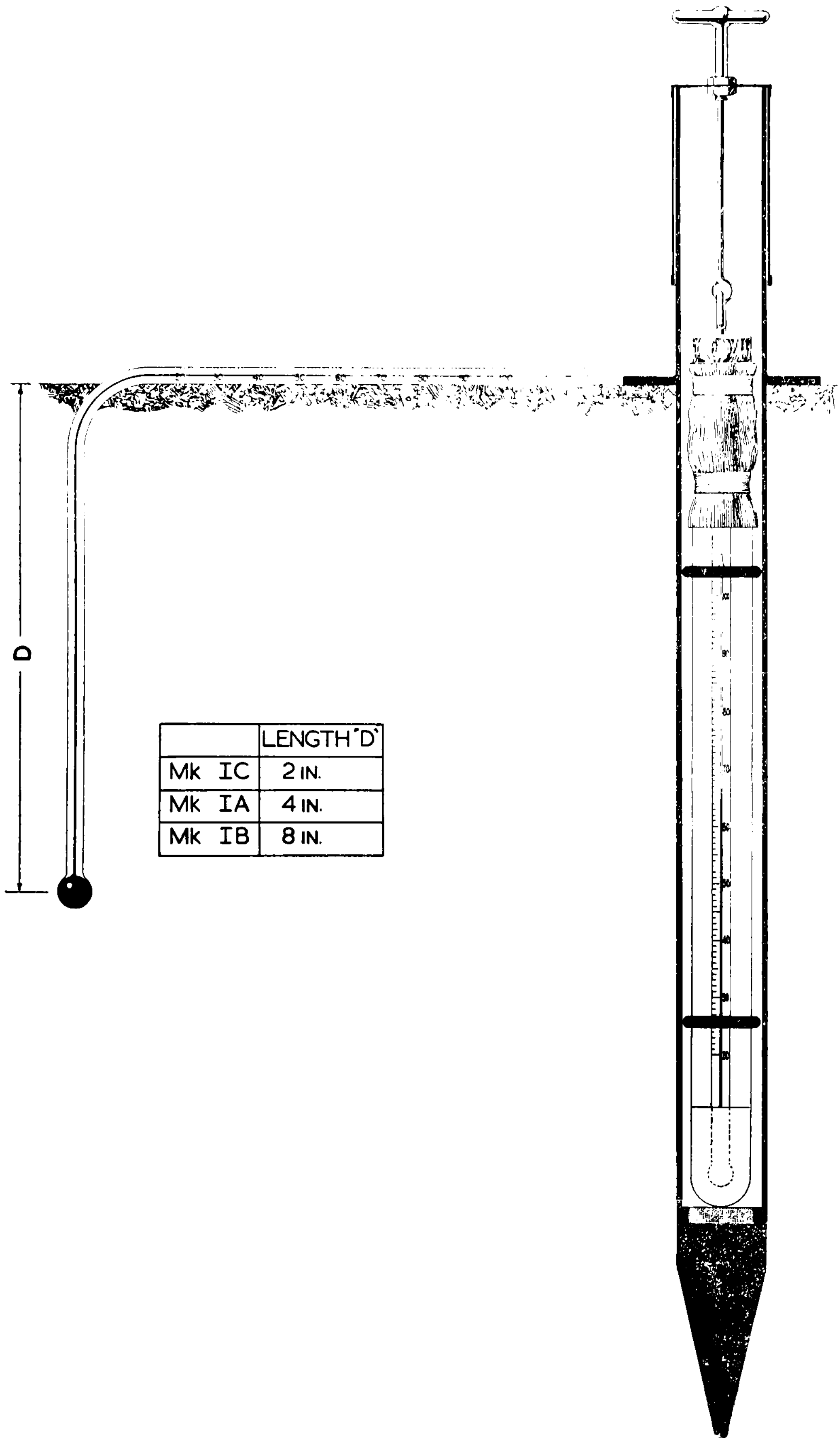
Measurement of temperature at 2 in., 4 in., and 8 in.—The temperature at these depths below the surface is measured by the use of mercury-in-glass thermometers, in which a right-angled bend is introduced into the stem at such a position that when the horizontal part of the stem is in contact with the ground, the remainder being vertically downwards, the centre of the bulb is at the correct distance below the surface of the soil (Fig. 36). The capacity of the bulb is such that all the graduations come on the horizontal part of the stem.

Measurement of temperature at 1 ft. and 4 ft.—To measure the temperature at these depths thermometers are suspended in earth thermometer tubes (Fig. 36). The tubes (Stores Ref., Met. 290 and Met. 292 for the 1-ft. and 4-ft. tubes respectively) for the two depths are similar in design and differ only in their length. They are made of seamless, mild-steel tubing of $1\frac{1}{4}$-in. bore, with a cone of solid steel fitted to the lower end. A rubber disc 1 in. in diameter is cemented into a recess in the top of the steel cone. Brazed on to the outside of the steel tube is a circular steel flange 3 in. in diameter in such a position that the distance from the base of the flange to the top of the rubber disc is $12\frac{1}{2}$ in. and $48\frac{1}{2}$ in. in the 1-ft. and 4-ft. thermometer tubes respectively. When in position the centre of the thermometer bulb is $\frac{1}{2}$ in. above the top of the rubber disc and the base of the flange is on a level with the surrounding soil, so that the thermometer is at the correct depth.

The cap on the tube is made of sheet copper and provided with a brass handle to which is soldered a piece of brass wire, terminating in an eye. The brass wire hangs down inside the cap. The thermometers themselves are enclosed in glass tubes and provided with a hook ; in the 1-ft. tube the hook is attached directly to the eye of the brass wire, but in the 4-ft. tube the thermometer hook is attached to a length of brass chain which in turn is attached to the brass eye. The lengths of the chain, thermometer tube and brass wire are such that in each case the thermometer tube just rests on the rubber disc at the base of the metal tube. A description of the thermometer itself and its mounting is given on p. 120.

When installing the tube the surrounding ground should be disturbed as little as possible ; the tube should be driven in until the flange on the outside of the tube is level with the surrounding ground. Any water collecting during the time when the cap is off should be removed as soon as possible by means of a sponge or other absorbent material tied to the end of a stick. An observation is made by withdrawing the cap and drawing out the thermometer. To prevent any errors on account of differences between the air temperature and the earth temperature, the lag coefficient of the thermometer has to be made very high, as described on p. 120. If there is snow on the ground it should be removed carefully from the top of the cap and replaced afterwards. None should be allowed to fall inside the tube.

The presence of the metal earth tube will modify the surrounding earth temperature to a small extent by virtue of the fact that the thermal conductivity of the metal tube is greater than that of the surrounding earth. The magnitude of this effect is small however. Table IX shows the difference between the mean temperatures



	LENGTH 'D'
Mk IC	2 IN.
Mk IA	4 IN.
Mk IB	8 IN.

FIG. 36—RIGHT-ANGLED EARTH THERMOMETER AND SYMONS-PATTERN EARTH THERMOMETER WITH STEEL TUBE

recorded at various depths in a clay tube and a tube made of German silver [6,20]. The differences would be expected to be rather greater for a steel tube, whose conductivity is about 1·5 times that of German silver. The thermal conductivity of the German silver was about 5 times that of the clay tube.

TABLE IX—CLAY-TUBE TEMPERATURE MINUS METAL-TUBE TEMPERATURE, POTSDAM

Period : 5 years

Depth	Mean difference October to March	April to September	Whole year
cm.	*degrees Fahrenheit*		
50	−0·02	−0·04	−0·04
100	−0·04	−0·02	−0·04
200	−0·12	+0·04	−0·05

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

3.2. LIQUID-IN-GLASS THERMOMETERS

3.2.1. General

The change in length of the column of liquid in the stem, Δl, is related to the change in volume of the liquid, ΔV, relative to the bulb, by

$$\Delta V = A \Delta l$$

where A is the cross-sectional area of the bore of the stem and

$$\Delta V = V_0 (\gamma_l - \gamma_g) \Delta T,$$

where V_0 is the volume of the liquid at a standard temperature, γ_l and γ_g are the cubical coefficients of expansion of the liquid and the glass respectively, and ΔT is the change in temperature.

Thus $$\Delta l = \frac{V_0 (\gamma_l - \gamma_g)}{A} \Delta T. \qquad \text{......(31).}$$

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

The cross-section of five types of stem used in thermometry are shown in Fig. 37 ; (*a*) is a plain round stem with a fine circular bore which is used in most mercury meteorological thermometers ; (*b*) has a similar bore but with a " lens front " which produces a magnified image of the mercury thread when viewed from the direction indicated by the arrow ; (*c*) is the stem of a spirit thermometer, its bore is much larger than that of a mercury thermometer ; and (*d*) is the stem of a " red-reading " mercury thermometer. This has an approximately semi-circular bore with the flat side at such an angle that, when viewed through the lens front, the surface of the mercury reflects an image of a strip of red enamel placed in the stem. The general arrangement can be seen from Fig. 37. In all these thermometer stems a strip of white enamel behind the bore serves as a suitable background against which to view the mercury or spirit. Type (*e*) has a much smaller diameter stem, of capillary tubing dimensions, without an enclosed enamel strip to serve as a background. It has a separate rectangular scale attached to the stem.

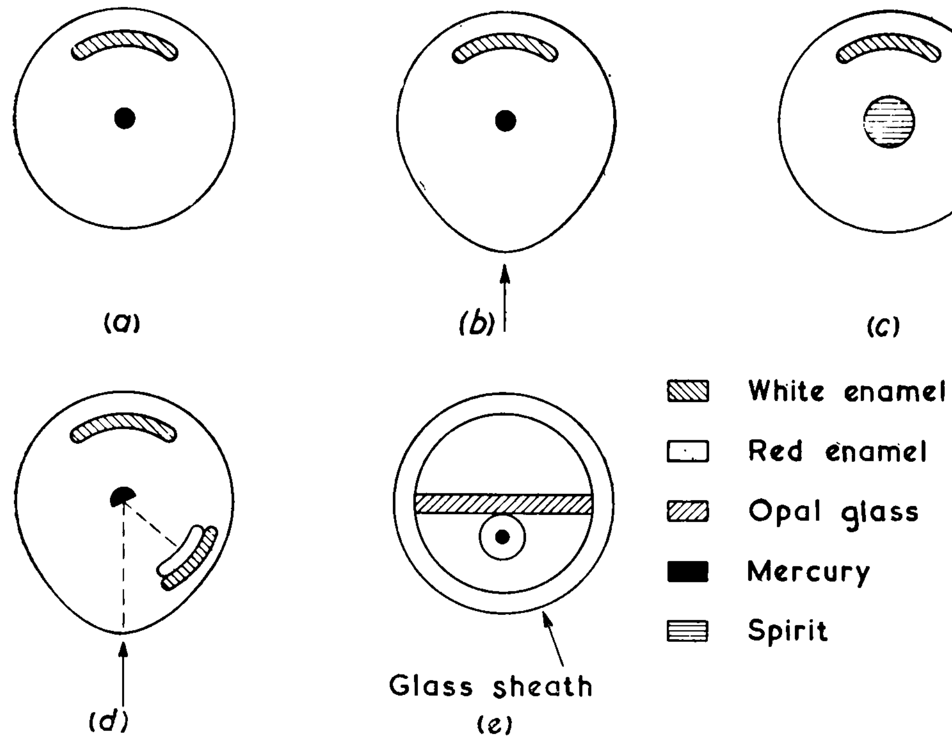


FIG. 37—TYPICAL CROSS-SECTIONS OF THERMOMETER STEMS

The scale may be engraved directly on the thermometer stem or on a separate piece of glass to which the stem is attached (e.g. type (*e*) above). In both cases the scale should be protected for meteorological work by enclosing the thermometer in a cylindrical glass sheath. Many thermometers with the scale engraved on the stem are, however, used without a sheath because of manufacturing difficulties, and where extra robustness is essential a mount may be used.

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

(i) Elastic errors

(ii) Errors caused by the emergent stem

(iii) Parallax errors

(iv) Changes in the volume of the bulb produced by exterior or interior pressure

(v) Capillarity

(vi) Errors in scale division and calibration

(vii) Inequalities in the expansion of the mercury and glass over the range considered.

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

Elastic errors.—There are two kinds of elastic errors, reversible and irreversible. The first is of importance only when a thermometer is exposed to a large range of temperature in a short period of time. Thus, if a thermometer is checked at the steam point and shortly afterwards at the ice point, it will at first read slightly too low and then the indicated temperature will slowly rise to the correct value. This error depends on the make of glass employed in the thermometer, and may be as much as 2°F., but with the best glass it should be only 0·05°F., and would be proportionately less for smaller ranges of temperature. The effect is of no importance in meteorological measurements, apart from the possibility of error in the original calibration.

The irreversible changes may be more significant. The bulb of the thermometer tends to contract slowly over a period of years, and thus causes the zero to rise. The greatest change will take place in the first year and then the change will gradually decrease. This alteration can be reduced by heat treatment of the bulb and by using the most suitable glass, but even with the best glass the change may be about 0·02°F. a year at first. For accurate work, and especially with inspectors' thermometers, the zero should be redetermined periodically and the necessary corrections applied.

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

$$\frac{x\,A(\gamma_l - \gamma_g)\,(T - T_s)}{A} = x\,(\gamma_l - \gamma_g)\,(T - T_s),$$

where γ_l, γ_g and A have the same definition as given on p. 104. The expansion of the bore has again been neglected.

If the mean length of 1°F. on the scale is y cm. then the error in degrees Fahrenheit, ΔT, is given by

$$\Delta T = \frac{x\,(\gamma_l - \gamma_g)\,(T - T_s)}{y}$$

$$= n\,(\gamma_l - \gamma_g)\,(T - T_s), \qquad \ldots\ldots(32)$$

where n is the number of degrees whose length equals x cm. For most mercury-in-glass thermometers $(\gamma_l - \gamma_g)$ is approximately equal to 0·00009/°F. In any numerical evaluation of ΔT it is usually difficult to measure T_s, the mean temperature of the stem. The error rarely exceeds a few tenths of a degree even in extreme cases.

Errors due to parallax.—If the thermometer is not viewed with the eye in the plane which is perpendicular to the stem of the thermometer and passes through the top of the mercury column, parallax errors will arise (see Fig. 38). The error increases with the thickness of the stem of the thermometer and the angle between the actual line of sight and the correct line of sight. This error can only be avoided by taking great care when making an observation. With thermometers suspended vertically, as in a Stevenson screen, the eye must be brought down to the horizontal level of the top of the mercury column.

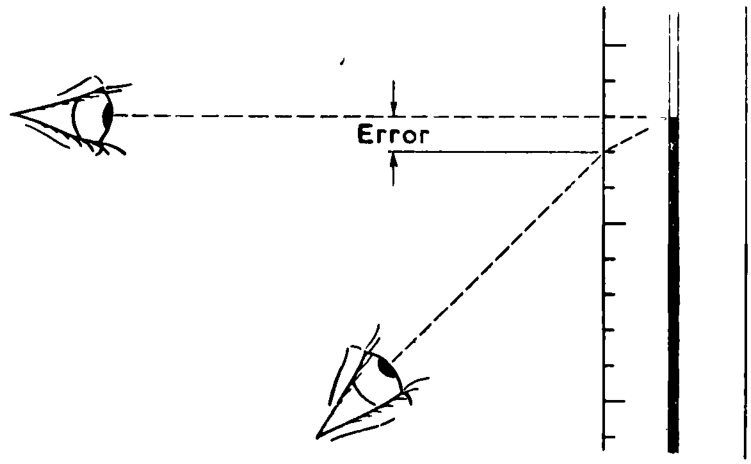


FIG. 38—ILLUSTRATING ERROR DUE TO PARALLAX

Mercury thermometers.—The cubical coefficient of expansion of mercury is 0·000101/°F., and that of most glasses lies between 0·000010/°F. and 0·000015/°F.; the expansion coefficient of the glass is thus an important fraction of that of mercury and γ_g cannot be neglected in the equation linking Δl and ΔT. As neither the cubical coefficients of expansion of mercury and glass nor the cross-sectional area of the bore of the stem are strictly constant over the range of temperature and length of stem being used, the scale value of unit length of the stem varies along the stem, and the thermometer has to be calibrated against a standard thermometer before it can be used.

The mercury used to fill the thermometer should be chemically clean and free from gases, and after it has been introduced into the thermometer a vacuum is normally produced in the stem before sealing, although in some ordinary thermometers an inert gas such as nitrogen is placed in the stem above the mercury. Mercury thermometers are limited to measuring temperature above the freezing point of mercury (—37·9°F.).

Spirit thermometers.—The expansion coefficients of the liquids used in spirit thermometers are very much larger than that of mercury, and their freezing points are much lower (ethyl alcohol freezes at —175°F.). They are used in minimum thermometers because they are colourless and because their larger expansion coefficient enables a larger bore to be used. Spirit thermometers are less accurate than mercury thermometers of similar cost and quality. Beside having the general errors of liquid-in-glass thermometers (p. 105) they have errors peculiar to themselves.

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

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

The column of a mercury thermometer can also break, but this happens much less frequently than with spirit thermometers. A mercury thermometer with a broken column should be swung in the way described for maximum thermometers (p. 116).

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

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

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

National Physical Laboratory certificates.—Meteorological Office liquid-in-glass thermometers are normally sent to the National Physical Laboratory for testing before acceptance. Their errors at a number of points along the scale are determined by total immersion, and recorded on a certificate which should always accompany the thermometer. Except where otherwise stated the errors are determined with an accuracy of $\pm 0\cdot 1$°F. and at about 15–20°F. intervals along the scale. The National Physical Laboratory also ensures that the thermometers comply with the appropriate specification.

General notes on making temperature observations.—The thermometers should be kept clean and the bulbs bright. After cleaning a dry bulb 10–15 min. should be allowed to elapse before any readings are taken. Care should always be taken to avoid errors due to parallax when making the actual readings. Most thermometers are read to the nearest 0·1°F. and the appropriate correction, as given on the National Physical Laboratory certificate for that thermometer, is applied, although maximum and minimum temperatures are then usually rounded off to the nearest whole degree. If necessary the required correction should be obtained by interpolation between those given. The best way to estimate to the nearest 0·1°F. when the graduation marks are only given for every 1°F. is to visualize the space between the graduation marks divided first into half, as at B in Fig. 39 and then each half division divided again, into quarters of a whole division, as at C and D. If the top of the mercury column falls into the first quarter the correct number of tenths will be 1 or 2, and of these the observer must judge which is appropriate. Similarly the values 0·3 and 0·4 lie in the second quarter, with 0·5 exactly on the half division. In this way it is possible for a careful observer to make an estimate which is correct to the nearest 0·1°F. In Fig. 39 the points V, W, X, Y and Z read 0·3, 1·1, 2·6, 3·4 and 4·8 respectively.

The approach of the observer to read the thermometer usually disturbs the surroundings in one way or another, so that the observation should be made as rapidly as is consistent with accurate readings. It is quite easy to make errors of

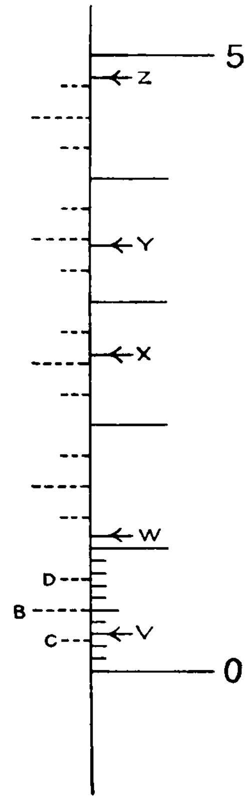


FIG. 39—ESTIMATING TENTHS OF A DEGREE

1°, 5° or 10°F. so that, having taken the reading to the nearest 0·1°F., as soon as possible a check should be made that the tens and unit figures are correct. When using the normal arrangement of thermometers in a Stevenson screen the best order of reading is dry bulb, wet bulb, maximum, minimum.

3.2.2. Ordinary thermometers (mercury-in-glass)

Sheathed type (Mk 2A, Mk 2B, Mk 2C and Mk 2D).—The specification of these thermometers (Stores Ref., Mk 2A Met. 1014, Mk 2B Met. 1015, Mk 2C Met. 960, Mk 2D Met. 961) is that given in "Meteorological thermometers" issued by the British Standards Institution[21]. They are sheathed thermometers of the mercury-in-glass type (Fig. 40) evacuated above the mercury, graduated on the stem and protected by a glass sheath. The stem is circular with an enamel back and the bulb is substantially spherical. They are graduated for total immersion and graduation marks are made for each degree Fahrenheit. Each 10°F. is figured, the minus sign being placed above the negative numbers.

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

The stem is protected by an outer glass sheath not greater than 0·55 in. in outside diameter and hermetically sealed to the stem at a point near the bulb. The top end of the stem is securely supported inside the sheath by a ring of rubber or cork, fitted inside the sheath and over the stem and placed so as not to obscure the graduated scale. The end of the sheath is finished in the form of a button, as shown in Fig. 40, so that it can be easily and securely suspended from the clip at the top of the thermometer stand in the Stevenson screen.

TABLE X—DIMENSIONS OF METEOROLOGICAL THERMOMETERS CONFORMING TO BRITISH STANDARDS[21]

Type	Overall length including sheath	Stem diameter Sheathed type	Distance from bottom of bulb to bottom of scale not less than	Bulb diameter Spherical	Bulb diameter Cylindrical	Length of parallel portion of bore above and below scale not less than
	in.	in.	in.	in.	in.	in.
Ordinary						
Mk 2A Mk 2B Mk 2C	12·5–13·0	0·20–0·25	2·0	0·35–0·45	..	0·4
Mk 2D	12·5–13·0	0·20–0·25	2·0	0·45–0·55	..	0·4
Maximum						
Mk 2A Mk 2B Mk 2C Mk 2D	12·5–13·5	0·20–0·25	..	Not greater than 0·65	Not greater than stem diameter	0·4
Minimum						
Mk 2A Mk 2B Mk 2C Mk 2D	12·5–13·5	0·20–0·25	..	0·35–0·45	Not greater than stem diameter	0·4

TABLE XI—RANGES AND TOLERANCES OF METEOROLOGICAL THERMOMETERS CONFORMING TO BRITISH STANDARDS[21]

Type	Filling	Range	Maximum allowable error: Below −38°F.	−38° to +32°F.	+32° to +80°F.	Above +80°F.	Maximum change of error in an interval of 20°F.: Below +32°F.	+32° to +80°F.	Above +80°F.
		°F.	°F.	°F.	°F.	°F.	°F.	°F.	°F.
Ordinary									
Mk 2A	Mercury	0 to +130	..	−0·5 to +0·3	−0·3 to +0·1	−0·3 to +0·1	0·4	0·2	0·2
Mk 2B	Mercury	−20 to +110	..	−0·5 to +0·3	−0·3 to +0·1	−0·3 to +0·1	0·4	0·2	0·2
Mk 2C	Mercury	−40 to + 90	..	−0·5 to +0·3	−0·3 to +0·1	−0·3 to +0·1	0·4	0·2	0·2
Mk 2D	Spirit	−60 to + 70	±1·0	±0·4	±0·2	..	0·4	0·2	..
Maximum									
Mk 2A	Mercury	+15 to +145	..	−0·5 to +0·3	−0·3 to +0·1	−0·3 to +0·1	0·4	0·2	0·2
Mk 2B	Mercury	0 to +130	..	−0·5 to +0·3	−0·3 to +0·1	−0·3 to +0·1	0·4	0·2	0·2
Mk 2C	Mercury	−20 to +110	..	−0·5 to +0·3	−0·3 to +0·1	−0·3 to +0·1	0·4	0·2	0·2
Mk 2D	Mercury	−40 to + 90	..	−0·5 to +0·3	−0·3 to +0·1	−0·3 to +0·1	0·4	0·2	0·2
Minimum									
Mk 2A	Spirit	−10 to +120	..	±0·4	±0·2	±0·4	0·4	0·2	0·4
Mk 2B	Spirit	−30 to +100	..	±0·4	±0·2	±0·4	0·4	0·2	0·4
Mk 2C	Spirit	−50 to + 80	±1·0	±0·4	±0·2	..	0·4	0·2	..
Mk 2D	Spirit	−90 to + 60	±1·0	±0·4	±0·2	..	0·4	0·2	..

From Tables X and XI it will be seen that the scale is such that there are less than 18°F./in. This is sufficiently open to allow the position of the end of the mercury column to be read to the nearest 0·1°F. The limitations on the rate of change of the error along the scale means that a reliable estimate of the required correction should be able to be made at any point on the scale. After application of the correction, the temperature recorded should represent the mean temperature of the thermometer bulb to an accuracy of $\pm 0 \cdot 1$°F. In the table it will be seen that greater negative errors are allowed than positive errors. This is because of the tendency of the zero of the mercury thermometer to rise on account of secular change in the glass. Negative errors will then tend to decrease and positive errors to increase.

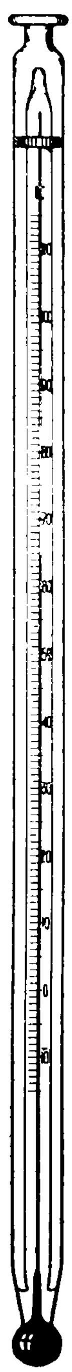


FIG. 40—ORDINARY SHEATHED THERMOMETER

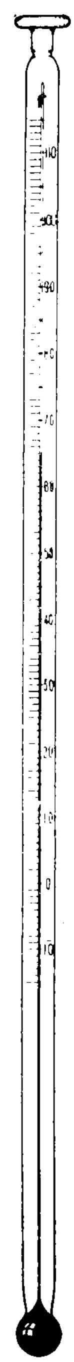


FIG. 41—ORDINARY SOLID-STEM THERMOMETER

Mounted solid-stem thermometers are stronger than sheathed thermometers, and for this reason they are generally used at sea. However, solid-stem thermometers, whether mounted or not, suffer from the disadvantage that the graduation marks are exposed to the weather and may deteriorate. Unmounted solid-stem thermometers are less expensive then sheathed thermometers but, in addition to the disadvantage just mentioned, they are more fragile.

Solid-stem thermometers (Mk 2A, Mk 2B and Mk 2C).—As a war-time substitute for the sheathed thermometers, a solid-stem thermometer (Fig. 41) was introduced. These thermometers conform to the details for solid-stem thermometers given in " Meteorological thermometers "[21]. They have no outer sheath and the ends of the thermometers themselves are finished in the form of a button. The diameter of the stem is increased and lies between 0·28 and 0·35 in.

These thermometers can be used in a Stevenson screen in place of the sheathed type. The graduation markings are exposed to the atmosphere, and consequently the blacking tends to wear out with use, but when necessary it can be renewed by rubbing the stem of the thermometer with shoemaker's " heel ball ", a dark-coloured crayon, or a black-lead pencil, and wiping off the surplus.

The temperature range covered (the solid-stem type Mk 2A, Mk 2B and Mk 2C correspond to the sheathed type Mk 2A, Mk 2B and Mk 2C), permissible errors at a point on the scale, permissible rate of change of error along the scale, and main dimensions of these thermometers are given in Tables X and XI.

Mounted thermometers (Mk 2A, Mk 2B, and Mk 2C).—For extra strength and robustness ordinary solid-stem mercury thermometers may be mounted on a plastic, porcelain or vitreous-enamelled-metal mount. These thermometers (Fig. 42) have spherical bulbs and the top of the stem is made in the form of a nib to fasten in the top of the mounting. They are used in the louvered screens installed aboard ships for the measurement of air temperature and also for measuring sea temperature (in conjunction with the earlier type of sea-temperature bucket).

There are 3 nominal ranges in use :—Mk 2A, 0° to +130°F. (Stores Ref., Met. 1213) ; Mk 2B, −20° to +110°F. (Stores Ref., Met. 1214) ; and Mk 2C, −40° to +90°F. (Stores Ref., Met. 1215). The last is limited at its lower end by the freezing point of mercury (−37·9°F.). The scale is engraved on the stem with graduation marks every 1°F. ; the graduation marks for every 10°F. are also reproduced and numbered on the mount, on the right-hand side of the thermometer stem. The graduation marks on the stem of the thermometer are always used in observing the units and tenths of a degree, the marks on the mount being used only for the ten's figure. If there is any slight discrepancy between the graduation marks on the mount and the corresponding marks on the thermometer stem, the mark of the stem should always be taken as correct. In addition to the normal graduation marks there are etched on the side of the stem, in very small numerals at the appropriate places, such of the following graduation marks as fall within the range of the thermometer :

−32°, −12°, 12°, 32°, 62°, 82°, and 112°.

These marks are used by the National Physical Laboratory when testing the thermometers, and can also be used to ensure that the thermometer has not been fixed to the wrong mount.

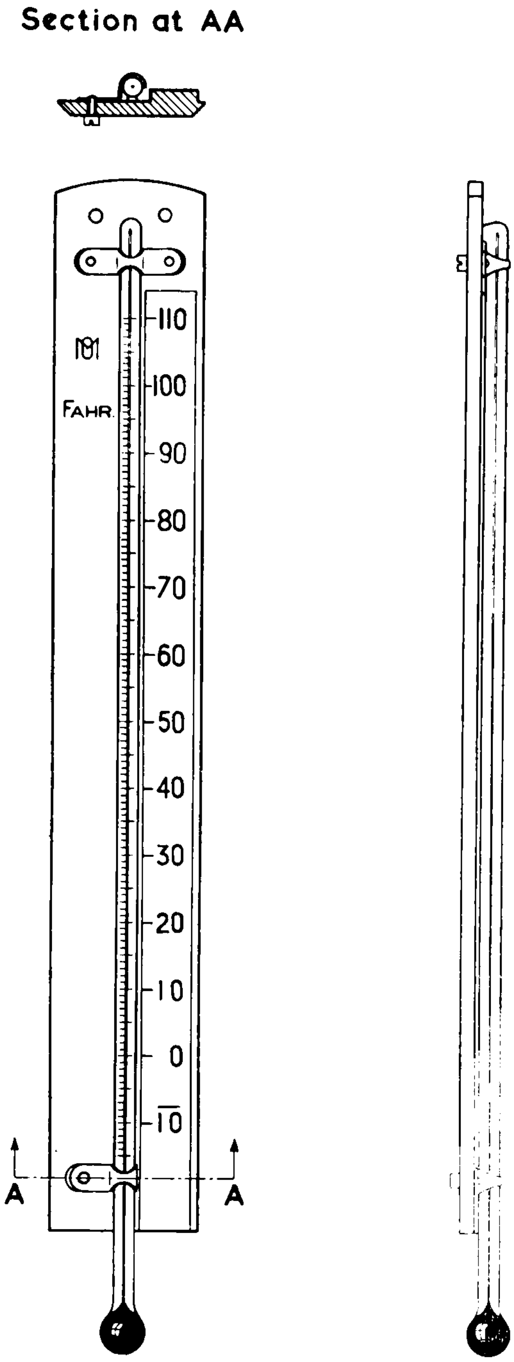


FIG. 42—PORCELAIN-MOUNTED THERMOMETER

The stem diameter is between 0·20 and 0·25 in. and the overall length of the stem and bulb does not exceed 10·8 in. Apart from these requirements the thermometers comply with the British Standard for meteorological thermometers, the essential requirements of which regarding scale value, errors, etc. are set out in Table XI.

Mounts.—The mounts may be made of white glazed porcelain, unbreakable plastic, or enamelled metal. They are rectangular in shape apart from a slightly curved top edge. The length of the mount is 9·55 ± 0·15 in., width 1·35 ± 0·05 in. and thickness 0·15 to 0·18 in.; the long edges are bevelled. Two clips of German silver hold the thermometer in position, and the nib at the end of the thermometer stem is let into a hole at the top of the mount and fixed with plaster of Paris. When the thermometer is in position the distance from the bottom of the mount to the bottom of the thermometer bulb is between 1·0 and 1·5 in. Two small holes are drilled in the top of the mount and are used in suspending it.

The graduation marks on these thermometers are exposed to the atmosphere and the blacking may need replacing at intervals using the method recommended for solid-stem thermometers.

Thermometers for Assmann psychrometers.—The thermometers used in Assmann psychrometers are mercury-in-glass thermometers with a cylindrical bulb and stem ; a flanged cylindrical brass cap is cemented on the top of the stem and a cylindrical brass sleeve near the bottom of the stem (Fig. 43). Both the sleeve and cap are chromium plated. There are two distinct patterns :

(i) One with a solid stem and an enamel back.

(ii) One with a stem of type (*e*) (see p. 104) mounted in a sheath which protects both the stem and scale.

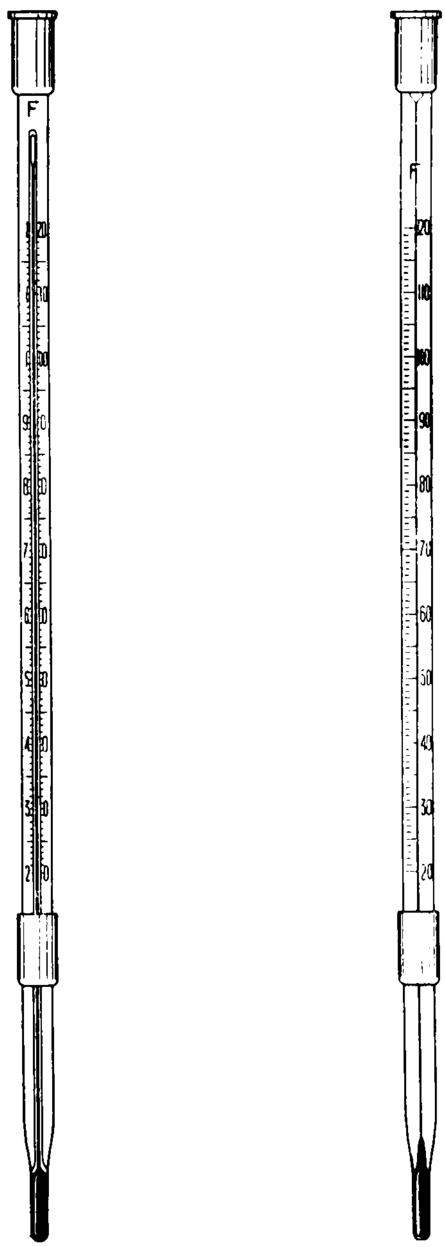


FIG. 43—ASSMANN THERMOMETERS

There are two different ranges, 0° to 100°F. (Type II) (Stores Ref., Met. 176 for both patterns) and 20° to 120°F. (Type I) (Stores Ref., Met. 582 and Met. 551 for solid-stem and sheathed type respectively). The graduation marks are for every 1°F. and are figured every 10°F. ; no graduation mark is hidden by the brass sleeve. Table XII gives the main dimensions, permissible errors at a point, and permissible rate of change of error in an interval.

TABLE XII—DIMENSIONS AND ALLOWABLE ERRORS OF THERMOMETERS FOR ASSMANN PSYCHROMETERS

Solid-stem and sheathed types I and II

Overall length	Diameter of stem or sheath	Diameter of bulb not exceeding	Length of bulb	Diameter of capillary stem pattern (ii)	Permissible error at a point		Permissible change in error in an interval of 20°F.	
					<32°F.	>32°F.	<32°F.	>32°F.
		inches			*degrees Fahrenheit*			
11·0 ±0·3	0·25 to 0·30	$\frac{3}{16}$	0·75 ±0·125	approx. $\frac{1}{16}$ in. outside diameter	+0·3 to −0·5	+0·1 to −0·3	0·4	0·2

The scale range of 100°F. is at least 6 in. in length (i.e. not more than 17°F./in.). This is the current specification ; some older thermometers may have a slightly more cramped scale. The sheathed type of thermometer also has a datum marking on the outside of the sheath directly in front of the 30°F. graduation (or 32°F. in the case of some older thermometers) ; this can be used to check that the position of the scale has not altered relative to the capillary tube. The brass sleeve is securely cemented to the stem or sheath of each thermometer in such a position that its upper edge is 8¼ in. (±1/16) from the upper edge of the cap. The external diameter of the sleeve and cap are such that they fit closely into place in the psychrometer.

3.2.3. Maximum thermometers

Sheathed maximum thermometers.—The principle of the maximum thermometer (Stores Ref., Mk 2A Met. 962, Mk 2B Met. 1016, Mk 2C Met. 963, Mk 2D Met. 1017) is described on p. 86. It is very similar in construction to the ordinary sheathed thermometer, but the diameter of the button on the end of the maximum thermometer is slightly larger than the diameter of the sheath. This helps in preventing the thermometer slipping off its stand in the Stevenson screen. Details of the dimensions, ranges, permissible errors at a point and the permissible rate of change of error along the scale are given in Tables X and XI. The range used should be chosen to suit the conditions expected. The graduation marks are similarly spaced and figured to the ordinary thermometer, but the figures appear upright when the thermometer is in a horizontal position, with the bulb on the left (Fig. 44). The figures are placed symmetrically about the line to which they refer.

The mercury column of some maximum thermometers is liable to run up the bore a little when the thermometer is lying at its normal slope in a Stevenson screen. Some thermometers do this under vibration even when they do not do it without

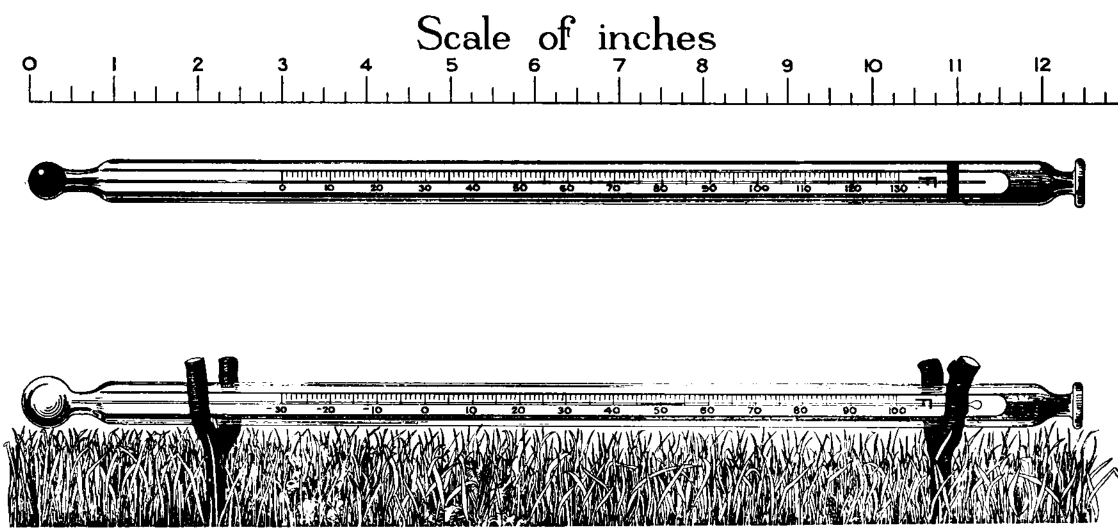


FIG. 44—SHEATHED-PATTERN MAXIMUM AND MINIMUM THERMOMETERS

vibration. It may be due to surface tension, but the result is that the readings, if taken in the normal manner, may be up to $\frac{1}{2}$°F., or even more, above the true reading. Each maximum thermometer should be tested, preferably on an overcast morning with some wind, by noting the reading after setting, to the nearest 0·1°F., while the thermometer is still held in a vertical position, bulb downward. It should then be replaced in the screen, taking care to keep the bulb always below the stem of the thermometer, and the door of the screen opened and closed once or twice in the usual manner so that the thermometer is exposed to a normal amount of vibration. If, after observing the reading of the thermometer without moving it, the reading has risen by more than 0·1° or 0·2°F. and the dry bulb shows that this is not due to a rise in temperature, this will demonstrate that the mercury column has risen, due to the effect mentioned above. To obtain correct readings from thermometers which show this fault the thermometer should be removed from the stand and tilted slowly until the bulb is about 6 in. below the opposite end, and then the reading taken. This will ensure that the mercury column has run back to the constriction.

Setting of maximum thermometers.—Difficulty is experienced by the manufacturers in making the constriction of exactly the right size, and if it is too wide the thermometer acts as an ordinary thermometer. As a result the constriction of a maximum thermometer is often on the small side and difficulty will be experienced in setting it. If maximum thermometers are reset as follows it will be found that even with a narrow constriction the mercury column can then be reset without undue strain. Fig. 45 illustrates the recommended way of holding the thermometer. The motion should be a steady swing backwards and forwards, not sideways, and without any jerking. This should be done in a place free from obstructions. The mercury column should be as close to the bulb as possible, i.e. resting against the constriction, at the beginning of the swing. If it is not it may strike violently against the constriction when the thermometer is swung and cause damage to the stem at that point. A tiny crack can occur which does not reach the surface, but which may be sufficient to cause the thermometer to act partially as an ordinary thermometer when the temperature falls.

The maximum thermometer in use should be tested periodically, to see that the mercury column does not in fact retreat through the constriction when the temperature falls, by warming the thermometer, noting the temperature reached and leaving it in a horizontal position. Any change in reading can then be seen. It is always important to check that the reading of the maximum thermometer is at least as high as the highest dry-bulb reading recorded since the thermometer was last set. After setting, the reading of the maximum thermometer should be compared with the dry-bulb reading ; the difference should not exceed 0·4°F.

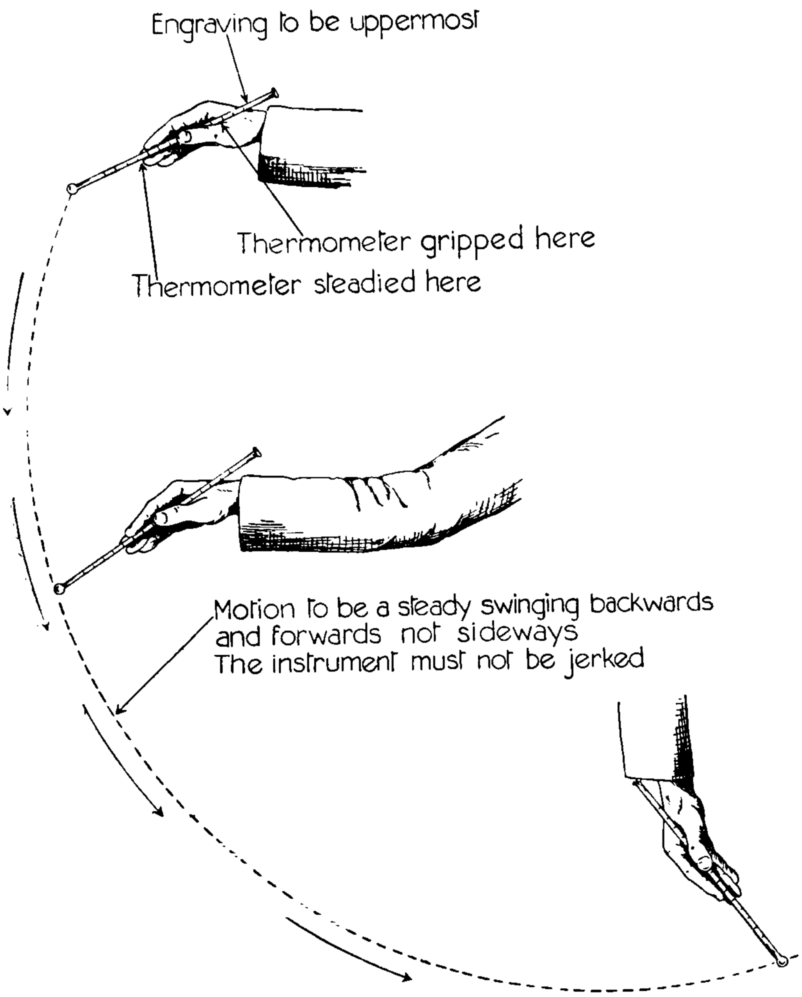


FIG. 45—SETTING THE MAXIMUM THERMOMETER

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

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

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

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

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

Solid-stem maximum thermometers.—The solid-stem maximum thermometer was introduced as a substitute for the sheathed type during war time. It is not now recommended for use. Its specification is based on the sheathed maximum thermometer (see p. 115), except that the thermometer is not provided with a sheath and the stem diameter is increased to lie within 0·28 and 0·35 in. The end of the thermometer itself is made into the form of a button.

The range normally used is 0–130°F. The blacking in the graduation marks may need renewing after a long period of use ; this can be done in the way described for the ordinary solid-stem thermometers (p. 112). These thermometers are used in the Stevenson screen in exactly the same way as the sheathed types, and similar methods of checking the readings should be used.

Special care must be taken in resetting these thermometers as they are very liable to break at a point just above the bulb. The instructions given above should be carefully followed, especially with regard to the method of holding the thermometer and the absence of jerking.

Errors in maximum thermometers due to change in temperature since the maximum.—The length of the mercury column above the constriction will contract when the temperature falls from the maximum, and this will introduce a slight negative error. The magnitude may be calculated from the formula for the error due to the emergent stem of a mercury thermometer. Suppose the maximum temperature were 80°F. and the air temperature only 60°F. when the maximum was read. The length of the mercury above the constriction would vary slightly with different thermometers but would be equivalent to about 95°F. The resultant error would then be :

$$\begin{aligned} \text{error} &= -\,95 \times 20 \times 0{\cdot}00009 \\ &= -\,0{\cdot}17°\text{F}. \end{aligned}$$

This utilizes equation (32), putting a value of 0·00009 for $(\gamma_l - \gamma_g)$. The error is thus usually small, even in extreme conditions.

3.2.4. Minimum thermometers

The principle of minimum thermometers is outlined on p. 86. The several special types of error peculiar to spirit thermometers were also outlined earlier. A broken liquid column can usually be remedied by holding the thermometer with the bulb downward and tapping lightly and rapidly against the fingers or something elastic and not too hard. This should be continued for some time (5 minutes or more if necessary), and afterwards the thermometer hung with the bulb downward for at least an hour to allow any spirit adhering to the glass to drain down to the main column. If this treatment is not successful a more drastic method is to cool the bulb in crushed solid carbon dioxide, or in a freezing mixture of ice and salt, while keeping the upper part of the stem warm. The liquid will then slowly distil back to the main column. The use of solid carbon dioxide will be the quicker way.

These thermometers are also exposed just above a grass-covered earth surface in the open to obtain the " grass minimum temperature ". This approximates to the minimum temperature of the surface of the earth throughout the period (which is mainly a night period).

Sheathed minimum thermometers.—The sheathed minimum thermometers (Stores Ref., Mk 2A Met. 1018, Mk 2B Met. 1019, Mk 2C Met. 964, Mk 2D Met. 965) are the standard types of minimum thermometer in use in the Meteorological Office, and in general construction they conform with the other sheathed thermometers (Fig. 44). Details of the dimensions, graduation markings, ranges, permissible errors at a point, and permissible rate of change of error along the stem are given in Tables X and XI. One main difference between these thermometers and the mercury sheathed thermometers is that an elongated safety chamber is provided, so that the temperature of the thermometer may be raised to 120°F. without damage. This is necessary if the thermometer is to be used as a grass minimum thermometer. The bulbs on these thermometers are larger than the bulbs on the ordinary and maximum thermometers, and this, together with the fact that the alcohol has a much lower thermal conductivity than mercury, means that the lag of the thermometer is appreciably greater than the other sheathed types. This is not a serious drawback as the rate of change of temperature is usually small near the minimum temperature.

When replacing the thermometer in the screen it should be inserted stem first and the bulb should be kept higher than the stem during the process. As with the maximum thermometers after resetting, the temperature indicated should not differ by more than 0·4°F. from the dry bulb. If the instrument is reading low it is probable that some of the spirit has passed to the top of the stem. This should be remedied as set out above. The notes dealing with discrepancies between the readings of the maximum and minimum thermometer and the readings of the dry bulb over the same period (p. 117) should be carefully studied.

Use as a grass minimum thermometer.—The sheathed minimum thermometer can be exposed as described on p. 101 for use as a grass minimum thermometer (Fig. 44). Normally it is exposed at sunset, the readings taken next morning and then the instrument brought under shelter during the day. If it is exposed to strong sunshine so that its temperature rises to well above the air temperature, the spirit tends to distil and collect in the top of the bore. This however can be prevented by the use of a black metal shield (Stores Ref., Met. 2739) placed over the outer sheath of the thermometer at the end remote from the bulb. The shield absorbs more heat from the sun than the rest of the thermometer and consequently reaches a higher temperature. Vapour is thus prevented from condensing in the upper part of the bore, and any vapour which has already condensed there evaporates and condenses lower down the stem at the top of the spirit column. When using this device the time of resetting the thermometer (normally at the time of the last observation before sunset) is not altered, but the thermometer can be left in position throughout the day. The metal sheath should be repainted with black paint as required. If the thermometer is brought under cover during the day it is wise to construct a special bracket for it inside the Stevenson screen, so that the thermometer can be placed somewhere definite each day and be in safety. This bracket should support the thermometer in a vertical position, with the bulb downwards.

Solid-stem minimum thermometer.—The solid-stem minimum thermometer was a war-time substitute for the sheathed type. It is not now recommended for use. Its specification is based on that for the sheathed type (see p. 119) except in the following main features. The thermometer is not protected by a glass sheath, the stem diameter is enlarged and lies between 0·28 and 0·35 in. The end of the thermometer itself is formed into a button. As the stem is not enclosed in a sheath and the graduation marks are exposed to the atmosphere, this thermometer should not be used as a grass minimum thermometer. After a period of use the blacking may need to be renewed; this should be done in the manner described earlier (p. 112).

The breaking of the spirit column should be dealt with in a similar manner to that described for the sheathed minimum thermometer, but greater care should be taken in tapping the thermometer, as it is weaker than the sheathed type.

3.2.5. Earth thermometers

Ordinary earth thermometer Mk 1 (Symons pattern).—The Symons earth thermometer (Stores Ref., Met. 258) consists of a mercury-in-glass thermometer enclosed in a glass tube, and is designed to be suspended in an earth thermometer tube (Fig. 36). The scale covers a range from 20° to 100°F., with graduation markings every 1°F., enumerated every 10°F., and a spacing of not more than 12 degrees to the inch. This makes it easy to read to the nearest 0·1°F. An expansion chamber is provided at the top of the stem.

The permissible errors at any point on the scale are ±0·4°F. for temperature below 32°F. and ±0·2°F. for temperature between 32° and 100°F., while the maximum change in error in an interval of 10°F. should not exceed 0·2°F. below 32°F. and 0·1°F. above 32°F.

The thermometer is mounted centrally inside a case of stout glass tubing. Its bulb is embedded in a layer of paraffin wax, and the centre of the bulb is ½ in. above the base of the tube; the wax extends to a distance of 1½ in. above the base of the tube. To the upper end of the thermometer stem is fused a piece of glass tubing with a bulb-shaped end, which is also fused to the outer tube. This fixes the thermometer rigidly in position. A plug made of rosewood is attached to the top of this assembly by means of a piece of rubber tubing, which is bound in position with copper wire. A brass screw eye is fitted to the top of the wooden plug and is used to attach the thermometer to the fitting of the earth tube. Two rubber rings fit tightly around the outer tube to prevent damage to the thermometer when it is being inserted and withdrawn (see Fig. 36).

The large lag coefficient caused by the layer of wax surrounding the thermometer bulb ensures that the change of temperature of the thermometer during reading is very small. This large lag coefficient can be tolerated because the rate of change of temperature of the earth at depths of 1 ft. or more is very slow. When making an observation the thermometer is withdrawn and read quickly to the nearest 0·1°F., the thermometer tube meanwhile being kept in the shade.

Right-angled earth thermometers Mk 1A, Mk 1B, Mk 1C.—For measuring earth temperature at shallower depths, mercury-in-glass thermometers with the stem bent at right angles below the lowest graduation are used (Fig. 36). The bulb can be sunk into the ground to the required depth, and the scale read with the thermometer *in situ*.

The bulb is spherical with an outside diameter of $0\cdot50\pm0\cdot05$ in., and the stem is $0\cdot25\pm0\cdot05$ in. in diameter. The curve in the stem has a radius of about 1 in.; with curves of smaller radius the chance of breakage would be much increased. The dimension D in Fig. 36 (the distance from the centre of the bulb to the underside of the horizontal portion of the stem) is 4 in., 8 in., or 2 in. according as to whether the thermometer is a Mk 1A (Stores Ref., Met. 259), Mk 1B (Stores Ref., Met. 468), or Mk 1C (Stores Ref., Met. 710) respectively. A distance of at least 1 in. is left between the beginning of the right-angled bend and the first graduation mark. The range of the thermometer is from 20° to 100°F., with graduation marks every 1°F., enumerated every 10°F., and with the graduations spaced so that there are no more than 18 degrees to the inch. These thermometers are not graduated for total immersion, as are all the other thermometers described, but only for immersion up to the beginning of the right-angled bend (i.e. for an immersion of (D − 1) in.). The remainder of the thermometer is kept at air temperature. A safety chamber is provided at the end of the stem. The permissible errors at a point and the permissible rate of change of error along the scale are the same as those for the earth thermometer (ordinary) Mk 1 (p. 120).

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

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

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

The site for the thermometers should be a level piece of bare ground about 2 ft. 6 in. square, typical of the surrounding soil for which information is desired; weeds should be removed by hand from the site as they appear. In the event of a snowfall the snow should be removed to take the readings and afterwards replaced.

With a crow-bar or other convenient instrument holes should be drilled at the centre of the site rather more than 2 in., 4 in., or 8 in. deep, as required. A little fine soil should be placed at the base of each hole, the exact amount being adjusted so that, when the thermometer bulb in each case rests at the bottom of the hole, the horizontal, graduated portion of the stem is in contact with the surrounding soil. The hole can then be carefully filled with soil, remembering that the bulb is very fragile. A shallow, narrow trench should then be made beneath the horizontal part of the stem by scooping out a little of the soil; the clear space should be between ⅛ in. and ½ in. deep. Once installed the thermometer should not be disturbed.

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

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

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

The thermometer is calibrated with the stem at room temperature, but at times, in very bright sunshine especially, the temperature of the stem is markedly different from that. The resultant " emergent stem " error can be calculated from equation (32). If the earth temperature is 45°F. a length of mercury column equivalent to about 65°F. is exposed ; if the stem temperature is 120°F. and it was calibrated at a temperature of 60°F. the error is

$$- 65 \times 60 \times 0{\cdot}00009 = - 0{\cdot}35°\text{F.}$$

This is an extreme case, but it shows that the error may become appreciable, as temperatures are measured to the nearest 0·1°F.

3.2.6. Thermometer protectors (air)

The thermometer protector (Stores Ref., Met. 404) is used as a protective support for the porcelain or enamelled-metal-mounted thermometer (Fig. 46) ; it is particularly useful for mounting these thermometers in screens for use on ships. It consists of a recessed mahogany stock provided at the base with a brass guard. The thermometer mount rests with its base on a brass support on the bottom of the stock, and it is held at its upper end by means of a brass clamping plate, which is screwed to a metal fitting passing over the top of the stock. A spring is attached to the clamping plate to grip the mount firmly. When the thermometer has to be removed for any reason the clamping plate should first be taken out by unscrewing the two fixing screws.

The guard is made of brass strip ; it consists of two U-shaped main pieces attached to the base of the stock and strengthened by transverse strips. The protector may be suspended by a brass hook attached to the top of the stock.

3.2.7. Inspector's thermometers

It was mentioned on p. 105 that all liquid-in-glass thermometers experience gradual changes of zero. For this reason it is desirable to check them against an inspector's thermometer about once every two years. Two types of inspector's thermometer are used in the Meteorological Office—the ordinary inspector's thermometer (Stores Ref., for range 30° to 80°F. Met. 425, for range 50° to 100°F. Met. 576) and the inspector's soil thermometer (Stores Ref., Met. 528) with vulcanite tube (Stores Ref., Met. 529) and with steel pin (Stores Ref., Met. 530).

Inspector's ordinary thermometer.—This is a mercury-in-glass thermometer graduated in fifths of a degree and covering the range 30° to 80°F. for the ordinary pattern and 50° to 100°F. for the tropical pattern. Inspector's thermometers held at Meteorological Office outstations will be recalled for re-calibration about once every five years.

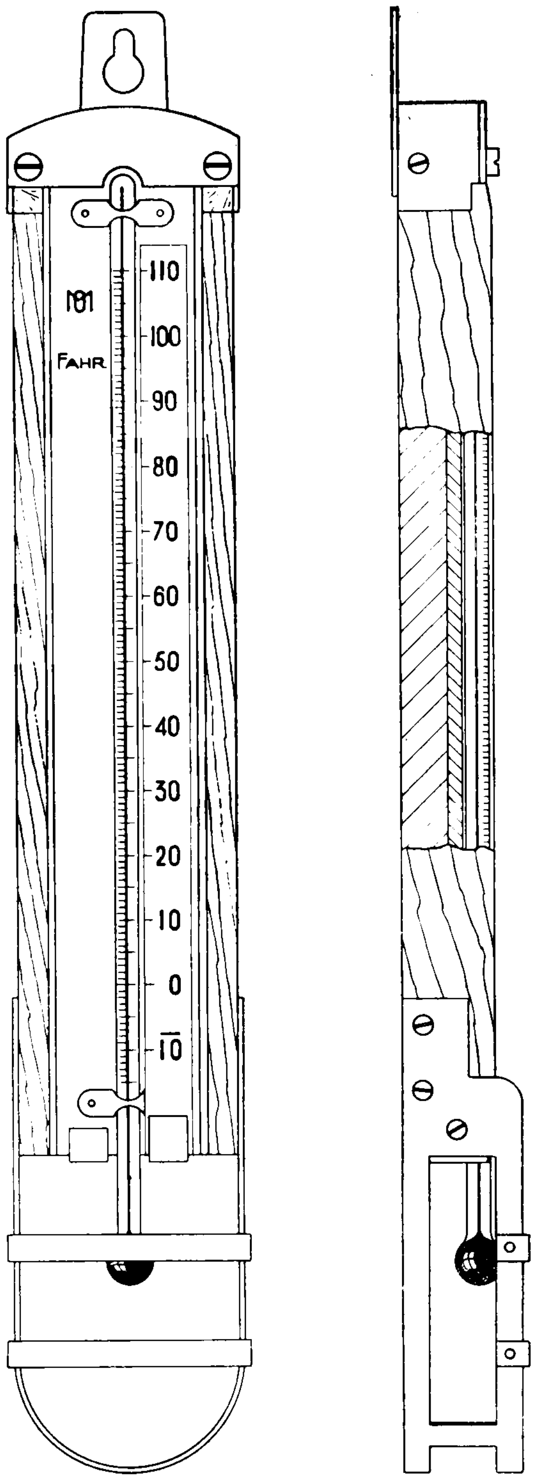


FIG. 46—AIR THERMOMETER PROTECTOR

This inspector's thermometer is used for checking all liquid-in-glass thermometers, including the earth thermometer but excluding the bent-stem soil thermometer. The check is carried out by immersing the inspector's thermometer and the thermometer, or thermometers, to be tested in a deep vessel of water ; it is generally better to work indoors especially if the sun is shining.

All the thermometers to be tested should be placed in the water which should be as nearly as possible at room temperature, and earth thermometers should be carefully arranged so that the bulbs are at about the depth at which the inspector's thermometer will be during the test. Earth thermometers should be left for at least 30 min. to allow the wax in which the bulbs are embedded to take up the temperature of the bath. Each thermometer should then be taken in turn with the inspector's thermometer and the two held with their bulbs close together and moved backwards and forwards through the water for about a minute and then read. It must be possible to read both thermometers without changing depth of immersion —subject to this the bulbs should be as deep in the water as possible. Most Meteorological Office thermometers are calibrated for total immersion, but provided the difference between the temperature of the water and the temperature of the air is not more than 10°F. the emergent stem correction is trivial. Usually, with the bulbs at the same depth, the tops of the columns of spirit or mercury will not be very close together. Particular care should therefore be taken to avoid errors of parallax. These comparisons should be made at least three times for each thermometer and the means of the three readings should be taken.

The correction for ordinary mercury-in-glass thermometers should not differ from the National Physical Laboratory figure by more than 0·2°F. If the difference is greater than this the thermometer should not be used for accurate (e.g. psychrometric) work until it has been re-calibrated.

When testing a maximum thermometer care must be taken that the mercury column has been properly shaken down to the temperature of the bath. A simple and effective means of securing this is to immerse the bulb of the thermometer in the bath for a minute or two, then remove the thermometer from the bath and hold it at arm's length, wave it vigorously for several seconds so as to cause the thermometer to act as a wet bulb, and therefore to reduce its temperature below that of the bath and at the same time to shake down the mercury. Then place the bulb in the bath again and note that the mercury initially rises. The correction should not differ from the National Physical Laboratory correction by more than 0·3°F. The maximum thermometer should be cooled down as described above before each of the three, or more, comparisons.

If a spirit thermometer reads too low it should be examined carefully for detached droplets of spirit in the upper part of the tube, and if these are there they should be shaken down. After this has been done the correction should not differ from the National Physical Laboratory correction by more than 0·5°F.

The large lag of the earth thermometer makes it difficult to get a good calibration check unless the temperature of the water can be held very steady. If the test is carefully made in water whose temperature is not changing by more than 2°F. in 30 min. the correction should not differ from the National Physical Laboratory certificate by more than 0·3°F.

A minus correction of a spirit thermometer or a plus correction of a mercury thermometer should lead one to suspect the comparisons and these should therefore be repeated.

Inspector's soil thermometer.—The testing of 2-in., 4-in. and 8-in. right-angle soil thermometers is difficult, but they can be tested *in situ* by inserting in the ground near to them the inspector's special soil thermometer which has an armoured bulb and marks engraved on the vulcanite tube at distances of 2, 4 and 8 in. from the bulb. A steel pin is provided for making the necessary hole in the ground and it may be necessary to hammer this pin in. The armoured thermometer should be pushed carefully and vertically into the ground about an inch away from the point where the 4-in. thermometer enters the ground until the 4-in. mark on the inspector's thermometer is flush with the ground surface. The 2-in., 4-in. and 8-in. thermometers should be read. Water at a temperature about the mean of the three, should be poured gently so that it will run into the ground along the thermometer stems. When the conditions are steady, the armoured and 4-in. thermometers should be read. The inspector's thermometer should then be inserted an inch away from the 8-in. thermometer until the 8-in. mark on the inspector's thermometer is flush with the surface, and a comparative reading obtained. The 2-in. thermometer should then be tested in a similar way.

If the apparent index correction of a soil thermometer exceeds half a degree, the thermometer should be removed and tested in water. If the existence of such an error is confirmed by the water test, the stem should be examined for gaps in the mercury column, and any such gaps should be eliminated by shaking. If the index correction cannot be reduced to less than 0·2°F., the thermometer needs replacement.

3.3. ELECTRICAL RESISTANCE THERMOMETERS

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

i.e. $$r_T = r_0 \{1 + a(T - T_0)\} \qquad \ldots\ldots(33)$$

where r_T is the specific resistance at temperature T, r_0 is the specific resistance at some standard temperature T_0 and a normally lies between 0·0021 and 0·0031/°F. For large intervals of temperature and for some alloys a more exact relationship must be used

i.e. $$r_T = r_0 \{1 + a(T - T_0) + b(T - T_0)^2\}. \qquad \ldots\ldots(34)$$

The constants, a and b, for any particular resistance element are determined by calibration.

Table XIII shows representative values of r_0 (at 18°C.) and corresponding values of a (equation (33)) for some common metals and alloys.

TABLE XIII—VALUES OF THE SPECIFIC RESISTANCE AT ROOM TEMPERATURE AND THE TEMPERATURE COEFFICIENT OF RESISTANCE OF SOME COMMON METALS AND ALLOYS

Substance	$r_0 \times 10^6$	$a \times 10^4$/°F.	Substance	$r_0 \times 10^6$	$a \times 10^4$/°F.
	ohm cm.			ohm cm.	
Silver	1·63 to 1·66	+22	Iron	12 to 45	+34
Copper	1·59 to 1·78	+24	Constantan ..	49	−0·2 to +0·06
Platinum ..	11·0	+21	Manganin ..	42 to 44	+0·01 to +0·3
Nickel(electrolytic)	9 to 11	+34	Nichrome ..	110	+0·9

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

Another type of resistance element which can be used is a thermistor, which is made from mixtures of various metallic oxides, compressed together and heat treated in various ways. These have a very high negative temperature coefficient of resistance. In general the resistance, R, of a thermistor can be expressed by the equation

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

where a and b are constants and T is the absolute temperature of the thermistor. They can be obtained in the form of small beads, rods or blocks.

Their advantages from the thermometric point of view are :

(i) Their change in resistance with temperature is much larger than that of metals ; thus a typical element has a resistance of 100 ohms at 100°F., 1,500 ohms at 0°F. and 56,000 ohms at −100°F. Also the percentage change in resistance given by

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

at about 50°F. is 2·5 per cent./°F. compared with 0·21 per cent./°F. for platinum. This enables the voltage across a Wheatstone bridge to be reduced for a given sensitivity. The effect on the temperature measurement of a change in temperature (and thus a change in resistance) of the leads to the thermometer element is also much reduced, and in most meteorological cases would be negligible.

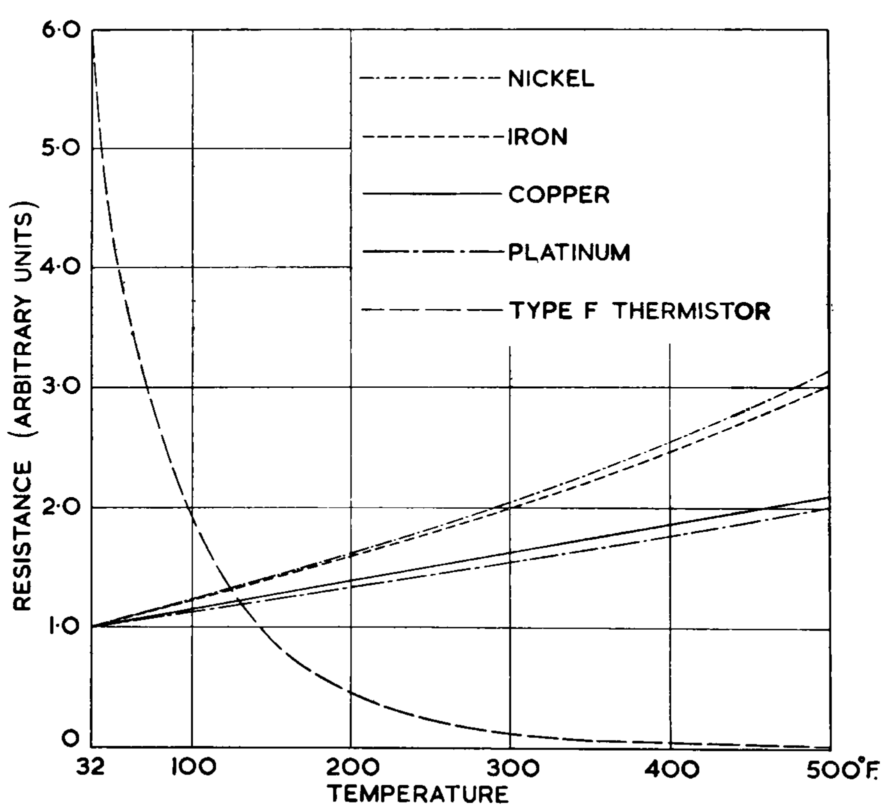


FIG. 47—VARIATION OF RESISTANCE WITH TEMPERATURE

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

The change in resistance with temperature for some metals and for a typical thermistor is shown in Fig. 47.

3.3.1. Construction of resistance elements

Resistance thermometer elements usually consist of a coil wound on an insulating former and protected by a sheath of suitable shape and size. For meteorological work the sheath should be weatherproof to protect the winding. If a very small lag coefficient is required, a thin wire stretched on an insulating frame in the open can be used. This is practically insensitive to radiation, but only small currents should be used or the self-heating effect would be appreciable. The heating effect varies sharply with the wind speed, and can be used to measure the wind (p. 200).

Meteorological Office aircraft resistance thermometer element Mk I.— The Meteorological Office aircraft resistance thermometer element (Stores Ref., Met. 2732) as described by Brewer[22] is used in conjunction with the balanced-bridge air thermometer indicator for measuring air temperature (Fig. 48). Although it is mainly used on aircraft it may have other applications. The element consists of a platinum resistance wire wound on a flat rectangular mica former stiffened by two copper strips, which also act as the leads to the end of the resistance wire. This assembly is then covered with thin mica strips for electrical insulation and is finally inserted into an outer metal bulb. The bulb is flattened to exclude as much air as possible and is soldered on to a flange, and the whole assembly is mounted

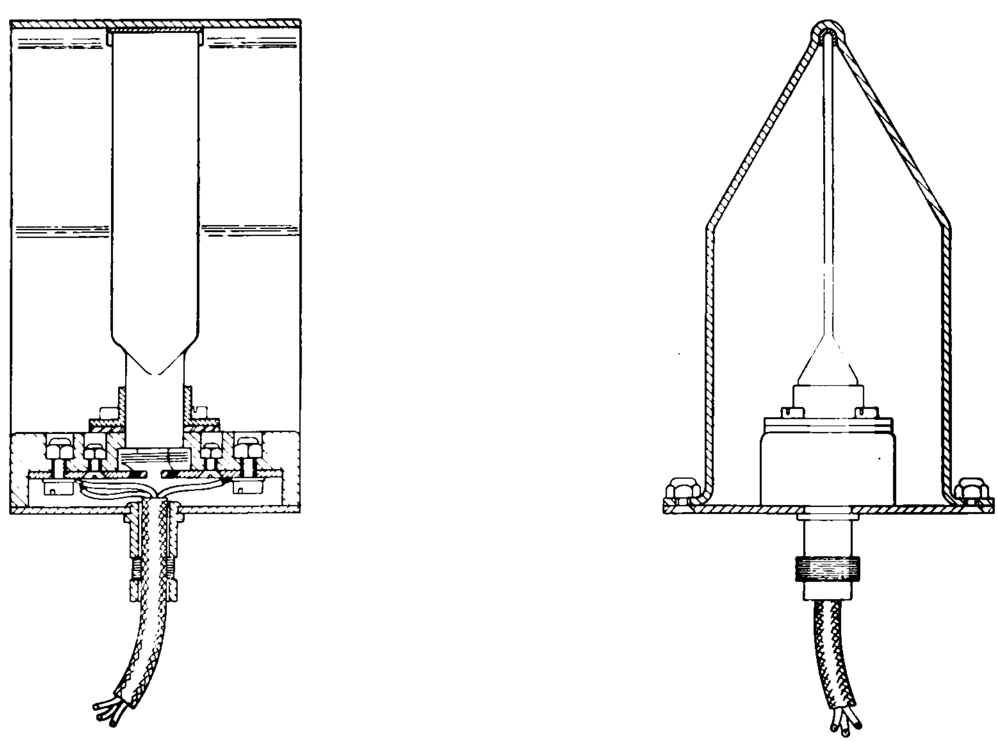


FIG. 48—METEOROLOGICAL OFFICE AIRCRAFT RESISTANCE THERMOMETER ELEMENT MK I

on a connector block. One end of the copper strip from the platinum element is soldered to one brass connector, while the other copper strip is soldered to a length of eureka wire (a ballast resistance which can be used to adjust different batches of platinum wire to the same temperature-resistance law) and thence to the other brass connector.

Each element is provided with 3 ft. of three-core cable, which enters through the base plate of the assembly *via* a ferrule and thence to the brass connectors. The blue and green covered wires of the cable are connected together and joined to one brass connector and the red wire to the other. The cavity in the base of the connecting block is then filled with an insulating material, to prevent water reaching the electrical circuit. The ferrule is securely pressed into position and finally rivetted ; it has a flared end to prevent chafing of the cable. A radiation shield made of aluminium supports the element at its other end.

The resistance of the element at various temperatures is given in Table XIV ; the tolerance at each temperature throughout the range is $\pm$ 0·2 ohm. Details of its installation and its use as a wet-bulb element on aircraft will be found in later parts of this Handbook.

TABLE XIV—STANDARD VALUES OF THE RESISTANCE OF THE METEOROLOGICAL OFFICE AIRCRAFT RESISTANCE THERMOMETER ELEMENT MK I

Temperature	Resistance	Temperature	Resistance
°F.	ohms	°F.	ohms
−110	77·30	+ 10	105·03
− 90	81·97	+ 30	109·55
− 70	86·63	+ 32	110·00
− 50	91·25	+ 50	114·04
− 30	95·87	+ 70	118·55
− 10	100·46	+100	125·25

Coiled electrical resistance thermometer element.—The coiled element (Plate XI) is made of platinum wire, wound in the form of a coil about 1·3 in. long and 1·5 in. in diameter.

3.3.2. Measurement of resistance

At present there are two main types of circuit with which the resistance thermometer element is used ; the balanced-bridge and the cross-coil or ratiometer circuits. A typical balanced-bridge circuit is shown in Fig. 49 ; by a suitable

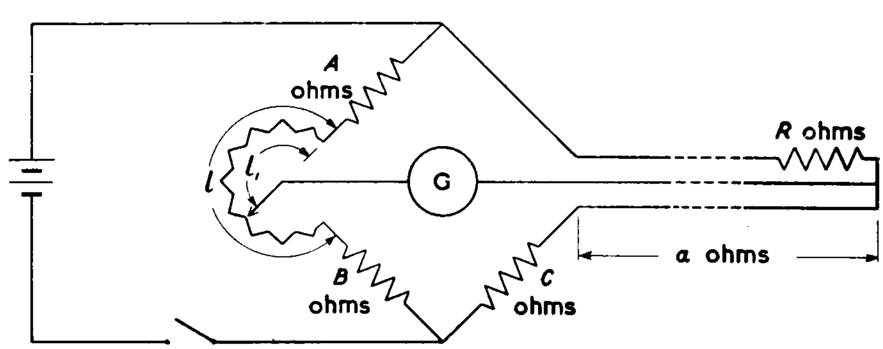
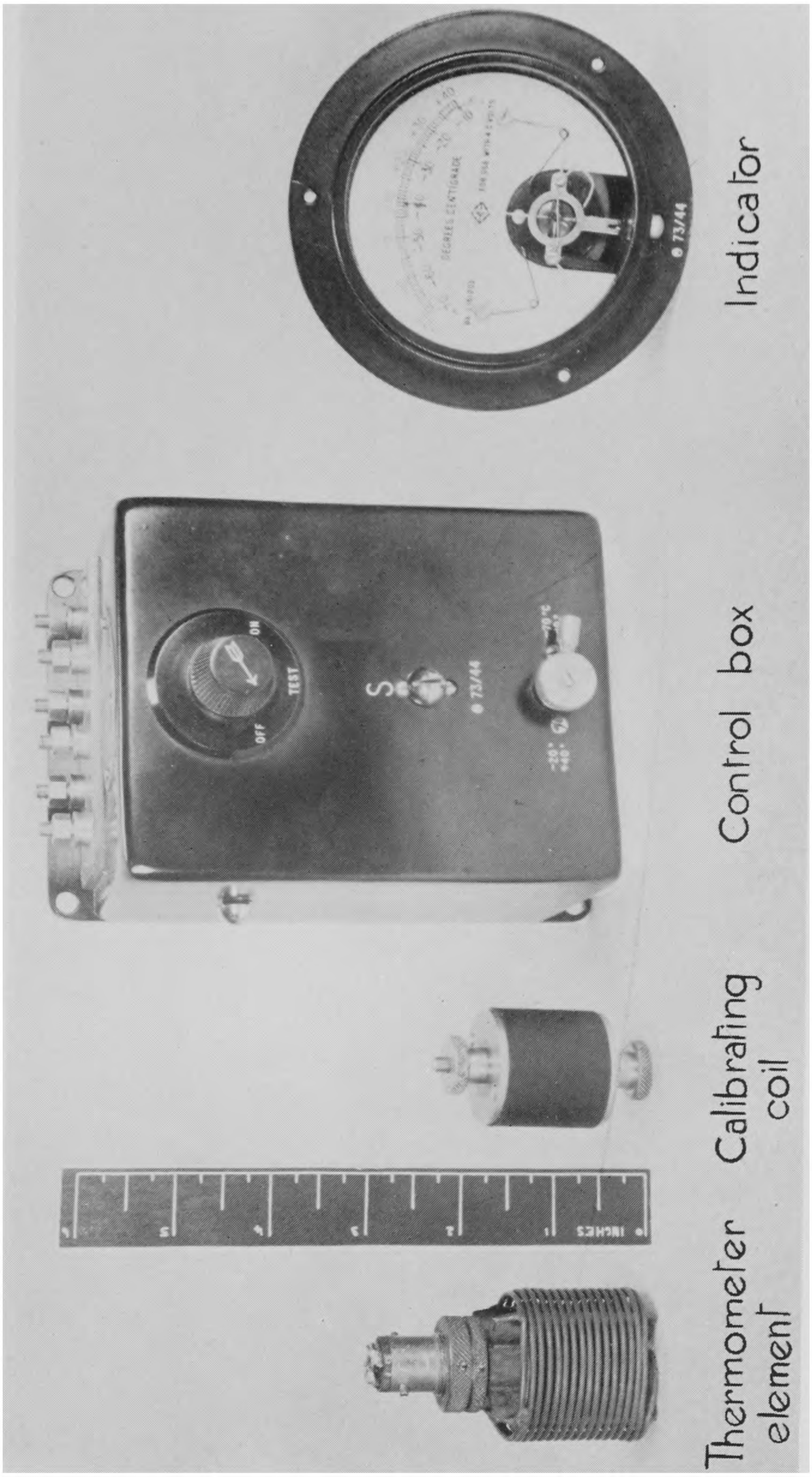
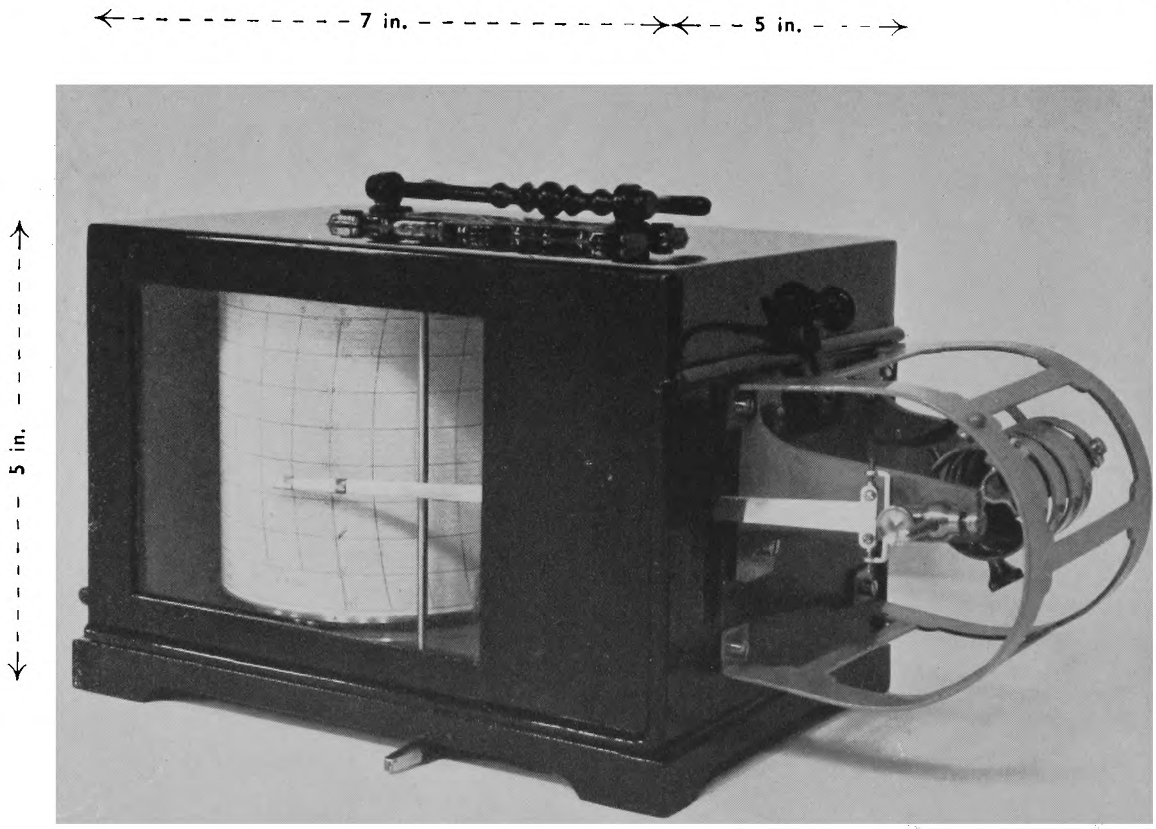


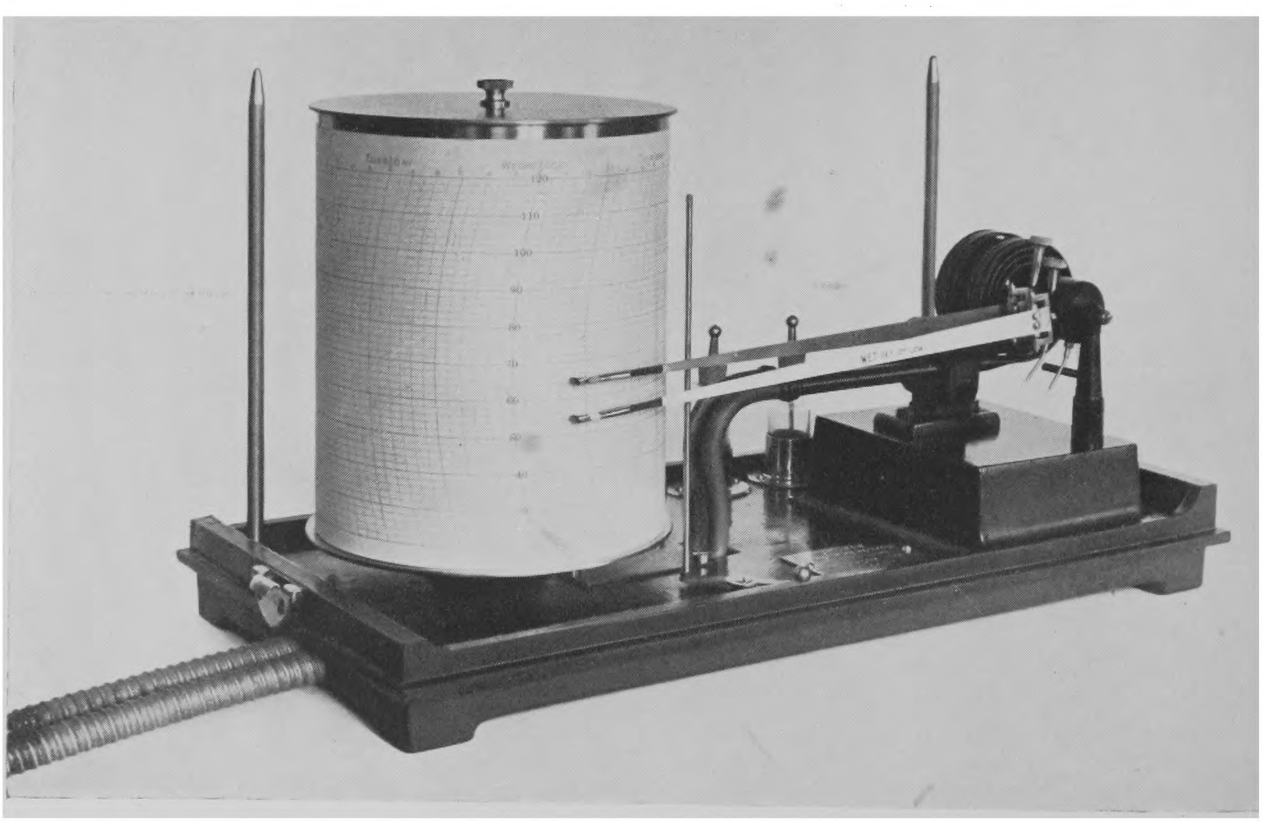
FIG. 49—BALANCED-BRIDGE CIRCUIT FOR MEASURING RESISTANCE WITH THREE-LEAD COMPENSATION



COILED ELECTRICAL RESISTANCE THERMOMETER MK II



METEOROLOGICAL OFFICE BIMETALLIC THERMOGRAPH MK II



MERCURY-IN-STEEL THERMOGRAPH, DRY AND WET BULB adjustment of the contact on the slide wire the current through the galvanometer, G, can be reduced to zero. If l is the total length of the slide wire of resistance S, then the resistance of a length l_1, in the arm A, is $(l_1/l)S$. As, in general, the resistance of the leads to the thermometer element is appreciable and changes with temperature, a three-lead compensation circuit is often employed (as in Fig. 49) ; the galvanometer is connected directly to one end of the thermometer element so that the other two leads (of resistance a) are then in different arms of the bridge.

When the bridge is balanced the following relation holds :

$$\frac{A+\left(\frac{l_1}{l}\right)S}{B+\left(\frac{l-l_1}{l}\right)S}=\frac{R+a}{C+a}$$

$$= k \text{ (say).}$$

A, B, C and R are the values of the resistances shown in Fig. 49, R being the resistance of the thermometer element,

i.e. $$R = kC + (k-1)a.$$

The position of the contact gives the value of k.

When $k = 1$ the resistance of the leads has no effect on the point of balance and the compensation is perfect ; as A is normally made equal to B this is when the contact is in the centre of the slide wire. At other points of contact the compensation is not perfect. With a platinum resistance thermometer element, k could vary from about 0·79 to about 1·27 for an interval of temperature from $-110°$ to $+100°$F. If T is the temperature of the element as indicated by the position of the contact on the bridge wire the value of $\partial T/\partial a$ is $(k-1)\ \partial T/\partial R = 4{\cdot}45\ (k-1)$°F./ohm for a platinum resistance element of resistance 110 ohms at 32°F. The maximum value of this is about 1·1°F/ohm change in resistance of the leads, for the values of k given above. Twelve feet of copper cable, of the type normally used in connecting the resistance elements, has a resistance of about 0·1 ohm, which may change by about 0·05 ohm for a change in temperature of 180°F. ; this corresponds to a maximum temperature error of about 0·06°F. Thus, for meteorological instruments in which this form of circuit is used, no significant error will arise from changes in temperature of the leads provided the length of the leads is kept reasonably short.

A more serious error could arise if a different length of cable from that for which the instrument was calibrated were actually used in connecting the resistance element to the remainder of the instrument. To keep the error from this cause to within a maximum of $\pm$ 0·10°F. the length of cable should not differ by more than 12 ft. from the standard length, assuming the cable resistance to be about 1/120 ohm/ft.

The four-lead circuit shown in Fig. 50 is sometimes used. A Wheatstone bridge circuit can also be used by omitting the slide wire and measuring the out-of-balance current through the galvanometer. This current will bear a definite relation to the resistance of the element and thus to the temperature, but it will also depend on the electromotive force supplied to the bridge and the sensitivity of the galvanometer, which is dependent to a certain extent on the temperature of the galvanometer. The balanced-bridge method is independent of the last two factors (except that a large fall in the electromotive force or galvanometer sensitivity would make the instrument more sluggish and make it harder to determine the point of balance) and is much to be preferred.

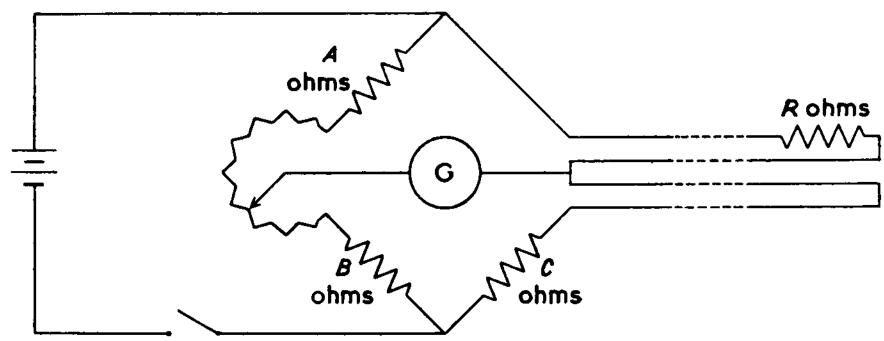


FIG. 50—BALANCED-BRIDGE CIRCUIT FOR MEASURING RESISTANCE WITH FOUR-LEAD COMPENSATION

The cross-coil galvanometer or ratiometer has an iron core with a non-circular cross-section (usually elliptical), so that the field intensity in the space between the core and the permanent magnet is not uniform. There are two moving coils, fixed at a constant angle to one another and connected so that the currents through them give rise to two opposite torques. It can then be shown that, to a good approximation, the deflection is a function of the ratio of the two currents. Suitable circuits for the use of this type of galvanometer with the resistance thermometer element are shown in Fig. 51 ; the deflection of the galvanometer is a function of

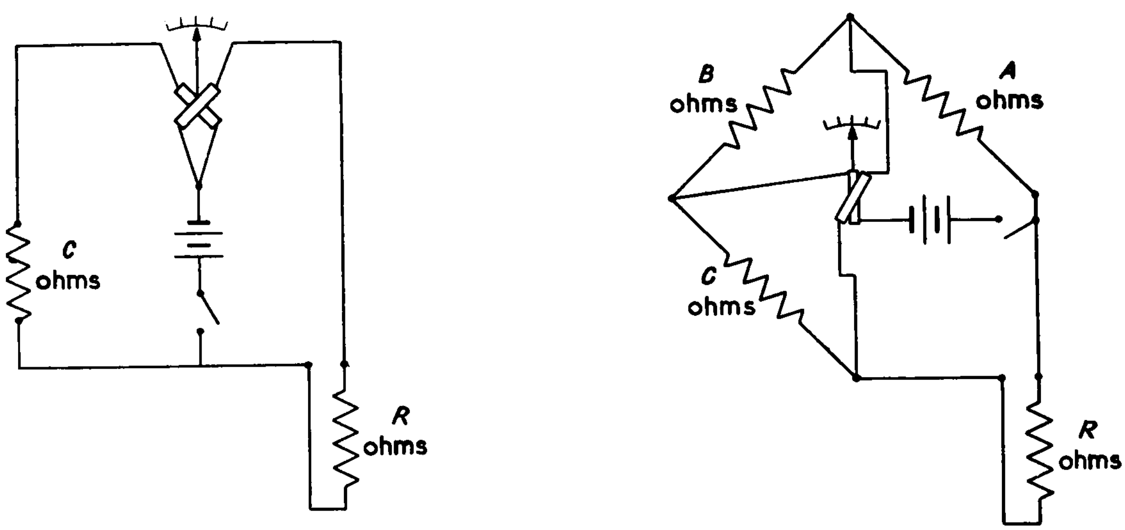


FIG. 51—RATIOMETER CIRCUITS FOR MEASURING RESISTANCE

the resistance of the thermometer element and thus can be calibrated in terms of temperature. Voltage fluctuations of up to about $\pm$ 10–20 per cent. do not affect the accuracy of the result. This is a very much larger variation than could be allowed with the out-of-balance Wheatstone bridge method. The advantage of the ratiometer method is that no adjustment by the observer is necessary.

3.3.4. Errors due to self heating of the resistance element

The passage of the current through the resistance element evolves heat, and thus the temperature of the element becomes higher than the surrounding medium.

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

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

The lag coefficient of the thermometer element, λ, is however given by equation (25)

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

and therefore

$$\Delta T = \frac{\lambda}{C}\frac{I^2R}{J}, \qquad \ldots\ldots(35)$$

where C is the thermal capacity of the thermometer element.

For the Meteorological Office aircraft resistance thermometer element Mk 1, passing a current of 20 mamp., ΔT is of the order of $\frac{1}{4}$°F. when it is immersed in a strongly stirred bath of petrol, and also $\frac{1}{4}$°F. when used on an aircraft (ventilation speed about 200 kt.), so that in this case the error is taken care of during calibration. If however the resistance element is used, say, in a screen on the ground with the same current and with a ventilation of, say, 10 kt., as opposed to 200 kt., ΔT will rise to approximately $(200/10)^{0\cdot 7} \times \frac{1}{4}$°F. = 2°F. since the lag coefficient of this element varies as $v^{-0\cdot 7}$ approximately (see p. 90). No reliance can be placed on the computed value since the simple theory outlined above is far from exact, but it does indicate that the error would be appreciable and would have to be allowed for or reduced.

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

The required temperature T is then given by

$$T = \frac{4T_1 - T_2}{3} \text{ and } d = \frac{T_2 - T_1}{3}. \qquad \ldots\ldots(36)$$

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

3.3.5. Meteorological Office balanced-bridge aircraft thermometer indicator Mk 1B

The Meteorological Office balanced-bridge aircraft thermometer indicator Mk 1B (Stores Ref., Met. 2828) is used in conjunction with two Meteorological Office aircraft thermometer resistance elements (one as a dry bulb and one as a wet bulb) to measure the air temperature and humidity around an aircraft in flight (Fig. 52). It is based on an instrument described by Brewer[22]. The dry- and wet-bulb temperatures are measured independently, one after the other. The indicator comprises a Wheatstone bridge circuit, used in the balanced-bridge manner, the position of the slider at balance indicating the temperature of the element directly on a suitable scale. The range is from — 110° to + 100°F.

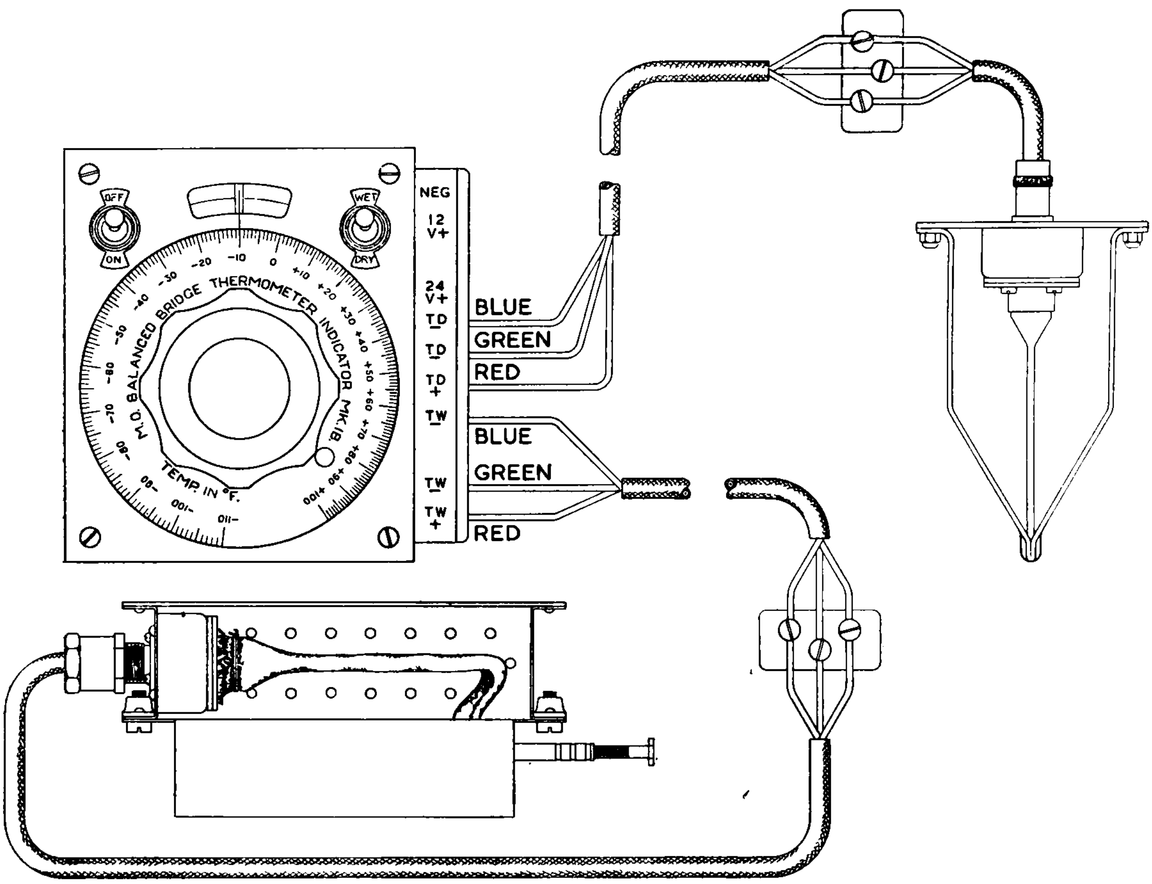


FIG. 52—METEOROLOGICAL OFFICE BALANCED-BRIDGE AIRCRAFT THERMOMETER INDICATOR MK IB

The circuit is shown in Fig. 53 ; Z_{24} and Z_{12} are ballast resistances to reduce the voltage across the bridge to approximately 4 V., from either 24 V. or 12 V. according to the supply which is used. R_d and R_w are fixed balancing resistances, which are used in the bridge when the dry- and wet-bulb resistances, respectively, are connected in the bridge circuit. A and B are equal resistances which form part of the opposite arms of the bridge, while balance is made by adjusting the position of the contact C on a length of resistance wire ; the shunt resistance, S, adjusts the range which the indicator can cover. A three-lead compensation circuit is employed.

All the fixed resistances are wound with wire having a high specific resistance and low temperature coefficient. The sliding contact is of softer material than the slide wire itself and is non-corrosive, so that the wear on both the slide wire and the contact is kept to a minimum. The slide-wire contact is driven by a slow-motion drive (between 6 to 1 and 12 to 1) and the actuating knob is large so that it can easily be adjusted with a gloved hand. The position of the sliding contact is shown on a circular scale, covering not less than 315 angular degrees, which moves round with the contact, the reading being made against a white fixed mark placed immediately below the zero of the galvanometer. The scale is engraved for every whole degree, with a minimum distance of 0·04 in. between each graduation mark at any point of the scale.

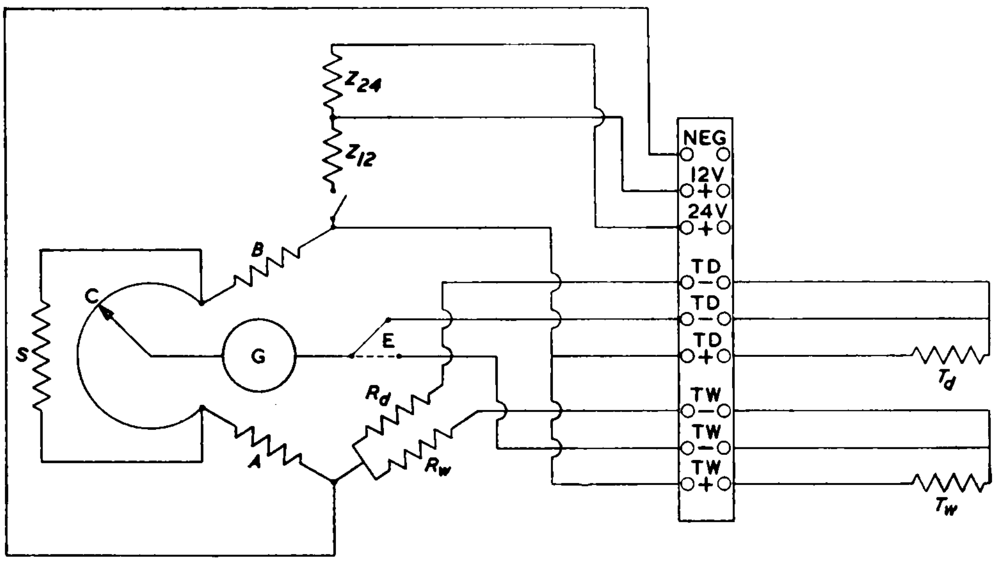


FIG. 53—WIRING DIAGRAM OF AIRCRAFT THERMOMETER INDICATOR MK IB

The galvanometer is of the moving-coil type, suitably damped to permit rapid adjustment of the bridge, and its sensitivity is such that a deflection of 1/10 to 1/5 in. from the zero should correspond to the bridge being out of balance by about 1°F. Mechanical stops or shaped pole pieces restrict the motion of the pointer to about ½ in. on either side of the zero. The scale plate behind the pointer is marked with two radial lines, symmetrically placed about the zero position to enable the balance point to be found. A small screw for adjusting the zero is provided beneath the scale plate.

Each instrument is calibrated with the elements with which it is going to be used, including 3 ft. of connecting cable, and a correction card is issued with the instrument. These corrections cover the whole scale, at intervals of about 20°F. The necessary terminals are fitted on the right-hand side of the case and are clearly identified by markings similar to those shown in Fig. 52. Switches are provided to switch the power supply on or off, and to change over from one external circuit to the other. The second switch is included in the galvanometer lead, so that any variation in the contact resistance will not affect the result obtained.

Installation.—The installation of the instrument in aircraft and a description of the wet-bulb housing will be dealt with in Part II of this Handbook, but the general principles of the wiring can be seen from Figs. 52 and 53. The leads from the resistance element consist of a length of three-core cable with red, green and blue covered cores, the blue and green being connected to one end of the element and the red to the other. If the element is being exposed at some distance from the indicator a further length of the cable should be used ; the cable attached to the element should be joined to a terminal block and fresh cable run from the terminal block to the indicator. It is important that the wiring diagram shown should be adhered to and all the three leads used. The red core from the dry bulb goes to TD+, the red core from the wet bulb to TW+, the blue and green cores from the dry bulb to the two TD— terminals and the blue and green cores from the wet bulb to the two TW— terminals. Either a 12- or 24-V. d.-c. supply should be used, a bank of accumulators forming the most reliable source.

The connexions should be tested when they are finished. Set the right-hand switch to DRY and turn the indicator knob until the dial reads the approximate air temperature. Then turn the left-hand switch to ON, and verify that when the knob is turned the pointer of the galvanometer moves in the same direction as the upper edge of the scale. If this is not so the connexions have been wrongly made.

If the indicator is to be used at some considerable distance from the element a specially calibrated scale will be needed.

Routine method of use.—The use of the indicator is straightforward once it is connected up. The routine that should normally be followed is given here :—

(i) Set selector switch to DRY

(ii) Set dial to approximate air temperature

(iii) Switch ON

(iv) Rotate knob until galvanometer pointer is midway between the two fiducial lines

(v) Read dial

(vi) Repeat with the selector switch set to WET to obtain the wet-bulb reading

(vii) Apply any necessary corrections from the correction card.

The dial is set to the appropriate air temperature, before switching on, to reduce the out-of-balance current through the galvanometer.

Maintenance and repair.—As the indicator and element have been calibrated together as one unit, if any defect occurs in either the whole outfit should be returned to the Instrument Provisioning Branch of the Meteorological Office. If any new parts have to be supplied the outfit would probably have to be re-calibrated.

General maintenance of the instrument involves keeping the contacts and connexions clean and sound, and giving the whole external circuit regular inspections to detect any deterioration as soon as possible.

Accuracy and sources of error.—Under normal operating conditions the scale can be set and read to about $\pm \frac{1}{4}$°F. The correction to be applied to the reading observed, however, may be up to $\pm$ 1·5–2·0°F., and variations in this correction along the scale can, at times, introduce uncertainties of the order of $\pm\frac{1}{4}$°F. as to the correct correction to apply at any particular point, so that the air temperature may be obtained to only $\pm\frac{1}{2}$°F. on occasions. This does not include any uncertainty due to any airspeed corrections when used on aircraft. When being tested, the indicators are read to the nearest 0·1°F., and the corrections are given to that order of accuracy.

The normal position for the indicator is with the front face vertical and the galvanometer needle pointing vertically upward ; variations from the normal position up to 90° tilt in any direction, and variations in the ambient temperature from 0–120°F. should not affect the reading by more than ± 0·4°F. Even temperatures of − 40° and + 180°F. should not derange the instrument or cause seizure. The lag of the complete instrument is small, especially when used on aircraft (see Table VI, p. 90).

3.3.6. Meteorological Office balanced-bridge aircraft thermometer indicator Mk 1

The Meteorological Office balanced-bridge thermometer indicator Mk 1 is an earlier model of the Mk 1B with provision for one measuring element only (a dry bulb). Its principle, method of operation and accuracy are similar to that of the Mk 1B, except for those special features of the Mk 1B which relate to the second element.

3.3.7. Other electrical resistance thermometers

An early Meteorological Office resistance thermometer for use on aircraft in which the resistance element (either a Meteorological Office knife-type bulb or a coiled-coil type) is in a Wheatstone bridge network in which the out-of-balance current is measured by means of a centre-zero galvanometer (Plate XI). Two ranges of temperature (− 20° to + 40°C. and − 70° to − 10°C.) are covered by providing for the alteration of one of the resistances in the bridge network. Small changes in the battery electromotive force can be allowed for by switching a known resistance into the circuit in place of the thermometer element and adjusting a series resistance until the galvanometer records a certain predetermined value. An adjustment can also be made to allow for the actual value of the resistance of the leads.

The accuracy with which the instrument can be read is not so good as that of the balanced-bridge instrument, and is probably at best ± ½°C. In addition, it is subject to errors which are characteristic of the out-of-balance Wheatstone bridge method (p. 129) ; these may be reduced by frequent tests and adjustments of the setting knob and using well charged accumulators, but cannot be entirely eliminated. The lag of the instrument is small (see Table VI, p. 90).

In an earlier model of this thermometer the indicator covered the range −70° to + 20°C. in one step only. The scale was thus more contracted, and the indicator was less easy to read because the front face of the galvanometer was cylindrical (with its axis vertical) and the galvanometer pointer moved bodily from right to left ; parallax errors were thus difficult to avoid.

3.3.8. Recorders

Thermographs can be constructed using the two main types of resistance thermometers. In place of the direct-reading galvanometer in the ratiometer or out-of-balance Wheatstone bridge methods a recording galvanometer can be used. This may be a thread recorder (see Chapter 1) or a mirror galvanometer recording photographically. The thread recorder does not give an absolutely continuous trace, but the markings would be close enough together for most practical purposes. A mirror galvanometer could give an absolutely continuous trace, but the records cannot be seen as they are being made and have to be developed first. Both recorders would need to be frequently standardized to allow for any change in the electromotive force across the circuit.

A more accurate result would be obtained by using a recording potentiometer. In this instrument the movement of a galvanometer coil is used to direct the motion of a sliding contact (or rolling contact) along a resistance wire in such a direction as to reduce the current through the galvanometer to zero. The position of the recording pointer is governed by the position of the contact on the wire.

The recording potentiometer mechanism has more force available to move the indicating pointer, so that a pen may be used to record directly on the chart.

3.4. THERMO-COUPLES

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

$$(E - E_0) = \alpha(T - T_0) + \beta(T - T_0)^2 ,$$

where E is the contact electromotive force at a temperature T and E_0 is the electromotive force at some standard temperature T_0, α and β being constants. If there are two junctions, at temperatures T_1 and T_2, the net electromotive force E_n (the thermal electromotive force) is given by $(E_1 - E_2)$, where E_1 is the contact electromotive force at temperature T_1 and E_2 is the contact electromotive force at temperature T_2. E_n can also be represented by a quadratic formula of the type given for $(E - E_0)$ to a good approximation ;

$$\begin{aligned} E_n &= E_1 - E_2 \\ &= a(T_1 - T_2) + b(T_1 - T_2)^2 , \end{aligned} \qquad \ldots\ldots(37)$$

where a and b are constants for the two metals concerned.

For most meteorological purposes, it is often possible to neglect the value of b, as it is always small compared with a. Table XV gives the value of the thermal electromotive force for some metals when used in contact with platinum. In a combination of any two metals in the table, without platinum, the resultant electromotive force can be obtained by algebraically subtracting one of the electromotive forces from the other. Positive signs in the table indicate that the current flows into the platinum through the cold junction. The electromotive forces are given in microvolts per degree Fahrenheit difference in temperature between the junctions, for temperatures between 32° and 212°F. Copper-constantan junctions are suitable for use in meteorological measurements.

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

TABLE XV—ELECTROMOTIVE FORCES PRODUCED BY VARIOUS METALS IN CONJUNCTION WITH PLATINUM

Metal	Electromotive force produced per degree Fahrenheit difference	Metal	Electromotive force produced per degree Fahrenheit difference
	μV.		μV.
Iron ..	+8·1 to +8·3	Lead ..	− 2·3 to − 2·5
Gold ..	+3·1 to +4·4	Nickel ..	− 6·6 to −10·8
Copper ..	+4·0 to +4·2	Cobalt ..	− 8·4 to −11·1
Zinc ..	+3·3 to +4·4	Constantan	−16·9 to −19·3
Manganin	+3·2 to +4·6	Bismuth	−35·1 to −40·1

capacity. Newly manufactured junctions should, however, be aged before use, and for this purpose an electric current is passed through them for several hours.

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

3.4.1. Methods of measurement of the electromotive force

There are two main methods of measuring the electromotive force produced ; (i) by measuring the current produced in the circuit with a sensitive galvanometer, and (ii) by balancing the thermo-electric electromotive force with a known electromotive force, so that no current actually flows through the thermo-couples themselves.

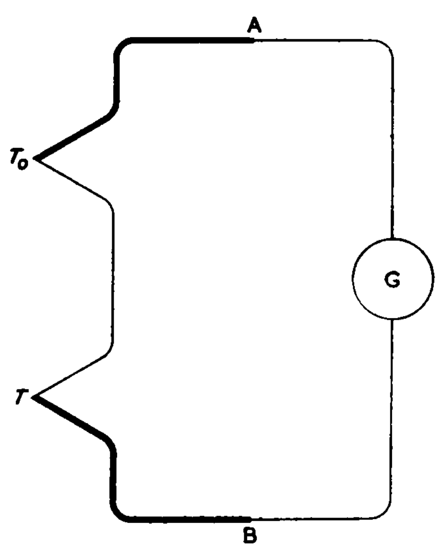


FIG. 54—SIMPLE CIRCUIT FOR MEASURING THERMO-ELECTRIC ELECTROMOTIVE FORCES

In (i) the galvanometer is connected directly in series with the two junctions (Fig. 54). It should be noted that if the leads from A and B to the galvanometer are not of the same metal as used in the thermo-couple leads to these points the temperatures of the junctions at A and B should be the same, or subsidiary thermo-electric electromotive force may be set up and vitiate the results. The deflection of the galvanometer will depend on the resistance of all parts of the circuit and on the sensitivity of the instrument. It will be best to calibrate the circuit at several temperatures over the range required ; the change in resistance of the thermo-couple with temperature will be allowed for in this way, but the temperature of the external leads and the galvanometer itself should be kept as constant as possible. If it is not possible to keep the temperature of the leads approximately constant, the resistance of the galvanometer itself will have to be made high compared with the remaining resistance in the circuit, so that changes in the remaining resistance will have comparatively little effect on the current produced (i.e. the galvanometer would be acting as a voltmeter).

The principle of the potentiometer circuit is shown in Fig. 55. The resistance AB is a uniform wire connected in series with a cell, a switch and a variable resistance. There is thus a uniform drop of potential along the wire when the switch is closed. Enclosed in the thermo-couple circuit is a portion, AC, of this wire (where C is a movable contact), and this circuit is so arranged that the potential drop along AC and the thermo-electric electromotive force tend to drive currents in opposite

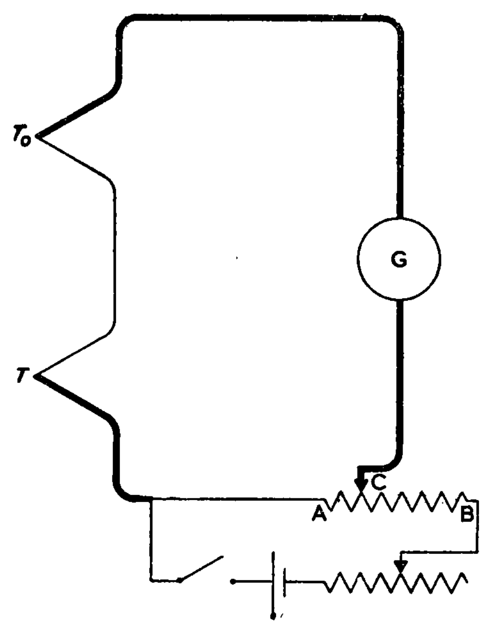


FIG. 55—POTENTIOMETER METHOD OF MEASURING THERMO-ELECTRIC ELECTROMOTIVE FORCES

directions through the galvanometer. The position of C is adjusted until the galvanometer shows no deflection ; the thermo-electric electromotive force is then equal to the potential drop along AC which is given by (AC/AB) E_s, where E_s is the total potential drop along the resistance AB. E_s is normally standardized to some known value before the circuit is used by inserting a standard cell in place of the thermo-couple and, with the contact C at the extreme end B, adjusting the variable resistance in series with the battery and AB until there is no deflection in the galvanometer. In this way no current passes through the thermo-couple at the point of balance and, consequently, variations in the temperature of the leads can have no effect on the result.

3.4.2. Sources of error

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

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

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

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

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

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

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

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

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

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

3.4.3. Application to meteorological instruments

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

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

A thermo-couple balloon psychrometer for measuring the wet- and dry-bulb temperature of the air is described in Chapter 4. The thermo-couple principle is also used in thermopiles, which are used to measure the intensity of radiation (see Chapter 8).

3.5. BIMETALLIC THERMOGRAPHS

3.5.1. Theory of the bimetallic strip

Consider a bimetallic strip AC of length l (Fig. 56), clamped at one end and composed of thicknesses h_1 and h_2 of metals I and II. Let E be the value of Young's modulus and α be the coefficient of expansion of the metals, with suffixes $_1$ and $_2$ for the two metals. Let 2ψ be the angle subtended by the bimetal at the centre of curvature O of the strip ($\angle$COA in Fig. 56). Then it can be shown (see " Analysis of bi-metal thermostats " by Timoshenko[23] for a full discussion) that the small movement ΔS in the end C caused by a small change in temperature ΔT is given approximately by

$$\Delta S = \left\{\frac{l^2 A}{2(h_1 + h_2)}\right\} (\alpha_1 - \alpha_2) \left\{\frac{f(\psi)}{\psi}\right\} \Delta T, \qquad \ldots\ldots(38)$$

where

$$\frac{1}{A} = \frac{1}{2} + \frac{E_1 h_1^3 + E_2 h_2^3}{6(h_1 + h_2)^2} \left(\frac{1}{E_1 h_1} + \frac{1}{E_2 h_2}\right) \qquad \ldots\ldots(39)$$

and

$$f(\psi) = \left(\frac{\psi^2 + \sin^2 \psi - 2\psi \cos \psi \sin \psi}{\psi^2}\right)^{\frac{1}{2}}. \qquad \ldots\ldots(40)$$

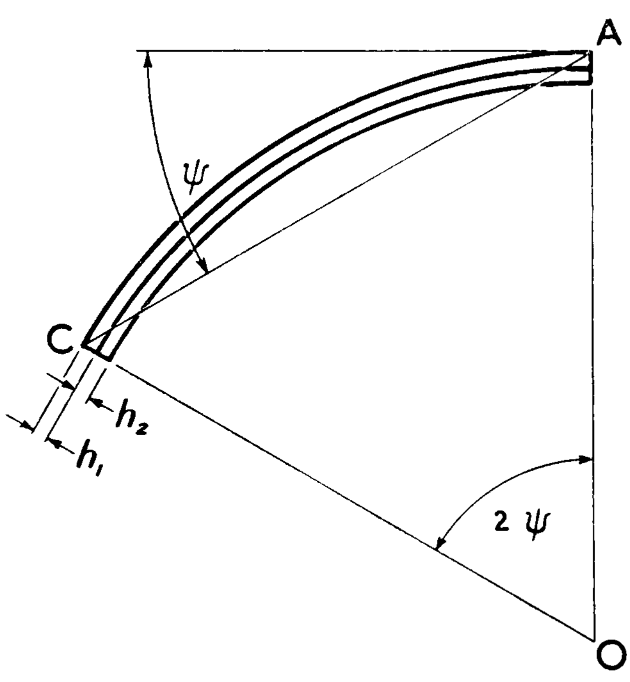


FIG. 56—PRINCIPLE OF THE BIMETALLIC STRIP

Also, the change in ψ for a change in temperature from T_0 to T is given by

$$(\psi - \psi_0) = \frac{lA}{2(h_1 + h_2)}(T - T_0). \qquad \ldots\ldots(41)$$

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

TABLE XVI—VALUE OF $f(\psi)/\psi$ FOR DIFFERENT VALUES OF ψ

ψ	0°	30°	60°	120°	180°	360°
$f(\psi)/\psi$	1·000	0·970	0·885	0·601	0·318	0·159

The sensitivity is greatest for a straight bimetallic strip, inversely proportional to the thickness of the strip, proportional to the square of the total length of the strip and proportional to the difference in the coefficients of expansion of the two metals.

The stiffness of the strip is also important in the design of the instrument for, other things being equal, the greater the stiffness the better the record, because there is more force available to overcome friction in the mechanism. It can be shown that the displacement S of the end of the strip caused by a couple of bending moment M is given by

$$S = \frac{l^2 f(\psi) 6M}{\psi E(h_1 + h_2)^3} \qquad \ldots\ldots(42)$$

where $E = \frac{1}{2}(E_1 + E_2)$,

i.e. the stiffness (proportional to $1/S$) is proportional to $(h_1 + h_2)^3$, while the deflection due to a change in temperature is proportional to $1/(h_1 + h_2)$. The lag coefficient, which will be approximately proportional to the mass of metal, will vary directly as $(h_1 + h_2)$. A compromise has thus to be reached between these factors in any given design.

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

3.5.2. Sources of error

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

If the strip is cooled considerably below its lower temperature limit there is a risk that the welding may be damaged and the strip rendered useless.

3.5.3. Meteorological Office bimetallic thermograph Mk II

The main base of the Meteorological Office bimetallic thermograph (Stores Ref., Met. 577) is a gunmetal casting providing support for the clock and drum and also the support for two horizontal arms which serve as the framework to carry the temperature element, Plate XII. The temperature element consists of a bimetallic strip, coiled in the form of a left-handed helix with the metal with the greatest coefficient of expansion on the outside. One end of the helix is rigidly anchored to a setting arm, which in turn is attached to one arm of the frame. A setting screw enables the setting arm to be rotated about the horizontal axis passing through the centre of the helix against the pressure of a phosphor bronze spring. Coinciding with the horizontal axis of the helix is a stainless steel spindle which can revolve freely in a bush in the arm carrying the setting screw, and which passes through the other arm of the frame. This spindle also passes through a hole drilled at right angles to the axis of a small brass column which is fixed rigidly by a screw to the free end of the helix. Another screw ensures that the column cannot rotate relative to the spindle. The pen arm is carried by a normal Meteorological Office pattern gate suspension which is attached to the end of the spindle that extends beyond the frame. A small screw normally fixes the suspension rigidly to the spindle, but if loosened it enables the position of the pen arm to be altered relative to the spindle.

As the temperature changes, the end of the helix rotates around its axis and at the same time causes the spindle and pen arm to rotate. Adjustment of the setting screw causes the whole helix to rotate about the axis and also alters the position of the pen arm. Several alternative positions are provided for attaching the column to the end of the helix ; they enable the total length of the helix in use to be altered within certain limits. Changing the length of the helix alters the value of $d\psi/dT$ (see equation (41)), and consequently the scale value of the instrument can be adjusted. The helix is copperplated and cellulosed as a protection against corrosion ; a brass guard is fixed to the main casting to protect it against accidental mechanical damage without obstructing the free flow of air past the element.

The clock is mounted on the main base, has either a daily or weekly movement, and carries an " S " type drum (or one of similar external dimensions). The outer case is made of sheet copper, and is hinged to the main base along the end further from the thermometer element ; it does not cover the element and guard. It has a glass window opposite the drum and is provided with a brass carrying handle. The pen may be lifted from the chart when necessary by a pen-lifter arm.

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

Method of use.—Two different ranges, with corresponding charts, are used in the British Isles ; the winter chart has a range from $-10°$ to $+70°$F. and the summer chart from $+20°$ to $+100°$F. The proper date for changing from one set of charts to the other varies somewhat with the locality ; for the London area, for example, the changes should normally be made about the middle of October and the middle of April. When changing from one set of charts to the other the instrument has to be re-adjusted. This should be done either with the instrument in a Stevenson screen on a cloudy, windy day at a time when the temperature is practically constant, or in a room whose temperature is constant. A new chart should be fitted to the drum, taking care that corresponding lines on the overlapping and underlying portions are co-incident and that the chart is as near to the bottom flange of the drum as possible (with the base of the chart touching it in at least one place). The pen should be replaced on the chart, and then the instrument left for a period of half-an-hour or more to reach equilibrium with its surroundings ; if it is exposed in a room a position out of direct sunlight should be chosen and a thermometer suspended with its bulb close to the bimetallic helix. In later instruments a brass clip on the element guard provides a suitable support. The thermometer should then be read (the ordinary dry-bulb thermometer should be used if the thermograph is in the Stevenson screen) and the pen arm adjusted until the indicated temperature on the chart is the same as that of the thermometer. This adjustment should be done roughly at first, by loosening the screw holding the pen arm to the pen-arm spindle, moving the pen arm to approximately the correct position and then tightening the screw. Any necessary fine adjustment can be carried out by use of the setting screw. After making the adjustment once, the thermograph should be left for a further period undisturbed, and then the result checked. Some further slight adjustment may be necessary because of the effect of the observer on the thermograph when making the previous adjustment. This secondary effect should however be small and easily corrected. The temperature at which the setting is made should lie about the middle of the range of the new chart if possible.

The instrument is now ready for use ; the general instructions for autographic instruments with regard to time marking, fitting of charts on to drums, changing of charts, care of pens, tabulating the charts, winding the clock, and general cleanliness should be carefully followed. Time marking can be done by carefully depressing the pen arm slightly with the finger. As in all autographic instruments the pressure of the pen on the chart should be reduced to the minimum necessary to give a clear record.

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

A useful way to obtain a check on the scale value of the instrument is to plot the readings of the dry bulb at the main hours of observation against the observed readings of the thermograph. There will be some scatter, but the best fitting line should be at an angle of 45° to either axis. If this is not so, the scale value will be in error and the slope of the line will give the amount of the error. This can be corrected by altering the point of attachment of the end of the helix to the column connecting it to the pen-arm spindle ; if the scale is too contracted (i.e. high temperature registering too low and low temperature registering too high) the point of attachment has to be moved nearer to the free end of the helix. If on the other hand the scale is too expanded (high temperature registering too high and low temperature registering too low) the point of attachment of the column should be moved away from the free end of the helix. Movement of the point of attachment of the helix to the column by one hole alters the scale value by about 5 per cent. This adjustment is not easy to carry out at an outstation, because of the difficulty of testing to see if the required result is obtained. If the first adjustment is not quite correct it is usually fairly simple to get the correct result by proportion.

Maintenance and repair.—The bimetallic coil should be handled carefully to avoid mechanical damage, and should be kept clean. The bearings of the spindle should be kept clean, and oiled at intervals by the sparing use of a little good clock oil. The general instructions in Chapter 1 about the maintenance of the pen and clock should be followed. The instrument is very simple mechanically, and, provided precautions are taken to keep the friction to a minimum and to prevent corrosion, it should give good service.

Accuracy and sources of error.—In the thermograph mechanism itself, friction is the main source of error. One cause of this is often bad alignment of the helix with respect to the spindle. Unless accurately placed it acts as a powerful spring, and, if rigidly anchored, it pushes the spindle hard against one side of the bearings. With modern instruments this should not however be a serious trouble. Friction in the bearings can be minimized by lubricating sparingly with a little good clock oil. Friction between the pen and the chart can be kept to a minimum by suitable adjustment of the gate suspension.

When new instruments are tested, the maximum error allowed in the measurement of the range when the temperature of the thermograph is changed by 50°F. over any interval between 0° and 100°F. is 1°F. With careful adjustment and attention the instrument should therefore give clear records which are readable and accurate to about $\pm \frac{1}{2}$°F. over most of the range used.

The instrument described above is the latest pattern Mk II thermograph. Some earlier models differ slightly in details of the adjusting mechanism and other parts, but the principles of operation are the same.

3.6. MECURY-IN-STEEL THERMOGRAPHS

3.6.1. Principle

The mercury-in-steel thermometer depends on the use of a coiled Bourdon tube to measure the change in volume of the mercury contained in a steel bulb. The bulb is connected with the Bourdon tube by means of a length of capillary tubing, so that the indicator unit may, if necessary, be placed at a distance from the thermometer element. A magnified cross-section of the capillary tubing is shown in Fig. 57 ; it is provided with an outer covering to prevent corrosion and the whole system is completely filled with mercury under very high pressure, approximately 1,000 lb./in.^{2} is normally used. The Bourdon tube consists of a flat hollow tube coiled into a number of turns, sealed off at the end, and attached to a horizontal spindle through the centre of the coil. Its internal volume depends on the radius of curvature of the coils (larger volume with increased radius), and consequently when the temperature of the mercury in the system varies and the volume change has to be taken up by the Bourdon tube, it is forced to unroll or contract. The movement of the end of the coil is transferred as an angular rotation of the horizontal spindle, and this spindle can carry a pointer moving over a scale, or a pen arm recording on a chart and drum.

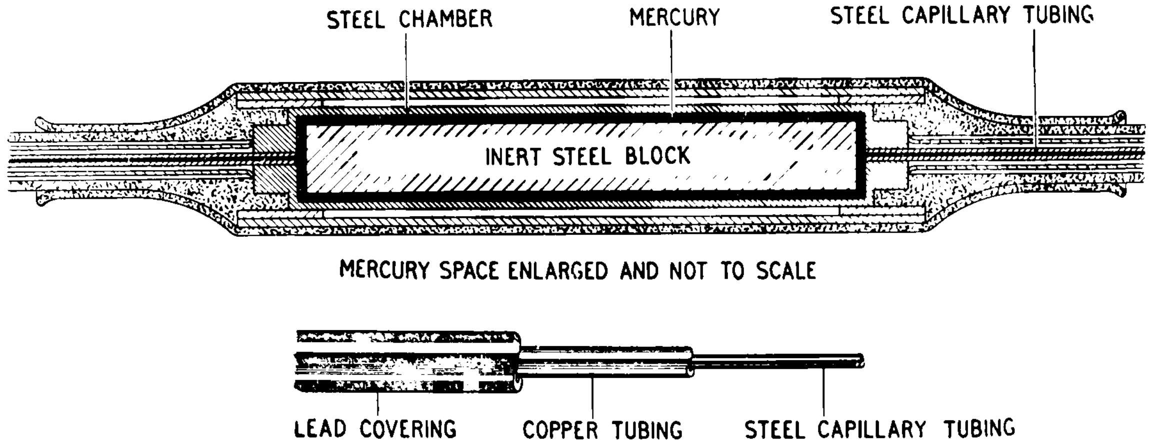


FIG. 57—CROSS-SECTION OF CAPILLARY TUBING AND TEMPERATURE-COMPENSATING LINK OF MERCURY-IN-STEEL THERMOGRAPH

The clearances and diameter of the capillary tubing are exaggerated somewhat for clarity

Compensation for the temperature of the capillary tubing.—It is desired to record only the changes in volume of the mercury brought about by changes in temperature of the steel bulb, and thus it is necessary to compensate for changes in temperature of the capillary tubing, especially when long lengths are used. This is achieved by enclosing in the bore of the capillary tube a certain volume of invar (a nickel steel with a very low coefficient of expansion), or other similar material, either in the form of a continuous wire or as slugs in local enlargements of the bore. If γ_s, γ_i and γ_h are the cubical coefficients of expansion of the steel tube, the invar, and mercury respectively, V_t the internal volume of the capillary tube and V_i the volume of the invar, then the increase in volume of the mercury minus the increase in the space in the tube available for it, for an increase in temperature of the capillary tubing of T degrees is given by

$$\{\gamma_h(V_t - V_i) - (\gamma_s V_t - \gamma_i V_i)\}T. \qquad \ldots\ldots(43)$$

For perfect compensation this must be zero. This gives a relation between the volume of the invar and the volume of the tube which must be satisfied.

$$V_i(\gamma_h - \gamma_i) = V_t(\gamma_h - \gamma_s)$$

$$\frac{V_i}{V_t} = \frac{\gamma_h - \gamma_s}{\gamma_h - \gamma_i}. \qquad \ldots\ldots(44)$$

If the invar is in the form of a wire running throughout the length of the capillary tube, insertion of normal values for the coefficients of expansion shows that the diameter of the invar would need to be about 0·9 of the diameter of the bore. Zero errors will also be introduced if the difference in height between the thermometer bulb and the recording mechanism is different from that for which the calibration has been carried out, on account of the excess or deficit of pressure in the Bourdon tube acting in the same way as a change in volume.

It is advisable to specify, in advance, the relative positions of the bulb and recorder, but differences in height up to about $\pm$ 25 ft. can be satisfactorily corrected by altering the zero adjustment.

This type of instrument is used in the Meteorological Office as a distant-recording thermograph.

3.6.2. Mercury-in-steel thermograph (dry and wet bulb)

The mercury-in-steel thermograph (dry and wet bulb) (Stores Ref., Met. 593 with 100 ft. of capillary tubing, Met. 467 with 130 ft. of capillary tubing and Met. 2004 with any other length of capillary tubing not exceeding 130 ft.) consists of two mercury-in-steel thermographs recording the dry- and wet-bulb temperatures on a single chart and drum (Plate XII). To prevent the pens fouling one another the wet-bulb pen is set to record 10°F. below its actual value. The two bulbs are housed, side by side, in a white wooden screen with louvered sides (p. 100) and are connected by two separate twin capillary tubes to Bourdon tubes which have a common horizontal axis. A pen arm is connected to each Bourdon tube. The maintenance of the wet bulb and the use of the instrument as a psychrograph is dealt with in Chapter 4 ; the description here will be limited to its use, maintenance, installation and properties as a thermograph.

The cylindrical bulb is approximately 7 in. long and 1 in. in diameter, made of steel and covered with a tin sheath as a protection against corrosion. It is supported in position in the screen by means of an iron framework, and its junction with the capillary tubing is covered with a stout lead sheath which reaches to the outside of the screen. The capillary tubing is also covered with lead ; it is moderately flexible and may be bent into a curve of radius 1 in.—a sharper curve would cause damage. The length of the capillary tubing between the bulb and the recording mechanism may be either 100 or 130 ft. according to the model. Temperature compensation of the capillary tube is provided by a certain volume of invar, either in the form of slugs alone inserted into local enlargements in the bore of the capillary tubing, or as both slugs and invar wire running the length of the capillary tubing.

The recording unit consists of the Bourdon tubes mounted on a rectangular base, with the leads from the capillary tubing entering at one end and then coming up through the centre of the base. The Bourdon tubes themselves are made of hardened and tempered steel, and are supported in a vertical plane with their common axis parallel to the short side of the base. A clip is used to attach the tube, near its inner end, to the horizontal spindle which carries the pen arm. The two spindles of the twin-pen recorder are arranged concentrically. It is possible to adjust the position of attachment of the clip on the Bourdon tube and the position of the spindle relative to the other end of the clip, by loosening the appropriate locking screws. The first adjustment affects the scale value of the instrument and should not normally be altered ; the second adjustment can be used to alter, roughly, the position of the pen on the chart if any zero error has developed. A fine adjustment mechanism is, however, also provided at the end of the pen arm. In later instruments this is in the form of a screw with a milled head which can be turned by hand, but in earlier instruments a special adjusting tool (Stores Ref., Met. 1924) had to be used.

The clock and drum are in one unit, and the clock has a weekly movement ; the pen arms (dry bulb Stores Ref., Met. 564, wet bulb Stores Ref., Met. 423) are suspended in a form of gate suspension, so that the pressure of the pen on the paper can be varied. The range of the instrument is normally from 20° to 120°F., but as the wet bulb is normally set to read 10°F. below the true temperature, the true range of the wet-bulb readings is 30° to 130°F. The instrument can, however, also be adjusted for the range 0° to 100°F. and charts graduated accordingly can be obtained. Alternatively in very cold weather the dry bulb can be set 10°F.

too high and the wet bulb set correctly. When the pen arm reaches the bottom of the scale a stop comes into action on the pen-arm spindle and prevents any further movement. This is to prevent the possibility of the pen arm moving off the drum and getting caught below the flange, which would damage the mechanism when the temperature rose again. New instruments will probably be provided later with an extended range, which can be set at 0° to 120°F. or – 20° to 100°F. according to the season of the year. If possible the bulbs should not be exposed to temperatures outside the instrument range, but if absolutely unavoidable the pens should be removed from the charts until the temperatures become normal.

Red and purple ink are supplied so that the two records may be easily distinguished ; the ends of the pen arms (and the corresponding bulbs) are also marked red and blue respectively, the wet-bulb pen being marked red. A glass case covers the recorder to keep it free from dust ; it can be removed by unclipping the fastenings at each end and lifting the cover vertically upwards. Two vertical guide bars are fixed to the base of the recorder and fit into two guide holes in the base of the cover.

Installation.—When the instrument is received the capillary tubing will be in coils ; as much of the tubing as is required should be unwound along the floor without twisting. The recording mechanism should be installed on a suitably strong shelf at a convenient height, preferably where it will receive as little vibration and be exposed to as little risk of mechanical damage as possible. When deciding on the position of the screen the best exposure within the range of the capillary tubing should be chosen, according to the principles set out on p. 93. If any holes have to be drilled for the passage of the capillary tubing they should be at least 1 in. in diameter so that the thermometer bulbs and the enlargements in the capillary tube used to house the slugs of invar may be passed through. In no circumstances should the capillary tubing be separated from the recorder or the bulb. The capillary tube should not be bent into a radius of curvature of less than 1 in. One side of the screen used to house the bulbs will have to be unscrewed to allow entry of the bulbs ; the neck of the bulb should be clamped in the frame, with small pieces of rubber to act as washers, at a point 8–9 in. from the far end of the bulb.

If necessary the capillary tubing can be buried underground in its passage to the screen ; care should be taken that it does not come up against anything with sharp edges (e.g. bricks or rubble). It can however be laid on the ground if it is not likely to be damaged. A special conduit would have to be provided if a road or perimeter track had to be passed. Any excess capillary tubing should be neatly coiled up near the recorder, and fastened in a position where it is not likely to be damaged. The tubing between the recorder and the screen should be fixed in position, where possible, by clips with rubber packing. The clips must not on any account be driven through the tubing itself.

Method of use.—When the instrument is first installed it will be necessary to check the readings, particularly if there is a difference in height between the bulbs and the recorder (a change of about 1°F. is caused for every 20-ft. difference). The difference in height should not however normally exceed 25 ft. The checking should be done on a cloudy day when the temperature is nearly constant ; this is specially necessary with the mercury-in-steel instrument because of the large lag coefficient of the bulbs (see Table VI, p. 90). After allowing ample time (one hour is suitable) for the bulbs to assume the air temperature, a comparison should be made between the reading of a thermometer placed beside the bulbs in the screen and the readings of the recorder. Another possible method of checking is to immerse the bulbs, just before installing in the screen, in a bucket of water. The water should be well stirred, and after its temperature, as measured by a mercury-in-glass thermometer, has become constant the bulbs should be immersed in the water for a period of 10–15 min., while the water is still being stirred. The temperature recorded by the instrument should then be compared with the temperature as indicated by the mercury-in-glass thermometer. The wet and dry bulbs should be tested in this way before any wick is applied to the wet bulb, and the position of the wet-bulb pen adjusted so that the reading on the chart is 10°F. too low. The wet-bulb reservoir can then be filled and the wick put on. Full details of the maintenance of the wet bulb are given in Chapter 4.

The special type of tool used for the adjustment of the readings of the pen arm on some older type instruments consists of two parts, the outer part fitted with two prongs for easing up the locking collar, and the inner part which is a screw-driver for turning the adjusting screw. To carry out an adjustment, place the screwdriver on the adjusting screw and, sliding the outer part down, engage the prongs in the holes on the locking collar and ease it back ; turning the screwdriver will now cause the pen arm to rise or fall. The pen arm should be set to the correct reading, and the locking collar then screwed up. If very low temperatures are expected the dry-bulb pen may be set 10°F. high and the wet-bulb pen at its correct reading. This will ensure a record of the dry-bulb temperature down to nearly 10°F.

When in regular use the general instructions for the use of autographic instruments with regard to time marking, changing the charts, tabulating the charts, care of the pens, and general cleanliness should be carried out.

Routine checking of the dry bulb can be carried out on cloudy, windy days when the temperature is sensibly constant, or by comparison of the readings of a minimum thermometer placed in the screen with the minimum recorded on the chart. Owing to the large lag of the instrument a mean error using several check readings will be more accurate than any single reading. Changes in the setting of the zero should be carried out, if necessary, on the basis of a mean error, but no attempt should be made to alter the scale value of the instrument. If serious errors are detected at Meteorological Office stations instruments should be returned to the Instrument Provisioning Branch.

The checking of the wet bulb is discussed in Chapter 4.

Maintenance and repair.—The bulb should be periodically inspected to see whether any cracking or breaking down of the coating is taking place; this leads to corrosion of the steel of the bulb and eventual breaking down of the instrument. The bulbs should be kept clean, and in particular the wick of the wet bulb should be changed as often as necessary (see Chapter 4). In the same way the capillary tubing should be inspected at intervals for any cracks in the outer covering, and to ensure it remaining in good condition. As a temporary expedient, if a crack in the lead sheathing is found, adhesive tape may be wound around the damaged part, but the instrument would have to be returned to the manufacturers to make a permanent repair. Before applying the tape it is a good plan to force some thin oil through the crack to protect the steel from any moisture which may have entered. In no circumstances should an attempt be made to solder the capillary tube, or any other part of the bulb-capillary tube–Bourdon tube system.

The recording mechanism should be kept clean and dry.

Accuracy and sources of error.—One main advantage of this type of instrument is the comparatively large force available to move the recording mechanism which ensures that the friction errors are less than in bimetallic thermographs, and results in a clear and detailed record. The accuracy achieved should normally be of the order of $\pm$ 0·5°F., but may fall to $\pm$1·0°F. at the extreme ends of the range of the thermometers. The difference between the temperatures of the wet and dry bulbs should be obtainable with an approximately similar accuracy. These figures refer to the accuracy with which the temperatures of the thermograph bulbs are measured, and not necessarily to the accuracy with which the corresponding free-air temperatures are measured. The part of errors that can be attributed to the imperfections of the compensation for changes in the temperature of the capillary tube are mainly less than $\pm$ 0·5°F., but may rise above that slightly in extreme circumstances.

The chief disadvantages of the instrument as a remote-recording thermograph are that the length of the capillary tubing is limited to less than 130 ft. (thus restricting the choice of exposure) and the large lag coefficient of the bulb. Also it can only be used in temperatures above the freezing point of mercury (— 38°F.).

3.7. PHOTOGRAPHIC THERMOGRAPH (DRY AND WET BULB)

The photographic thermograph is used to record the dry- and wet-bulb temperatures indicated by two mercury-in-glass thermometers, exposed in a wooden louvered screen, by photographing the position of two small bubbles of air, one of which is in the mercury in the stem of the dry-bulb thermometer and one in the stem of the wet-bulb thermometer.

The optical arrangements are shown in Fig. 58. The part of each mercury column which contains the air bubble is illuminated by the image of an extended light source, which is focussed on the rear of the thermometer stem by means of a

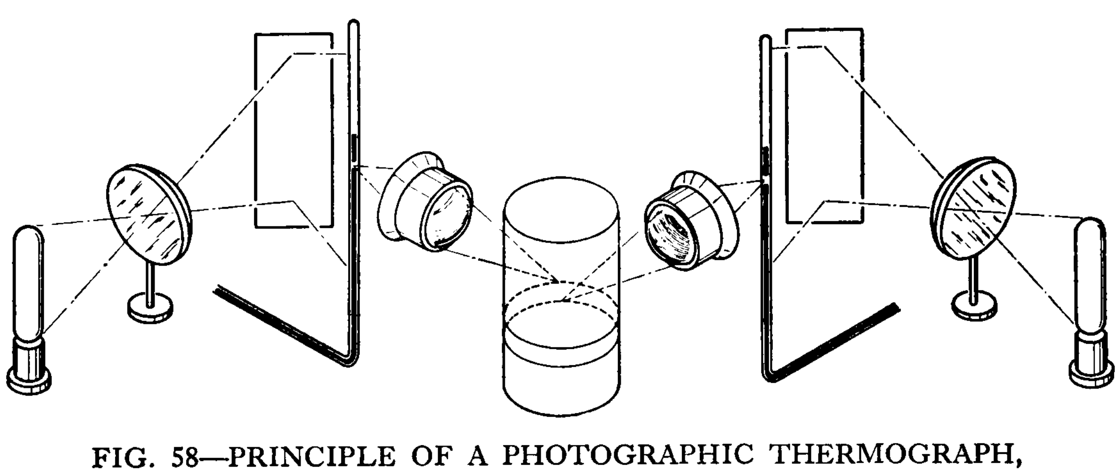


FIG. 58—PRINCIPLE OF A PHOTOGRAPHIC THERMOGRAPH, DRY AND WET BULB

condenser lens and mirror ; two photographic lenses are then used to form images of the mercury column and bubble on a sheet of sensitized paper wrapped on a revolving drum (which has its axis parallel to the thermometer stems). The images of the bubbles are arranged to fall one below the other, with the wet-bulb image separated from the dry-bulb image, so that they can never overlap. Time marks are provided on the record every 1 or 2 hr. by means of a shutter which interrupts the beam of light for a short period ; the drum normally revolves once in 48 hr.

Both thermometers should have, as nearly as possible, the same uniform scale value over the whole range of temperatures, so that once one point on the record is identified (by means of a check reading of another pair of thermometers with the same-sized bulbs and similar exposure) the remainder of the record can be evaluated. Any small constant difference in scale value between the dry- and wet-bulb thermometers may be allowed for by altering the magnification of the optical system. The thermometer stems may be moved up and down as the mean temperature varies throughout the year, as the range covered by the instrument when stems are in one position is only about 50°F. For details concerning the care of the wet bulb see Chapter 4.

The advantage of the instrument is that it is simple and quite reliable mechanically and free from friction errors. The accuracy of the record is practically equal to the accuracy of the thermometers themselves, and is higher than a bimetallic or mercury-in-steel thermograph ; readings can be made to the nearest 0·1°F. Its disadvantages are :—

(i) The bulbs of the thermometers have to be large, to reduce the emergent stem error and to enable the bore of the stem to be large enough to contain the air bubble and yet have a reasonable scale value, and consequently the instrument has a large lag coefficient.

(ii) The records cannot be inspected before the paper has been developed.

(iii) The temperatures have to be evaluated from the record and cannot be read directly.

(iv) There is a difficulty in arranging an adequate exposure of the thermometers. A darkened enclosure has to be provided for the recording mechanism and the thermometer bulbs have to be within about 2 ft. of the outside of this.

The thermometer bulbs are sometimes housed in a screen attached to the outside wall of a building which can hold the recording mechanism, but the exposure of the thermometers suffers, especially if the building is heated. A better solution has been found in one case, however, by building a louvered screen large enough to enclose the whole mechanism.

3.8. TEST THERMOMETERS AND CALIBRATION

3.8.1. Inspector's thermometers

Inspector's thermometers (Stores Ref., Met. 425 for temperate range and Met. 576 for tropical range) are used to check the readings of ordinary meteorological thermometers at outstations and elsewhere. They are solid stem mercury-in-glass thermometers with spherical bulbs (Fig. 59) covering a range of only 50°F. and graduated for every 0·2°F. A temperate model covers the range 30° to 80°F. and a tropical model 50° to 100°F. Graduations which are a multiple of 10°F. are numbered, and the intermediate 5°F. lines are distinguished by a small arrowhead.

Each thermometer is graduated for total immersion, and is provided with an enlarged safety chamber at the top of the stem. The total length of the scale (50°F.) is at least 7·5 in. long, i.e. there are not more than 7°F. to the inch. This provides for an exceptionally open scale, and, together with the 0·2°F. graduations, enables measurement to be made to the nearest 0·1°F. with ease, and if necessary to the nearest 0·02°F. The general dimensions of the thermometer are as follows :—

Length of stem : not exceeding 11 in.

External diameter of bulb (at right angles to the stem) : 0·35 ±0·05 in.

External diameter of stem : 0·25 in. approximately.

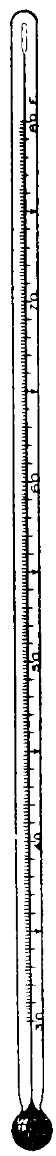


FIG. 59—INSPECTOR'S THERMOMETER

The permissible errors at any point are — 0·3° to + 0·1°F., and the permissible change of error over an interval of 20°F. is 0·2°F. The measurements for the National Physical Laboratory certificate are made with an accuracy of ± 0·05°F., but the corrections are given to the nearest 0·02°F. These errors should always be taken into account when using the thermometer. The graduations on the thermometer may in time become faint. If so, they can be re-blackened by rubbing the stem with dark crayon or shoemaker's heel-ball.

3.8.2. Testing of thermometers

The large-scale testing of all Meteorological Office liquid-in-glass thermometers before issue is carried out by the National Physical Laboratory with a view to determining their errors. There, routine methods of comparing thermometers, in large batches, with standard thermometers have been developed. The thermometers should, however, be checked subsequently at intervals (of the order of 2–4 yr.) if their errors are to be known with accuracy. The ice point may be checked by nearly filling a Dewar flask with crushed ice made from distilled water and moistening it with more distilled water. An ordinary thermos flask will accommodate most total immersion thermometers up to their ice point ; the thermometer should be inserted so that the least possible part of the mercury or spirit column emerges from the ice. A reading of the indicated temperature can be made after an interval of at least 15 min. has elapsed to allow the thermometer to take up the temperature of the melting ice.

For checking a thermometer at other temperatures, an inspector's thermometer may be used together with a liquid bath in a Dewar flask or a very well lagged container. Any convenient way of heating the bath may be used ; the liquid may be water at temperatures above 32°F., but petrol or trichlorethylene cooled by solid carbon dioxide can be used at temperatures below 32°F. The inspector's thermometer and the thermometer under test should be suspended independently of the container, not touching the sides, and, as the bath cannot be completely full of liquid and it is not usually transparent, some means of raising the thermometer quickly through a small distance should be provided. The most difficult problem is to secure uniformity of temperature throughout the liquid ; a small motor-driven stirrer suspended in the bath or a vigorous current of air bubbled through the liquid is the best, but if this is impossible a manual stirrer that will not damage the thermometers should be used ; a goose or chicken feather has been recommended. As the thermometers will, in general, have different lag coefficients ample time must be left before taking a reading, and it is best to make a series of readings until steady conditions prevail. The thermometers should be immersed to as near the top of the liquid columns as possible to avoid emergent stem error. Maximum thermometers can only be tested on rising temperature. By very careful procedure it is then possible to compare the readings of two thermometers to an accuracy of $\pm$ 0·1°F., but errors up to 0·2° or 0·3°F. are easy to make. Inspector's thermometers used in the Meteorological Office are returned to the National Physical Laboratory every 5 yr. for re-calibration.

The method used to check aircraft resistance thermometers is to immerse the elements completely in a bath of petrol in a Dewar flask, cooled by solid carbon dioxide, or heated if necessary, and thoroughly stir the liquid by bubbling air through it. An accurate platinum resistance thermometer is used to obtain the temperature of the bath.

The bimetallic thermographs are checked in the Provisioning Branch of the Meteorological Office by fixing them in position with the bimetallic element in a bath of water. The temperature of the bath can be varied and measured by means of a mercury-in-glass thermometer and compared with the readings of the thermograph. Comparisons are made at two temperatures, and from these any necessary changes in the zero point and magnification can be found.

Mercury-in-steel thermographs are checked at two points in a similar manner. A test is also made of the compensation for capillary temperature ; the capillary tube is immersed in a water bath and has its temperature altered while the temperature of the bulb is kept constant in another water bath. The temperature of the capillary tube is varied over a range of about 50°F.

CHAPTER 4

MEASUREMENT OF HUMIDITY

4.1. GENERAL

4.1.1. Definitions

There are various ways in which the amount of water vapour in the atmosphere may be specified ; the most common are :—

(i) Mixing ratio (or humidity mixing ratio)

(ii) Specific humidity (or moisture content)

(iii) Vapour pressure

(iv) Absolute humidity (or density of water vapour)

(v) Dew point and frost point

(vi) Relative humidity.

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

$$r = \frac{m_v}{m_a}. \qquad \text{......(45)}$$

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

$$q = \frac{m_v}{m_v + m_a} \qquad \text{......(46)}$$

$$= \frac{r}{1 + r}.$$

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

$$e = \frac{r}{0{\cdot}622 + r}\,p, \qquad \text{......(47)}$$

where p is the atmospheric pressure,

or $$r = \frac{0{\cdot}622e}{p - e}.$$

Similarly
$$q = \frac{r}{1+r}$$
$$= \frac{0 \cdot 622e}{p - 0 \cdot 378e}.$$

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

When the air temperature is below 32°F. it is possible to have saturation over either a supercooled liquid-water surface or over an ice surface, and different values of the saturation vapour pressure are found in the two cases. The two sets of values can be represented by e_w and e_i ; e_w refers to saturation over liquid water and covers all temperatures up to the critical temperature of water (about 370°C.), and e_i refers to saturation over ice at temperatures of 32°F. or below. At 32°F. e_w and e_i are equal. The values of e_w and e_i given in the tables are those with reference to a plane surface of pure water or ice ; over a curved surface the saturation vapour pressure changes, becoming higher over a convex surface and lower over a concave surface. It is also less over a solution of an electrolyte than the corresponding value over pure water at the same temperature.

The deviation of the behaviour of water vapour from the laws governing a perfect gas can usually be neglected for meteorological purposes. It can also be noted that when e is small compared with p then
$$r \simeq q \simeq \frac{0 \cdot 622e}{p}.$$

The values of e_w and e_i can be found in "Hygrometric tables"[24] for all temperatures likely to be needed in meteorological observations at ground level in this country, but if the values at other temperatures are required these can be found in "Physical and chemical constants" by Kaye and Laby[25], where the values are given in millimetres and not millibars, for temperatures up to 360°C., or the "Smithsonian meteorological tables"[26], or can be found from the Meteorological Office humidity slide-rule Mk III (see p. 165).

Absolute humidity.—The absolute humidity, d_v, which is sometimes known as the vapour concentration, or vapour density, is defined as the ratio of the mass of water vapour, m_v, to the volume, V, occupied by the moist air with which it is associated.
$$d_v = \frac{m_v}{V}. \qquad \ldots\ldots(48)$$

It is thus equivalent to the density of the water vapour, and can be calculated from the vapour pressure and the temperature. If the vapour pressure is given in millibars and the temperature T in degrees Fahrenheit then
$$d_v = \frac{390 \cdot 1e}{T + 460} \text{ gm./m.}^3 \qquad \ldots\ldots(49)$$

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

When the vapour pressure is less than 6·107 mb. (the value of e_w at 32°F.) it is possible to find a somewhat similar temperature, T_f, such that the value of e_i at this temperature is equal to e. This temperature is called the frost point (or hoar-frost point) of the air and is higher than the corresponding dew point. It is the temperature to which the air has to be cooled at constant pressure before it becomes saturated with respect to ice. When $e = 6{\cdot}107$ mb., $T_d = T_f = 32$°F. The Meteorological Office practice is always to record and report the dew point, unless it is specifically stated otherwise.

If the air is supersaturated with respect to ice at air temperatures below 32°F. (i.e. e is greater than the corresponding value of e_i at the air temperature T) the frost point will be higher than the air temperature, and similarly if the air is supersaturated with respect to liquid water T_d is higher than T.

Supersaturation with respect to ice, at temperatures below 32°F., occurs in the atmosphere, but supersaturation with respect to liquid water is probably rare and of only local occurrence.

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

$$U = 100 \frac{e}{e_w}. \qquad \ldots\ldots(50)$$

At air temperatures below 32°F. there are then two possible values of U :—

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

and

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

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

This definition is the one adopted by the Meteorological Office. The International Meteorological Organization, however, in 1947 at Washington[8] defined the relative humidity as the percentage ratio of the actual mixing ratio to the saturation mixing ratio at the air temperature, i.e.

$$U = \frac{100r}{r_w},$$

where r_w is the saturation mixing ratio at the air temperature.

There is no difference between the numerical values given by these definitions at $U = 0$ per cent. of $U = 100$ per cent., but the difference (at mean-sea-level pressures) between 50 per cent. relative humidity on the Meteorological Office definition and the corresponding relative humidity on the International Meteorological Organization definition is 0·3 per cent. at an air temperature of 50°F., 2 per cent. at 100°F. and 7 per cent. at 150°F., the International Meteorological Organization definition giving the smaller values. The difference is thus usually appreciable only at high temperatures.

4.1.2. General principles of hygrometers

A hygrometer is an instrument used to measure the amount of water vapour in the air. There are six main classes :

(i) Chemical absorption type
(ii) Electrical absorption type
(iii) Diffusion type
(iv) Psychrometers
(v) Condensation type (dew-point hygrometers)
(vi) Instruments utilizing the change in dimensions of hygroscopic substances (e.g. the hair hygrometer, and the gold-beater's skin hygrometric element in a radio-sonde).

Chemical absorption hygrometer.—In the chemical absorption hygrometer a known volume of the air is thoroughly dried by chemical means, and then either (*a*) the weight of moisture absorbed by the drying agent is determined, or (*b*) the consequent change in volume of the air at constant pressure is measured, or (*c*) the consequent change in pressure of the air at constant volume is measured. As a single measurement takes an appreciable time, which may be as long as an hour, the method is only used for laboratory work or special research. In a typical instrument using method (*a*) air is drawn through two U-shaped drying tubes at a constant rate by running water out of an aspirator, the drying tubes being weighed before and after a known volume of air has passed through them. The volume of air is found by measuring the volume of water removed from the aspirator. From these measurements and other easily measurable factors it is possible to find the vapour pressure. Fuller details of these and the various other types of chemical absorption methods can be found in the " Dictionary of applied physics "[1].

Electrical absorption hygrometer.—The electrical absorption hygrometer utilizes the variation of the resistance of a thin electrolyte film containing a hygroscopic salt with the humidity. This principle is used in some hygrometric elements for radio-sondes, and in the Gregory humidiometer (p. 184).

Another type of absorption hygrometer is the optical instrument developed by E. Glückauf[27]. If a beam of monochromatic light falls on a thin transparent film, the intensity of the reflected light varies with the thickness of the film, because of interference effects. This phenomenon is used to measure the thickness of a thin hygroscopic film, and thus, as the thickness varies with the humidity, the humidity itself can be found.

Diffusion hygrometer.—This hygrometer consists of a chamber closed to the outside air except for a porous plate set in its wall. The air in the chamber is subjected to the continuous action of either a wetting or a drying agent, and the consequent diffusion through the porous plate produces a change in the pressure of the enclosed air. The value of this pressure change, when a steady state is reached, is simply related to the vapour pressure of the outside air and the temperature of the instrument.

The pressure difference is measured by a manometer connected to the chamber. If the other limb of the manometer is merely left open to the air, the variability of the reaction of the hygrometer, which is extremely sensitive to temperature, gives rise to false readings. To help reduce this effect the second limb of the manometer can be connected to a similar chamber containing nothing but air, or to one in which a process opposite to that in the first chamber (drying instead of wetting, or *vice versa*) is taking place. Even with these refinements, this type of hygrometer is still very sensitive to temperature changes.

Psychrometer.—The psychrometer consists essentially of two thermometers exposed side by side ; one is an ordinary thermometer, perfectly dry, known as the dry thermometer or dry bulb, while the other has its temperature element surrounded by a piece of thin wet material or covered by a film of water or ice, and is known as the wet thermometer or wet bulb. The temperature of this thermometer is generally lower than that of the dry bulb, because of evaporation of water from the wet bulb, and the drier the air the more intense will be the evaporation and the greater the difference in temperature between the two ; the vapour pressure can be deduced from the two readings. Any type of thermometer may be used, and they may be exposed in a thermometer screen, aspirated by a fan, or used in aircraft. It is important to distinguish between psychrometers having forced ventilation and those which have not, because the depression of the wet-bulb reading below the dry-bulb reading depends on the speed of the air past the bulbs when the wind speed is low. A general discussion on psychrometers is given by Wylie[28].

Condensation hygrometer.—With the condensation type of hygrometer, the dew point of the air is determined directly. A polished surface is cooled and the temperature at which a dew or hoar-frost deposit does not grow or diminish is measured. These instruments are not at present used in routine meteorological observations, apart from the aircraft frost-point hygrometer, which will be dealt with in Part II of this Handbook. Reference may be made to the " Dictionary of applied physics "[1].

Hygrometers responding to relative humidity.—Hygrometers using hygroscopic substances which change in length when the relative humidity changes may be used as indicating instruments at ground level. The hair hygrograph is widely used as a continuous recording instrument and both hair and gold-beater's skin are used as hygrometric elements in radio-sondes. It should be noted that both these substances measure the relative humidity with respect to liquid water, not with respect to ice, even at temperatures below 32°F.

Comparison of different hygrometers.—The chemical absorption hygrometer is the most accurate for laboratory work ; for the reasons stated above, it is unsuitable for routine meteorological measurements. The accuracy of the psychrometer is dependent on the exposure of the thermometers ; the most accurate method is to draw a current of air past the thermometer elements by means of a fan (e.g. as in the aspirated psychrometer Mk II) keeping the bulbs suitably shielded from radiation, and when this is done reliable results can be obtained. When the wind speed past the thermometer elements exceeds 7–9 kt. the depression of the wet bulb with a normal-sized mercury-in-glass thermometer is practically independent of the wind speed, but for wind speeds less than this the depression of the wet bulb usually decreases as the wind speed decreases. Thus while the exposure of the dry- and wet-bulb thermometers in a Stevenson screen without any artificial ventilation is very simple, the values of the constants to be used in working out the result are uncertain to the extent that the wind speed past the wet bulb may vary from zero up to 7 kt. or more. Usually, however, the wind speed does not vary appreciably from the value of 2–4 kt., which is normally assumed when calculating the humidity from the screen readings. The chief errors are likely to occur when the air is hot and dry and the wind very light.

The chief difficulties in the use of the dew-point hygrometer are in judging when the deposit is neither growing nor diminishing, and in ensuring that the temperature recorded is that of the surface on which the deposit is made. Provided proper precautions are taken this method is reliable, and it can be used at very low temperatures at which other hygrometers are unreliable. It is not used for routine meteorological observations at ground level as no simple means of continuously cooling the polished surface has yet been devised. It also requires a certain amount of care and skill to operate.

The last type of hygrometer, using hair or gold-beater's skin, is probably the least reliable ; the controlling elements are not sufficiently uniform for standard instruments to be made without much individual adjustment and calibration with reference to a standard (usually an aspirated psychrometer). They are also affected by zero drift and hysteresis when the humidity drops to a very low value for any length of time, and thus require constant checking against the standard.

The speed of response of the different types of hygrometer to varying humidity is dealt with more fully when describing each instrument separately. The main features are however :

Chemical absorption hygrometer.—The usual form of the chemical absorption hygrometer is inherently incapable of measuring humidity over short periods but special forms of this type could be developed.

Electrical absorption hygrometer.—The lag of the electrical absorption type of hygrometer can be made quite small (of the order of seconds) at room temperature but it increases as the temperature falls. Within certain limits it decreases with an increase in the speed of the air past the element.

Psychrometer.—The lag of the psychrometer depends on the individual lags of its thermometers. The lag of the dry-bulb thermometers has been discussed in Chapter 3. For most psychrometers the lag of the wet bulb is somewhat less than a dry bulb of similar size and ventilation. The different lags of the dry and wet bulbs can lead to errors in the indicated humidity when the humidity is changing. The lags may be equalized by reducing the size of the dry bulb or increasing its ventilation (see " A study of the aspiration psychrometer " by Spilhaus[29]).

Condensation hygrometer.—The lag of the dew-point hygrometer is controlled mainly by the speed at which the observer can manipulate the cooling device, the least increase in deposit which can be seen by the observer, and the lag of the thermometer recording the temperature of the dew-point surface. Automatic instruments have also been devised in which the lag can be made quite small if desired.

Hygrometers responding to relative humidity.—The lags of the hair and gold-beater's skin elements are complicated functions of humidity and temperature and also, to some extent, of the ventilation. At normal ground temperatures the numerical values compare well with the psychrometer, but as the temperature falls the lags increase rapidly and become very large at temperatures below − 20°F. The lag of hair can be reduced by flattening it between rollers under high pressure, but this treatment halves its tensile strength.

The manner of variation with temperature of the lags of these elements is shown in Table XVII (though the figures given there should not be regarded as exact). The parameter chosen to represent the lag is the time required to indicate 63 per cent. of a change in relative humidity. This corresponds to the lag coefficient appropriate to an exponential response curve, but in this case, since the response curve is not exponential, it can be regarded only as an approximation to such a coefficient.

TABLE XVII—VARIATION WITH TEMPERATURE OF THE LAGS OF HAIR AND GOLD-BEATER'S SKIN HYGROGRAPHS[30]

Time required to indicate 63 per cent. of a change in relative humidity

	Temperature (° C.)					
	20°	10°	0°	−10°	−20°	−30°
			seconds			
Ordinary hair	30	40	55	175	400	800
Hair rolled flat	10	10	12	15	20	30
Gold-beater's skin	6	10	20	50	100	200

4.2. PSYCHROMETERS

4.2.1. General

The vapour pressure, e, is determined from the readings of the dry- and wet-bulb thermometers by substitution in an equation of the form (due originally to Regnault and August and Apjohn) :

$$e = e'_w - Ap(T - T'), \qquad \ldots\ldots(51)$$

where T is the temperature of the dry bulb

T' is the temperature of the wet bulb

e'_w is the saturation vapour pressure over water at the temperature of the wet bulb T'

p is the atmospheric pressure at the place of observation

A is a constant which depends to some extent on the wind speed past the wet bulb.

This formula can be derived theoretically on certain simplifying assumptions as to what happens at the wet bulb. A simple derivation is that given by A. F. Spilhaus[29]. Suppose a mass, m_1, of air passes the wet bulb in unit time, and in so doing cools from the temperature T to T', and a mass, m_2, of this air becomes saturated with water vapour in the same time. As the wind speed past the wet bulb increases it would be expected that m_2 would approach m_1. The equality of the heat given out and absorbed by the two processes leads to the equation

$$e = e'_w - \frac{m_1 c_p p(T - T')}{m_2 x \mathrm{L}}, \qquad \ldots\ldots(52)$$

where c_p is the specific heat of air at constant pressure, L is the latent heat of evaporation of water at temperature T', and x is the ratio of the density of water vapour to air at the same temperature and pressure.

Comparing this with equation (51) it is seen that

$$A = \frac{m_1 c_p}{m_2 x \mathrm{L}}.$$

The experimental values of L show that it is not quite constant, but can be represented in the form $\mathrm{L}_{T'} = \mathrm{L}_{32} - \alpha(T' - 32)$ where $\mathrm{L}_{T'}$ and L_{32} are the values of L at T' and 32°F. respectively and α is about $0 \cdot 0006\ \mathrm{L}_{32}$. This would lead to an expression for A of the form

$$A = A_{32}\left\{1 + \frac{\alpha}{\mathrm{L}_{32}}(T' - 32)\right\},$$

where A_{32} is the value of A at 32°F. This is, however, a refinement which is not considered necessary in British practice in which A is considered constant for any given wind speed.

When the temperature of the wet bulb is below 32°F. it may be covered with either supercooled water or ice. If it is covered with ice the latent heat of evaporation is increased by the value of the latent heat of fusion of ice into water; i.e. L will increase from about 596 cal./gm. to 675 cal./gm. This results in a sudden change in the value of A when the wet bulb freezes. To avoid any uncertainty as to the value of A when the wet-bulb temperature is below 32°F. precautions must be taken to ensure that the wet bulb is covered with ice and not supercooled water. The Meteorological Office tables for use with psychrometers have been drawn up for these conditions, e'_i, the saturation vapour pressure over ice at the temperature of the wet bulb, being used in place of e'_w in equation (51) whenever the wet-bulb temperature is below 32°F.

Lag of the psychrometer.—The behaviour of the dry bulb when the temperature of the air changes has been discussed in Chapter 3 (p. 89). It can be shown[29] that the value of the lag coefficient, λ_w, of the wet-bulb thermometer is given by

$$\frac{1}{\lambda_w} = \frac{m_1 c_p}{C_w} + \frac{m_2 x \mathrm{L} \beta}{C_w p}$$
$$= \frac{m_2 x \mathrm{L}(Ap + \beta)}{C_w p},$$

where β is approximately equal to de'_w/dT' at the temperature T', and C_w is the thermal capacity of the wet bulb, including water and muslin. The corresponding value for the dry bulb is given by

$$\frac{1}{\lambda_d} = \frac{m_1 c_p}{C}.$$

C will be less than C_w because of the muslin and water on the wet bulb, but the effect of the additional factor in $1/\lambda_w$ normally causes λ_w to be less than the lag coefficient of a dry bulb of the same size and exposed to the same ventilation.

The lag coefficient of the wet bulb varies with the speed of the air past the bulb in a similar manner to the dry bulb, and may also be represented by the formula $\lambda_w = k(\rho v)^{-n}$. Some indications of the values of λ_w for various types of thermometers, used both as dry and wet bulbs is given in Table VI, p. 90. It also gives the values of the exponent n (in the above equation).

When the speed of ventilation is high it may be assumed that $m_2 = m_1$ ($= m$ say). The ratio of the lag coefficients of dry- and wet-bulb thermometers of the same size, ventilation and approximately the same thermal capacity will then be given by

$$\frac{\lambda_w}{\lambda_d} = \frac{mc_pC_w}{C}\left[\frac{1}{mc_p + \dfrac{mx\mathrm{L}\beta}{p}}\right] \simeq \left[\frac{1}{1 + \dfrac{x\mathrm{L}\beta}{pc_p}}\right] \text{ if } C \simeq C_w.$$

The values of this ratio, for various temperatures, are given in Table XVIII for a pressure of 1000 mb.

TABLE XVIII—RATIO OF WET-BULB LAG TO DRY-BULB LAG

T'(°F.)	86	68	50	32	14	-4
λ_w/λ_d	0·21	0·31	0·44	0·57	0·71	0·85

The main trend given in this table is borne out in practice, but the actual values of λ_w/λ_d will be greater than those given because C_w will be greater than C due to the film of water and the covering of muslin.

Practical formulae.—The equations used by the Meteorological Office for calculating e from surface psychrometer observations are :

(i) for a Stevenson screen exposure (air speed past the wet bulb approximately 2–4 kt.)

$e = e'_w - 0{\cdot}444\,(T - T')$ for values of T' equal to or above 32°F.

$e = e'_i - 0{\cdot}400\,(T - T')$ for values of T' below 32°F.

(ii) for use with ventilated psychrometers (e.g. Assmann psychrometer) air speed past the bulbs in excess of about 7 kt.

$e = e'_w - 0{\cdot}37\,(T - T')$ for values of T' equal to or above 32°F.

$e = e_i' - 0{\cdot}33\,(T - T')$ for values of T' below 32°F.

These equations are used in the design of the humidity slide-rules and in the various hygrometric tables (see p. 165). Pressure has been assumed to be 1000 mb. throughout, and no account has been taken of any change in latent heat of evaporation of water with temperature. Any necessary corrections are, however, small for observations in the British Isles and below a height of about 1,500 ft. These equations are for temperature measured in degrees Fahrenheit and vapour pressure in millibars. For aircraft observations and observations at high-level stations the numerical constants in the above equations are multiplied by $p/1000$, where p is atmospheric pressure at the level of observation. If the mean pressure at any place where regular observations are made differs from 1000 mb. by more than 50 mb. it is best to recompute the tables to allow for this or to use the Meteorological Office humidity slide-rule Mk III (see p. 165).

There is no absolute uniformity in the various equations used by different countries to compute the vapour pressure from the readings of a psychrometer ; in " Hygrometric tables "[24] examples of the equations used in other countries are given for comparison with British practice.

Care of the wet bulb.—The wet-bulb thermometer element should be covered with a single thickness of muslin or cambric which must be clean and free from dressing or grease ; this can be ensured by washing in water containing ammonia and rinsing in distilled water. For cylindrical bulbs a close-fitting muslin sleeve is best, while for spherical bulbs the standard circular muslin cap (Stores Ref., Met. 512), already threaded with a cotton thread to serve as a wick, is the most suitable. The cap is placed over the thermometer bulb, the thread pulled tight, wrapped once or twice around the stem above the bulb, and then tied leaving the ends free to be used as the wick. The object in all wet-bulb coverings is to make the muslin stretch smoothly and closely over the element, avoiding creases as far as possible.

The muslin should always be changed before it gets dirty or contaminated ; more frequent changes will be needed at coast stations and stations near large industrial areas than in the open country. At coastal stations care has to be taken to avoid, as far as possible, the contamination of the muslin by spray from sea water, as this alters the saturation vapour pressure of the liquid on the wet bulb and causes an incorrect reading. This is especially likely to happen during a storm with an on-shore wind.

The water used for moistening the wet bulb should be either distilled water or, if this is not obtainable, rain-water. The distilled water should preferably be obtained from a chemist ; a supply from a garage should not be used as this is often contaminated with sulphuric acid. If hard water from a tap is used, the wet bulb and muslin soon become encrusted with the solid matter which was in solution ; the reading is then incorrect.

Whenever water is fed continuously to the wet bulb the relative positions of the dry bulb, wet bulb and water reservoir should be so adjusted that the reservoir does not affect the humidity of the air flowing past the wet bulb, that the air which has flowed past the wet bulb does not affect the dry bulb, and that the temperature of the water is reduced to the wet-bulb temperature by the time it reaches the wet bulb. The reservoir should have a narrow neck or be fitted with a perforated cap to allow the passage of the wick. A compromise has usually to be made between putting the reservoir too near the wet bulb and putting it so far away that the rate of supply of water to the wet bulb is insufficient in hot dry weather.

If the wet bulb is covered with supercooled water, this should be induced to freeze by touching it with a piece of ice or hoar-frost (on the end of a match stick for example). If there is no ice or hoar-frost available the fine point of a pencil may be used. The temperature of the wet bulb will then rise to 32°F. and after the water has all frozen it will slowly drop again ; the true reading is the temperature of the wet bulb when the reading has finally become steady.

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

Sources of error.—Errors in the psychrometer may be classified into two main classes : (*a*) errors in the thermometers themselves, dealt with in Chapter 3 and which are mainly overcome by applying any index corrections, and (*b*) other errors which affect the reading of the wet bulb. Middleton[5] summarizes those in class (*b*) as

(i) errors due to the conduction of heat down the thermometer stem
(ii) errors due to variability of ventilation
(iii) errors due to the muslin (or ice covering) on the bulb being too thick
(iv) errors due to dirty muslin and impure water.

All these errors (except overventilation) act in such a way as to increase the reading of the wet bulb, and thus increase the apparent humidity. The conduction of heat down the stem of a glass thermometer is not usually very great, and it has been implicitly taken into account when preparing the psychometric tables because the tables are based on experimental results using glass thermometers. Its magnitude depends on the depression of the wet bulb, but unless the thermometer is of unusual construction the error is not likely to be important. With a metal bulb of the mercury-in-steel type thermometer or with thermo-couples the error may be more serious.

The effect of ventilation has already been discussed ; errors under this head can usually be ascribed to using the wrong values of the psychrometric constant for the actual ventilation employed. To avoid uncertainty it is best to use an aspirated psychrometer whose speed of ventilation is above the critical value of about 7 kt. when accurate results are required. The remaining errors can be avoided or minimized by careful maintenance of the wet bulb on the lines indicated above.

The effect of errors in the reading of the depression of the wet bulb on the value of the relative humidity can be seen in Table XIX, which shows the approximate change in relative humidity and dew point caused by a change in the wet-bulb depression of 0·5°F., at different dry-bulb temperatures. This is for a psychrometer exposed in a Stevenson screen.

TABLE XIX—CHANGE IN RELATIVE HUMIDITY AND DEW POINT WHEN THE WET-BULB DEPRESSION INCREASES BY 0·5° F.

Dry bulb	Change in relative humidity	Change in dew point Mean relative humidity 100%	Change in dew point Mean relative humidity 40%
°F.	%	°F.	°F.
80	2	0·7	1·2
60	3	0·9	1·6
40	4	1·1	2·7
20	8	2·0	4·5
0	15	4·2	12·0

The very rapid increase of error when the temperature falls below 32°F. shows that great care is necessary when making readings with the wet bulb frozen. It is especially important then to apply any thermometer corrections.

Use of tables for evaluating results.—The dew point, frost point, relative humidity and vapour pressure may be evaluated from psychrometer readings with the aid of published tables. Those given in " Hygrometric tables "[24] should be used with Stevenson screen observations, while those of Form 2628* relate to aircraft and other aspirated psychrometers. The latter tables only give relative humidity, but they may be used in conjunction with " Hygrometric tables "[24] for the other quantities. The editions of these publications issued before 1948 give the relative humidity with respect to ice when the air temperature is below 32°F. ; later editions however give the relative humidity with respect to liquid water at all temperatures. Tables for determining the dew point and relative humidity are also contained in Appendix II of Part III of " Handbook of weather messages "[31]. These are fully in accord with the new Meteorological Office practice mentioned above.

The tables contain instructions for their use but the following points should be specially noted. When the wet-bulb temperature is close to 32°F. and an interpolation between the values given in the tables is necessary, this interpolation should not take place across the black line, which divides the table into portions referring to wet-bulb temperatures above 32°F. and portions referring to wet-bulb temperatures below 32°F., because of the discontinuity which occurs when the wet bulb freezes. The required values should be found by extrapolation of the values above the line downwards or those below the line upwards, according as to whether the wet-bulb temperature is above or below 32°F. The tables do not apply if the wet-bulb temperature is below 32°F. but the wet bulb is not covered with ice. Provision is made for cases when supersaturation with respect to ice occurs.

To assist in the calculation of the absolute humidity the value of the function $390 \cdot 1/(460 + T)$ is given in " Hygrometric tables "[24] for various values of T (see p. 155).

4.2.2. Meteorological Office humidity slide-rule Mk III

The Meteorological Office humidity slide-rule Mk III (Stores Ref., Met. 1036) is designed to enable the dew point, frost point, relative humidity, vapour pressure, mixing ratio and absolute humidity to be computed quickly and easily from psychrometer observations, either screen or aspirated, and either at ground level or in the upper air, and from radio-sonde and frost-point hygrometer data (Plate XIII). It consists of a stock and slide with scales on the front and back of each. This rule is made of ivory perspex which does not warp with changes of humidity and temperature.

Scale 1 on the front of the stock is a scale of temperature such that the distance of each graduation from an arbitrary zero is proportional to the saturation vapour pressure over water at that temperature. It covers the range from 5°F. to 80°F. Scale 2 on the slide and scale 2B on the reverse of the slide are linear scales of temperature such that the spacing between the 1°F. graduations is 0·440 and 0·370

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* London, Meteorological Office. Form 2628. Tables for deriving the dew point and depression of wet bulb on aircraft.

respectively of the distance corresponding to 1 mb. on scale 1. Thus if the reading of the wet-bulb temperature, T', on scale 1 is brought opposite the reading of the wet-bulb depression, $T - T'$, on scale 2, the zero of scale 2 will indicate on scale 1 a temperature such that the saturation vapour pressure at that temperature is equal to

$$e'_w - 0{\cdot}444\,(T - T'),$$

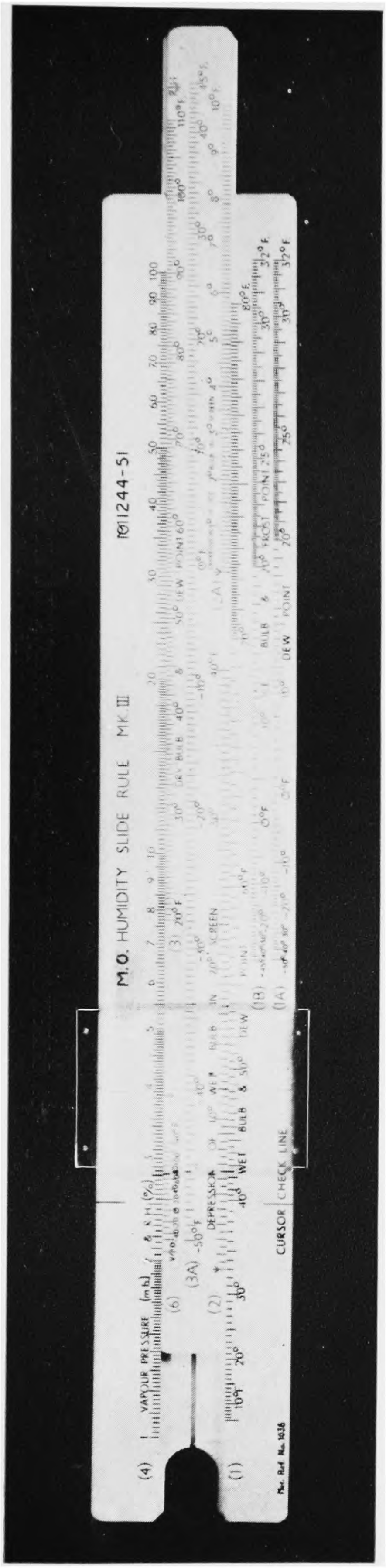
i.e. it will indicate the dew point, if the readings were obtained at a pressure of 1000 mb. from a psychrometer exposed in a standard screen and the wet-bulb temperature was 32°F. or above. Similarly scale 2B (in red) on the reverse of the slide can be used for aspirated psychrometer readings.

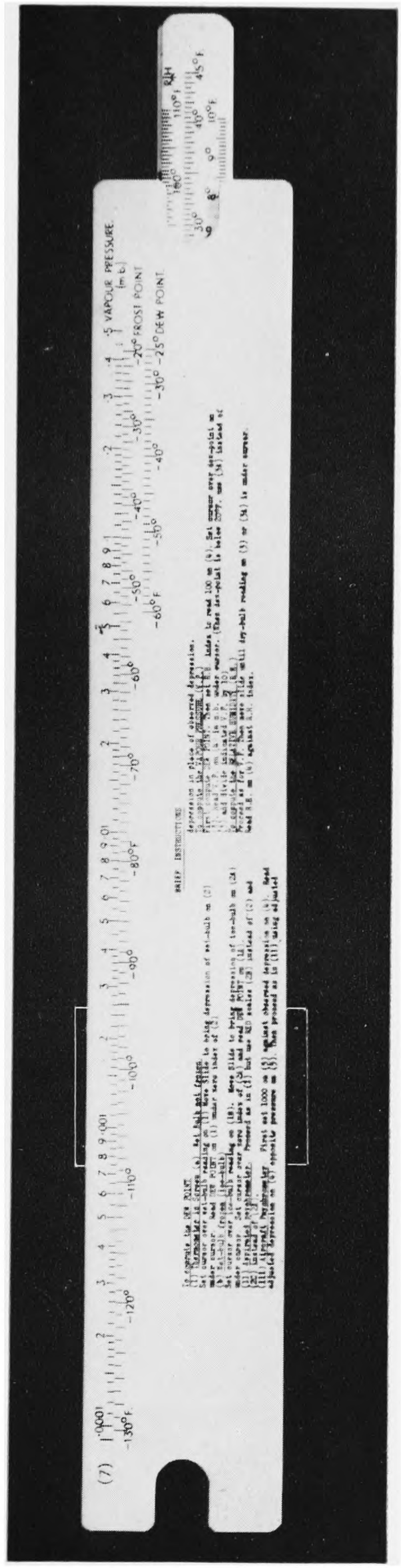
Scale 1A is a scale of temperature on the front of the stock similar to scale 1, but with a greatly increased scale value in terms of inches per millibar, so that it can cover the range from − 50° to + 32°F. without the graduations becoming unduly crowded. It uses a different arbitrary zero to scale 1. Scale 1B is similar to scale 1A, but is obtained by using the saturation vapour pressure over ice in place of the saturation vapour pressure over water. It uses however the same zero as scale 1A. Scale 2A on the slide and scale 2C (in red) on the reverse of the slide are linear scales of temperature from 0° to 10°F., such that the distance between graduations 1°F. apart is equal to 0·40 and 0·33 respectively of the distance corresponding to 1 mb. on scales 1A and 1B. These four scales can therefore be used in conjunction with each other to evaluate the dew point when the wet-bulb temperature is below 32°F., by setting the ice-covered wet-bulb temperature on scale 1B and reading the dew point on scale 1A, after setting the wet-bulb depression on either scale 2A or 2C, according to the type of pyschrometer.

Scale 3 is a scale of temperature on the top of the slide ranging from 20° to 110°F., such that the distance of each graduation from an arbitrary zero is proportional to the logarithm of the saturation vapour pressure over water at that temperature. Scale 3A is similar to scale 3, but the distance of each graduation from the same zero as used for scale 3 is proportional to the logarithm of ten times the saturation vapour pressure. It ranges from − 50° to + 45°F. These two scales which occur on both sides of the slide are used in conjunction with scale 4, which is an ordinary logarithmic scale from 1 to 100 using the same scale value as used for the logarithms in scales 3 and 3A. The R.H. (relative humidity) mark at the end of scale 3 is the point corresponding to a vapour pressure of 100 mb. ; thus if the R.H. mark is set opposite the 100 on scale 4 each temperature graduation on scale 3 is opposite the corresponding value of the saturation vapour pressure over water in millibars on scale 4, and each graduation of scale 3A is opposite a figure of ten times this quantity. The relative humidity can be quickly obtained by dividing the actual vapour pressure (found from the dew point) by the saturation vapour pressure at the dry-bulb temperature.

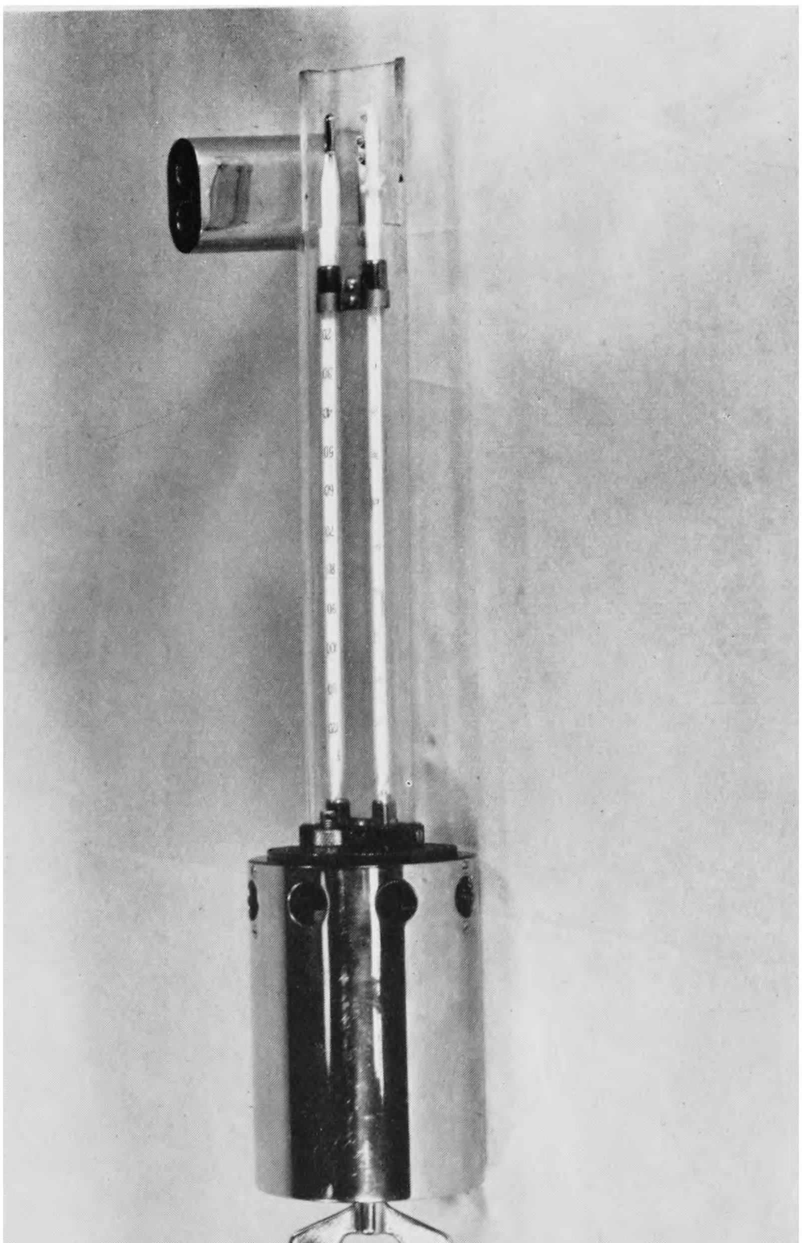
Scale 5 on the reverse of the slide is a logarithmic scale from 300 to 1,050 with the same scale value as scale 4, and is used for applying the pressure correction to the psychrometric readings from aircraft or at high-level stations, and for calculating the mixing ratio and specific humidity. Scale 6 is used to calculate the absolute humidity (vapour density). The distance of each temperature graduation, T°F., from the mark V.D. is proportional to the logarithm of the function $390{\cdot}1/(460 + T)$.

Scale 7 on the back of the stock consists of three parts ; the top is a simple logarithmic scale from 0·00009 to 0·500, the centre is a temperature scale from





METEOROLOGICAL OFFICE HUMIDITY SLIDE-RULE MK III



CLOCKWORK-ASPIRATED PSYCHROMETER MK II

with radiation shield removed

— 130° to — 20°F. such that each graduation is opposite the value on the top scale of the saturation vapour pressure over ice at that temperature, and the lowest scale is another temperature scale from — 60° to — 25°F. such that each graduation is opposite the value on the top scale of the saturation vapour pressure over water at that temperature. Scale 7 can be used to find the vapour pressure if the frost point or dew point is known, and to find the frost point given the dew point, and *vice versa*. There are, as yet, no internationally agreed values of vapour pressure over liquid water at lower temperatures than — 60°F.

Method of use.—The following procedures should be followed when using the rule. From the description of the basis of the scales given above it will be seen that the various parameters required are computed in accordance with the definitions given on p. 154 and the psychrometric equations given on p. 155.

To compute the dew point from psychrometric observations.—When using aspirated psychrometer observations at or near sea level, set the cursor over the value of the wet-bulb temperature on scale 1 and then bring the value of the wet-bulb depression ($T - T'$) on scale 2B (in red) beneath the cursor. Read the dew point on scale 1 against the zero of scale 2B.

If however the wet-bulb temperature is 32°F. or below and the wet bulb is covered with an ice film, set the cursor over the value of the wet-bulb temperature on scale 1B and bring the value of the wet-bulb depression on scale 2C (in red) beneath the cursor. The dew point is then read on scale 1A opposite the zero of scale 2C (using the cursor).

When using observations made in a standard screen at or near sea level proceed as in the two paragraphs above, but use scales 2 and 2A in place of scales 2B and 2C respectively.

When using aircraft observations, first set 1,000 on scale 5 against the wet-bulb depression on scale 4 ; then set the cursor over the value of the air pressure at observation level on scale 5 and read the " adjusted wet-bulb depression " on scale 4. If the wet-bulb depression is small, multiply it by 10 before the operation and divide the resulting value of the adjusted wet-bulb depression by 10. Then proceed as in the first two paragraphs of this section using the " adjusted wet-bulb depression " in place of the observed depression.

If the pressure at any surface observation level is 950 mb. or below it will be necessary to allow for this by computing an " adjusted wet-bulb depression ", as in the previous paragraph, and using this in place of the observed wet-bulb depression as in the third paragraph of this section.

To compute the vapour pressure.—Except in the case of radio-sonde data (see next subsection), first compute the dew point. Then set the index marked R.H. on the slide opposite 100 on scale 4. Set the cursor over the value of the dew point on scale 3 and read the vapour pressure (in millibars) on scale 4.

If however the dew point is less than 20°F. set the cursor over the dew point on scale 3A and divide the reading on scale 4 by 10.

To compute the dew point and vapour pressure given the relative humidity and the dry-bulb temperature (radio-sonde data).—Set the index marked R.H. on the slide opposite the observed relative humidity on scale 4. Set the cursor over the value of the dry-bulb temperature on scale 3 and read off the vapour pressure on scale 4.

If the dry-bulb temperature is less than 20°F. or the reading is off the scale, set the cursor over the value of the dry-bulb temperature on scale 3A and divide the reading on scale 4 by 10. If this also is impossible because the vapour pressure is less than 0·1 mb. or the relative humidity is very low set the R.H. index opposite n times the relative humidity, proceed as before, and divide observed vapour pressure by n if using scale 3 or by $10n$ if using scale 3A. Keeping the cursor set on the value of the vapour pressure on scale 4 move the slide until the R.H. index is opposite 100 on scale 4 and read off the dew point on scale 3.

If however the dew point is below 20°F. move the cursor to a reading on scale 4 equal to 10 times the vapour pressure and read the dew point on scale 3A. If the vapour pressure is below 0·1 mb. scale 7 must be used.

To compute the relative humidity.—Set the R.H. index opposite 100 on scale 4 and place the cursor over the value of the dew point on either scale 3 or 3A. Now move the slide until the value of the dry-bulb temperature on either scale 3 or 3A (according to which scale was used for the dew point) is beneath the cursor and read the relative humidity on scale 4 opposite the R.H. index.

On the few occasions when the dew point is less than 20°F. and the dry bulb more than 45°F., set the cursor over the value of the vapour pressure on scale 4 and move the slide until the dry-bulb temperature on scale 3 is beneath the cursor. Then read the relative humidity on scale 4 against the R.H. index. If in this case the vapour pressure is less than 1 mb. multiply it by 10 and proceed as above, but divide the observed relative humidity by 10.

To compute the absolute humidity.—Set the cursor over the value of the vapour pressure on scale 4, and adjust the slide until the value of the dry-bulb temperature on scale 6 is beneath the cursor. The absolute humidity can then be read on scale 4 against the index marked V.D. If the vapour pressure is low multiply it by 10, proceed as before, then divide the result obtained by 10. The result is in grammes per cubic metre.

To compute the mixing ratio and specific humidity.—Set the cursor over the value of the vapour pressure on scale 4 and bring the value of $(p - e)$ on scale 5 beneath the cursor. The value of the mixing ratio is then read on scale 4 against the index marked M.R. on scale 5. The result is in grammes per kilogramme. If the vapour pressure is low, set the cursor over the value of 10 times the vapour pressure, proceed as before and divide the result obtained by 10.

In both cases however use the correct value of $(p - e)$ and not $(p - 10e)$.

To obtain the specific humidity proceed in the same way, but bring the value of p instead of $(p - e)$ on scale 5 under the cursor. This is only an approximation to the correct value of $(p - 0{\cdot}378e)$ (see p. 155) but the error involved is usually very small.

To compute the dew point and vapour pressure from frost-point observations.— If the frost point is above − 20°F., set the cursor over the frost point on scale 1B and read the dew point on scale 1A. If the frost point is below − 20°F., read the dew point on the bottom line of scale 7 against the frost point on the centre line of scale 7.

For dew points above − 25°F. the vapour pressure can then be obtained as on p. 167. For dew points and frost points below − 25°F. the vapour pressure can be obtained by placing the cursor over the appropriate value of the frost point (centre line) or dew point (bottom line) of scale 7 and reading the vapour pressure on the top line of scale 7.

Maintenance.—The slide-rules are fitted with a spring at each end to control the friction between body and slide. The tension can be adjusted by a slight movement of the exposed end of the spring to the right or left with a pointed instrument. To increase the tension the spring should be turned clockwise and to decrease the tension counter-clockwise.

The slide-rule should always be used with care and never dropped or left lying around as the material of which it is made is brittle ; it should be kept away from extremes of temperature, and not exposed to direct sunlight, and not handled with soiled or stained fingers. If it is necessary to clean the surfaces, pure soap and water is best ; abrasives should not be used.

Comparison with Meteorological Office humidity slide-rule Mk II.—The Meteorological Office humidity slide-rule Mk II is an earlier version ; it differs from the Mk III as follows :

(i) There are no scales corresponding to scales 3A, 5 and 7 on the Mk III rule ; i.e. the Mk II rule cannot be used for upper air observations or determining the mixing ratio or specific humidity.

(ii) The scales equivalent to 1A, 1B, 2A and 2C on the Mk III slide-rule have the same scale value (millibars per inch) as scale 1 on the Mk III slide-rule, and are thus more contracted and cannot be used to such low temperatures.

(iii) The scale equivalent to 3 on the Mk III slide-rule is based on the saturation vapour pressure over ice for temperature below 32°F., i.e. the relative humidity is obtained with reference to saturation over ice and not with reference to saturation over liquid water at these temperatures.

(iv) An extra linear scale of millibars is engraved on the lower half of the stock, with the same scale value (millibars per inch) as the equivalent scale to scale 1 on the Mk III slide-rule and having the same zero. The scale is placed just beneath the slide so that the vapour pressure and dew point can be determined simultaneously. This scale is not however absolutely necessary as the vapour pressure can be determined without it.

4.2.3. Screen-type psychrometers

The simplest type of psychrometer is a pair of mercury-in-glass thermometers, one dry bulb and one wet bulb, exposed in a thermometer screen (either a large, Stevenson or small type) without any further ventilation. This combination is often known as Mason's hygrometer. The general arrangement of the thermometers in the screens has been described in Chapter 3 (p. 96) ; the wet bulb is supported in a similar manner to the dry bulb (vertical in the large and Stevenson screens and horizontal in the small screen), and is of a similar type to the dry bulb (i.e. an ordinary sheathed thermometer or the solid stem substitute). Details of these thermometers can be found in Chapter 3. The muslin surrounding the wet bulb is kept permanently moist by means of a wick, consisting of a number of threads of cotton (No. 8 cotton is a suitable size) running from the muslin into a reservoir of distilled water, or rain-water. Capillary action causes water to rise up to the wick to replace the water which evaporates from the muslin surrounding the thermometer bulb.

The general instructions with regard to the maintenance of the muslin covering the wet bulb (see p. 163) should be carried out. In country districts it generally suffices to change the muslin once a fortnight but near towns this should be done more frequently. At coastal stations the muslin, wick and water should be changed at any time that it is suspected that spray from sea water may have entered the screen. An interval of at least 15 min. should elapse between the changing of the muslin and the taking of an observation ; a longer time will be needed if the clean water supplied is not approximately at the temperature of the air.

The wick connecting the muslin to the water reservoir should be kept as straight as possible ; if it is allowed to hang in a loop, water will drain from the lowest part and thus soon empty the reservoir. The position of the reservoir should be adjusted so that the length of wick exposed to the air is about 2–3 in. in the British Isles. The rate of supply of water will be insufficient if the reservoir is too far below the wet bulb, if the wick is too thin, if the muslin is not fitting tightly to the thermometer bulb or if either the wick or muslin have become dirty.

An arrangement of the wick and water reservoir known as the Bamford water bottle (Stores Ref., Met. 877) is sometimes used in marine screens. The water bottle (Fig. 60) is fitted with a cork through which passes a glass tube which is bent twice at right angles ; the wick passes through the tube into the interior of the bottle. The water bottle is then mounted upside down, with the cork at the bottom. A flow of water takes place along the wick but not directly out of the tube, and the free liquid surface is not exposed to the air.

The Meteorological Office constant-water-level bottle (Stores Ref., Met. 516) can also be used (Fig. 61). This is a similar device which enables a large volume of water to be used without large changes in the level of the liquid surface into which the wick dips.

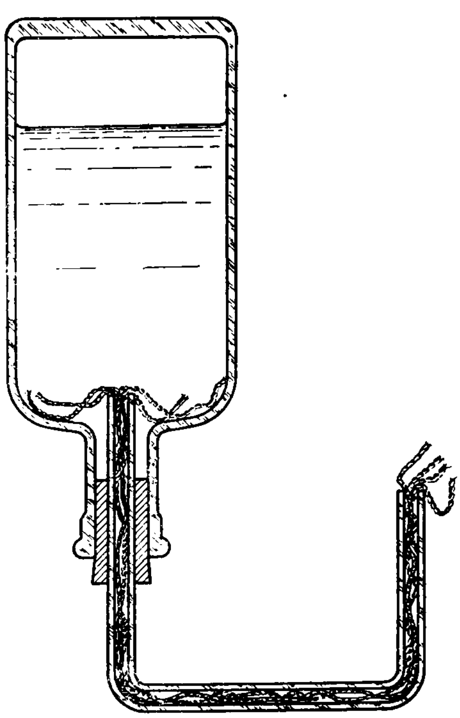


FIG. 60—BAMFORD WATER BOTTLE

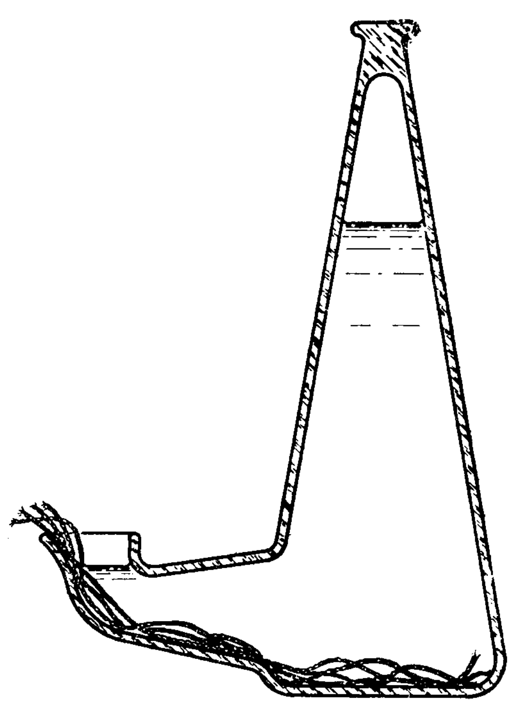


FIG. 61—METEOROLOGICAL OFFICE CONSTANT-WATER-LEVEL BOTTLE

These two devices are especially useful in hot dry conditions when the normal reservoir as used in the British Isles is much too small.

At coastal stations the following procedure may be used to minimize the risk of the wet bulb becoming impregnated with salt.

(i) The water on the wet bulb may be continuously changed by raising the level of the reservoir slightly above the level of the wet bulb while keeping the wick straight between the two. Water will then drip slowly from the thermometer bulb itself. The reservoir will, however, need to be refilled very much more frequently.

(ii) The reservoir may be raised so that it completely covers the bulb of the thermometer between the observations. At least 10 min. before the observation the reservoir is lowered to its normal position and the thermometer bulb exposed freely but with the wick still dipping into the reservoir.

When the wet-bulb temperature is below 32°F. the instructions for managing and ensuring a frozen wet bulb (p. 163) should be carefully followed. If the wet bulb has to be painted with ice-cold water, at least 15 min. should elapse before an observation is taken. It is best to take two or more readings at intervals of about 5 min. to ensure that the maximum depression of the wet-bulb temperature is obtained.

The main source of error in the measurement of humidity by this method is likely to be class (*b*) (see p. 164). Although there is little resistance to the free circulation of the air there may be times when the air flow does not provide sufficient ventilation of the wet bulb. On these occasions, especially on hot dry days, the humidity will be over-estimated.

4.2.4. Aspirated psychrometers with mercury-in-glass thermometers

Clockwork-aspirated psychrometer Mk II.—The clockwork-aspirated psychrometer Mk II (Stores Ref., Met. 869) consists essentially of a perspex duct in which are supported two Assmann-type thermometers (see p. 114) and through which a current of air is drawn by means of a fan driven by a powerful clockwork motor (Plate XIV). The thermometers are supported in the duct by means of metal clips, and their bulbs are surrounded by a highly polished double-walled radiation shield (held in position with a spring catch) which can be removed when it is necessary to moisten the wet bulb. The duct unit, complete with thermometers, is attached to the housing by two knurled headed nuts, and can be easily taken off when it is necessary to remove a thermometer. To refit the duct the two knurled screws should be inserted in the two slots at the head of the duct, and then the the duct rotated through a small angle in a clockwise direction and the knurled screws tightened.

The clockwork motor runs for at least 10 min. on one winding, and should give adequate aspiration of the thermometer bulbs for at least 8 min. out of the 10. A suspension ring is fitted in the key at the top of the motor housing so that the instrument may be hung from a metal support fitting (provided as an accessory) with the thermometers vertical. The whole instrument, together with tubular sleeving wick for the wet bulb (Stores Ref., Met. 1909) and an injector for moistening the wet bulb, is supplied unassembled in a stout wooden box fitted with a hinged lid.

Installation and exposure.—For measurements of air temperature and humidity for normal synoptic purposes the metal psychrometer support fitting is screwed into a thin post or other similar support in an open situation, and the instrument suspended from it with the air inlets 4 ft. above ground level. The instrument should be fixed on the windward side of the support, especially if the wind is light or there is strong sunshine. If no support is available the instrument should be held in the hand, as far as possible from the body and always to the windward. In this case the instrument may be tilted slightly so that the lower inlets face the wind, but care should be taken not to point the instrument in the direction of the sun. The tubes should be well clear of any object at a temperature differing appreciably from that of the air; errors can be caused by the proximity of the observer's body, for example. The polished coaxal tubes are normally sufficient protection against radiation.

Method of use.—The wet bulb should be prepared by cutting a suitable length of wet-bulb sleeving, slipping it over the thermometer bulb and then tying it with cotton at the top and bottom. No frayed edges should be left and the muslin should fit closely round the thermometer bulb, completely covering it and at least $\frac{1}{4}$ in. of the stem.

The following procedure should then be used to obtain an observation of the dry- and wet-bulb temperatures :

(i) Assemble the instrument.

(ii) Moisten the wet bulb. The injector, consisting of a hollow rubber tube to which is attached a piece of glass tubing, should be used for this. First remove the radiation shield, then fill the injector with distilled water and pass the glass tube up over the wet bulb. Now gently squeeze the rubber bulb until the water rises to the top of the glass tube, and leave it there for about 15 sec. or so until the muslin is thoroughly soaked. The bulb can then be released and the tube withdrawn. Any overflow of water should be removed from the perspex duct, and then the radiation shield replaced. It is an advantage if the temperature of the water is approximately equal to the wet-bulb temperature of the air but this cannot always be arranged.

(iii) Wind the clockwork motor. This should be done fully, but care should be taken not to overwind the motor.

(iv) Place the instrument in its correct position (see p. 171).

(v) Begin to read the wet bulb at intervals of about 10 sec. after $1\frac{1}{2}$ min. have elapsed since placing the instrument in position. When the wet-bulb temperature has ceased to fall, as shown by at least three consecutive readings, the dry- and wet-bulb temperatures should be read. If the last three readings of the wet-bulb temperature do not agree to within 0·2°F., because of fluctuations both up and down, it is better to take a mean value of both the dry- and wet-bulb temperatures over an interval of about a minute. The thermometers should be read to the nearest 0·1°F.

(vi) Apply any necessary index corrections to the thermometer readings, as given in the National Physical Laboratory certificate.

The wet bulb should be managed in accordance with the general principles outlined earlier (p. 163), especially with regard to treatment when the wet-bulb temperature is below 32°F., cleanliness of muslin and use of suitable water.

Observations should only be taken when the aspiration fan is rotating at its normal speed ; if there is any slackening in the rate of its rotation, as shown by a drop in the pitch of the note produced, the clockwork spring should be rewound before taking any further readings.

The Meteorological Office humidity slide-rule Mk III may be used to obtain the value of the dew point or other humidity parameters from the observations, using either scale 2B or 2C (in red) for the wet-bulb depression. Alternatively, the tables given in Form 2628 (see p. 165) or Marvin's meteorological tables [32] may be used. As shown in " Hygromatic tables "[24] these latter tables, used in America, are based on a different psychrometric equation. The numerical results are, however, negligibly different in most cases from those obtained by means of the simpler equation used in the Meteorological Office.

Maintenance and repair.—The radiation shield covering the thermometer bulbs should be kept highly polished to minimize the effect of radiation. A clean chamois leather should be used. The bearings of the clockwork motor are well greased and oiled and should not normally require attention. If necessary, the motor may be removed by first unscrewing the winding key and then undoing the six screws holding the motor in place. Light clock oil should be used on the fast-moving parts and grease on the winding mechanism.

If the thermometers have to be removed, the duct should be detached from the fan and motor housing and the thermometers pulled out ; they are held in position by a spring clip at their lower ferrules. This is more easily carried out if the radiation shield is removed first.

Accuracy and sources of error.—The main sources of error in a psychrometer are those due to faulty handling of the wet bulb (see p. 163). In this instrument however there should be no uncertainty due to inadequate ventilation, as tests have shown that the speed of aspiration of the wet bulb is in excess of the minimum speed required throughout the first 8 min. after a full winding of the motor. The average dry- and wet-bulb temperatures of the air should therefore be obtained with an accuracy of about $\pm 0 \cdot 1$°F., except possibly when there are especially large fluctuations, provided care is taken over the preparation of the wet bulb and the making of the observations.

Assmann psychrometer.—The Assmann psychrometer (Stores Ref., Met. 175) is an earlier type of aspirated psychrometer using a clockwork-motor-driven fan (Fig. 62). The Assmann-type mercury-in-glass thermometers are suspended in a chromium-plated, highly polished frame with their bulbs surrounded by two coaxal metal tubes through which air is drawn by means of a fan at the top of the central (hollow) column.

The metal shields surrounding the thermometers can be detached by unscrewing the ivory retaining pieces. The clockwork motor of this instrument is not so powerful as that of the clockwork-aspirated psychrometer Mk II and the air speed past the wet bulb is lower ; consequently the results obtained with this instrument are less reliable.

Installation and method of use.—The installation and method of use of this instrument should follow closely the details given for the clockwork-aspirated psychrometer Mk II. It is important that the radiation shield should be unscrewed

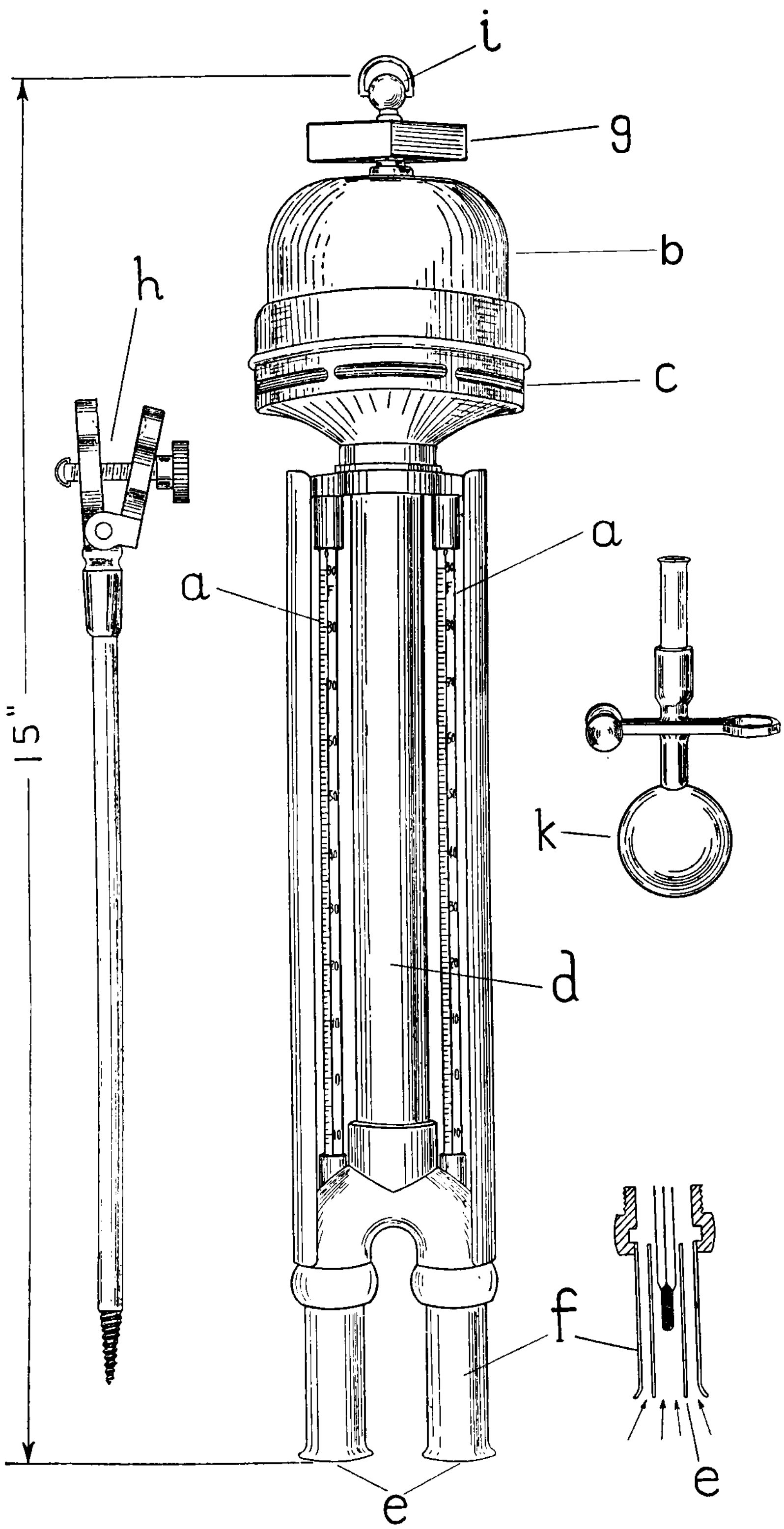
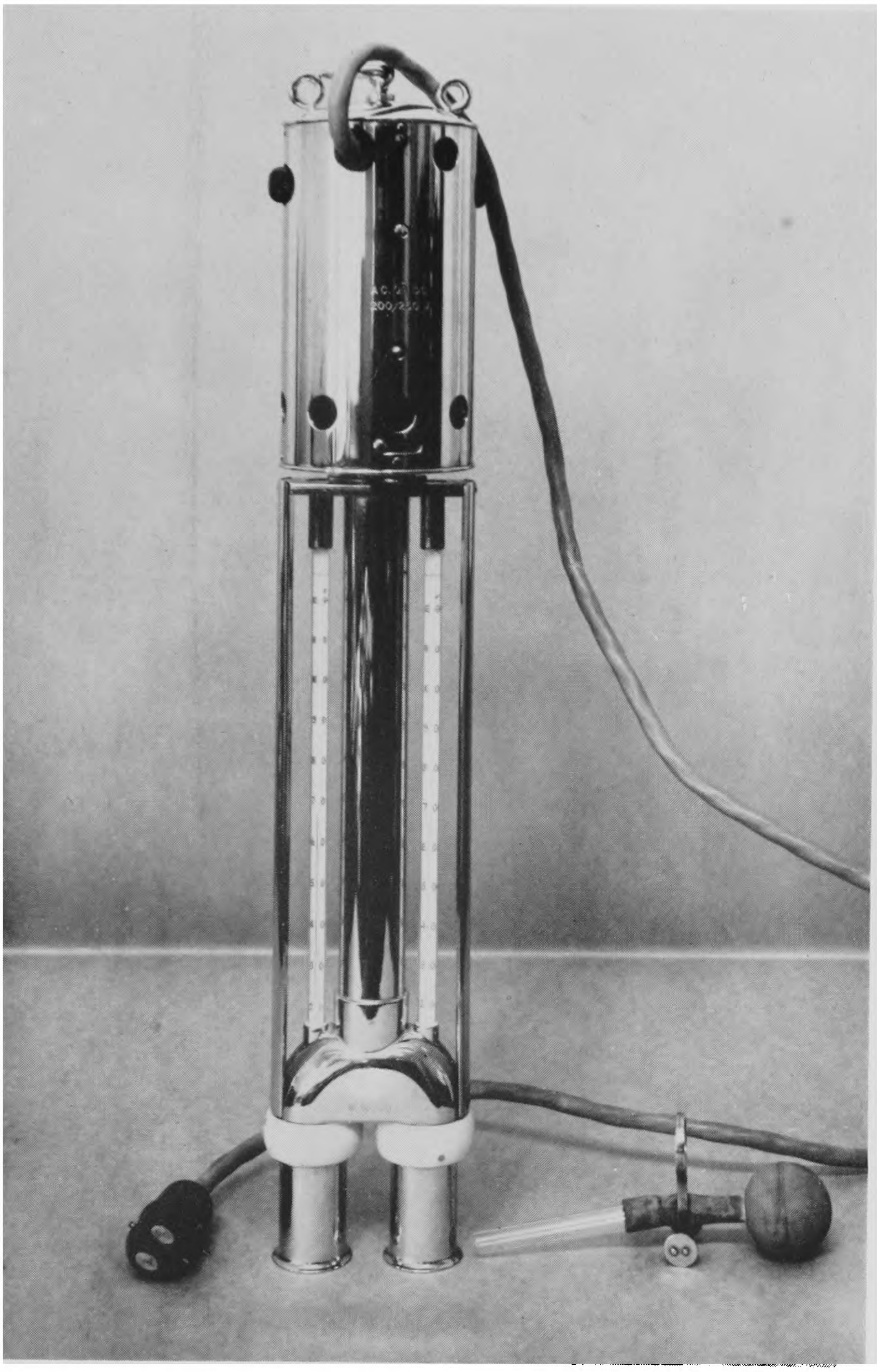
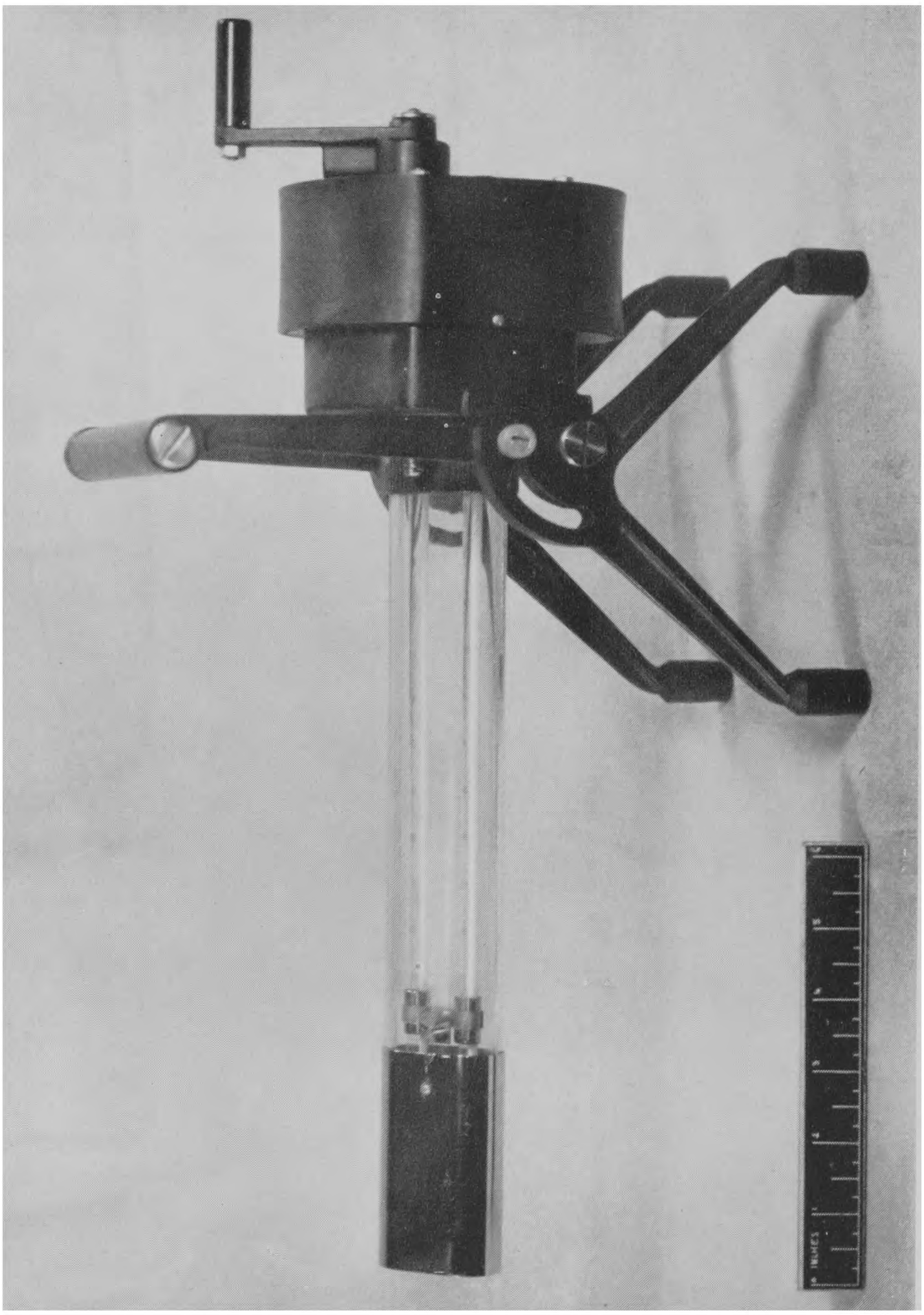


FIG. 62—ASSMANN PSYCHROMETER

a—Thermometers
b—Dome containing clockwork
c—Fan and air outlets
d—Main air duct
e—Air inlets
f—Polished tubes protecting thermometers
g—Key for winding clockwork
h—Clamp for supporting the instrument
i—Point of support of the instrument; the clamp holds the ball securely but allows the instrument to hang vertically
k—Injector for wetting muslin of wet bulb



ELECTRIC ASSMANN PSYCHROMETER



HAND-ASPIRATED PSYCHROMETER

before wetting the muslin, so that it can be verified that the muslin is properly in position, has no frayed edges and is in good condition. Because of the lower ventilation speed, the wet-bulb thermometer will however take longer to reach its final temperature. The instrument should be turned so that the sides of the frame shield the thermometers from direct sunshine.

When the wind speed in the open exceeds about 8–10 kt., a wind shield, supplied with the instrument, should be fitted around the windward half of the fan outlets to prevent the wind from interfering with the outflow of air from the fan. The shield is clipped on and should be arranged so that the outflowing air, which has a tangential motion as well as a radial motion, flows out of the wider part of the shield.

Maintenance.—The frame, motor housing and radiation shield should be kept well polished, using a clean chamois leather. The bearings of the clockwork motor should be oiled occasionally, using a little good clock oil. To remove the dome, first unwind the key and then undo the screws holding the dome to the main body. The clockwork should be completely run down before this is attempted. The bearings of the aspiration fan can be cleaned if necessary by means of a match stick cut to a point.

Accuracy.—As pointed out above, the results obtained with this instrument, especially in hot dry weather with the maximum solar radiation, will not be so reliable or consistent as with the clockwork-aspirated psychrometer Mk II.

Electric Assmann psychrometer.—The frame and thermometer support of the electric Assmann psychrometer (Stores Ref., Met. 545) is of the same general sign as the clockwork Assmann psychrometer, but a universal 200–230 V. a.-c./d.-c. motor in a cylindrical housing is used to drive the aspirating fan (Plate XV). As the motor is much more powerful than the clockwork Assmann motor the air speed past the bulbs is much higher—about 20 kt. This results in a maximum wet-bulb depression and a reduced lag coefficient of the thermometers.

The aspiration rate can be controlled to a certain extent by opening or closing a ring shutter behind the eight air-exit holes in the fan housing. In normal use however the holes should be fully open to allow the maximum ventilation.

Installation and method of use.—The installation and observational technique follow closely that described for the clockwork-aspirated pyschrometer Mk II. As however the ventilation of the wet bulb is much greater, one wetting may only last for about 6 min. in low relative humidities. If a long series of observations is being made, the wet bulb should therefore be remoistened frequently. After each remoistening a further 1½–2 min. will usually have to elapse before the wet-bulb thermometer again reads correctly, unless the distilled water used is already at the wet-bulb temperature.

Accuracy and sources of error.—The discussion given under this heading for the clockwork-aspirated psychrometer Mk II (p. 173) applies equally well to the electric Assmann psychrometer.

Hand-aspirated psychrometer.—A few aspirated psychrometers have been produced (Stores Ref., Met. 838) with the duct and thermometers arranged as in the clockwork-aspirated psychrometer Mk II but fitted with an aspirating fan turned manually by means of a handle working through a train of gears (Plate XVI).

The gearing (40 : 1 in these models) ensures a high fan speed with a reasonable rate of rotation of the handle. A pair of folding legs are fitted to the fan housing, which, together with a fixed handle, enable the instrument to be rested on any convenient support with the thermometer duct horizontal.

The observational technique follows closely that outlined for the clockwork-aspirated psychrometer Mk II, but instead of winding the clockwork motor the handle of the fan drive should be rotated at between 50 and 120 revolutions per minute.

Thêse instruments are likely to be of considerable use on ships, but it is hoped to produce a somewhat lighter and more convenient model before a more extended use is made of them.

4.2.5. Whirling or sling psychrometers

The small portable type of whirling or sling psychrometer (Stores Ref., Met. 2522) sometimes used by the Meteorological Office consists of two mercury-in-glass thermometers mounted in a boxwood frame which is provided with a handle and spindle, by means of which the frame and thermometers may be rotated quickly about a horizontal axis (Plate XVII). In this way the thermometer bulbs pass rapidly through the air, and they are ventilated as effectively as the bulbs of the aspirated psychrometer. The end of the muslin covering the wet bulb dips into a small cylindrical water tank at the end of the frame.

The frame should be rotated rapidly so that the thermometer bulbs pass through the air at a speed of at least 7 kt. With the pyschrometer illustrated the thermometer bulbs are 7 in. from the spindle, so that it should be rotated at a rate of at least three revolutions per second.

The psychrometer should always be rotated in front and to windward of the observer and in the shade. The effect of radiation on the reading is then not great while the thermometers are being rotated, but when the psychrometer is held steady to be read the effect may be serious. With a little practice a technique can be developed of stopping the instrument smoothly. Several test readings should be taken after the first 30 sec. or so of rotation, until it is observed that consecutive readings of the dry- and wet-bulb temperatures agree to within 0·2°F. This should normally take 1½–2 min., but may be longer in some circumstances. The steady readings should then be noted to the nearest 0·1°F. The wet bulb should be managed in accordance with the instructions on p. 163.

The disadvantages of the whirling psychrometer are :

(i) The thermometers are subject to radiation especially when they are being read.

(ii) During periods of precipitation some snow or rain will collect on the dry-bulb thermometer, and thereby affect the indicated air temperature by causing it to act in some degree as a wet-bulb thermometer. This can be minimized by taking the readings under some kind of shelter.

4.2.6. Mercury-in-steel thermograph (dry and wet bulb)

A description of the mercury-in-steel thermograph (dry and wet bulb) and full details about its operation and maintenance as a thermograph will be found in

Chapter 3 (p. 144). This section deals with the use of the instrument specifically for measuring and recording humidity.

The wet bulb is covered with muslin (Stores Ref., Met. 546) which is in the form of a rectangle with an open hem along one side. The hem is fitted over the bulb of the wet thermometer, and the remainder of the wick fitted into the water reservoir, using the small metal rod as a weight to keep it in position. The reservoir entrance slit for the muslin is narrow so that the humidity of the air surrounding the thermometer bulbs is not affected by the water in the reservoir. It is important to ensure that the whole of the thermograph bulb is covered with moist muslin, and, if possible, the wick should be extended to cover some of the connecting tube. This precaution reduces the amount of heat which is conducted along the connecting tube to the thermometer bulb. Middleton[5] found, on occasions, a temperature difference of more than 1°F. between the ends of the wet bulb of a mercury-in-steel thermometer.

The muslin on the wet bulb should be changed regularly, and should not be allowed to become dirty or contaminated. Only distilled water or rain-water should be used in the reservoir, and the reservoir itself should be washed out thoroughly every three months or so. If the water in the reservoir is allowed to become slightly acid a deposit quickly accumulates on the wet bulb. If records are required when the wet-bulb temperature is below 32°F., the wet bulb will have to be painted occasionally with ice-cold water. This should not, however, be done when the dry-bulb temperature is below about 24°F., as otherwise the wet-bulb pen will come into contact with the dry-bulb pen on the chart with possible damage to both. The times when the wet bulb is painted should be noted on the record, as allowance will have to be made for the irregularities in the trace of the wet bulb at these points. If 20–120°F. charts are being used the dry bulb should be set 10°F. high and the wet bulb set to read correctly, whenever the air temperature is expected to fall below 32°F. If temperatures below 20°F. are expected in these circumstances, the pens should be lifted from the drum to avoid possible damage when the temperature rises again.

When checking the readings of the instrument the large lag coefficients of the thermometer bulbs must be considered (see Table VI, p. 90), and the fact that the lag of the wet bulb is considerably less than that of the dry bulb. The instrument readings and those of a Stevenson screen psychrometer (or better still an Assmann psychrometer) should be compared on a cloudy and windy day when the temperature is constant. If an Assmann psychrometer is used the wet-bulb temperature will not be immediately comparable ; it is necessary to evaluate the vapour pressure and then compute what the reading of a wet-bulb thermometer in a Stevenson screen would be. If a serious error in the wet-bulb reading is found it is best to remove the wet-bulb wick, dry the bulb thoroughly, and then check the readings for both bulbs in the way described on p. 147. Whenever possible a mean value of any error should be found from a number of observations and the position of the pens adjusted accordingly.

Errors in the reading of the wet bulb mainly arise from classes (*a*) and (*b*) (see p. 164). The errors in class (*a*) will be greater than for glass thermometers unless precautions are taken. As regards errors in class (*b*), similar considerations will apply to this instrument as to the Stevenson screen psychrometer. On calm, hot, dry days the calculated humidity will be too high.

4.2.7. Photographic thermograph (dry and wet bulb)

The readings of a mercury-in-glass thermometer can be recorded photographically, by projecting the image of a small air bubble in the mercury column on to a sheet of bromide paper carried on a revolving drum as described on p. 149. In the photographic thermograph the image of the bubble in the wet-bulb thermometer falls on the paper vertically below that of the dry bulb, so that corresponding portions of the records of the dry and wet bulb are in the same vertical line. The wet bulb is managed in a similar way to that in a Stevenson screen.

4.3. HAIR HYGROGRAPH

4.3.1. Behaviour of the hair

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

Human hair is one of the most sensitive of these substances, and has been widely used in hygrographs since the eighteenth century, when the first known hair hygrograph was made by de Saussure. The change in length of the hair has been found to be a function of the change in relative humidity with respect to liquid water (both above and below a temperature of 32°F.) and not of the actual amount of water vapour in the air.

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

TABLE XX—AVERAGE ENLONGATION OF A HAIR AS A PERCENTAGE OF THE TOTAL ELONGATION FOR 100 PER CENT. CHANGE IN RELATIVE HUMIDITY

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

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

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

A. F. Spilhaus[33] found that the dependence of dU/dt on U and $(U - U_f)$ could be expressed in the form

$$\left| \frac{1}{U} \frac{dU}{dt} \right| = K \left| (U - U_f) \right|^n,$$

where K and n are constants which vary with the other conditions mentioned above. Thus for a given value of $(U - U_f)$, $| dU/dt |$ is greater when the indicated humidity is high than when it is low. It is found that n is approximately 1 for increasing humidities, but varies up to 1·5 for decreasing humidities, while K is greater for increasing humidities than for decreasing humidities. The differences in the value of K normally more than counteract the differences in n, so that for values of $| U - U_f |$ up to about 50 per cent., $| (1/U) (dU/dt) |$ is greater for increasing humidities than decreasing.

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

The lag of the hair increases (i.e. K decreases) as the temperature falls, and below temperatures of $-20°$F. K is very close to zero. This places a serious limitation on the usefulness of the hair as an indicator of humidity for upper air work and at very low temperatures on the ground.

Some numerical values are given in Table XVII, p. 160.

Effect of tension on the hair.—If a stress is applied to the hair it is found[33] that for an extension of up to 2 per cent. the hair behaves like an elastic body with a constant value of Young's modulus (i.e. extension proportional to load), but above the elastic limit the extension increases rapidly. The hair breaks at the same extension for all humidities, but the load required is largest for the lowest humitity.

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

Application to hygrographs.—The change of length of a hair or group of hairs with change in relative humidity can be made to move the pen arm of a hygrograph in varous ways. Three types of mechanism are illustrated in Fig. 63.

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

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

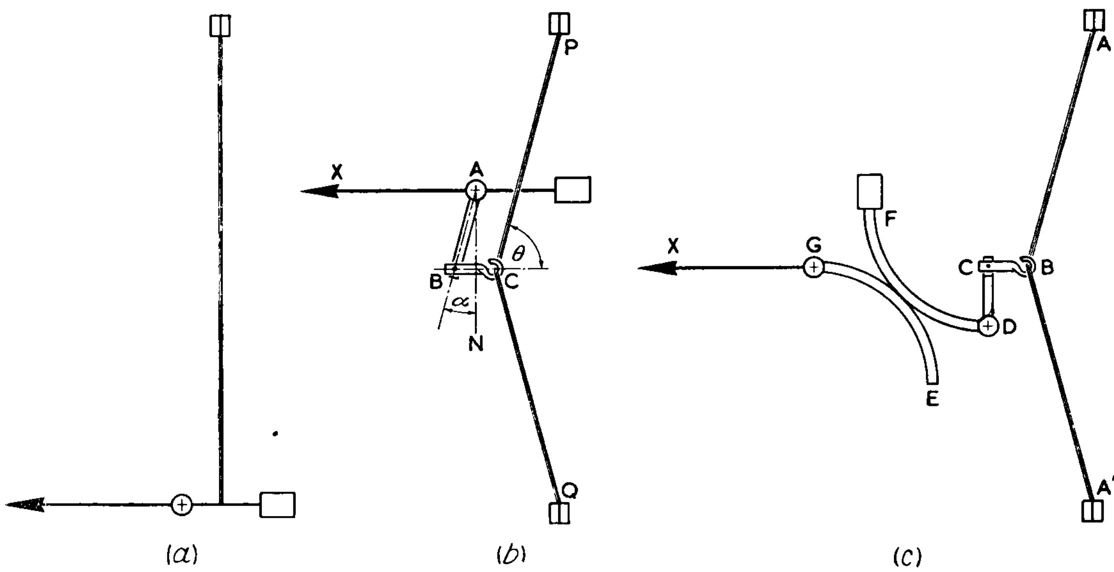
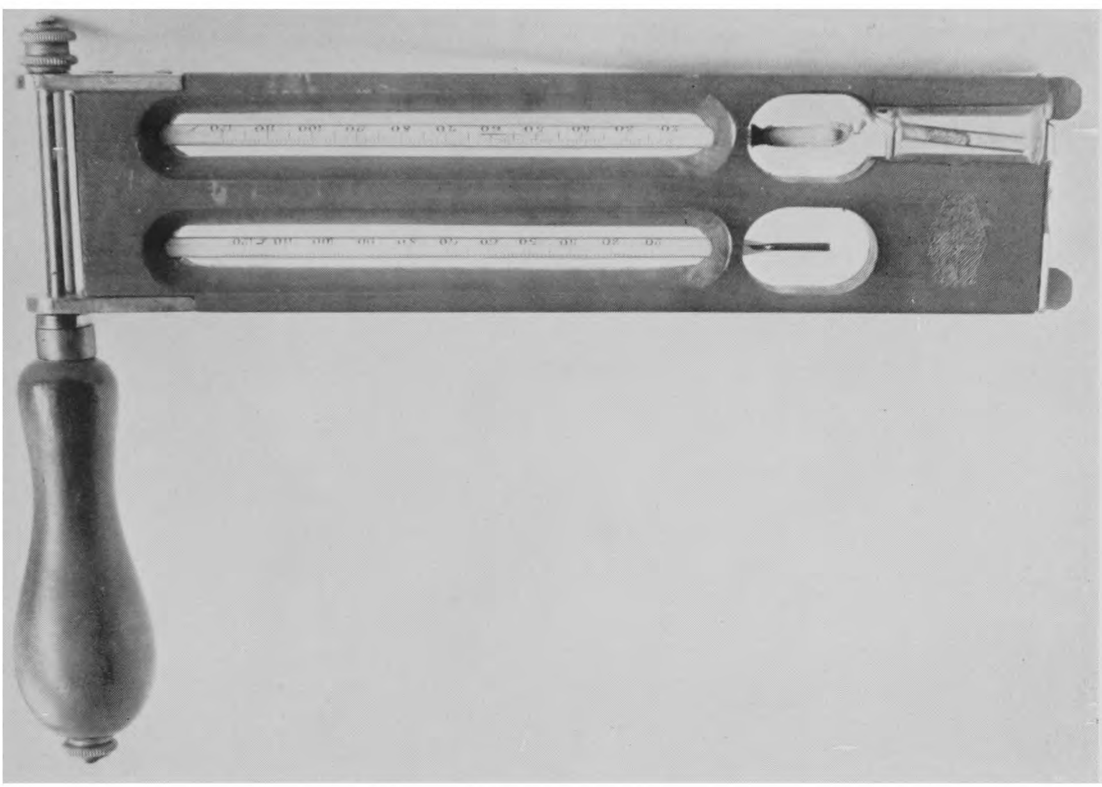


FIG. 63—PRINCIPLES OF HYGROGRAPH MECHANISMS

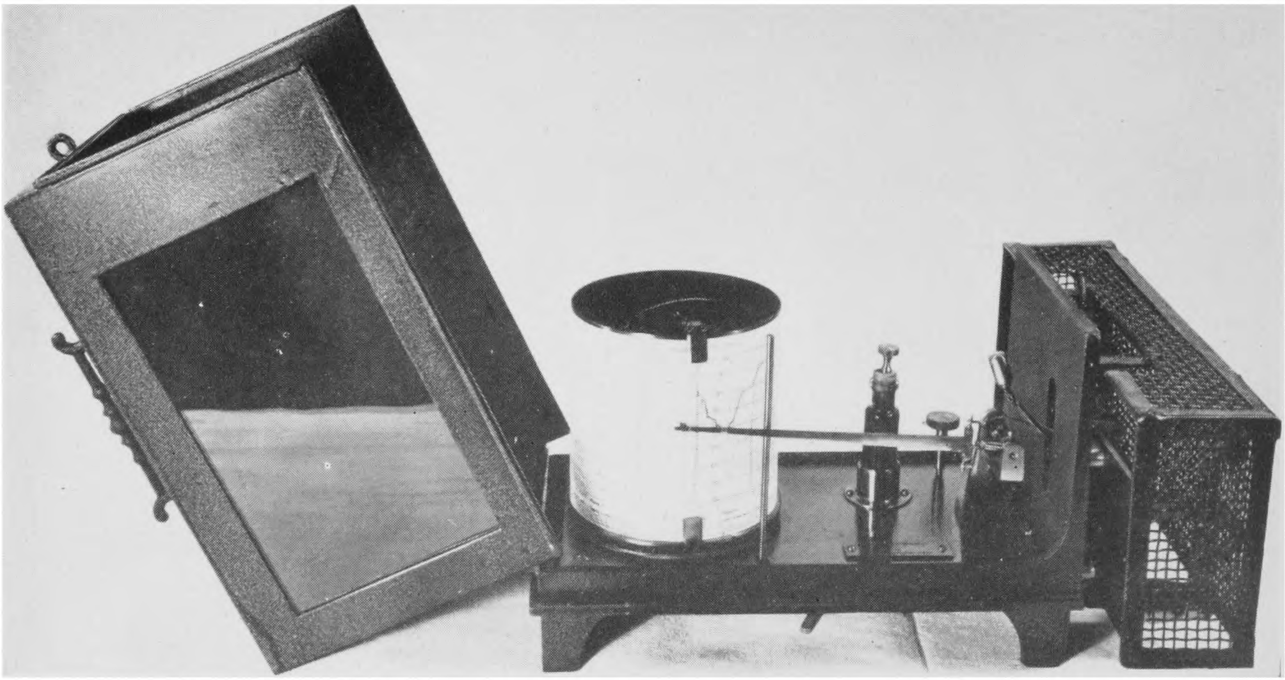
Type (*c*) is more complicated ; the change in length of the hair causes the lever system BCD to rotate about a horizontal axis D to which is attached a quadrant DF. The pen arm GX rotates about the horizontal axis G, to which is also attached a quadrant GE. The two quadrants bear upon one another and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

4.3.2. Meteorological Office hair hygrograph

The mechanism of the Meteorological Office hair hygrograph (Stores Ref., Met. 532) is type (*c*) described above ; details of the working parts are shown in Fig. 64 and Plate XVIII. A bundle of hairs J is held between the two jaws AA_1 and caught up at approximately the centre by a hook B on the lever C, the jaws and lever, together with its spindle, being mounted on the hair-movement plate. The distance apart of the jaws can be adjusted within limits by means of a setting screw I, which is turned by a setting key supplied with the instrument. Large adjustments can be made after slackening the capstan-headed nut H. It is possible



WHIRLING PSYCHROMETER



METEOROLOGICAL OFFICE HAIR HYGROGRAPH

GREGORY HUMIDIOMETER ELEMENT

to adjust the position of the hook B on the lever C. The quadrants D and E are attached to the lever C and to the axis of rotation of the pen arm in the hygrograph mechanism type (*c*) (p. 180). A small spring F helps to keep them in contact. This enables a linear scale to be used on the chart. The small weight, placed at the upper end of the hair-movement quadrant, is such that the force applied by the hook on the hairs, when the quadrants are in their mean position, is 16 gm. weight. The normal type of gate suspension is used for the pen arm (though not shown in Fig. 64), and one of the normal patterns of clocks (p. 9) is used with a short drum and either a daily or weekly movement.

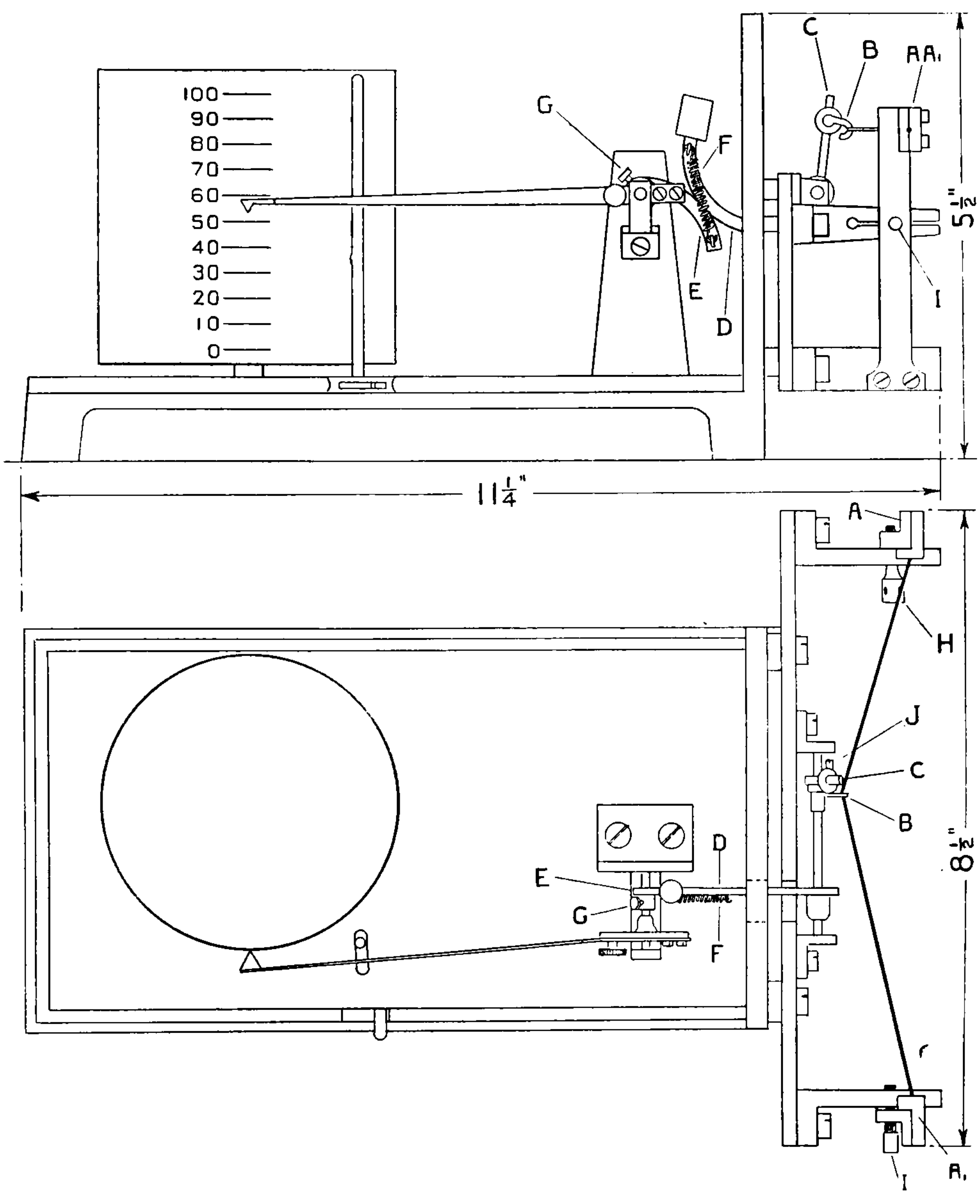


FIG. 64—ELEVATION AND PLAN OF METEOROLOGICAL OFFICE HAIR HYGROGRAPH

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

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

Installation and method of use.—The instrument should be placed on the centre baseboard of a large screen and the general instructions for operating recording instruments (see p. 4) should be followed. One particular point to note, however, is that when making a time mark the pen should always be depressed and not moved towards higher humidity ; this is necessary because the hairs must not be strained in any way.

Care of the hairs.—Careful attention should be paid to the condition of the hairs. They should be kept clean and free from dust by washing with distilled water regularly—about once a week normally but more frequently at stations where the hair is exposed to salt spray or large concentrations of fumes and dust. The wire cage should be removed and the water applied with a soft camel's-hair brush. Great care should be taken not to handle the hair with the fingers or any portion of the skin, as the presence of any oil or grease adversely affects the performance of the hair. The washing of the hair also helps to minimize the " creeping " of the zero, especially when the hair has been exposed to low humidities.

If it is suspected or known that the hairs have become affected by oil or grease, the bundle should be removed from the instrument and soaked in ether or petrol for a short time (up to one hour). A convenient way of doing this is to secure both ends of the bundle to a cork fitted to a test tube containing the liquid, the hairs being kept in moderate tension by means of a small weight suspended from the centre of the bundle (a wire paper clip for example). Care should be taken to handle only the extreme ends of the bundle, the parts which actually fit into the jaws themselves when replacing the hair in the instrument. When replaced, the hairs should be parallel to one another and not twisted rope fashion. The same length of hair should be left between the two jaws as before removing the hairs for cleaning, to minimize the corrections to the zero position and magnification.

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

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

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

The magnification can be very nearly proportionately increased or decreased by raising or lowering the hook B on the lever C (Fig. 64), the hook being fixed in place by means of a small screw. Another possible adjustment is to rotate the pen arm relative to the pen-arm quadrant (after loosening the fixing screw) ; a clockwise rotation of the pen arm relative to the pen-arm quadrant (when viewed from the front of the instrument) reduces the magnification over the whole range, but the reduction is slightly greater towards the bottom of the scale than towards the top. Anticlockwise rotation of the pen arm has the contrary effect, increasing the magnification over the whole range with a slightly greater increase in magnification in the lower part of the scale. It should always be remembered when handling this instrument that the hairs are much weaker when the humidity is high than when the air is dry.

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

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

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

When tested before issue, in a special cabinet, with plenty of time for the instrument to reach equilibrium, the errors at any point of the scale above 20–30 per cent. do not normally exceed about ± 5 per cent., but the sensitivity is about ± 1 to 2 per cent. At any particular time when in use the errors may exceed these limits because of the lag of the instrument, but in steady conditions and with regular checking the same limits should continue to apply.

4.4. ELECTRICAL ABSORPTION-TYPE HYGROMETERS

4.4.1. Gregory humidiometer

The sensitive element of the Gregory humidiometer consists of a strip of cloth, or length of tape, impregnated with a hygroscopic salt (lithium chloride), whose resistance is a function of the relative humidity of the atmosphere to which the cloth is exposed. The resistance is usually found by applying a constant a.-c. voltage to a network containing the humidiometer element and measuring the resultant current. Direct current cannot be used because of polarization effects.

Plate XVIII illustrates a typical element ; it consists of a strip of finely woven Egyptian cotton stretched around a framework of silver rods, mounted on a cylindrical perspex holder. Every alternate rod is connected together, forming two sets of electrodes, so that the intervening strips of cotton are in parallel with each other. Because of the non-linear form of the change in resistance with humidity (a typical element had a resistance of 52 ohms at 100 per cent. relative humidity, 3,800 ohms at 50 per cent. relative humidity and 113,000 ohms at 30 per cent. relative humidity) the scale of the indicator cannot usually be made uniform, being very open in the centre of the range and crowded towards low and high humidities. The circuit details can, however, be arranged so that the whole range can be covered in a number of steps, and any particular part of the scale can be amplified if necessary.

The resistance of the element is also a function of its temperature, and a correction has to be applied to the observed reading if the temperature of the element differs from the standard at which it was calibrated, normally 15°C. (59°F.). The corrected reading is obtained graphically from a series of curves supplied with the instrument. The difference between corrected and uncorrected readings when the air temperature differs from the standard by 10°C. (18°F.) is about 5 per cent. relative humidity when the relative humidity is 30 per cent. and about 3 per cent. when the relative humidity is 90 per cent.

Like hygrometers in which hair or gold beater's skin are used, the response of this instrument to changes of relative humidity does not follow a simple exponential form.

The chief merits of this instrument are its ready application to distant indicating and recording and its sensitivity over limited ranges of relative humidity. Its main disadvantages are the non-linearity of the scale, the variations with temperature, the need for protection against direct contact with water droplets (to prevent any lithium chloride being washed away) and appreciable lag at low temperatures.

4.4.2. Bureau-of-Standards electrical hygrometer

The electrical resistance hygrometer developed by Dunmore and others[34,35] operates on a similar principle to the Gregory humidiometer. The electrical resistance is measured of a thin plastic film containing a hygroscopic salt (usually lithium chloride) deposited on an insulating base between two metallic electrodes. It is used as the humidity element in some radio-sondes. Its main disadvantages are the increase in lag at low temperature and the variations of the indication with temperature. Its advantages are similar to those of the Gregory humidiometer, except that as it is used mainly in radio-sondes most models are not designed to have a long life.

4.5. CALIBRATION OF HYGROMETERS

The chemical absorption-type hygrometers and the dew-point hygrometers require no calibration in the sense of comparison with standard instruments. The psychrometer has, in effect, been calibrated already, as the hygrometric equations, as used in practice, are based on the comparison of many psychrometric readings with either absorption or dew-point hygrometers. These results are assumed to hold for all psychrometers provided certain conditions regarding the ventilation and care of the wet bulb are fulfilled.

The hygrometers and hygrographs using the change in dimensions of hygroscopic substances are, however, a stage further removed from the absolute instruments ; each individual instrument has to be calibrated before use. The routine methods of checking the performance of a hair hygrograph have been described, and also a method of providing a rough recalibration of the instrument if it is not too far out of adjustment. Before a new hair hygrograph is brought into service it is adjusted until 5 or more readings, at various relative humidities from 20–30 to 95–100 per cent., are in as good agreement with the true relative humidities as possible, the errors at these selected points being normally $\pm$ 5 per cent. or less, and on a very good instrument $\pm$ 2 per cent. or less.

Calibration of hygrographs and hygrometers is usually performed by placing the instruments in special cabinets in which the relative humidity of the air can be varied and in which the air is circulated and made homogeneous by means of a fan. The relative humidity can be increased by spraying in water in the form of a fine mist, or by passing the air through warm water, and can be decreased by passing the air over a desiccant such as silica gel.

A very convenient method of obtaining a constant relative humidity is to circulate the air in a closed cabinet over a tray containing a saturated solution of a hygroscopic salt. The vapour pressure over these solutions is less than the corresponding saturation vapour pressure over water at the same temperature, and over a small range of room temperature an approximately constant relative humidity is obtained. Suitable materials are zinc chloride, lithium chloride, calcium chloride, calcium nitrate, sodium chloride, potassium chloride and sodium carbonate, but many others can be used[36]. Table XXI gives the relative humidity over saturated solutions of these salts at various temperatures. Where the value is given in a bracket there is some uncertainty as to the actual value, and it is advisable to check it against observations made with an aspirated psychrometer.

TABLE XXI—RELATIVE HUMIDITY OVER SATURATED SOLUTIONS OF DIFFERENT MATERIALS AT DIFFERENT TEMPERATURES

	Temperature				
	36°F.	50°F.	59°F.	68°F.	77°F.
			per cent.		
Sodium carbonate	..	99	(95)	92	87
Potassium chloride	(88)	88	87	86	(86)
Sodium chloride	(75)	77	77	76	76
Calcium nitrate	(64)	..	56	56	51
Calcium chloride	(41)	38	35	32	31
Lithium chloride	(16)	..	(15)	15	(13)
Zinc chloride	(10)	10	(10)	10	..

CHAPTER 5

MEASUREMENT OF SURFACE WIND

5.1. GENERAL

5.1.1. Definition and units

This chapter is limited to the description of ground instruments for the measurement of the horizontal component of the wind in the lowest layers ; instruments for measuring winds in the upper atmosphere will be dealt with in Part II of this Handbook.

The velocity of the wind is a term used to embrace both its speed (or rate of movement in its instantaneous direction) and its direction. Wind velocity is thus a vector quantity and wind speed a scalar quantity. The speed may be indicated in any of the following units :

(i) knots (or nautical miles per hour)

(ii) metres per second

(iii) kilometres per hour

(iv) miles per hour

(v) feet per second.

The relation between these various units is given in Table XXII, in which any horizontal line gives the same speed in different units.

TABLE XXII—RELATION BETWEEN DIFFERENT SPEED UNITS

kt.	m./sec.	m.p.h.	Km./hr.	ft./sec.
1	0·515	1·152	1·853	1·689
1·943	1	2·237	3·600	3·281
0·868	0·447	1	1·609	1·467
0·540	0·278	0·621	1	0·911
0·592	0·305	0·682	1·097	1

The direction of the wind is specified relative to true north at the place of observation and refers to the direction from which the wind is blowing. It can be expressed as a bearing in degrees from true north (in a clockwise direction) or as a compass point (using 8, 16 or 32 points according to the accuracy required). Table XXIII gives the exact equivalent in degrees, and the sectors to the nearest whole degree, corresponding to the 32 points of the compass.

It should be realized that anemometers and anemographs (like all other meteorological instruments) do occasionally become defective, and it is therefore advisable that observers should continue to estimate the wind force on the Beaufort scale at regular intervals. This will keep them in practice in case the instruments do break down, and will also help to show up serious instrumental errors which are not otherwise obvious.

TABLE XXIII—WIND DIRECTION IN COMPASS POINTS AND DEGREES

Compass direction	Exact equivalent in degrees	Sector in degrees	Compass direction	Exact equivalent in degrees	Sector in degrees
	°	°		°	°
N.	360·00	355– 5	S.	180·00	175–185
N'E.	11·25	6– 16	S'W.	191·25	186–196
NNE.	22·50	17– 28	SSW.	202·50	197–208
NE'N.	33·75	29– 39	SW'S.	213·75	209–219
NE.	45·00	40– 50	SW.	225·00	220–230
NE'E.	56·25	51– 61	SW'W.	236·25	231–241
ENE.	67·50	62– 73	WSW.	247·50	242–253
E'N.	78·75	74– 84	W'S.	258·75	254–264
E.	90·00	85– 95	W.	270·00	265–275
E'S.	101·25	96–106	W'N.	281·25	276–286
ESE.	112·50	107–118	WNW.	292·50	287–298
SE'E.	123·75	119–129	NW'W.	303·75	299–309
SE.	135·00	130–140	NW.	315·00	310–320
SE'S.	146·25	141–151	NW'N.	326·25	321–331
SSE.	157·50	152–163	NNW.	337·50	332–343
S'E.	168·75	164–174	N'W.	348·75	344–354

The surface wind velocity is rarely constant over any appreciable period of time, and it is usually varying rapidly and continuously. The variations are normally irregular both in period and amplitude. This property is known as " gustiness " or turbulence. For most purposes the mean velocity (both speed and direction) is required, and for synoptic purposes should be taken as the average over a 10-min. period.

A gust of importance to aviation has been defined[8] as a positive deviation (or departure) of the wind from the mean velocity (over a 10-min. period) in excess of 10 kt. during at least 1 sec. but not more than 20 sec. For other purposes a numerical value, G, of the gustiness can be obtained by using the expression

$$G = \frac{v_{\text{max}} - v_{\text{min}}}{v_{\text{mean}}}$$

where v_{max} is the maximum speed recorded, v_{min} is the minimum speed recorded and v_{mean} is the mean speed, the values being taken over a period of about 10 min. This definition takes no account of the frequency (or period) of the velocity changes.

5.1.2. General principles of wind-direction indicators and recorders

The wind direction is usually indicated by means of a wind vane. This is essentially a body mounted unsymmetrically and free to turn about a vertical axis ; it takes up a position so that the direction of the resultant force on it due to the pressure of the wind passes through the vertical axis, and so that the centre of pressure is to the leeward of the axis. A pointer attached to it shows the direction from which the wind is blowing. This is probably the oldest meteorological instrument, very ornate wind vanes being used as far back as Roman and Greek times. The first recording apparatus was apparently introduced in the seventeenth century by Wren.

The desirable properties of a wind vane may be set out as follows :

(i) It should turn about its pivot with the minimum friction.

(ii) The vane should be properly balanced, otherwise it will show a bias towards a particular direction if its support is not truly vertical.

(iii) The vane should be designed to produce the maximum torque, for a given change in wind direction, in relation to its moment of inertia.

(iv) Resonance of the vane to natural fluctuations of the wind should be avoided, and as far as possible there should be sufficient damping to make the instrument approximately dead beat.

(v) It should be installed with special care to ensure that its axis is exactly vertical and that the direction indicators are correctly orientated with respect to true north.

Vanes have been constructed of numerous shapes and sizes ; several are indicated in Fig. 65 ; (*a*) consists simply of a flat plate ; the splayed vane type (*b*) has a somewhat better response to varying wind direction ; (*c*) has an aerofoil type of cross-section and is widely used in Meteorological Office instruments—it is superior to (*a*) and (*b*) in its speed of response and stability ; (*d*) is of an unconventional pattern but has a very quick response to variations in wind direction. The wind direction can be directly observed by comparing the vane pointer with fixed rods mounted closely beneath the vane and pointing due north, east, south, and west. The observer should stand as nearly as possible beneath the vane to avoid parallax errors.

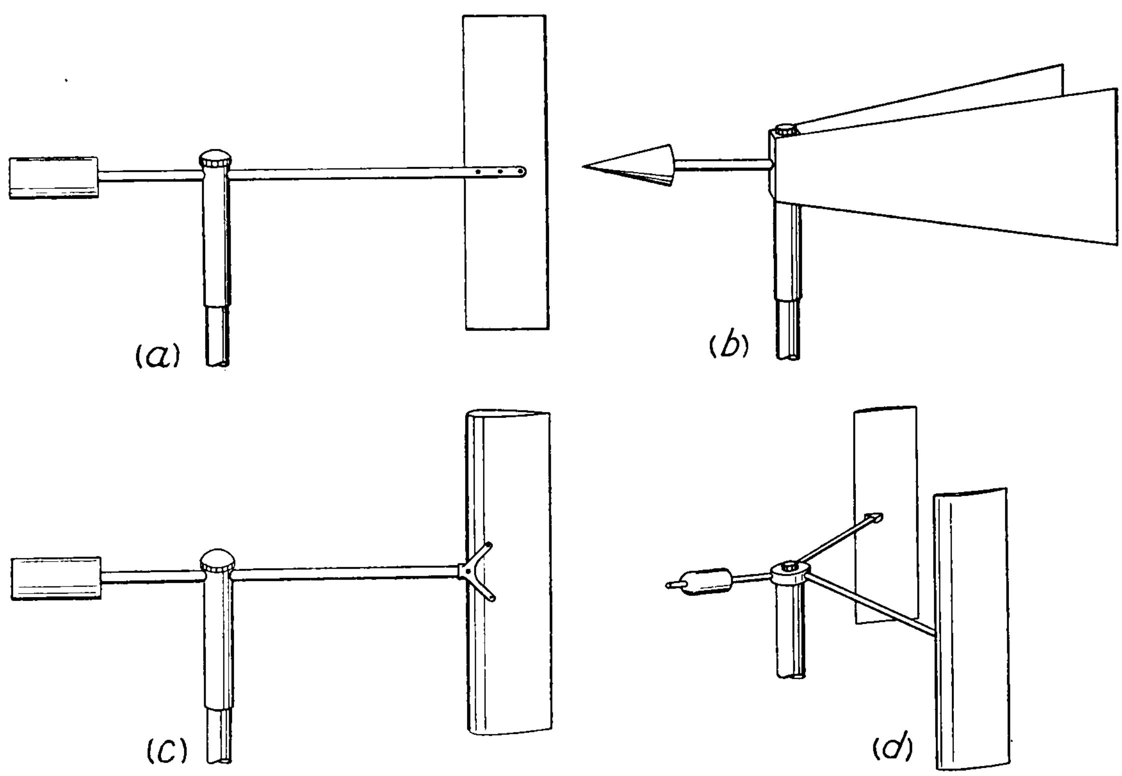


FIG. 65—TYPES OF WIND VANES

Indication may be provided at a distance by various methods. If the vane is mounted directly above the room in which the information is required a simple extension rod from the vane shaft can provide a mechanical means of indication. In other cases recourse can be made to some electrical system. This can be done by attaching a movable contact to the vane spindle, and letting this move over a number of fixed contacts so that small electric lights show the nearest compass point to the actual direction of the vane. If the number of fixed contacts is eight, 16 compass points may be indicated as it can be arranged for either one or two lights to be on at the same time.

Continuous remote indication (as opposed to the discontinuous method just outlined) can be provided by using two self-synchronous motors ; e.g. of the desynn type (using d.c.) or the magslip, selsyn or autosyn types (using a.c.). The transmitting unit is mounted directly beneath the vane and its rotor is connected to the vane spindle. The movements of the vane are then reproduced on the dials of the receiving unit.

Continuous recording of the wind direction is not straightforward since the possibility that the vane may rotate several times through 360° has to be allowed for. One solution of this problem is found in the twin-pen recorder of the Meteorological Office pressure-tube anemograph Mk II (see p. 217) ; an alternative is the Baxendell type of recorder in which the drum carrying the chart rotates and the pen moves along it at a constant rate. A pair of self-synchronous motors may be used if remote recording is required.

5.1.3. Speed of response and accuracy of wind-direction indicators

In a steady wind a well balanced and constructed wind vane will indicate the wind direction with an accuracy of $\pm$ 1°, except perhaps in very low wind speeds. The response of a wind vane to a sudden change in wind direction is however more complicated than the response of most other meteorological instruments because of the mechanical inertia involved. If the vane is held at an angle to the wind stream and then released it does not in general approach its true direction asymptotically, but executes a periodic motion about its true position with an amplitude decreasing approximately exponentially. For small deviations, the deviation, θ, of the angle of the wind vane from the true wind direction can be represented by the equation

$$\theta = \theta_0 e^{-t/\lambda} \sin\left(\frac{2\pi t}{T} + \phi\right), \qquad \ldots\ldots(53)$$

where T is the period of the oscillation and t is the time. λ and T depend on the dimensions and moment of inertia of the vane and the speed of the wind. λ is somewhat analogous to the lag coefficient of a thermometer (p. 89). The total amplitude of the oscillations is reduced to 10 per cent. of its initial value in $2 \cdot 3\ \lambda$ sec.

For the wind vane of the Meteorological Office pressure-tube anemograph Mk II it has been shown[37] that λ is approximately equal to $25/v$ sec. where v is the wind speed in knots, e.g. $\lambda = 5$ sec. when $v = 5$ kt. and $\lambda = 1$ sec. when $v = 25$ kt.

The period of oscillation, T, is also inversely proportional to the wind velocity so that T/λ is independent of v and therefore the ratio in which the amplitude of successive swings is decreased (approximately 3 : 1) is independent of the wind speed. For the vane of a pressure-tube anemograph Mk II the approximate value of T at various values of v is given in Table XXIV.

If the wind vane is subjected to a varying wind in which the direction is given by $\psi_0 + \psi \sin 2\pi t/\tau$ where ψ_0 is the mean direction and ψ is the amplitude of the wind direction and τ is the period of the variation, then the general solution of the equation of motion of the vane is of the form

$$\theta = \theta_0 e^{-t/\lambda} \sin\left(\frac{2\pi t}{T} + \phi\right) + \frac{\psi}{A}\sin\left(\frac{2\pi t}{\tau} - \gamma\right), \qquad \ldots\ldots(54)$$

where γ is a constant and A is a complicated function of λ, T and τ, which has a minimum value when τ is nearly equal to T. After the free oscillations are damped

TABLE XXIV—NATURAL PERIOD OF OSCILLATION OF THE VANE OF THE PRESSURE-TUBE ANEMOGRAPH MK II

Wind speed	Period of oscillation
kt.	sec.
12	2·3
24	1·2
36	0·7
42	0·6

out the ratio of the amplitude of the forced oscillations to that of the varying wind direction is $1/A$. The values of this for the vane of the pressure-tube anemograph Mk II in winds of 12 and 36 kt. are given in Table XXV.

TABLE XXV—RESPONSE OF THE VANE OF THE PRESSURE-TUBE ANEMOGRAPH MK II TO WIND-DIRECTION OSCILLATIONS

Periodic time of wind fluctuations	Ratio of amplitude of forced oscillations to that of actual wind direction	
	Wind speed 12 kt.	Wind speed 36 kt.
sec.		
0·1	0·002	0·02
0·5	0·054	0·81
0·8	0·15	3·19
1	0·26	1·90
3	1·90	..
5	1·22	1·02
10	1·05	1·01
20	1·01	1·00

The exaggerated swings in the neighbourhood of resonance between the natural period of the vane and the period of the wind fluctuations are clearly shown in this table. The forced oscillations lag behind the true wind oscillations by the amount γ, the value of which in the two cases given above is shown in Table XXVI.

TABLE XXVI—TIME LAG OF THE VANE OF THE PRESSURE-TUBE ANEMOGRAPH MK II IN WIND-DIRECTION OSCILLATIONS

Periodic time of wind direction	Time lag of forced oscillations behind wind oscillations	
	Wind speed 12 kt.	Wind speed 36 kt.
sec.	sec.	sec.
0·1	0·05	0·05
0·5	0·24	0·22
0·8	0·38	0·13
1	0·47	0·07
2	0·66	..
3	0·21	..
5	0·15	0·04
10	0·12	0·04

These results apply to the head and vane only of the pressure-tube anemograph Mk II, but the moment of inertia of the remainder of the recording apparatus is so small compared with that of the vane and head (less than 1 per cent.) that its effect is negligible. Friction has been neglected, but in a well designed vane its effect should be unimportant except at very low wind speeds.

The effect of adding some form of artificial damping to the vane (a force which would act only when the vane was moving and which would be approximately proportional to the rate of rotation and in such a direction as to tend to reduce its velocity) would be to decrease the value of λ and increase the natural period of oscillation. If the damping were increased so that T became infinite the vane would be said to be " dead beat " and its motion would be aperiodic ; if the damping were still further increased the vane would be " overdamped " and would then take a longer time to approach within a given angle of its correct position. The optimum condition for speed of response is when the vane is dead beat, but it must be remembered that the forces acting on the vane depend on the wind speed so that it is not possible for a vane to be truly dead beat at all times. It is better for it to be slightly underdamped than overdamped.

5.1.4. General principles of wind-speed indicators and recorders

Wind speed indicators or anemometers may be divided into three main groups:

(i) Rotation anemometers, such as the cup anemometer and the propeller or windmill type.

(ii) Pressure anemometers. These are of two main types : the first depends on the relation between the hydrostatic pressure and velocity at any point in a moving fluid, and the second depends on the pressure exerted by the stream of air on a suitably mounted plate or other solid body.

(iii) Anemometers which depend on the thermal conductivity of the air.

Rotation anemometers.—*Cup anemometers.*—The cup anemometer normally consists of three or four cups mounted symmetrically about a vertical axis so that the diametral plane of each cup is vertical. As the force on the concave side of any cup, due to the wind, is greater than that on a convex side in a similar position, the cup wheel rotates. For any given anemometer the speed at which the wheel rotates depends, to a good approximation, solely on the wind speed, provided the wind speed is steady and is greater than the minimum required to set the cups in motion ; the lower limit is due to the effect of friction on the bearings of the cup wheel. The rate of rotation does not depend on the direction of the wind, nor to an appreciable extent on the density of the air. Three main methods are used to determine the speed of rotation of the cups. In the first an electrical contact is made after a known number of revolutions of the cup wheel. This may be used in conjunction with a buzzer and stop watch or with any electrical counting device. In the second the cup wheel is connected to a mechanical counting system which records, in effect, the number of revolutions of the cup wheel since the record was started. In the third system the cup wheel is linked to a small electrical generator and the instantaneous speed of rotation is obtained by measuring the electromotive forces generated.

The first two systems can only be used to obtain the mean wind speed over a period upwards of a minute, but the third method gives practically instantaneous readings.

Theory of cup anemometers.—It was assumed by Robinson, who first developed the cup anemometer and brought it into general use, that the ratio of the speed of the wind to the speed of the cup centres was a constant and equal to 3, but measurement at various wind speeds and with different sizes of anemometer showed that this ratio (called the factor of the anemometer) was variable and depended on the wind speed and, in a complicated fashion, on the dimensions of the instrument. If v is the speed of the wind and V is the linear speed of the cup centres it is possible to express the relation between them for a given anemometer in the form of a power series

$$v = a + bV + cV^2 + \dots.$$

in which a, b, c, ... are constants. The best design is that in which the constant a and the coefficient of V^2 and higher powers of V are zero or very small. It is however impossible at present to predict theoretically the best dimensions of the anemometer, and improvement in design has followed from controlled experiments in the wind tunnel. These have followed three main lines :

(i) Determination of the relation between v and V

(ii) Determination of the static torque on one or more cups at rest

(iii) Determination of the dynamic torque

In each case various diameters of cups, shapes of cups, lengths of supporting arms and diameters of supporting arms have been tried. From these it has been concluded, among other things, that :

(i) A three-cup system is better than a four-cup system, because the torque on a three-cup system is more uniform throughout the whole revolution and because, using the same material, the three-cup system gives a larger torque per unit weight.

(ii) A cup of semi-conical shape is superior to a hemispherical shape (see p. 194).

(iii) Beaded edges to the cup make it less sensitive to wind-stream turbulence than plain edges.

In addition the tests have indicated more suitable dimensions for a good combination of properties, and, as a result, modern cup anemometers are much lighter and smaller and generally have a larger ratio of cup diameter to the diameter of the circle described by the cup centres than the old types of instrument. They respond to much lower wind speeds.

Methods of use of cup anemometers.—For general meteorological use it is usual to assume a constant factor for the instrument. The factor which gives the best representation in the range 15–40 kt. is usually chosen. This inevitably results in rather large percentage errors in winds whose speeds are below 5 kt., but the absolute errors remain quite small and it simplifies the computation or indication of the result. With modern designs the errors in the indicated speeds in steady winds above 5 kt. and up to 80–100 kt. should not exceed about 1 kt. With the cup generator anemometer it is possible to allow for the major departures from linearity in the graduation of the indicator.

For more accurate work and especially in light winds with a very sensitive anemometer a relation of the form

$$v = v_0 + bV$$

can be used ; v_0 is the maximum value of v for which V is zero. With a very sensitive anemometer v_0 may be as low as 0·4 kt.

Behaviour of cup anemometers in gusty winds.—The cup wheel accelerates more quickly with an increase in wind than it decelerates in a falling wind, so that the mean speed recorded by the anemometer in a variable wind is higher than the true mean wind. Schrenk[38] has attempted a theoretical analysis of the magnitude of the errors involved in a sinusoidal variation in the wind speed. He has related the over-estimation of the cup anemometer with a dimensionless parameter K, given by

$$K = \frac{0 \cdot 55 \rho R^2 r^2 T v}{I}, \qquad \ldots\ldots(55)$$

where T = period of the variation in the wind speed
v = mean speed of the wind
ρ = density of the air
R = radius of the circle described by the centres of the cups
r = radius of the cups
I = moment of inertia of the rotating parts.

Fig. 66 shows a family of curves that Schrenk derived showing the relation between the over-estimation of the anemometer (expressed as a fraction of the mean wind velocity) and K, for various values of the amplitude of the fluctuation $\Delta v/v$. It is seen that K decreases (and thus the over-estimation increases) with increasing values of I, with decreasing wind speed, decreasing period of the fluctuations, and increasing amplitude of the fluctuations. The numerical scale on the left is for sinusoidal variations and a four-cup anemometer with hemispherical cups. The scale on the right-hand side is for irregular fluctuations.

Wind tunnel experiments[39] have shown that Schrenk's curves are approximately correct, apart from a tendency to under-estimate errors corresponding to low values of K. This discrepancy is probably not significant considering the practical difficulties of accurate measurement, and the approximate nature of Schrenk's treatment.

Speed of response of a cup anemometer to changing winds.—A few experiments have been carried out in a wind tunnel in the Instrument Development Division of the Meteorological Office on the speed of response of the cup generator anemometer. Table XXVII gives the time for the anemometer to record a speed of 63 per cent. and 90 per cent. of the true wind speed when suddenly exposed to the

TABLE XXVII—SPEED OF RESPONSE OF THE CUP GENERATOR ANEMOMETER STARTING FROM REST

Air speed (constant) v	Time to reach $0 \cdot 63v$ from rest	Time to reach $0 \cdot 90v$ from rest
kt.	sec.	sec.
35	0·25	1·2
26	0·4	1·8
17·5	0·8	3·0
13	1·2	4·0
9	1·8	6·2

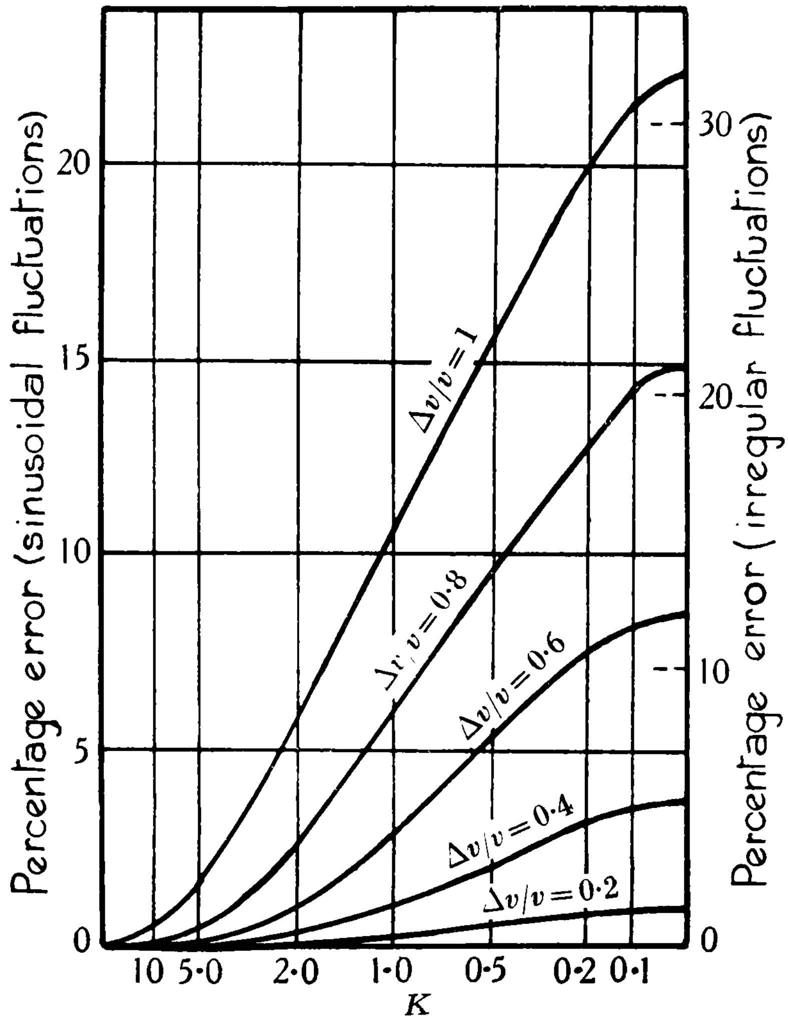


FIG. 66—ERRORS OF CUP ANEMOMETERS IN FLUCTUATING WINDS (SCHRENK)

wind with the cups initially at rest. Table XXVIII gives the time for the anemometer reading to rise from v_i to $v_i + 0{\cdot}63\ (v - v_i)$ and to $v_i + 0{\cdot}90\ (v - v_i)$, where v is the actual wind speed and v_i is the indicated wind speed at any time after the anemometer was exposed. These results show that the response of the anemometer to sudden changes in wind speed is not exponential. It can be seen that, generally speaking, the speed of response increases as the wind speed increases. No tests have been made on decreasing winds.

TABLE XXVIII—SPEED OF RESPONSE OF THE CUP GENERATOR ANEMOMETER FROM INITIAL SPEED v_i

Air speed v	Initial speed v_i	Time to reach $v_i + 0{\cdot}63(v - v_i)$	Time to reach $v_i + 0{\cdot}90(v - v_i)$
kt.	kt.	sec.	sec.
35	17·5	0·7	1·3
35	26	0·7	1·1
26	13	1·1	1·95
26	17·5	1·3	1·8
17·5	9	1·7	3·2
17·5	13	1·85	2·95
13	9	2·6	4·0

Vane anemometers and air meters.—This type of anemometer has a horizontal spindle with a set of light vanes mounted on radial arms, and a counter mechanism. The axis of the spindle has to be parallel to the wind direction and thus the instrument needs to be mounted on a wind vane or similar device for meteorological use. If bearing friction could be neglected the vane speed u in a wind speed v would be such that the wind velocity relative to the blades was parallel to the vane surface. If the blades at rest are inclined at an angle θ to the wind direction then

$$u = v \tan \theta.$$

As θ is usually in the range 40–50°, u and v are approximately equal, instead of the vane speed being about one-third of v as in the case of the cup anemometer. This fact, together with the short length of the vane arms, means that the rate of rotation is very high, and as a consequence this type of anemometer is unsuitable for measuring wind speeds above about 30 kt. They respond however to very low wind speeds (below 0·5 kt. in a good instrument). Ower[40] has analysed the characteristics of the instrument, including friction, and has shown the effect of the following factors on the performance of the instrument :

(i) Neglect of air-density variations up to 10 per cent. does not lead to errors greater than 1 per cent. in wind speed. The error is less the higher the wind speed.

(ii) Optimum blade angle for good response in low winds is about 40°.

(iii) In variable winds, as with the cup anemometer, the mean wind speed is over-estimated ; the error is, however, less than 1 per cent. for a sinusoidal variation of wind speed of amplitude 10 per cent. of the mean wind speed with an instrument of normal dimensions. The error increases as the square of the amplitude and may therefore be significant in some natural winds.

(iv) Small errors in setting the anemometer in the correct wind direction are not significant ; with a normal instrument the error in the indicated speed reached only 2 per cent. for an error of 20° in the direction of the anemometer.

With these instruments, as with cup anemometers with a counting or contact mechanism, the mean wind speed over a known interval of time is determined. For accurate work each individual instrument should be calibrated in the conditions of use. Some instruments have adjustments for starting or stopping and for bringing the pointer back to zero as required. This should not be used in accurate work as the approach of the observer to start or stop the mechanism would interfere with the readings. It is best to set the instrument in place and start it, and then retire to a suitable distance and time the rate of revolution of the counter pointer with a stop watch.

The instruments are normally supplied with the counter graduated in feet ; there may also be instructions to add a certain small correction to the observed wind speed. This, however, should always be checked by calibration as the error of a vane anemometer is rarely constant over the entire speed range.

Pressure anemometers.—*Theory of pressure-tube anemometers.*—Bernouilli's equation relating the hydrostatic pressure, p_s, at a point on a horizontal stream-line of a moving fluid to the velocity, v, at that point may be written

$$p_s + \tfrac{1}{2}\rho v^2 = p_t \text{ constant}$$

where ρ is the fluid density. p_t is known as the " total head " and is usually considered to be made up of two parts, the static head p_s and the velocity head $\frac{1}{2}\rho v^2$.

It is possible to deduce v from a measurement of the difference between the total head and the static head. This can be done with a pitot-static tube (Fig. 67). The air entering the mouth of the double-walled tube, which is pointed in exactly the opposite direction to the air flow, is brought to rest so that the pressure inside the mouth is equal to the total head ; the static pressure is experienced in the wall of the tube which is in communication with the outside air through the holes drilled in the wall at right angles to the axis of the tube at that point. The difference in pressure between these two spaces is measured by connecting them to opposite limbs of a sensitive manometer.

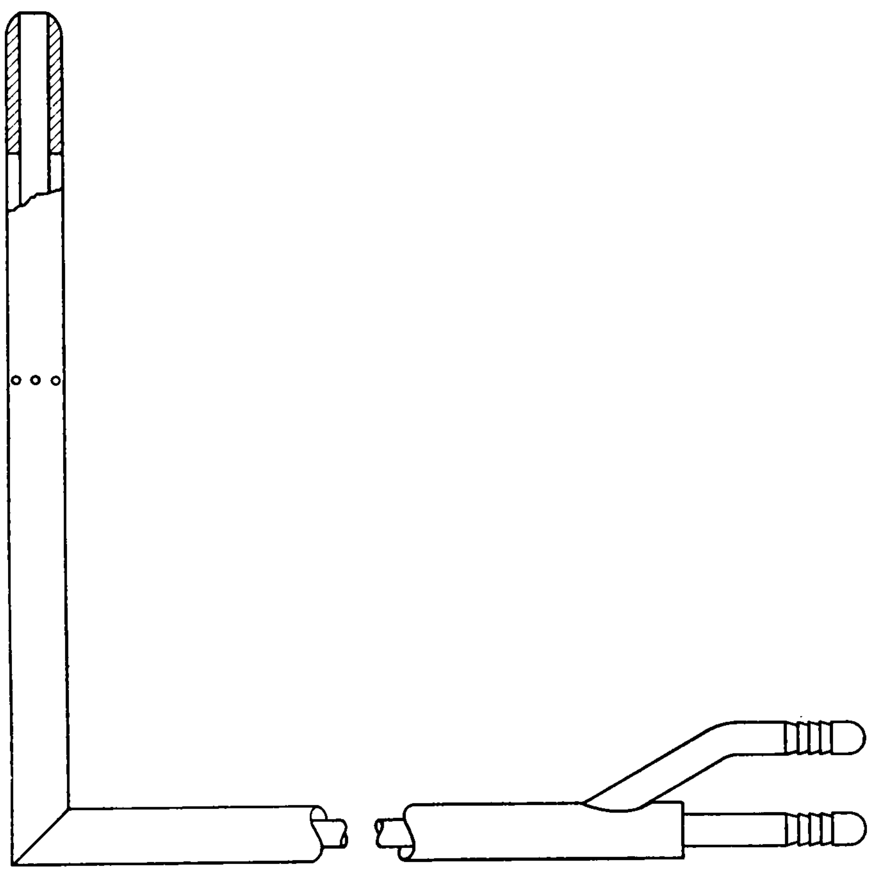


FIG. 67—PITOT-STATIC TUBE

An adaptation of this method is used in the Meteorological Office pressure-tube anemograph. It was not found practicable to measure the static pressure in this instrument ; instead the static-pressure holes are drilled in the vertical portion of the tube which supports the wind vane and pitot tube. A result of this is that, instead of measuring the true static pressure at these holes, the air pressure in the tube leading from the holes is reduced below the static pressure by an amount equal to $c\rho v^2$, where c is a constant less than $0{\cdot}5$. The difference Δp between the total head and the suction head is thus given by

$$\Delta p = \tfrac{1}{2}\rho v^2 (1 + 2c) \; ;$$

c varies with the size and shape of the openings but for a standard instrument it may be determined experimentally. The difference in pressure Δp can then be used to determine v.

The reading of the instrument depends on the value of the air density, and corrections should be applied when the conditions depart radically from those assumed when the instrument was calibrated.

Methods of measuring the difference in pressure.—Two main methods of measuring Δp have been devised for anemometers. The pressure-tube anemograph Mk II has a sensitive float manometer, the inside of which is so shaped that the movements of the float are proportional to $\sqrt{(\Delta p)}$, i.e. they are directly proportional to the wind speed. A modification of this instrument, the anemobiagraph, has a cylindrical-shaped float but with springs attached to it, so that, again, a linear scale of velocity is obtained.

The other main method, used principally on board ships where the float manometer cannot be used, is to use an aneroid movement to measure the change in pressure. The scale is not linear, and as it depends on the elastic properties of the thin metal diaphragm (see Chapter 2, p. 18) it is subject to slow changes with time. Sensitive manometers for use with pitot-static heads in wind tunnels are described on p. 256.

Response of the Meteorological Office pressure-tube anemograph Mk II to changing wind speed.—The response of the Meteorological Office pressure-tube anemograph Mk II to changing wind speed has been investigated in the wind tunnel. Table XXIX gives the time taken for the float to move from the zero position to $0{\cdot}63v$ and $0{\cdot}90v$, where v is the air speed to which the head is suddenly exposed. Table XXX gives the time required for the indicated speed to change from v_i to $v_i + 0{\cdot}63\,(v - v_i)$ and to $v_i + 0{\cdot}90\,(v - v_i)$.

TABLE XXIX—SPEED OF RESPONSE OF THE PRESSURE-TUBE ANEMOGRAPH MK II FROM REST

with 7 ft. of connecting tubing

Air speed v (constant)	Time to reach $0{\cdot}63v$ from rest	Time to reach $0{\cdot}90v$ from rest
kt.	sec.	sec.
52	1·0	1·7
43·5	1·1	1·7
35	1·0	1·7
26	1·1	1·7
17·5	1·4	2·0
13	1·6	2·2
9	2·4	3·5

TABLE XXX—SPEED OF RESPONSE OF THE PRESSURE-TUBE ANEMOGRAPH MK II FROM INITIAL SPEED v_i

with 7 ft. of connecting tubing

Air speed v	Initial speed v_i	Time to reach $v_i + 0{\cdot}63(v - v_i)$	Time to reach $v_i + 0{\cdot}90(v - v_i)$
kt.	kt.	sec.	sec.
35	17·5	0·6	1·0
35	26	0·4	0·7
26	13	0·5	0·9
26	17·5	0·5	0·9
17·5	9	0·5	0·9
17·5	13	0·4	0·7
13	9	0·5	0·9

These tests were carried out with only 7 ft. of tubing (1-in. bore) between the head and the recording unit. The times are therefore shorter than would be obtained with a more normal length of tubing (40 ft. say) between the head and the float.

The effect of the tubing can be estimated from tests at the National Physical Laboratory[37]. A simple harmonic variation in pressure was applied to the recording unit through 100 ft. of 1-in. pipe and the ratio of the indicated pressure range to the applied pressure range was measured for various periods of oscillation. The results are given in Table XXXI for mean heights of the float corresponding to wind speeds of 52 and 18 kt.

The ratio of the indicated pressure range to the applied pressure range for any given periodic time decreases as the wind speed decreases. Fluctuations of the wind of period less than 10 sec. may thus be considerably damped out at low wind speeds. The float has a natural period of oscillation of about 1 sec., but as wind oscillations of this period will be considerably damped out by the connecting pipes it will not affect the accuracy of the results. As a consequence of these considerations mean values over not less than about 5 sec. should be taken whenever accurate results are needed. The diaphragm recorder would probably be rather more responsive to short-period variations in wind speed as less air has to flow into and out of the system.

When these precautions are taken, however, the instrument provides an accurate method of determining mean wind speeds, and gives a good indication of most gusts and lulls.

TABLE XXXI—RESPONSE OF THE PRESSURE-TUBE ANEMOGRAPH MK II TO PRESSURE VARIATIONS APPLIED THROUGH 100 FT. OF PIPING

Wind speed 52 kt.		Wind speed 18 kt.	
Periodic time of applied pressure variations	Indicated pressure range / Applied pressure range	Periodic time of applied pressure variations	Indicated pressure range / Applied pressure range
sec.		sec.	
4·6	1·0	10	0·96
2·3	1·0	4	0·70
1·65	0·42	2	0·47
1·15	0·14		

Pressure-plate anemometers.—If the wind pressure exerted on a flat plate (usually rectangular) placed normal to the wind direction is balanced by a restoring force brought about by the deflection of the plate, the deflection of the plate is a measure of the wind speed. The earliest anemometers worked on this pressure-plate principle, and consisted of a hanging plate pivoted about a horizontal axis and kept approximately normal to the wind. Hooke introduced them into Great Britain sometime before 1667, after they had first been made in Italy about 1570. They are not in general use, but very light instruments have been used for investigating atmospheric turbulence, using a cinematograph camera to record the movements of the plate. A compression spring can also be used to control the movements of the plate ; an advantage of this method is that if a very light plate and a stiff spring is used (implying a sensitive means of detecting the plate movement) the natural period of oscillation of the moving parts is very short and a good representation of individual gusts is obtained. Such an instrument is described by Sherlock and Stout[41]; its natural period of oscillation was about 0·01 sec. This instrument was kept in the correct direction (pointing directly into wind) by mounting it on a wind vane.

The force F on a plate held normal to the wind is given by

$$F = \tfrac{1}{2}c\,A\rho v^2\,, \qquad \ldots\ldots(56)$$

where c is a constant depending on the size and shape of the plate, A is the area of the plate, v is the speed of the wind and ρ is the air density.

Anemometers depending on the thermal conductivity of the air.—Anemometers have been constructed which depend on the fact that the rate of heat loss from a body, and thus its equilibrium temperature if it is being continuously heated, depends, among other things, on the velocity of the air flow past it.

King[42] has provided a theoretical treatment of the problem of the rate of loss of heat from cylindrical wires, and has shown that, if a wire is held normal to an air stream of speed v and temperature T_0, and is electrically heated by a current I so that its equilibrium temperature is T and equilibrium resistance is R, then:

$$RI^2 = (K + c\sqrt{v})\,(T - T_0)\,, \qquad \ldots\ldots(57)$$

where K is a constant determined by the radiative and convective heat losses from the wire in still air and c is a second constant depending on the physical properties of the air and the diameter of the wire.

If the temperature to which the wire is heated is kept constant (and thus R is constant), and provided T is sufficiently high (500°C. say) to enable the effect of variations in T_0 on the difference $(T - T_0)$ to be neglected, equation (57) can be simplified to

$$I^2 = I_0^{\,2} + B\sqrt{v}\,, \qquad \ldots\ldots(58)$$

where I_0 is the value of I when v is zero and B is a constant to be determined empirically. T and R may be kept constant by including the wire in a Wheatstone bridge network. Alternatively I may be kept constant by including in series with the wire a ballast resistance large compared with R; the potential drop across the wire will then be related to the wind speed.

The hot-wire anemometer itself usually consists of a length of platinum wire, a few centimetres long and 0·002–0·1 mm. in diameter, stretched between suitable supports and mounted on a base. One great merit of this type of instrument is its small lag coefficient. Dryden and Kuethe[43] have shown that the lag coefficient, λ, is given by

$$\lambda = \frac{4{\cdot}2\rho A^2 s\,(T - T_0)}{r_0 I^2}\,, \qquad \ldots\ldots(59)$$

where ρ is the density of the wire, A the cross-sectional area of the wire, s the specific heat of the wire, and r_0 the specific resistance of the wire at temperature T_0.

For the most rapid response it is thus necessary to use a very fine wire and as low a temperature excess as other requirements will allow. A platinum wire 0·0025 mm. in diameter can be used to respond with reasonable accuracy to fluctuations of about 100/sec. Another advantage for some purposes is that its greatest sensitivity is at low speeds. Speeds from a few centimetres per second up to 10–20 m./sec. can easily be measured with hot-wire anemometers.

The disadvantages of the instrument are that the wire is liable to fracture and that its calibration may change. It cannot, of course, be used in the open air when it is raining without special shields which, in turn, may affect the wind flow. Further details of these instruments are given by Kleinschmidt[6] and details of a very stable hot-wire using a thermo-couple to determine the temperature of the wire are described by Simmons[44].

5.1.5. Exposure of anemometers

The wind velocity near the surface of the earth varies rapidly with height and is also greatly affected by the presence of irregularities in the ground or by nearby obstacles such as trees or buildings. For synoptic reports of the surface wind and for general climatological records it is therefore necessary to define the height and condition under which the measurement should be made. The standard exposure is agreed to be over open level terrain at a height of 10 m. (33 ft.). Open terrain is defined as an area where the distance between the anemometer and any obstruction is at least 10 times the height of the obstruction above the ground level at the anemometer. This ideal exposure will rarely be obtainable in practice, but great care should be taken to ensure that the site actually chosen is the best possible.

The anemometer should be installed at such a height that its indications are reasonably unaffected by local obstructions, and represent as far as possible what the wind at 33 ft. would be if there were no obstructions in the vicinity. This will necessitate placing the anemometer at a height exceeding 33 ft. by an amount depending on the extent, height and distance of the obstructions, but it is impracticable to lay down any precise rules for determining this since local conditions differ so widely. A site on top of a large building or near trees should be avoided as far as possible, and the anemometer should be placed as far away as practicable from obstructions. A site on a steep hill or on the edge of a cliff will be unrepresentative of the general wind flow and should not be used. Besides giving incorrect values of the mean wind speed an obstructed exposure often has excessively high values of gustiness. These remarks do not apply, necessarily, to special investigations, in which exceptional exposures may be required.

It will often be necessary to mount anemometers at other than the ideal height; the wind velocities recorded will not then be representative of those at the standard height. In order that observations from different stations shall be comparable it is the practice in the Meteorological Office to correct the observed wind speed to what it is estimated the speed would have been at the standard exposure. For this purpose each anemometer is assigned an " effective height " ; this is the height over open level terrain in the vicinity of the anemometer which, it is estimated, would have the same mean wind speeds as those actually recorded by the anemometer. The mean variation of wind with height is assumed to follow the formula :

$$v_h = v_{10}\{0\cdot233 + 0\cdot656 \log_{10}(h + 4\cdot75)\}\,, \qquad \ldots\ldots(60)$$

where v_h is the wind speed at a height h m. and v_{10} is the wind speed at 10 m.; v_{10} can therefore be calculated when v_h and h are known.

No definite rules can be laid down for obtaining the effective height of any anemometer. It can only be estimated by taking into account the nature, extent, height and distance of the local obstacles and obstructions and the actual height of the anemometer itself. It may be desirable to have different effective heights for different wind directions. Table XXXII below gives the percentage correction to be applied to the readings of anemometers of various effective heights.

TABLE XXXII—CORRECTIONS TO BE APPLIED TO REDUCE THE OBSERVED WIND SPEED TO STANDARD CONDITIONS OF EXPOSURE

Effective height ft.	Correction
9–15	add 20%
16–25	add 10%
26–42	no correction
43–74	subtract 10%
75–140	subtract 20%

5.1.6. Mounting of anemometers and wind vanes

As local needs and conditions vary greatly it has not been practical to provide uniform mounting arrangements for anemometers and wind vanes. Cup anemometers and wind vanes are usually fitted with a socket in their base into which can be screwed one of the standard sizes of gas piping, and the details of the remainder of the mounting is left to be decided at the station itself. On Meteorological Office stations the provision of a suitable mast, or support on a building, is usually a Works Service.

A steel lattice tower is the best method of mounting these instruments because of the ease of subsequent inspection and overhaul. Designs have been prepared for 15-ft., 20-ft., and 30-ft. towers suitable for mounting on the tops of flat-roofed buildings or on the ground. These will be provided and installed as a Works Service at Meteorological Office stations, where it is considered necessary. A ladder is fixed permanently to these towers and a platform is fitted just beneath the head, so that the anemometer and wind vane may be inspected regularly.

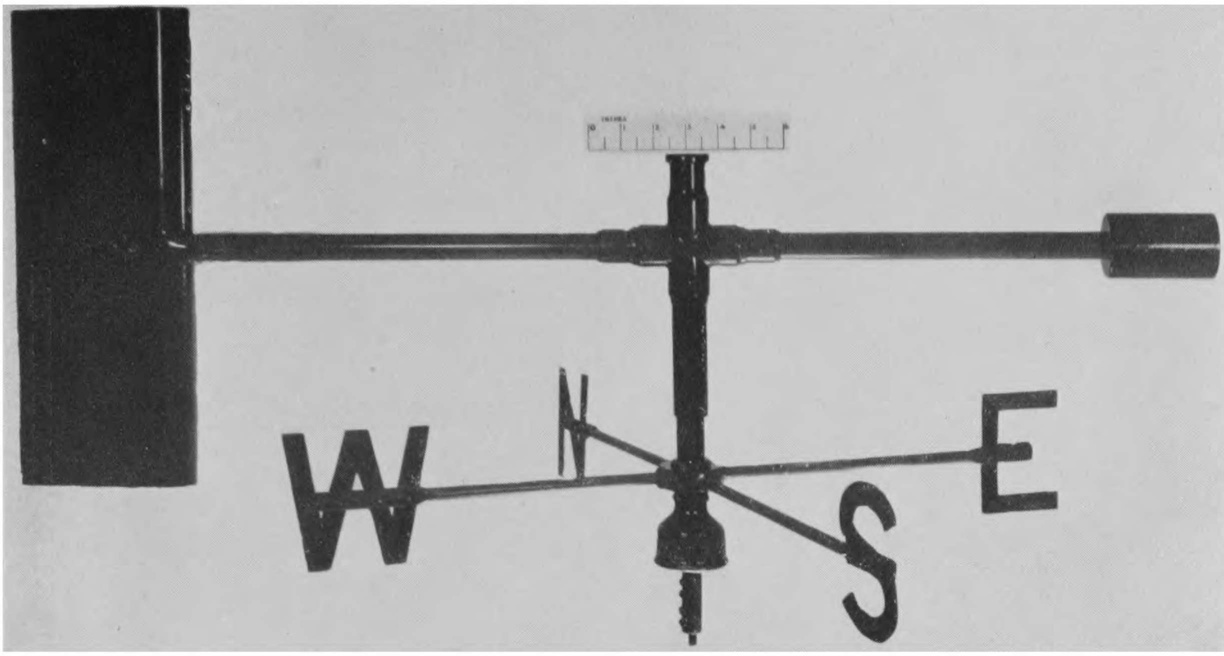
5.2. WIND VANES

5.2.1. Wind vane Mk II

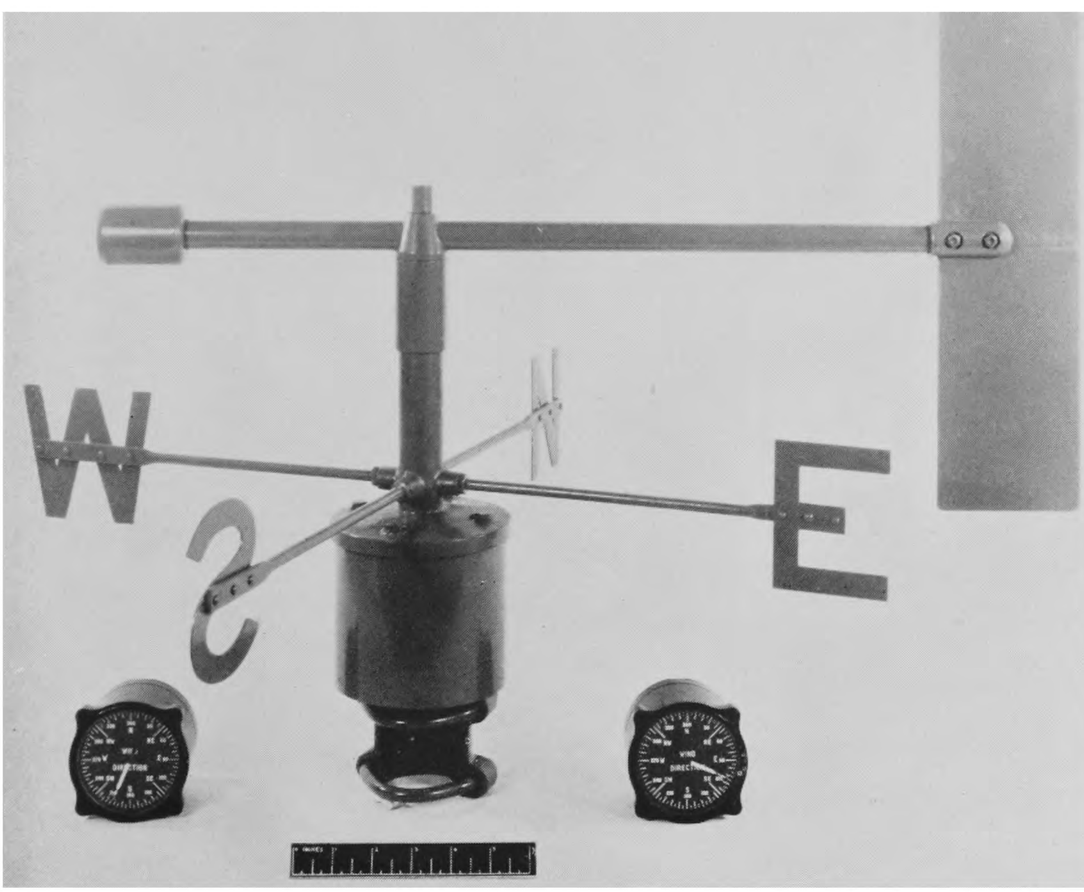
The wind vane Mk II (Stores Ref., Met. 638) consists of a horizontal arm carrying a rectangular fin of aerofoil cross-section mounted by means of a thrust race and brass bushes on a support fitting (Plate XIX) ; a short spindle is attached to the rotating arm and passes down the centre of the support fitting. The horizontal arm is balanced about its axis of rotation by means of a fixed weight attached to the end opposite to the fin. This unit is designed for attachment to either (*a*) a tubular steel pipe by means of a standard socket, when the vane is used alone or directly coupled by a spindle to a suitable dial, or (*b*) the top of the housing for the electrical transmission gear for the distant indication of the wind direction. In the latter case the combination becomes the remote-indicating wind vane Mk II.

The spindle has a connector attached so that a length of direction rod may be joined to it if required. If the direction rod is carried into the building on which the vane is mounted a simple direct-reading dial can often be improvised. Four fixed direction arms labelled N, E, S, and W can be attached below the vane to indicate the corresponding true directions.

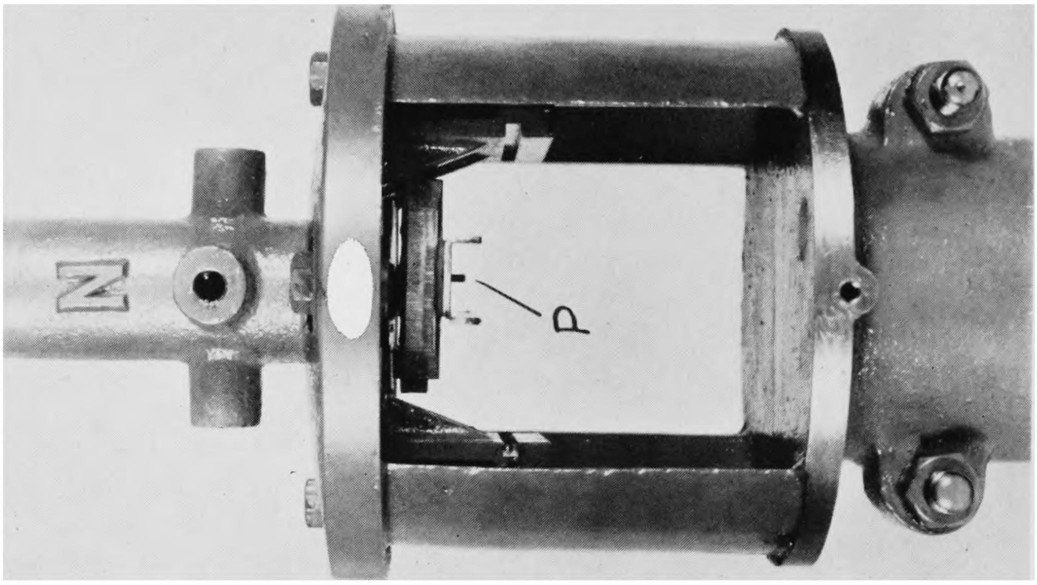
Installation.—The lower socket of the vane is screwed with 1½-in. gas thread and the vane is usually mounted on a suitable length of the corresponding gas pipe.

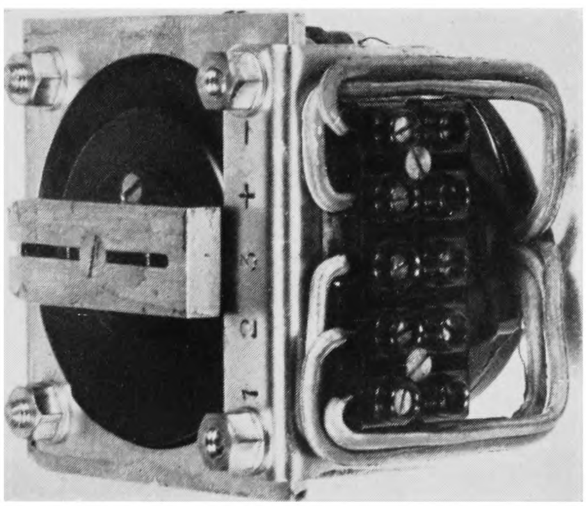


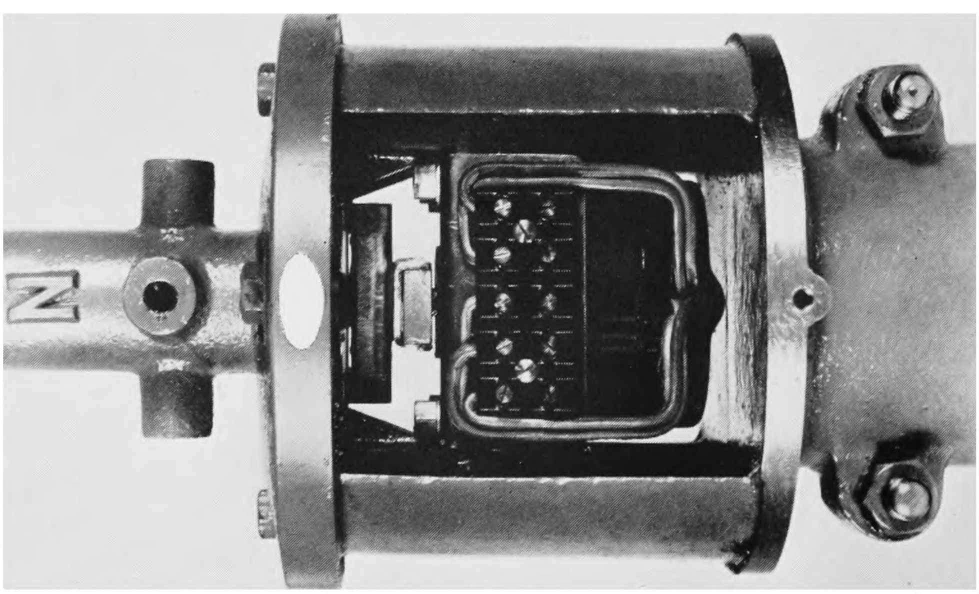
WIND VANE MK II



REMOTE-INDICATING WIND VANE MK IIIA







REMOTE-INDICATING WIND VANE MK IIIA SHOWING DESYNN TRANSMITTER

This pipe is not supplied with the wind vane as local requirements as to lengths vary considerably. Arrangements should therefore be made locally for the supply of this and for the actual mounting of the vane in a well exposed position ; the same principles should be applied as in the exposure of anemometers (see p. 201). If mounted away from buildings a wooden pole will probably be found the most suitable method with the length of gas pipe (about 3 ft.) held in position on it by means of side brackets. It should be noted that $1\frac{1}{2}$-in. gas piping has a nominal bore of $1\frac{1}{2}$ in., its external diameter being approximately $1\frac{29}{32}$ in. Great care must be taken to ensure that the axis of the vane, when installed, is truly vertical. If a direct-reading indicator is devised, a length of light rod can be connected to the spindle of the vane by means of the connecting link and taken down inside the gas pipe into the building in which the indicator is to be situated. A large pointer just below the ceiling and moving about a vertical axis over a suitable graduated scale will be convenient in some instances.

When the vane has been properly mounted the azimuth of the direction arms should be adjusted so that the north arm points directly to true north. The best method of ensuring this is to find a prominent fixed object bearing due north of the vane, and adjust the instrument until the arm points directly at this object.

Method of use.—When using the vane the observer should stand as close as possible to the base of the support of the vane to reduce parallax errors.

Maintenance and repair.—The thrust race and bushes are packed with a suitable anti-freezing grease at the time of manufacture and should not require attention during the normal life of the vane. At Meteorological Office stations if the vane becomes unbalanced or stiff it should be returned for replacement and repair to the Instrument Provisioning Branch.

Accuracy.—The response and accuracy of wind vanes has already been discussed (p. 190). The Mk II vane, being lighter than the pressure-tube anemograph Mk II vane (although the dimensions are also less) has slightly better response characteristics.

5.2.2. Remote-indicating wind vane Mk II

The remote-indicating wind vane Mk II (Stores Ref., Met. 648) is a modification of the Mk II vane designed to give distant indication of the vane direction. Attached to the spindle of the wind vane is a simple contact mechanism consisting of a brush which moves over a series of eight equally spaced fixed contacts arranged in a horizontal circle with the axis of the spindle passing through the centre. A second movable contact from the spindle makes continuous contact with a separate terminal. This mechanism is wired in series with a 3-V. or 4-V. d.c. supply and an indicator carrying 8 lamps, representing the directions N., NE., E., SE., S., SW., W. and NW. When the vane is pointing within $11\frac{1}{4}°$ of each of these cardinal values the single lamp representing the appropriate direction lights up ; at other times the two lamps nearest to the wind direction are lit. In this way 16 points of the compass can be indicated. This instrument has now been superseded in general use at Meteorological Office stations by the remote-indicating wind vane Mk IIIA.

5.2.3. Remote-indicating wind vane Mk IIIA

In the remote-indicating wind vane Mk IIIA (Stores Ref., Met. 2861) the movements of the wind vane are transmitted by the desynn system (Fig. 68) to a dial indicator which can be at a considerable distance from the vane (Plates XIX and XX). The transmitter has a toroidal wound circular resistance with three tappings at equidistant points. Two sliders make contact at diametrically opposite points and are made to rotate over this resistance by being connected mechanically to the wind-vane spindle; the sliders are connected to the terminals of a 12-V. d.-c. supply. The windings of the indicator are such as to produce the same effect as three symmetrically placed iron-cored coils with coplanar axes which intersect at a point. At the centre is placed a pivoted permanent magnet carrying the pointer. The tappings of the transmitter resistance are joined to the three windings of the indicator, and thus the distribution and direction of the currents in these will depend on the position of the sliders on the resistance. This is shown in turn by the position that the magnet takes up, for it aligns itself with the resultant magnetic field produced by the currents in the windings.

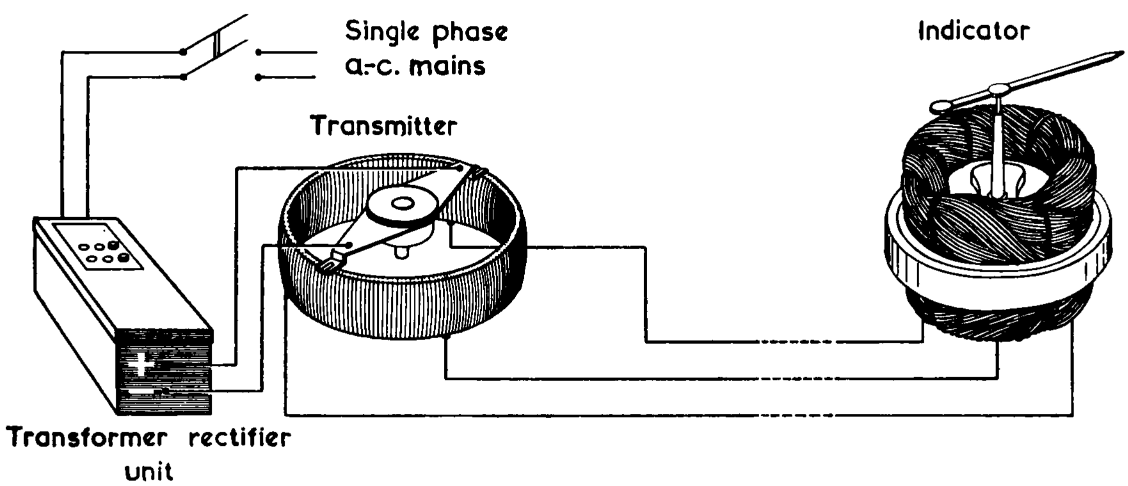


FIG. 68—DESYNN SYSTEM OF REMOTE INDICATION

The vane is similar in dimensions to the ordinary Mk II wind vane but it has a flat plate instead of the aerofoil cross-section fin because of ease in manufacture. The instrument runs off a 12-V. d.-c. supply obtained from a transformer-rectifier unit connected to the 230-V. a.-c. mains. Two direction indicators, connected in parallel, are normally used. The instrument will function with three or four indicators, but the accuracy with which each indicator follows the movements of the transmitter will be reduced. The resistance of each core of the three-core cable connecting the transmitter to the indicator should not exceed 50 ohms; the instrument will still function if this is exceeded but the accuracy will be reduced.

Installation.—Before installation the instrument should be temporarily connected up to make sure that the vane and pointer directions agree, although this will have been tested before issue so that it is unlikely to require adjustment. The following procedure should be used:

Set the vane on a bench or table, take out the housing screw and lower the housing to expose the terminal block. Take the back off one of the indicators and connect the terminal screws marked 1, 2 and 3 to the terminals 1, 2 and 3 of the terminal block respectively. Connect the + and — terminals on the terminal block to the + and — terminals on the transformer rectifier and connect this unit to the mains. When the balance weight of the vane points in the direction of the N embossed on the vertical column, the dial pointer should indicate N (360°). If it does not, it will be necessary to take out the desynn transmitter and alter the position of the split bar in Plate XX (*a*) and (*b*) relative to the spindle until the correct reading is obtained. To take out the transmitter, turn the vane until the steel pin, P in Plate XX (*c*), is to the rear (this direction may vary in different instruments) ; the transmitter can then be slid out of its slots to the front. The pinch screws of the split bar should then be loosened, the bar held in position and the spindle turned with a screw driver until the indicator pointer indicates the direction of the vane which allows the transmitter to be removed. The pinch screws can now be tightened, keeping the split bar horizontal and with its top surface flush with the top of the spindle, and the transmitter replaced in its slots.

The vane is mounted by means of its two base clips on a suitable piece of 2-in. gas pipe (i.e. pipe of nominal bore 2 in., outside diameter 2⅜ in.) at the top of a suitable mast or pole. The embossed N on the centre column should be set pointing to true north before the clips are tightened. The direction arms can then be screwed into their sockets.

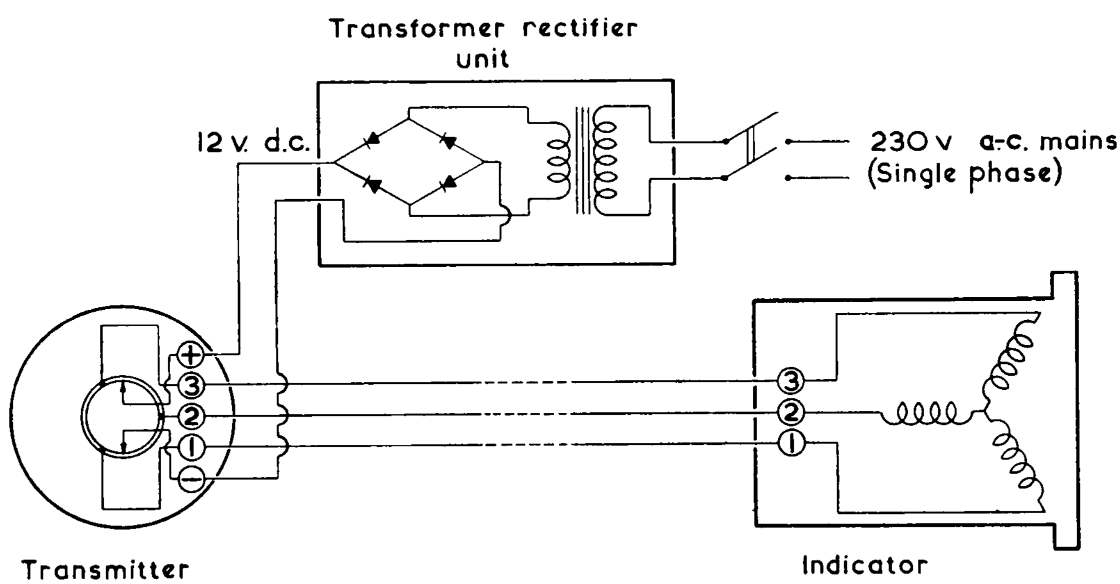


FIG. 69—WIRING DIAGRAM FOR REMOTE-INDICATING WIND VANE MK IIIA

Electrical connexion from the vane to the dials can be made with any suitable 3-core lead-covered cable as shown in the wiring diagram, Fig. 69. The vane end of the cable should be taken inside the (lowered) housing cover tube and up through the hole in the instrument base ; the cover may then be raised again and its retaining screw inserted. When two dials are used the second is connected in parallel with the first. The transformer rectifier output should also be connected to the transmitter unit using lead-covered cable ; its input should be connected to the 230-V. a.-c. mains. A switch should be provided between the transformer unit and the mains, but it has been found that the instrument will work most satisfactorily if this is left on continuously. If it is switched off for a period the pointer moves erratically for a time after switching on again. If the mains supply is not available a 12-V. battery of any kind may be used instead. The current drain is about 0·2–0·3 amp.

If the vane is at some considerable distance from the indicating dials it is preferable to mount the transformer unit as close to the vane as possible and not in the same building as the dials.

Maintenance and repair.—The vane spindle is carried in a ball-bearing and self-lubricating bush and needs no attention during normal life. The most likely part to need attention is the desynn transmitter ; if the pointer persists in moving erratically a new transmitter should be obtained (from the Instrument Provisioning Branch for Meteorological Office stations). The existing one should be disconnected and taken out as described earlier, and the new one, which already has a terminal block and split bar, fitted in its place and wired up. The indicator should then read correctly. If trouble still persists the indicator should be replaced and the wiring checked for insulation. It is important to realize that new components can be fitted, and not to dismantle the whole vane unnecessarily.

Accuracy.—If only one or two indicators are used the movement of the vane is followed in a steady wind with an accuracy of about $\pm 2°$. The lag coefficient of the transmitting system is probably less than ½ sec. and the natural period of vibration is about 12 c./sec. so that all the oscillations of the wind vane should be followed. If three indicators are fitted the accuracy in a steady wind falls to about $\pm 4°$, while with four indicators the accuracy is about $\pm 6°$.

5.3. CUP ANEMOMETERS

5.3.1. Cup counter anemometer Mk II

The cup counter anemometer Mk II (Stores Ref., Met. 2765) has a cup wheel consisting of three conical cups with beaded edges, Plate XXI. The spindle is connected by worm gearing to a revolution counter and the gear ratio is so chosen in relation to the factor of the anemometer that the counter indicates directly the run of wind in miles, tenths and hundredths. If the reading of the counter at two different times is taken the mean wind speed over the period can be determined. The counter mechanism has six figures and reads up to 9999·99 miles before repeating itself. This instrument is mainly used in acquiring wind-speed averages over long periods, and, having no provision for distant indication or for showing gusts, is not normally used at synoptic stations.

Installation.—The anemometer has a socket in its base with ½-in. British standard pipe thread tapped. A short length of appropriately threaded gas pipe should be screwed into this, and, if necessary, a length of larger-diameter piping (1½- or 2-in. nominal bore) should be attached to the end of the first piece of piping through a reducing socket. The ½-in. pipe is not sufficiently rigid to support the anemometer when used in lengths greater than about 1 ft. If the anemometer is being used in conjunction with a remote-indicating wind vane it may be mounted on a side bracket attached to the wind-vane support ; otherwise a separate mast or pole will be required. The principles to be observed in selecting a site have been outlined on p. 201, but it must be remembered that it is necessary to approach this anemometer fairly closely to read the counters.

Method of use.—The rate of increase of the counter reading gives the wind speed. It should normally be determined by observing the increase in reading over at least a 10-min. interval, but in strong winds a shorter interval may be sufficiently accurate. Alternatively the average wind speed over the period of a day or even longer may be found.

The instrument is unreliable in winds of less than 4–5 kt.

Maintenance and repair.—The instrument should be inspected and cleaned at intervals of three months according to the following routine :

(i) Place the instrument on a clear bench, remove the cap nut and lift the cup wheel off the spindle, taking care not to lose the washer which lies between the cap nut and the cup wheel casting. If the cup wheel is stuck to the spindle, loosen the cap nut but do not remove it ; support the cup wheel in one hand and strike the cap nut smartly with a mallet or screw-driver handle.

(ii) Clean the cup wheel thoroughly, checking that the cup retaining nuts are tight and that the cups are not loose on their arms.

(iii) Clean thoroughly the exterior of the counter box and the spindle tube.

(iv) Undo the six screws which hold the counter box to its lid and lift the lid and spindle assembly off the box ; the centre screw on the dial side is prevented from coming completely out by the dial window retaining frame so that the lid must be lifted off as this screw is undone.

(v) Clean the transparent dial panel, removing its frame if it is dirty inside ; do not scratch the panel (it is made of perspex, not glass). Clean the inside of the box, and dry it thoroughly if damp. Grease the screwed socket on the under side of the base.

(vi) Remove the grub screw which holds in the brass cap above the upper spindle bearing and take out the cap ; if obstinate the projecting rim of the cap can be held in a vice, using lead or fibre jaws, and the lid assembly twisted.

(vii) Remove the lower bearing end cap in the same way ; the lower steel race of the thrust bearing will come out with this cap, followed by the brass ball cage. The spindle can now be withdrawn, complete with worm and thrust-bearing top steel race, downwards.

(viii) Tap out the upper ball-bearing upwards, and clean both ball-bearings by immersion in petrol until all oil, grease or dirt is removed. The upper bearing is of the single-row rigid journal type, $\frac{1}{4}$-in. bore by $\frac{3}{4}$-in. outside diameter ; the lower is a flat-seated thrust-bearing $\frac{1}{4}$-in. bore by $\frac{21}{32}$-in. outside diameter by $\frac{1}{4}$ in. thick.

(ix) The upper bearing should be replaced if it is in a very bad condition, but if it revolves freely after cleaning it can be used again.

(x) Clean the spindle and worm, and lubricate the latter with a little thin oil. If the top bearing shows no sign of rust, lubricate it after cleaning with low-temperature grease.

(xi) Clean the counter wheels, and check that they are free on their spindles. These wheels and their pinions are purposely made an easy fit on their spindles and should run dry. If they are not free, remove the large wheel spindle by loosening the set screw which retains it and pushing out endways ; take off the wheels, clean their central holes and the spindle, and replace.

(xii) Reassemble in the following order :—top bearing (from above), spindle (from below), thrust-bearing ball cage, lower cap, lower cap grub screw, upper cap, upper cap grub screw.

(xiii) Replace the lid on the box and tighten up the six retaining screws. Reassemble the cup wheel on the spindle, replace the washer, and replace and tighten the cap nut. The anemometer can then be remounted on its support.

Accuracy.—The general accuracy of the cup anemometer has already been discussed. The cup counter Mk II has errors of less than 1 kt. at all normal wind speeds above about 5 kt. It normally begins to rotate at wind speeds of the order of 1½–2 kt., and between 2 and 5 kt. its indications depend to a large extent on the bearing friction and the state in which the instrument is maintained. If the friction seems excessive, the anemometer should be tested by being placed on a horizontal surface indoors in a place free from draughts and the cups rotated at a rate of 1 rev./sec. in the same direction as the wind would turn them. The time taken for the cups to come to rest after being released at this rate should exceed 60 sec.

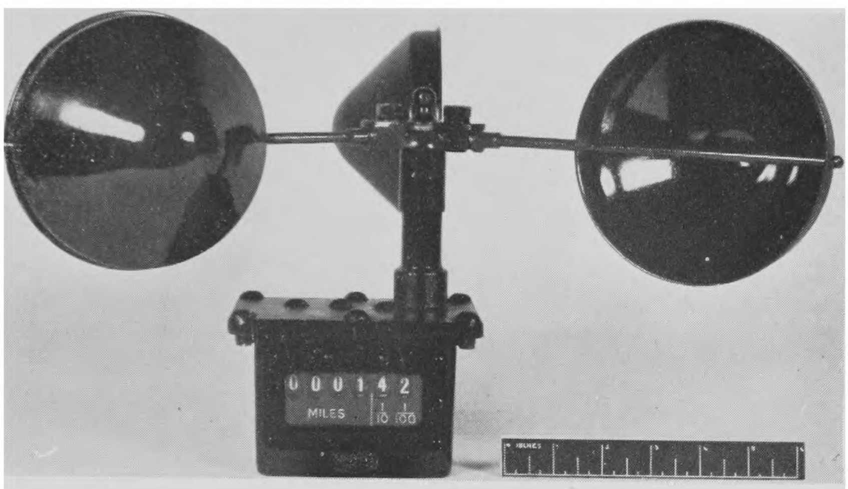
5.3.2. Cup counter anemometer Mk I

The Mk I instrument (Stores Ref., Met. 511), now obsolescent, differs from the Mk II in having a longer spindle and three beaded-edge hemispherical cups in place of the conical cups. Various types of spindle-bearing systems are employed. The method of operation is similar to that of the Mk II, and the anemometers should be cleaned and inspected at regular intervals (about every three months). The instructions given for the Mk II instrument can be used as a general guide but the details will be different.

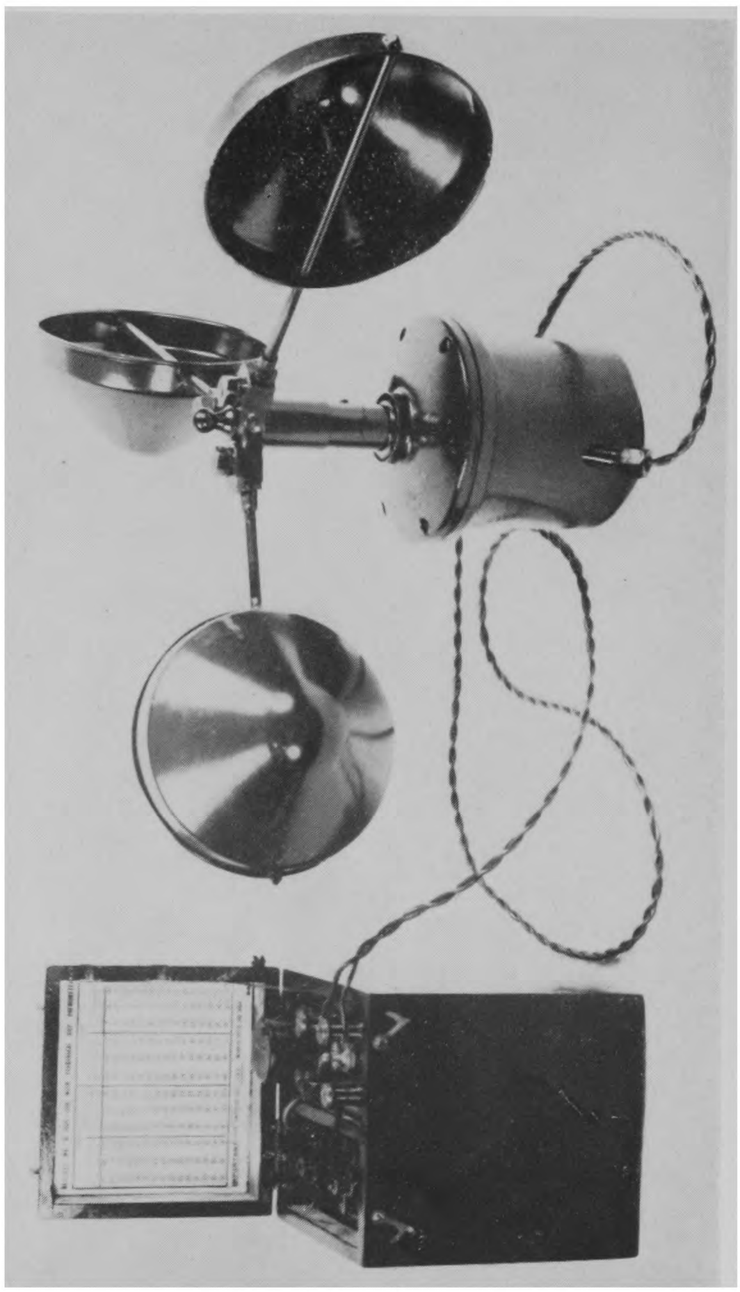
5.3.3. Cup contact anemometer Mk III

The cup contact anemometer Mk III (Stores Ref., Met. 2862) is the latest form of cup contact anemometer, Plates XXII and XXIII. The cup wheel has three conical beaded-edge cups, and the spindle controls a switch mechanism so that an electrical contact is made once for every 27 revolutions of the cup wheel. With this form of housing and cup dimensions this corresponds to a contact for every 1/20th of a mile of wind.

The mercury switch, which is used to make the contact, is operated by a falling weight, so that the time of contact is constant and independent of the wind speed. In this way the possibility of the contact remaining in the ON position during a calm, or of very long contacts in a light wind, is avoided and the current required is reduced. The anemometer spindle carries a worm which drives a worm wheel ; on the same spindle as the worm wheel is a loose sleeve carrying a weight and one carrying a cam. The worm wheel carries on one side a steel pin which can engage with another pin on the weight and thus cause it to rotate. When the weight approaches its highest position it engages with a pin on the cam and causes that to rotate also ; when the weight is just driven past its highest point it falls freely down to its equilibrium position and in so doing drives the cam round. This movement of the cam tilts the mercury switch momentarily, thus making the contact, and then allows the switch to regain its horizontal position and break the contact. The pin on the worm wheel has then about half a revolution to make before it re-engages with the pin on the weight and starts the process again. The time of electrical contact is about ½ sec.

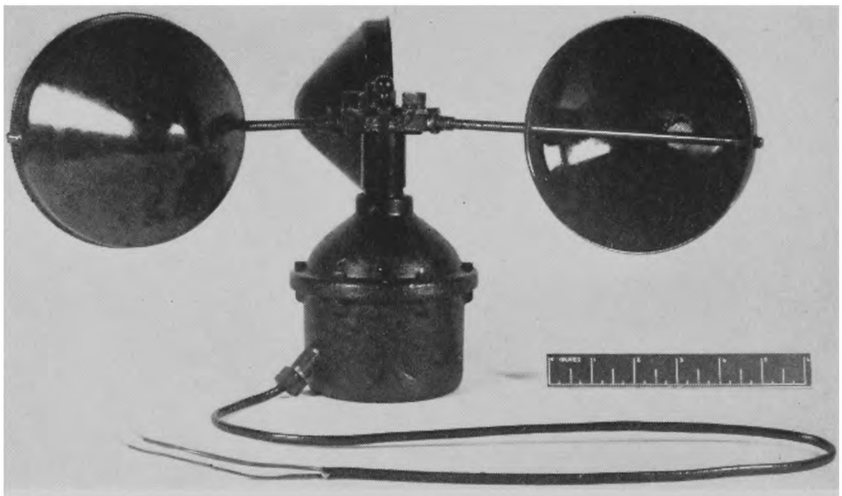


CUP COUNTER ANEMOMETER MK II

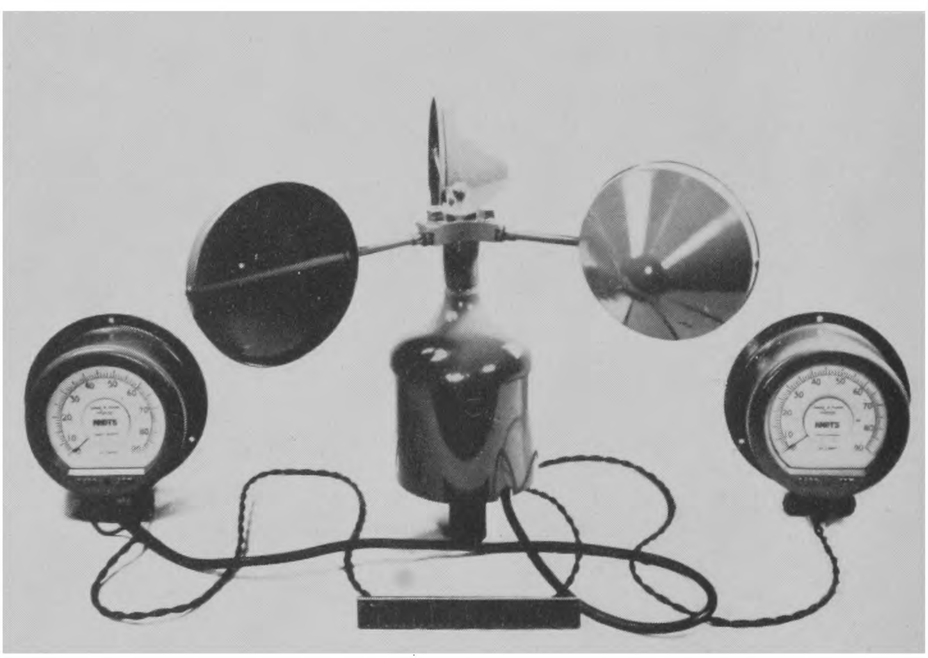


CUP CONTACT ANEMOMETER MK III AND PORTABLE RECEIVER

CONTACT MECHANISM OF CUP CONTACT ANEMOMETER MK III



CUP CONTACT ANEMOMETER MK II



CUP GENERATOR ANEMOMETER MK IB

The anemometer spindle has a cup and cone ball-bearing near the top which takes both the weight of the cup assembly and the journal load ; the bottom bearing is a plain guide bush and takes the journal load only. The anemometer can be used in conjunction with a buzzer, or lamp, and battery and stop watch to obtain the mean wind speed over a short period by measuring the average time between the contacts, or it can be converted into an anemometer of the counter type by connecting it to an electromagnetic counter assembly.

The cup contact anemometers are normally used in conjunction with the portable receiver Mk II (Stores Ref., Met. 634). This has a simple buzzer, operated from two 1½-V. dry cells, which gives an audible indication when the anemometer contact closes. Two type U batteries (Stores Ref., Met. 548) connected in series should be used, and they can be placed in the left-hand compartment of the receiver ; the positive (central) terminal of one cell is connected to the spade terminal of the receiver and the negative wire of the other is connected to the other left-hand terminal. The two leads from the anemometer are connected to the two terminals on the right-hand side of the receiver. An ON–OFF switch is included in the circuit.

In the lid of the receiver is a table giving the wind speeds for various frequencies of contacts. If this is in miles per hour it may be readily altered to knots, or, in the case of Meteorological Office stations, a card may be obtained from the Instrument Provisioning Branch.

Installation.—The instrument is sent out with the mercury switch sealed with tape to prevent movement and damage in transit. The leads from the switch are carried to a two-way terminal block inside the housing, and a cable outlet is provided in the housing wall. The base of the instrument has a socket screwed with ½-in. British Standard pipe thread by which the instrument can be mounted on a short piece of ½-in. gas pipe ; the installation should be carried out in the following order :

(i) Remove the screws which hold down the lid of the housing and lift off the lid. Take away the tape which holds the switch, and connect a short length of Ducel or similar twin cable to the terminal block, passing the cable through the outlet.

(ii) Replace the lid, but before screwing it up check that the switch is working correctly by connecting the other end of the cable to the portable receiver, or a lamp and battery in series, and spinning the cup boss. The switch should make a contact of about ½ sec. duration once every 27 revolutions of the spindle ; it is not necessary to count the revolutions but merely to see that the switch is not sticking in the ON position and that it gives a satisfactory short contact.

(iii) Screw down the lid, check the switch once more, and then prepare the instrument for mounting.

(iv) Insert the cup arms in their correct sockets in the boss, and tighten the retaining nuts hard with the spanner provided in the case.

(v) Mount the instrument on its pipe, taking care that it is truly vertical.

The short length of cable projecting from the housing is connected to the portable receiver or other indicator by a length of twin lead-covered cable. If the anemometer has to be mounted more than about 6–12 in. above its support a length of larger-diameter gas piping should be used. This can be connected to the short length of ½-in. gas piping by means of the reducing socket. When choosing the site the principles outlined on p. 201 should be carefully considered.

Method of use.—Each contact shows that the run of wind has increased by 1/20th of a mile. It is therefore easy to draw up a table giving the appropriate wind speed for a given time between individual contacts or between 10 contacts (at wind speeds above 30 kt.). If the mean wind over a long period is required a counter will have to be employed. When not required the portable receiver should be switched off to conserve the batteries.

Maintenance and repair.—Every three months the main cable should be disconnected and the anemometer taken down for examination and lubrication if necessary. The instrument should be placed on a bench or table, the cups detached from the boss, the lid of the switch housing taken off and the cable disconnected from the terminal block. The following procedure should then be followed :

(i) Remove the cap nut and lift the boss off the top of the spindle. Take out the small cheese-headed screw which fixes the top-bearing guard tube. Lift off the tube, and take off the spring, felt washer and two brass washers.

(ii) The top bearing can now be seen. Lubricate this with thin anti-freezing grease (A.M. Stores Ref., 34A/49). If there are signs of rust in the top ball-bearing, the instrument should be reassembled and returned, in the case of Meteorological Office stations to the Instrument Provisioning Branch, for complete overhaul.

(iii) The lower bearing is self-lubricating and requires no attention. The worm and worm wheel should be cleaned and lubricated with thin clock or cycle oil.

(iv) Check that the falling weight and cam revolve freely on their spindles without oil. The instrument can now be reassembled, and, after checking the switch action, replaced on its support and the wires reconnected.

Accuracy.—This instrument has the same general accuracy as the other Meteorological Office cup anemometers with three conical cups. The error in a steady wind should not exceed 1 kt. in the range 5–80 kt. The possible errors in fluctuating winds have been discussed. The cups should start rotating in a wind speed of 1½–2 kt., but the rate of rotation of the cups in wind speeds of 2–5 kt. depends largely on the bearing friction which in turn depends on the state in which the instrument is maintained.

5.3.4. Cup contact anemometer Mk II

The main differences between the Mk II and the Mk III cup contact anemometers are in the switch gear and the spindle-bearing system. In addition the housing of the switch gear and worm wheel of the Mk III is deeper and has a flatter roof. In the Mk II (Stores Ref., Met. 2764) the mercury switch is operated by a cam attached rigidly to the worm wheel and the contact remains closed during three revolutions of the cup wheel (Plate XXIV). The time of contact thus depends on the wind speed, and there is a risk that the switch may remain in the ON position during a calm. The difference in the bearings is a more minor matter ; in the Mk II the upper bearing is a single-row rigid journal-type ball-bearing while the thrust load is taken by the lower flat-seated ball-bearing (as in the Mk II cup counter anemometer). Apart from these differences the anemometers are very similar and are operated in the same way. The maintenance of the Mk II should follow the same general lines as that described for the Mk III.

5.3.5. Earlier types of cup contact anemometer

The earlier types of cup contact anemometer differ from the Mk II and Mk III in having a mechanical contact mechanism, a longer stem and hemispherical cups. The switching arrangements were not so reliable as the mercury switches now used and were subject to wear and deterioration. The advantage of the conical cups over the hemispherical ones has already been described.

5.3.6. Cup generator anemometer Mk IB

In the cup generator anemometer Mk IB (Stores Ref., Met. 955) a cup wheel of the same dimensions as the cup contact anemometer Mk III is used to drive a small 12-pole permanent-magnet dynamo (Plate XXIV). When the cup wheel rotates the motion of the permanent magnet induces an alternating electromotive force in the stator windings ; this electromotive force is applied to an indicator consisting of a moving coil galvanometer with a circular scale incorporating a metal rectifier. The magnitude of the electromotive force, and thus of the current which flows in the indicator, depends on the rate of rotation of the magnet and therefore the indicator can be graduated directly in terms of wind speed.

Each generator is made to a careful specification ; the standard relation between the terminal voltage and the speed of rotation is given in Table XXXIII, and the output of any cup generator should not differ from the standard by more than $\pm$ 0·025 V. at any speed of rotation, when checked on a voltmeter of similar characteristics to the indicator. These figures are based on a current drain of 5 mamp. at 10 V. in a non-inductive circuit.

TABLE XXXIII—CHARACTERISTICS OF THE CUP GENERATOR MK IB

Output from generator (V.)	0	1	2	3	4	5	6	7	8	9	10
Speed of rotation (rev./min.)	0	110	208	307	405	502	601	700	800	900	1,000

The indicator is adjusted to take exactly 5 mamp. a.c. at 10 V. when supplied from the 50-c./sec. a.-c. main. It is calibrated from 0 to 90 kt. with a pointer movement of approximately 270°, but owing to the characteristics of the rectifier and the anemometer movement itself the effective zero for reliable readings is 5 kt. The electrical resistance of the indicator and generator is such that one, two or three indicators may be connected in parallel from one generator without affecting the accuracy of the indication, but the total resistance of each core of the twin cable between the generator and the indicator must not exceed 10 ohms (approximately 550 yd. of 1/0·048 or equivalent twin cable).

By conforming to these standards it is possible to use any indicator with any generator within certain close limits of accuracy (p. 212). The relation between the wind speed in knots and the cup wheel revolutions per minute, with the standard design of cup wheel and generator housing, is given in Table XXXIV.

TABLE XXXIV—CHARACTERISTICS OF THE ANEMOMETER UNIT OF THE CUP GENERATOR ANEMOMETER MK IB

Wind speed (kt.)	5	10	15	20	30	40	50	60	70	80	90
Speed of rotation (rev./min.)	33	90	140	192	290	385	480	573	670	760	850

Installation.—The generator unit can be mounted on a piece of 2-in. gas pipe, screwed at the top to fit into the screwed socket at the base of the instrument, or, alternatively, the pipe can have a flat flange screwed or welded to it, to which the instrument base can be bolted. The pipe is then mounted firmly in a vertical position in a suitable exposure (see p. 201). A short length of twin rubber-covered cable emerges from the generator unit, and this should be connected to a length of lead-covered twin cable (1/0·048 or similar) which is taken close to one of the indicators. The lead-covered cable should be supported at intervals as the lead covering is rather brittle ; a short length of flexible cable should be used to connect the indicator to the lead-covered cable. If an extra one or two indicators are to be used these should be connected in parallel with the original indicator, using twin cable. Before mounting the generator unit it is advisable to check the following points :

(i) Make sure that the cup wheel is securely held on the tapered portion at the top of the shaft by means of the cap unit, a washer being placed beneath the cap nut.

(ii) See that the nuts which tighten the cup arms in their sockets are screwed up tightly.

The indicators should be mounted on a board with their dials vertical. When moving the indicators about it is advisable to short circuit the terminals by connecting them together with a piece of wire.

Maintenance.—The generator unit needs no maintenance during its normal life. If any trouble develops the complete instrument should, in the case of Meteorological Office stations, be returned to the Instrument Provisioning Branch for repair and overhaul.

Accuracy and sources of error.—The calibration of the instrument should be correct, in steady winds, within the following limits ; $\pm \frac{1}{2}$ kt. at speeds from 5 to 20 kt., $\pm$ 1 kt. from 20 to 60 kt. and $\pm 1\frac{1}{2}$ kt. from 60 to 90 kt. The minimum wind speed at which the cup wheel will begin to revolve from rest should not exceed $3\frac{1}{2}$ kt. The effect of fluctuating winds has already been discussed (p. 194).

5.3.7. Cup generator anemometer Mk IA

The cup generator anemometer Mk IA is an earlier model than the Mk IB but differs very little from it. There are two patterns in use in the Meteorological Office made by different manufacturers (Stores Ref., Met. 2571 and Met. 2858) the majority being of the first type. The dials of these instruments are graduated in miles per hour.

The general description and method of installing these instruments follows closely that of the Mk IB, except for minor differences in the case of the second pattern (Stores Ref., Met. 2858) ; this pattern is designed for use with two indicators connected in parallel, but if only one indicator is being used a substitutional resistance should be connected across the indicator terminals in place of the second indicator. Connexions to the indicators and the resistance are made by means of the screwed brass pillars provided ; these screw into tapped holes in the backs of the indicators and resistance and the leads are connected to their outer ends by means of the nuts provided. The substitutional resistance is not used if two indicators are connected to the generator.

The generator unit of the second pattern does not normally have the short length of cable attached to it. The cable outlet fitting should therefore be unscrewed and the two terminal blocks found just inside should be pulled out and a short length of twin flexible cable attached to them. The terminal blocks will be held in place again when the outlet fitting is screwed back. This length of cable can then be joined to the main lead-covered connecting cable.

5.3.8. Cup generator anemometer Mk I

The cup generator anemometer Mk I is the earliest of its type to be used in the Meteorological Office and it is now obsolescent. The main differences between this and the later models are :

(i) A 6-pole generator was used in place of the 12-pole generator in the present models. To reduce pointer flicker at low wind speeds, the number of poles was increased from 6 to 12, thus doubling the frequency of the a.-c. voltage generated.

(ii) The instrument was designed to be used only with one indicator.

5.3.9. Sensitive cup counter anemometer Mk I

The sensitive cup counter anemometer Mk I (Stores Ref., Met. 639) is a portable instrument for the accurate measurement of medium and light winds[45] (Plate XXV). It has very light, conical-shaped cups of 5·2-cm. inside diameter, the centres of which move in a circle of 7·4-cm. radius. It is thus very much smaller (and lighter) than the normal Meteorological Office cup anemometer. The spindle carries a pinion which engages with a gear train so that the number of revolutions of the cup wheel can be obtained from a set of pointers on a dial face. The main pointer reads up to 100 and smaller pointers give the hundreds and the thousands. The gear train is such that three revolutions of the cup wheel move the pointer two divisions. Two push levers enable the counter mechanism to be started and stopped and the zero reset as required.

The spindle is carried on plain lower and upper bearings ; this is satisfactory because the cup wheel is so light (the moving parts weigh about 50 gm.). The cup wheel is only a push fit on to the top of the anemometer spindle. The anemometer is not designed for very high winds, and should normally be restricted to use in wind speeds below 30 kt.

Installation.—The anemometer has a conical mounting bearing, which can fit into a machined counterpart on a metal mast. Alternatively, a simple but quite rigid mounting can be obtained by using a wooden mast. The instrument must always be handled carefully ; in particular the cups must not be deformed in any way. The counter mechanism should be treated with the care usually given to a stop watch or other similar mechanism.

Method of use.—The rate of increase of the counter reading is measured, and then converted into the corresponding wind speed by means of a calibration chart for that particular anemometer. The calibration card has a straight line marked upon it relating the wind speed to the counter reading in units per minute. A period of about 5–10 min. should be used, and the counter reading after the definite interval (as given by a stop watch or the seconds hand of an ordinary watch) should be noted. The counter should be started after being reset to zero. It is not necessary to take the reading immediately the interval is ended as the counter can be stopped at the correct time and the reading made at leisure. For very accurate work it is, however, advisable to take the counter readings from a distance to avoid any disturbance.

It is important to use the correct calibration chart which should always accompany the instrument. The cups begin to rotate in a wind speed of the order of 0·3–0·5 kt., varying slightly with different instruments and with the condition of the instrument.

Maintenance.—Little maintenance is required beyond keeping the instrument clean. No attempt should be made to dismantle the instrument, and if any faults develop it should be returned, at Meteorological Office stations, to the Instrument Provisioning Branch. If very accurate results are required, especially in light winds, it is advisable to have the instrument recalibrated about every 6–12 months, or before and after a series of experiments.

Accuracy.—It is found that the relation between the speed of the cup centres, v', and the wind speed, v, follows a linear relation

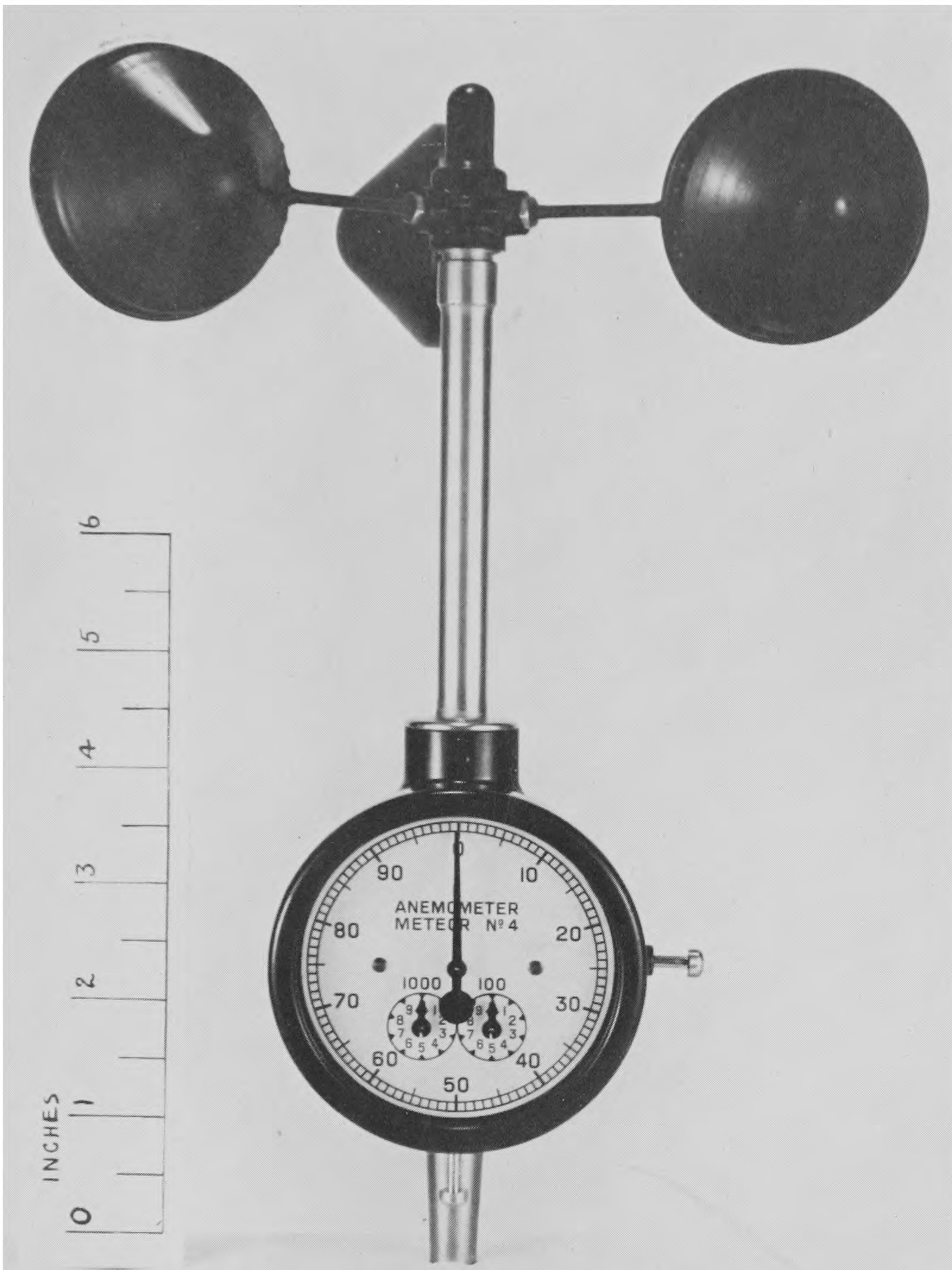
$$v = v_0 + kv'$$

with great accuracy (v_0 is the wind speed at which the cups just begin to move and k is a constant). As v_0 and k vary slightly from instrument to instrument it is necessary for each instrument to have its own calibration card if the best use is to be made of the instrument's potentialities.

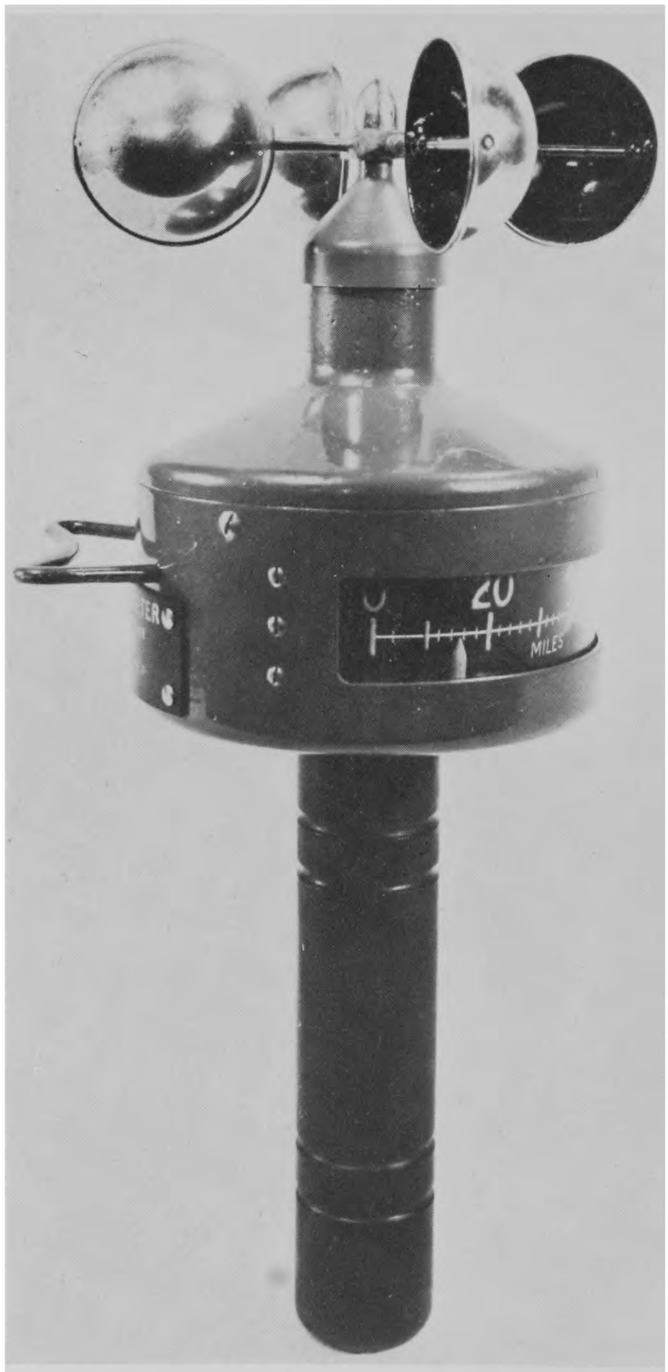
Because of its light weight the anemometer responds very quickly to wind changes and the errors in the mean wind speed recorded in gusty conditions are usually very small. These errors, as measured in a wind tunnel, are slightly less than those indicated by Schrenk's analysis for hemispherical-cup anemometers (see p. 194). The percentage uncertainty in the results obtained with this anemometer naturally increases at low wind speeds, and variations in friction probably prevent accurate results below about 0·8 kt. This is, however, a much lower speed than can be measured with the standard type of cup anemometer.

5.3.10. Magnetic drag cup anemometer

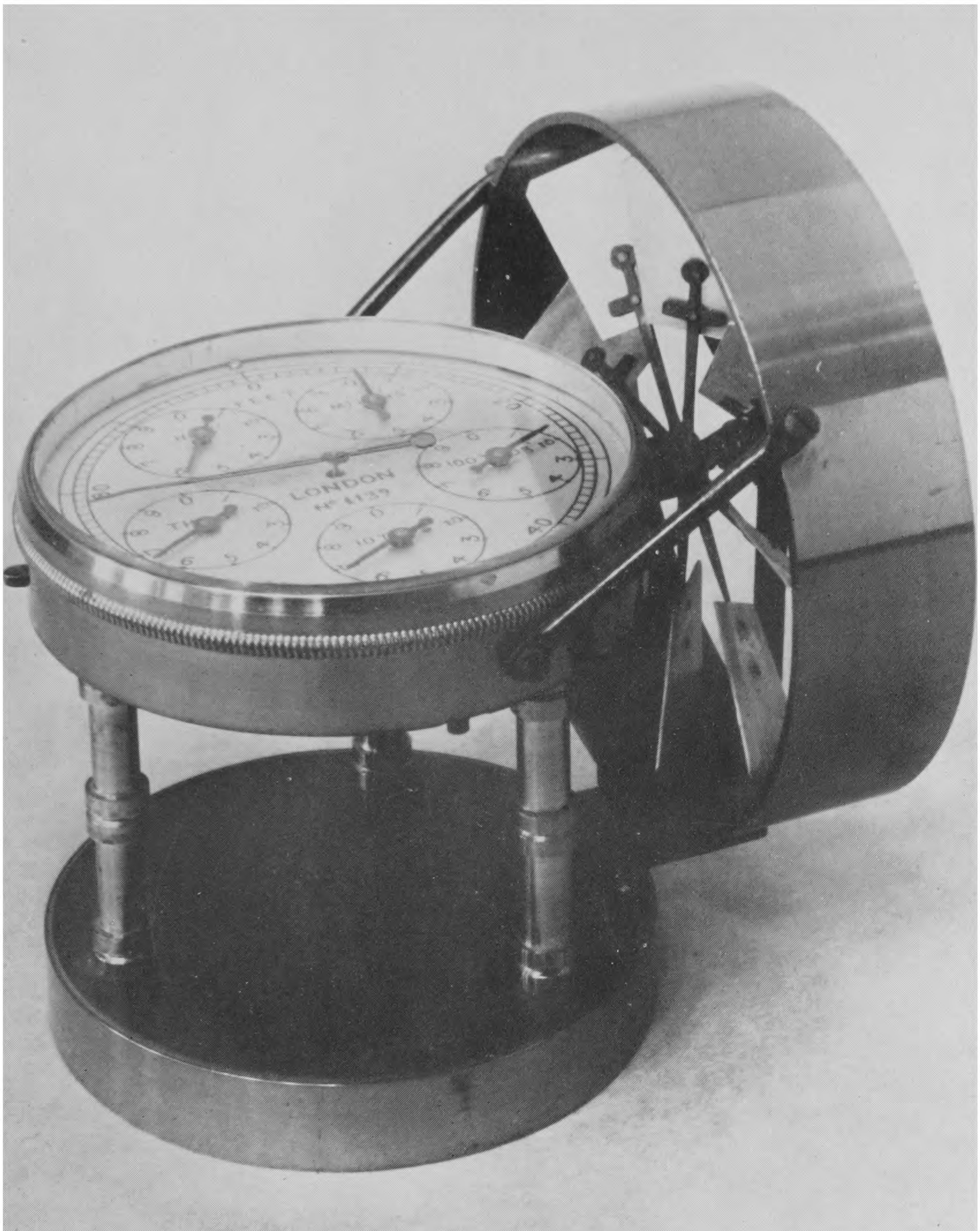
An alternative method of indicating the speed of rotation of the cup wheel of an anemometer, which is particularly useful for small hand instruments, is used in the magnetic drag cup anemometers. Attached to the spindle of the anemometer is a permanent magnet with a number of poles ; all the north poles lie on the surface of a cylinder and all the south poles lie on the surface of a concentric cylinder with a very narrow air gap between the pole faces. In this way a strong radial magnetic field is obtained. A light aluminium cylinder is supported between the pole faces, concentric with the poles themselves, and is constrained against



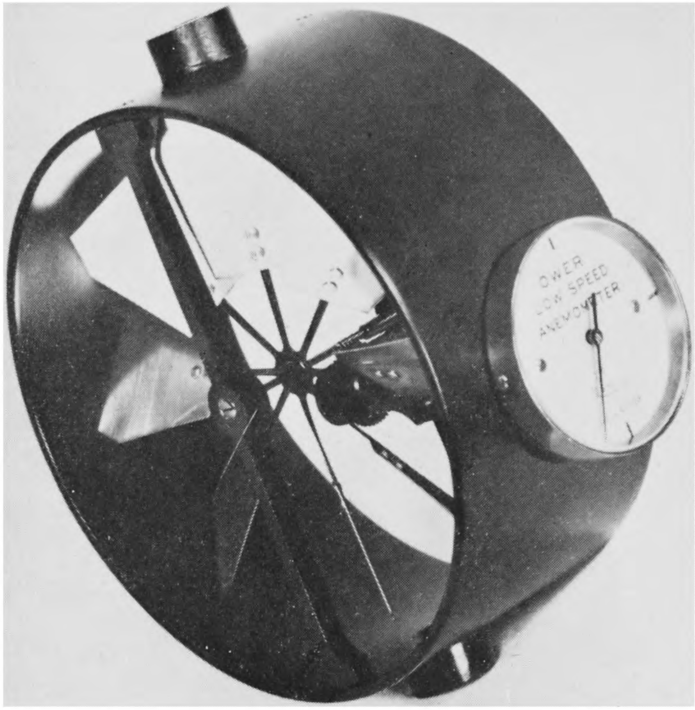
SENSITIVE CUP COUNTER ANEMOMETER MK I



METEOROLOGICAL OFFICE HAND ANEMOMETER



AIR METER, NORMAL PATTERN



OWER LOW-SPEED AIR METER

HIGH-SPEED AIR METER

rotation about its axis by a light hair spring. When the cup wheel, and therefore the permanent magnet, rotates, eddy currents will be induced in the metal cylinder and there will be a force tending to turn it about its axis. The deflection produced will depend on the magnitude of this force and thus on the rate of rotation of the cups. A suitable pointer can be made to indicate the wind speed directly.

Meteorological Office hand anemometer.—The Meteorological Office hand anemometer (Stores Ref., Met. 749) is based on the magnetic drag principle (Plate XXVI). It has four hemispherical beaded cups, $1\frac{1}{4}$ in. in diameter, with their centres moving in a circle of $1\frac{3}{8}$-in. radius. It is provided with a handle and the wind speed is indicated by a vertical pointer moving over a cylindrical scale. It is useful for obtaining a measure of the wind speed at 5–6 ft. above the ground.

The first instruments made had a scale graduated from 0 to 100 m.p.h., every 2 m.p.h. being marked above 10 m.p.h., together with the 5 m.p.h. graduation. Later instruments are graduated in knots (Stores Ref., Met. 1096).

The anemometer should be held at arm's length by the observer with its axis vertical, and in such a position that the observer's arm is perpendicular to the wind direction. This ensures that the disturbance of the air flow, caused by the observer's body, is reduced as much as possible.

The instrument should always be treated carefully and not dropped or jarred ; vibration and rough handling may cause a loss of magnetism in the permanent magnet and thus cause the readings to be low. Care must also be taken not to put the instrument down in stray alternating magnetic fields due to adjacent electrical apparatus such as motors, relays and transformers, as this also may cause a loss of magnetism. It should be recalibrated at regular intervals of about a year, and Meteorological Office anemometers should be returned to the Instrument Provisioning Branch for this purpose.

The instrument is not sensitive to wind speeds below about 2–3 kt. and is not accurate below about 5 kt. When new the errors in the other parts of the scale should not exceed 1–2 kt.

5.4. FAN ANEMOMETERS

5.4.1. Air meter (normal pattern)

A typical example of a fan anemometer is shown in Plate XXVII (Stores Ref., Met. 1). It has eight light blades, supported on short radial arms and mounted so that they can rotate about a horizontal axis. A cylindrical metal shield surrounds the blades. The run of wind in feet is shown by the indications of the dials in the rear of the meter, which are connected by a gear train to the spindle which carries the blades. The large hand moves over a scale from 0 to 100 ft. and subsidiary hands show the hundreds and thousands figures and on some instruments still higher multiples. The counter mechanism can be thrown in or out of gear by a lever protruding from the rim of the dial or from the shield surrounding the blades ; in this way the counter can be stopped even though the blades are rotating.

Installation.—The instrument is normally provided with a circular mounting plate graduated in degrees, to which the air meter can be fixed by means of a pin. It is intended that this assembly should be mounted on a pole at a convenient height (according to the purpose of the measurement). The meter should not be left permanently in position, as it is not a robust instrument and can easily be damaged ; it should be brought indoors after each observation. Any suitable pole can be used for mounting purposes (a broomstick for example) or some other support may be devised.

Method of use.—The plate is mounted so that the 360° graduation points to true north. The meter is then turned independently of the plate until the blades are stationary and show no tendency to turn one way or the other. When this happens the axis of rotation of the meter is perpendicular to the wind and the mean wind direction can be obtained. The meter is then turned through 90° until its axis is parallel to the wind direction and the dials are to the leeward.

The wind speed can now be obtained by determining the speed of rotation of the pointer. This can be done by starting the counter at the beginning of a definite period (say 2–4 min.) and stopping it again at the end of the period, and noting the dial readings before and after. The difference in the readings gives the run of the wind. This, however, means that the observer has to approach the instrument and in so doing he will interfere with the flow of the air. A more accurate method is to observe the counter from a distance and obtain the time for the main hand to revolve a given number of times (using a stop watch). The air speed can then easily be calculated. As explained earlier (p. 196) the readings of the instrument may not be correct at all wind speeds, and corrections usually have to be applied. These are normally given on a correction card supplied with the instrument.

Maintenance.—The instrument should be handled carefully at all times, kept clean and not left exposed to the weather. A small drop of good clock oil should be applied to the bearings of the spindle about once every 2–3 months if the instrument is in regular use.

Accuracy.—The main characteristics of fan anemometers have already been discussed (p. 196). The normal pattern responds to low wind speeds, down to less than 1 kt., but it is only accurate, even with the applied correction, at speeds above about 1·5–2 kt. ; at very low speeds variations in the friction of the bearing, due to the deposition of dirt or other causes, give rise to appreciable errors. It is also not suitable for measuring wind speeds above about 30 kt., because of the high rotational speeds involved and the fact that the blades may suffer permanent distortion causing a change in the calibration.

5.4.2. Sensitive air meter (Ower type)

The sensitive air meter (Plate XXVIII) is an anemometer specially designed for measuring low wind speeds (Stores Ref., Met. 1790). The ratio of the wind torque to the friction torque is kept as high as possible by using very light vanes and eliminating all gearing except for a worm drive, through which the rotation of the blade spindle is transmitted, with a 50–1 reduction to a pointer moving over a dial attached to one side of the casing. The only markings on the dial are four short radial lines at the ends of two mutually perpendicular diameters. The calibration of the instrument is given in terms of the relation between the wind speed and the number of revolutions per second of the pointer over the dial. This instrument gives consistent readings down to about 0·4 kt. when it is kept in good condition.

5.4.3. High-speed air meter

The high-speed air meter (Stores Ref., Met. 1976) is an air meter with only four blades in place of eight, and these blades are very much stronger and heavier (Plate XXVIII). It can be used in wind speeds from about 10 to 100 kt. The dials are usually arranged so that the main pointer rotates once for each 2,000-ft. run of wind. Its method of use and general operation are similar to the normal type.

5.5. PRESSURE-TUBE ANEMOGRAPHS

5.5.1. Direct-reading pressure-tube anemograph Mk II

Description.—The pressure-tube anemograph Mk II (Fig. 70) uses the pressure-tube principle (see p. 196). It consists of three main units :

(i) Head and vane

(ii) Mast or tower carrying the direction-transmitting rod and pressure and suction pipes and supporting the head

(iii) Speed and direction-recording unit—in a few instruments this may be separated into two distinct units or the direction-recording unit may be omitted.

LIST OF PARTS

ITEM No	DESCRIPTION
1	BRACING COLLAR
2	BRACING COLLAR SUPPORT
3	SMALL STEPS
4	MEDIUM STEPS
5	LARGE STEPS
6	PIPE CLIPS
7	SOCKET
8	TOP FITTING
9	REDUCING SOCKET 2½ in. TO 2in
10	REDUCING SOCKET 3in. TO 2½in
11	PIPE 2in GAS
12	PIPE 2½in. GAS
13	PIPE 3in. GAS
14	PIPE PRESSURE AND SUCTION
15	SADDLE PLATE
16	LEGS
17	FEET
18	SPREADER HOOK
19	RAG BOLT
20	STRAINER
21	EARTHING STRIP
22	BRACING WIRES

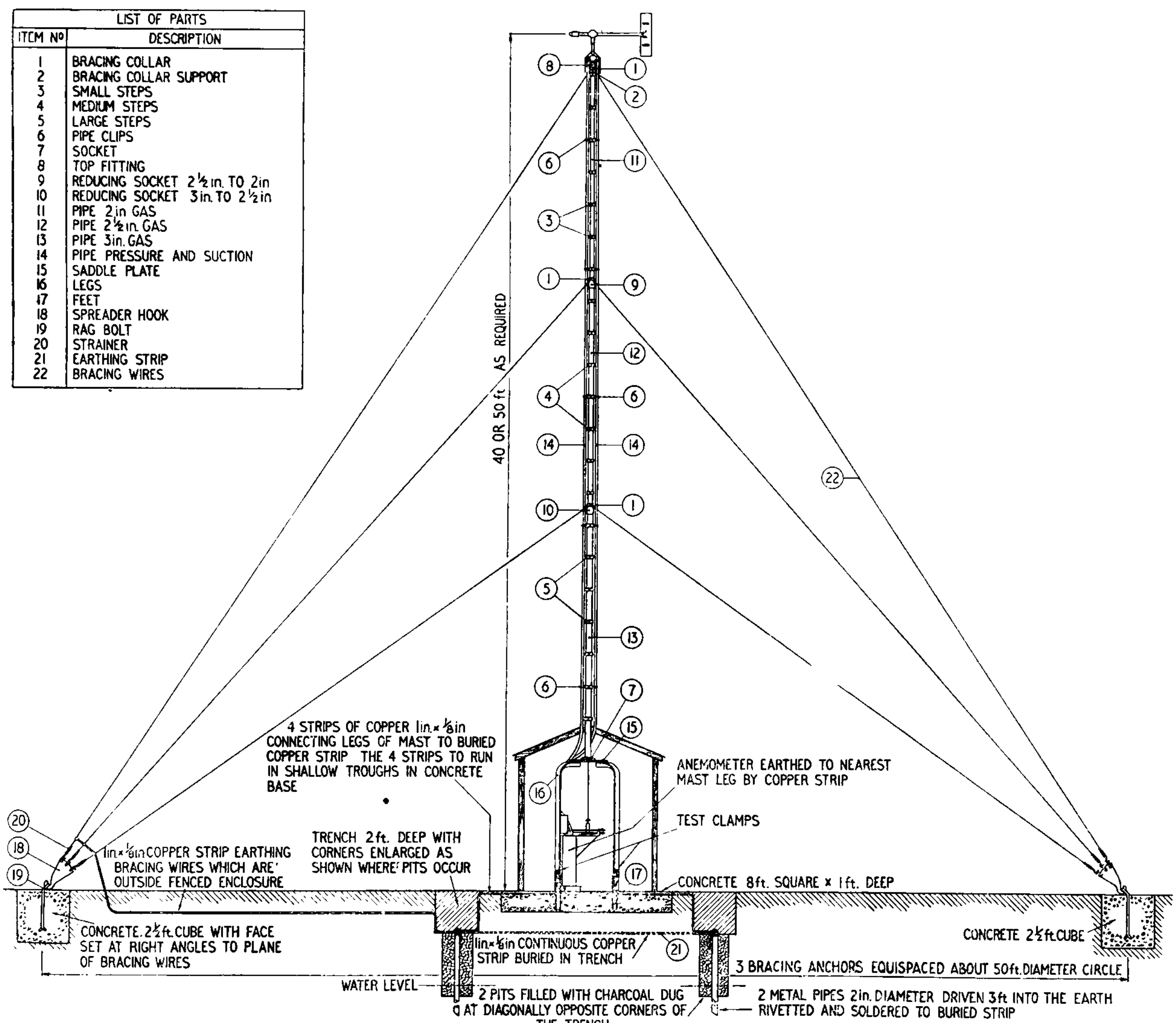


FIG. 70—METEOROLOGICAL OFFICE PRESSURE-TUBE ANEMOGRAPH MK II

The recording unit must normally be vertically below the vane and housed under cover ; a small wooden hut provides adequate shelter when the anemometer cannot be mounted in and above a more permanent building, but there should be provision for heating in winter in order to prevent the water in the tank of the recording unit freezing.

Head and vane.—The construction of the head will be understood from Fig. 71. The horizontal rotating part, with the fin at one end and the pressure inlet at the other, rests on the head proper and its weight is carried by means of a ball race ; the vane thus keeps the horizontal pressure inlet facing directly into wind. The

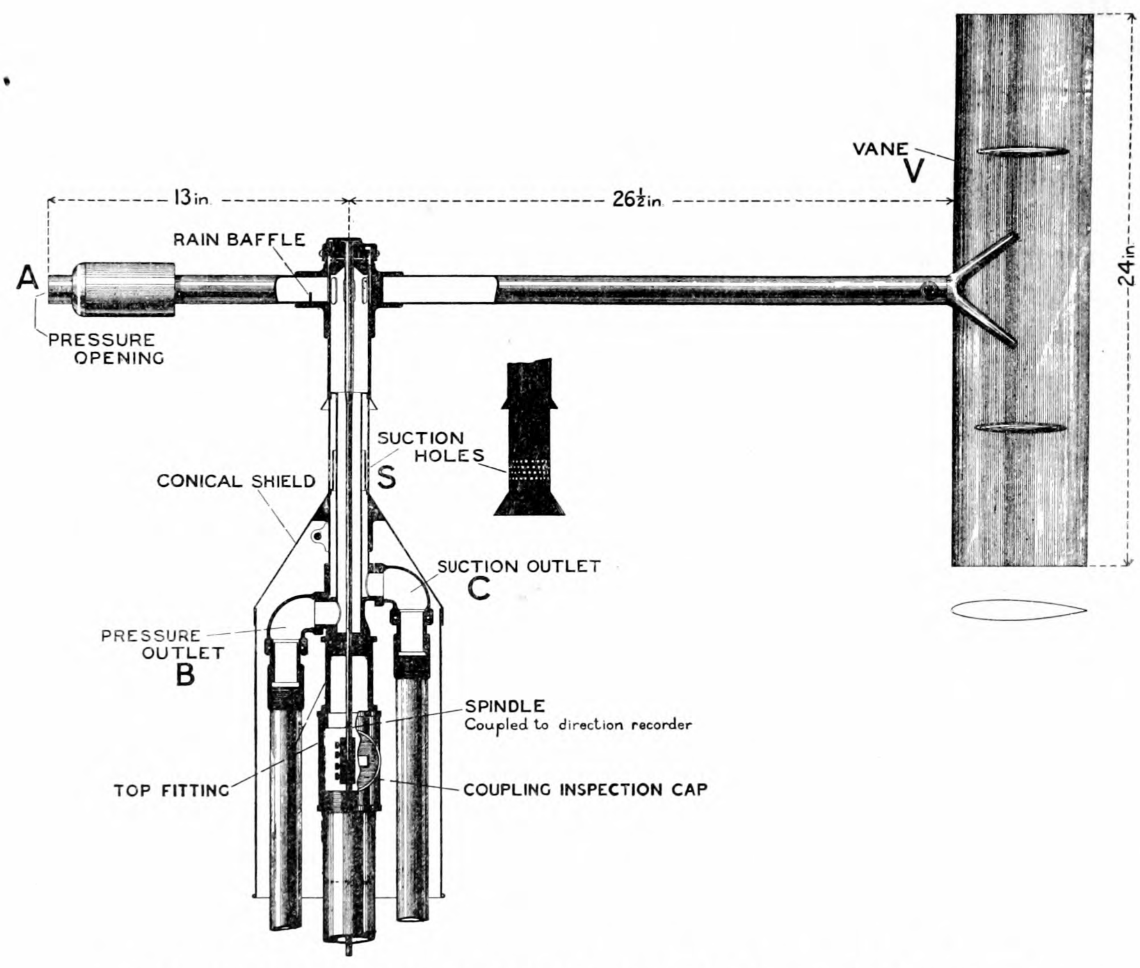


FIG. 71—HEAD OF PRESSURE-TUBE ANEMOGRAPH MK II

" total-head " pressure is transmitted through the central tube to the pressure outlet B, and thus by means of further tubing to the recorder. The central tube is surrounded by an outer tube S in which is drilled a series of suction holes in several staggered rows. The space between the tubes is connected to the suction outlet C and thence to the recorder ; the pressure in this system is below the true static pressure. The pressure and suction outlets are covered, by means of a cylindrical shield with a conical top, to present a symmetrical obstruction to the wind and therefore to eliminate changes of the suction effect with wind direction. The spindle passes down the centre tube from the top of the head unit, through an airtight seal, and is connected to a direction tube which passes down the centre of the supporting mast. The direction tube is then connected to the recorder.

Mast.—The complete anemograph mast*, Fig. 70, comprises :

(i) A set of iron pipes of varying diameters, the mast proper

(ii) The bottom structure which takes the weight of the mast

(iii) Sets of bracing units and stays for supporting the mast

(iv) Hooked collars for attaching the stays to the mast supported by special fittings

(v) Steps for climbing the mast

(vi) 1-in. bore iron, or copper, pressure and suction pipes and direction tubes.

The gas pipes forming the mast proper, when set up, taper towards the head, pipes of three or four diameters connected with reducing sockets being used according to the height of the mast. A flange is screwed to the free end of the pipe of the largest diameter and this is bolted to the saddle plate of the bottom structure. The saddle plate is bolted to four tee posts, each of which has a splicing piece bolted on at the foot. When the structure is set upright the free ends of the splicing pieces are buried in a concrete foundation.

The bracing unit consists of a rag bolt embedded in concrete to which is attached a spreader hook. This hook takes a number of strainers for tightening the galvanized iron wire stays attached to the hooked collars on the mast. The number of sets of bracing units, each of 3 or 4 stays, depends on the height of the mast. For a 40- or 50-ft. mast 3 sets well spaced, equidistantly if possible, are sufficient.

The pressure and suction pipes are attached to certain of the steps by pipe clips and pass from the outlet unions on the head to near the saddle plate. Iron or copper bends are attached at this point to lead the pipes round the saddle plate, and the final connexion to the recorder is made by two short lengths of 1-in. composition tubing.

Speed recorder.—The speed recorder, Fig. 72, is a specially designed float manometer which gives a deflection proportional to changes in $\sqrt{(\Delta p)}$, where Δp is the difference in pressure between the pressure and suction tubes. A bell-shaped float is placed mouth downwards in a cylindrical tank containing distilled water, and the pressure tube is connected to the space inside the float above the water surface by a vertical pipe which passes up the centre of the tank. The suction tube leads to the space outside the float above the water surface. The outer surface of the float at the water level is cylindrical but the inner surface is specially shaped to give the required scale.

Attached to the top of the float is a float rod which passes through an accurately machined collar in the top of the tank. It carries a pen arm and the pen records on a chart on a vertical drum driven by a 24-hr. clock. Attached to the top of the float rod is a small cup containing lead shot ; the zero position of the float can be adjusted by altering the number of lead shot. Stopcocks are provided in both the pressure and suction leads and these enable either side of the float to be put in connexion with the appropriate part of the head of the anemograph or in connexion with the air of the room.

A drainage plug is provided in the pressure tube, to drain off any water which may accumulate either as a result of rain blowing into the opening in the head or as a result of a careless movement of the float by hand causing the water level to rise above the level of the centre pipe. If sufficient water accumulates to block the

* Masts are gradually being replaced by lattice towers.

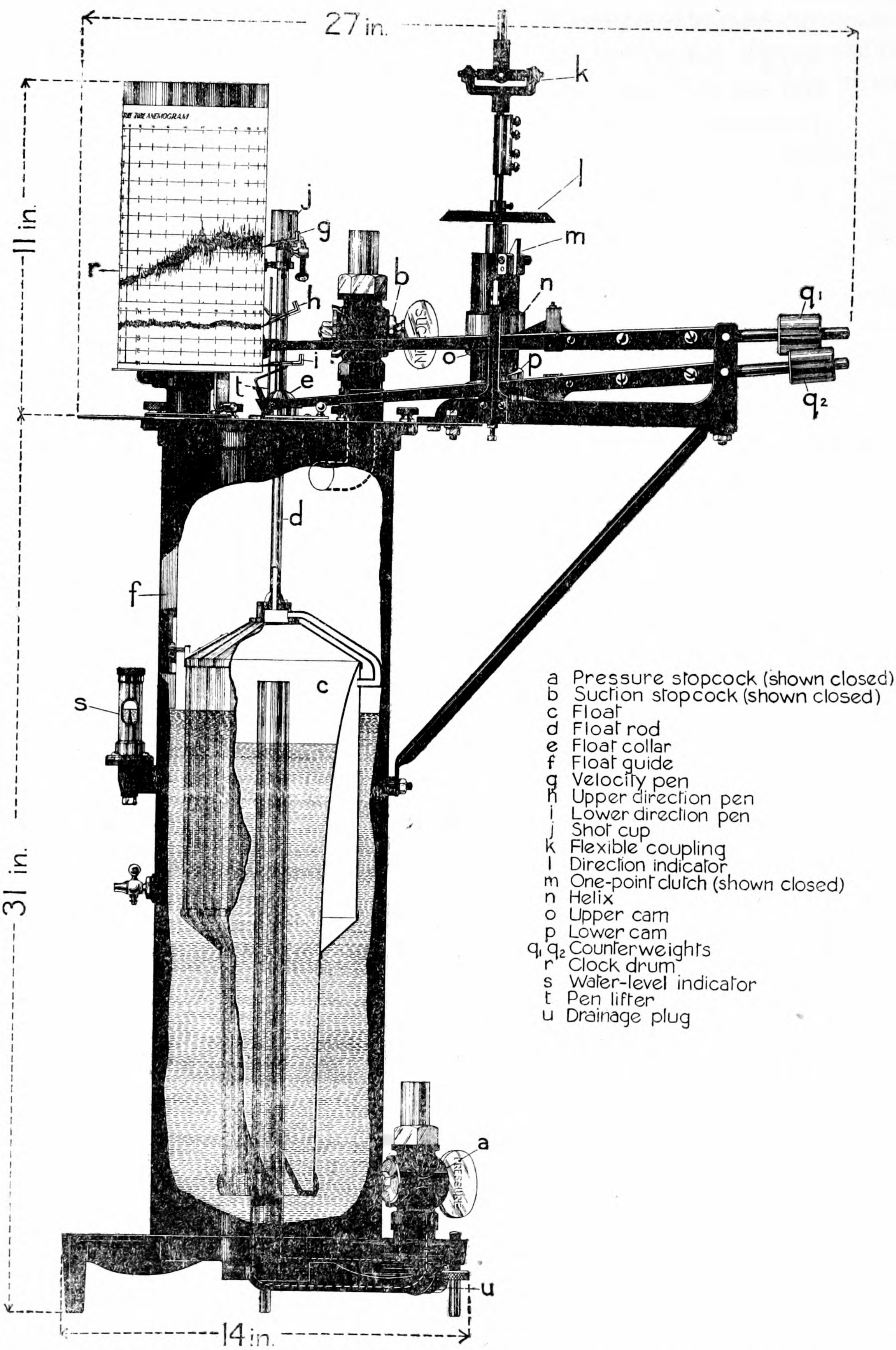


FIG. 72—RECORDING PORTION OF PRESSURE-TUBE ANEMOGRAPH MK II

bottom of the pressure tube completely the records obtained will be in error, because in general the water will act as a form of manometer and the pressure inside the float will not be equal to that in the pressure tube coming from the anemometer head. The gustiness as shown on the record will also be less than the true wind variations. The drainage plug should therefore be opened regularly especially after rain or any adjustment of the recording mechanism.

The float is prevented from rotating about its axis by means of a roller which rests in a vertical guide on the side of the tank. The water level, inside the tank but outside the float, is indicated by a simple gauge fixed to the outside of the tank. If it is not practicable to keep the water from freezing in winter a mixture of alcohol and glycerine of unit density may be used.

Direction recorder.—The direction record is made on the same chart as the speed record (Fig. 72). The chart ruling consists of a simple vertical scale in degrees from north through west, south and east to north. Two pens are used, and at any one time one of the pens rests on the top or the bottom north lines. If the wind direction, as shown by the acting pen, reaches the north line on which the other pen is resting, the acting pen immediately returns to the other north line, and further variations in the wind direction are shown by either pen according to whether the wind veers (in which case the lower pen becomes the acting pen) or backs (in which case the upper pen comes into operation).

This is achieved by connecting the direction tube to a vertical cylinder on which is cut a double helix. The upper pen arm is so balanced with counterweights that the upper pen always tends to rise, while the lower pen arm is balanced so that the pen tends to fall. The motions of both pen arms are controlled by cams which fit into the helix. If the wind oscillates about north the record will be obtained at the bottom and the top of the scale. A circular scale is fixed about the direction tube to provide an extra indication of the wind direction. The connexion between the direction tubing from the vane and the recording unit is made through a flexible coupling to take up any slight irregularities in the motion and to prevent excessive friction due to strain.

A typical record from this instrument is shown in Plate XXIX.

Clock and drum.—The drum is 127 mm. in diameter and the time scale on the chart is 15 mm./hr. ; the height of the drum is 219 mm. The general construction of the pressure-tube anemograph clock Mk IIIA is shown in Plate II facing p. 9. It is wound by moving the handle at its base to and fro. It also differs from the standard type of clock in its method of mounting and in the fact that its height above the plate on which it is mounted can be altered.

Theory of the instrument.—The difference in pressure, Δp, produced by the head of a pressure-tube anemometer for a wind speed v in air of density ρ is given by

$$\Delta p = \tfrac{1}{2}K\rho v^2,$$

where K is a constant factor determined by the design and dimensions of the head. Wind-tunnel calibrations of the Meteorological Office design of head show that $K = 1\cdot49$, and in air of standard density, $1\cdot226$ gm./m.^{3}, the following numerical relationships therefore apply

$\Delta p = 0\cdot00103v^2$ for Δp in inches of water and v in knots ......(61)

$\Delta p = 0\cdot0261v^2$ for Δp in millimetres of water and v in knots ......(62)

$\Delta p = 0\cdot093v^2$ for Δp in millimetres of water and v in metres per second ..(63)

The design of the float manometer to convert pressure readings into a linear scale of wind speed is based on the following considerations.

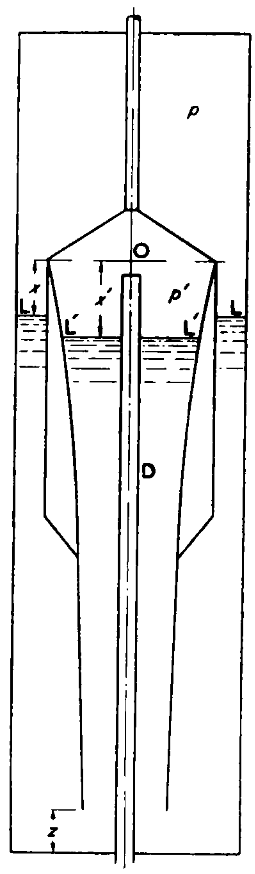


FIG. 73—DIAGRAM ILLUSTRATING THEORY OF FLOAT MANOMETER

Consider a point o in a plane fixed to the float (Fig. 73) and at the level of the water surface when no pressure difference exists between the outside and the inside. At any other time LL is the water level outside the float and L′L′ the water level inside the float. Let

z = height of the float above its zero position

x = depth of LL below o

x' = depth of L′L′ below o

p = pressure outside float

p' = pressure inside float

ρ' = density of the water

g = value of gravity

A = area of outer (cylindrical) cross-section of float

B = area of outer cross-section of the tube D up the centre of the float

C = area of cross-section of the container

Y = area of cross-section of the inside of the float at the level L′L′

W = weight of the float

w = weight of water inside the float.

The difference between the pressure inside and outside the float is measured by the difference in water level so that

$$p' - p = g\rho' (x' - x) . \qquad \ldots\ldots(64)$$

The downward forces on the float system are

$$W + w + pA + p' (Y - B) + p' (A' - Y) \qquad \ldots\ldots(65)$$

and the upward forces

$$p'A' + p\int dS + g\rho'\int (h - x)\, dS , \qquad \ldots\ldots(66)$$

where dS is the horizontal projection of any element of area extending round the outside of the float at a depth h below o, and A' is the cross-section area of the horizontal projection of the inside of the float (A' is practically equal to A).

Since $\int dS = A - B$, expression (66) may be written

$$p'A' + p (A - B) + g\rho' (h_m - x) (A - B) ,$$

where h_m is a mean depth.

In equilibrium the upward and downward forces are equal so

$$W + w = B (p' - p) + g\rho' (A - B) (h_m - x).$$

Making use of equation (64) this becomes

$$W + w = g\rho' B (x' - x) + g\rho' (A - B) (h_m - x)$$

$$= g\rho' A (h_m - x) - g\rho' B (h_m - x') . \qquad \ldots\ldots(67)$$

If now δx, $\delta x'$ and δw are the changes in x, x' and w when the float moves slightly, then from equation (67)

$$\delta w = - g\rho' A\delta x + g\rho' B\delta x' ,$$

also $\delta w = - g\rho'\delta x' (Y - B).$

Therefore $Y\delta x' = A\delta x. \qquad \ldots\ldots(68)$

As also the total amount of water in the instrument is constant

$$(Y - B)\, \delta x' = (C - B)\, \delta z - (C - A)\, \delta x. \qquad \ldots\ldots(69)$$

Since the scale of the instrument has to be linear in wind speed, i.e. z has to be proportional to $\sqrt{(p' - p)}$, then

$$x' - x = qz^2, \qquad \ldots\ldots(70)$$

where q is a constant. Therefore from equations (68) and (69)

$$(C - B)\, \delta z = C\delta x - B\delta x', \qquad \ldots\ldots(71)$$

and since $x - x' = 0$ when $z = 0$ then

$$(C - B)z = Cx - Bx'. \qquad \ldots\ldots(72)$$

Differentiating equation (70)

$$\delta x' - \delta x = 2qz\delta z \qquad \ldots\ldots(73)$$

and again from equations (68) and (69) eliminating δx

$$\delta z = \frac{CY - AB}{A(C - B)}\,\delta x', \qquad \text{......(74)}$$

and from equations (71) and (73)

$$\delta z = \frac{(C - B)}{C - B + 2Cqz}\,\delta x'. \qquad \text{......(75)}$$

Eliminating x from equations (70) and (72)

$$x' = z + \frac{Cqz^2}{C - B},$$

which may be written

$$1 + \frac{4q\,Cx'}{C - B} = \left(1 + \frac{2Cqz}{C - B}\right)^2. \qquad \text{......(76)}$$

Finally from equations (75) and (74) an expression can be obtained for z, and on substituting this in equation (76)

$$1 + \frac{4q\,Cx'}{(C - B)} = \frac{A^2(C - B)^2}{(CY - AB)^2}. \qquad \text{......(77)}$$

This equation gives the cross-section of the float as a function of the distance x' from the level o. If B were negligibly small this would reduce to

$$1 + 4qx' = \frac{A^2}{Y^2}. \qquad \text{......(78)}$$

The outside water level falls by only 0·3 cm. for a wind of 90 kt. in the standard instrument. This can be neglected, and for practical purposes it may be assumed that the level of the outside water is constant. If B were zero it would be absolutely constant.

For a standard float the values of the constants are as follows :

A = 184·85 cm.^{2} (outer diameter of the float 15·34 cm.)

B = 5·07 cm.^{2} (outer diameter of the inner pipe 2·54 cm.)

C = 324·29 cm.^{2} (inner diameter of tank 20·32 cm.)

q = 0·0800 (i.e. a scale value on the chart of 6 in. per 100 m.p.h. or 6·9 in. per 100 kt.).

This exposition of the theory underlying the construction of the float is based on that given by E. Gold[46].

Installation.—*Erection of the mast and hut.*—The erection of the mast, the building of any necessary hut for housing the recorder and the installation of lightning protection are normally arranged as Works Services at Meteorological Office stations. An outline of the work necessary is given here. Full drawings can be obtained if necessary from the General Instruments Branch of the Meteorological Office.

The following parts comprise the complete instrument :—

	Stores Ref.
Head, Mk II	Met. 24
Vane, Mk II	Met. 25
Shield, conical	Met. 485
Speed recorder, Mk II	Met. 26
Clock, Mk IIIA	Met. 519
Direction recorder	Met. 486
Direction tubing and fittings, including phosphor-bronze coupling rod ..	Met. 14
Flexible coupling	Met. 490
Box of accessories	Met. 5
Instructions	...
Complete mast, 40 or 50 ft.	Met. 15 or 15A
Pressure and suction piping consisting of 10-ft. lengths of 1-in. steel gas pipe with screwed sockets, one to each length	Met. 2392
15-ft. of 1-in. bore compo piping	...
2 unions, for connecting compo piping to pressure and suction piping ..	...
Top fitting to mast, for connecting head to mast with inspection plate giving access to top direction coupling sleeve	Met. 2831

The box of accessories should contain the following :—

Speed pen arm and holder*
Direction upper and lower pen arms and holders*
Box spanner
Shot tweezers
2 glass tubes for inking pens
Bottle of lubricating oil
Tin of petroleum jelly
2 tins of lead shot
Tin of spare pens and angle ink reservoirs
2 coupling sleeves for use above and below the flexible coupling
Set of taper pins for joining up direction tubing
Shot cup and guide collar for float rod
Bottle of ink
Pen lifter

The following work should be carried out (at Meteorological Office stations by Works Service) :

(i) Lay a concrete slab 8 ft. square by 12 in. thick, leaving grouting pockets for the tee-post feet (splicing pieces). Bolt the feet to the posts and the posts to the saddle, level up for correct setting with a spirit level on the saddle, and cement grout the feet in position.

(ii) Place the hooked collars and their supporting collars in position on the several lengths of tube, and then assemble and unite the various sections of the mast while it is on the ground and screw on the flange.

(iii) Clamp the supporting collars in position and rest the hooked collars on them. Attach to the hooks lengths of guy wires sufficient to reach the rag bolts, and then clamp the steps to the mast at equal intervals (about $1\frac{1}{2}$ ft.) throughout the length of the mast. Those steps which have pipe clips attached should be spaced as shown in the drawing (Fig. 70). The hooked and supporting collars are to be positioned as shown in the drawing. A space (about 2 ft.) should be left at the top of the mast so that the guy wires will not foul the shield of the head.

(iv) All screw joints should be treated with tallow or with graphite jointing compound before assembly to prevent rust.

(v) If the length of 2-in. pipe which forms the top section of the mast is fitted with a 2–$1\frac{1}{4}$-in. reducing socket and a short length of $1\frac{1}{4}$-in. pipe, remove

* These parts are sometimes sent out taped to the direction recorder.

these. Screw to the top of the 2-in. pipe the special gun-metal " top fitting ", and then screw the lower end of the head, which carries a $1\frac{1}{4}$-in. pipe thread, to the upper socket of the top fitting. The ball race should be temporarily covered until the mast has been erected and the vane put in position.

(vi) Screw the 1-in. pressure and suction pipes to their respective sides of the head, and lead them, screwing together the various sections, down the outside of the mast to within a short distance of the saddle plate. Petroleum jelly should be used for all brass and gun-metal unions to prevent leakage. The pipes are secured to the mast at intervals by the pipe clips which are fitted to some of the steps. At the lower ends of the pipes mark clearly which is pressure and which suction.

(vii) Stiffen the mast by lashing timber to it at the reducing sockets and then hoist it with a tackle. This will minimize the risk of fracture at the screwed joints. Let the mast down on to the saddle plate and bolt the flange to it.

(viii) Connect the guy wires to the strainers attached to the hooked foundation bolts which should be already embedded in concrete and spaced to the best advantage. Adjust the tension of the guy wires until the mast is upright and secure.

(ix) Earth the mast and, if necessary, the guy wires, as set out in the next section.

(x) The whole mast, when erected, should be given two coats of good weathering paint, preferably red oxide. This work is normally done by the contractor after the whole anemometer has been erected. The head and vane are not to be painted.

(xi) When the mast has been mounted and the correct position for the anemometer tank unit decided upon, a stand for the tank unit should be made on the concrete below the mast. The tank unit has three legs equally spaced on a circle $15\frac{3}{16}$-in. diameter, and the stand should take the form of three concrete blocks, one for each leg, raising the legs about 12 in. above floor level and leaving a space between the legs and under the tank where a small heater may be placed.

Protection from lightning when the anemograph is installed in a separate hut.—The mast and anemograph recording unit require protection against damage by lightning. An earth termination of not more than 10 ohms resistance is to be installed in accordance with the British Standard Code of Practice[47]*. The following items are to be connected to the earth termination by means of a 1-in. $\times$ $\frac{1}{8}$-in. copper strip which is to be kept as short as possible :

Each leg of the anemometer mast

The anemograph recording unit

Any guy rope which is in such a position that people frequently pass or stand by it.

Installation of instrument after the erection of the mast and hut.—After the erection of the mast an instrument mechanic (sent by the Instrument Provisioning Branch

* Details are shown in the Director-General of Works drawing M & E 2056/48.

at Meteorological Office stations) should complete the installation. The mechanic or fitter should include the following items in his kit :—

Blow lamp, flux and solder
Hacksaw frame and blades
Hand drill, No. 39 twist drill, taper breach or reamer
Large adjustable spanner, thin enough to use on the hexagons below the taps on the tank
Spirit level on flat base
Ball of stout string.

The following procedure should be used to set up the instrument :

(i) Unpack tank, withdraw float, carefully clean out tank and place on its stand. Connect suitable lengths of 1-in. compo pipe to the unions at the lower end of the mast pressure and suction pipes and connect the other ends to the correct unions on the tank.

The recorder is sometimes set up with its feet standing on a box. The latter is usually filled with concrete, but unless it is firmly fixed to the floor of the hut it is liable to be displaced if accidentally kicked and the orientation thereby altered. Wherever possible, the box should be screwed to the floor, but if this cannot be done strips of wood should be screwed to the floor against the sides of the box so that it cannot be shifted. If the feet of the anemometer rest directly upon the floor it is also liable to be shifted accidentally. If the feet are not otherwise fixed in position, cups are provided for them, the cups being screwed to the floor of the hut.

(ii) Adjust levelling screws until the top ring of the tank is level.

(iii) Temporarily put on the tank cover plate and screw on the direction recorder and its support stay, inserting the flexible coupling in the socket above the helix. Pass up the mast successive lengths of direction tube pinned together in turn. Each 5-ft. length of tube has one end reduced by swaging to fit inside the unswaged end of the next length, the swaged end being towards the top of the mast. The top length carries a short brass coupling spigot (A, Plate XXX) which is fastened to the vane spindle by the sleeve B. Each section of the tube is fastened to the next by a taper pin. When the tubing is felt to have reached the top of the mast (probably after 7 lengths have been fastened together), an assistant should climb the mast, unscrew the pressure and suction pipes from the head, unscrew the side inspection plate of the top fitting, and connect the spigot A to the vane spindle by means of the coupling sleeve B, to which access is obtained through the inspection hole of the top fitting. The lowest length of steel tube (D, Plate XXX) should project from the lower end of the mast. Insert into it temporarily the $\frac{1}{4}$-in. phosphor-bronze coupling rod C and note the correct length for it to project into the coupling sleeve above the flexible coupling to half the length of the sleeve. Withdraw the coupling rod and cut it off to this length, and fasten it securely to the lowest length of direction tube. Remove the direction recorder from the tank and take off the top again. Carry the conical shield and rotating portion of the vane up the mast and set in position. Be sure that this sits firmly on the two steel pins projecting above the ball race, which should be lubricated with petroleum jelly or anti-freezing grease before the vane is mounted on it.

(iv) Thoroughly clean the float and place it inside the tank, letting it down carefully and vertically over the central copper tube. Fill the tank with distilled water, avoiding splashing as much as possible, until the water level is correct by the point in the level gauge tube. The float must be kept on the bottom of the tank while the water level is adjusted. Put on the cover without damaging the paper washer and screw it down. Take care that the float roller engages with its guide thus preventing the float from rotating.

(v) Screw the direction recorder to the tank and screw on its supporting stay. Slide the upper coupling sleeve on to the lower end of the connecting rod (C, Plate XXX). Line the direction disc spindle up with the connecting rod and slide the coupling sleeve down on to the upper spigot of the flexible coupling, leaving the set screws loose for the final adjustment.

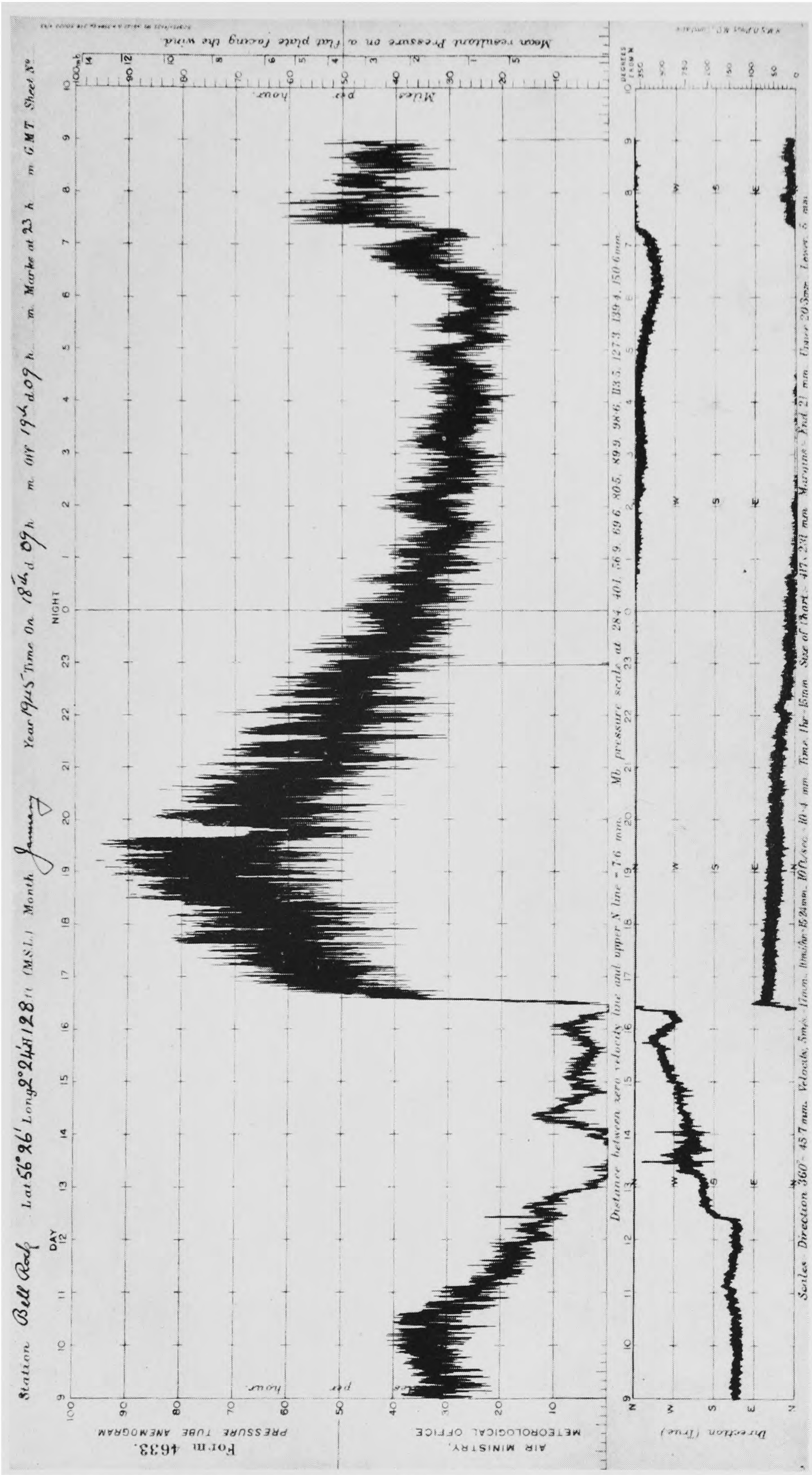
(vi) If necessary re-level the tank.

(vii) Put on the clock bracket, clock, drum and pen lifter, insert pens in their holders and pen holders in their sockets.

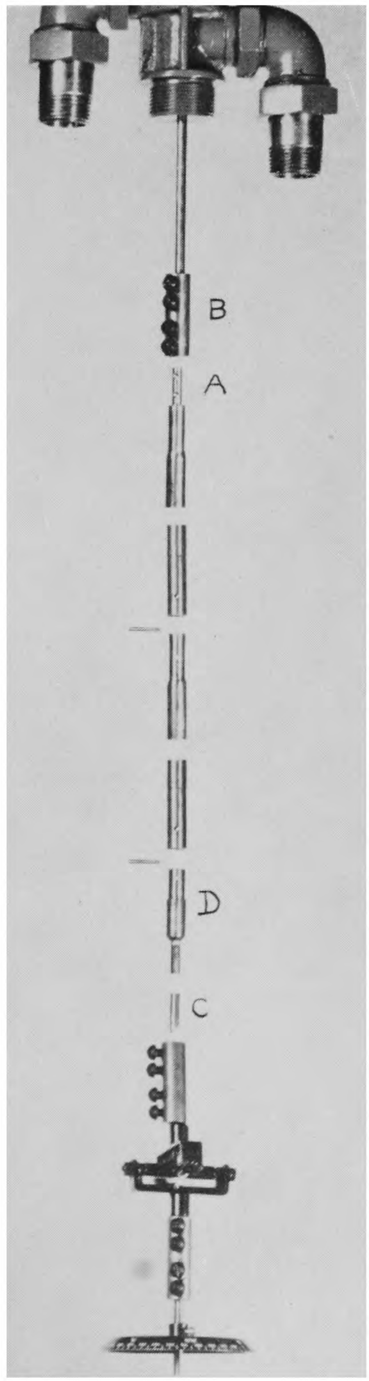
(viii) Place the shot cup temporarily on the top of the float rod, and again adjust the levelling screws until the float rod is exactly central in the hole with the float off the bottom of the tank. Remove the shot cup and put on the central guide collar ; then replace the shot cup and put the pen holder in its socket. Add shot to the cup until the float after being raised $\frac{1}{2}$ in. will just, and only just, sink to the bottom on being tapped gently. The setting line on the float rod should then be level with the top of the collar.

(ix) Check the adjustment of the direction recorder before orientation of the vane. Note the positions of the pens relative to the north lines of the chart when the pens are placed with the upper unit in its top position and the lower in its bottom position. Adjust the clock-drum height so that as little pen-height adjustment as possible is required. When both pens are on their respective north lines the direction-indicating disc should read N at the fiducial pointer.

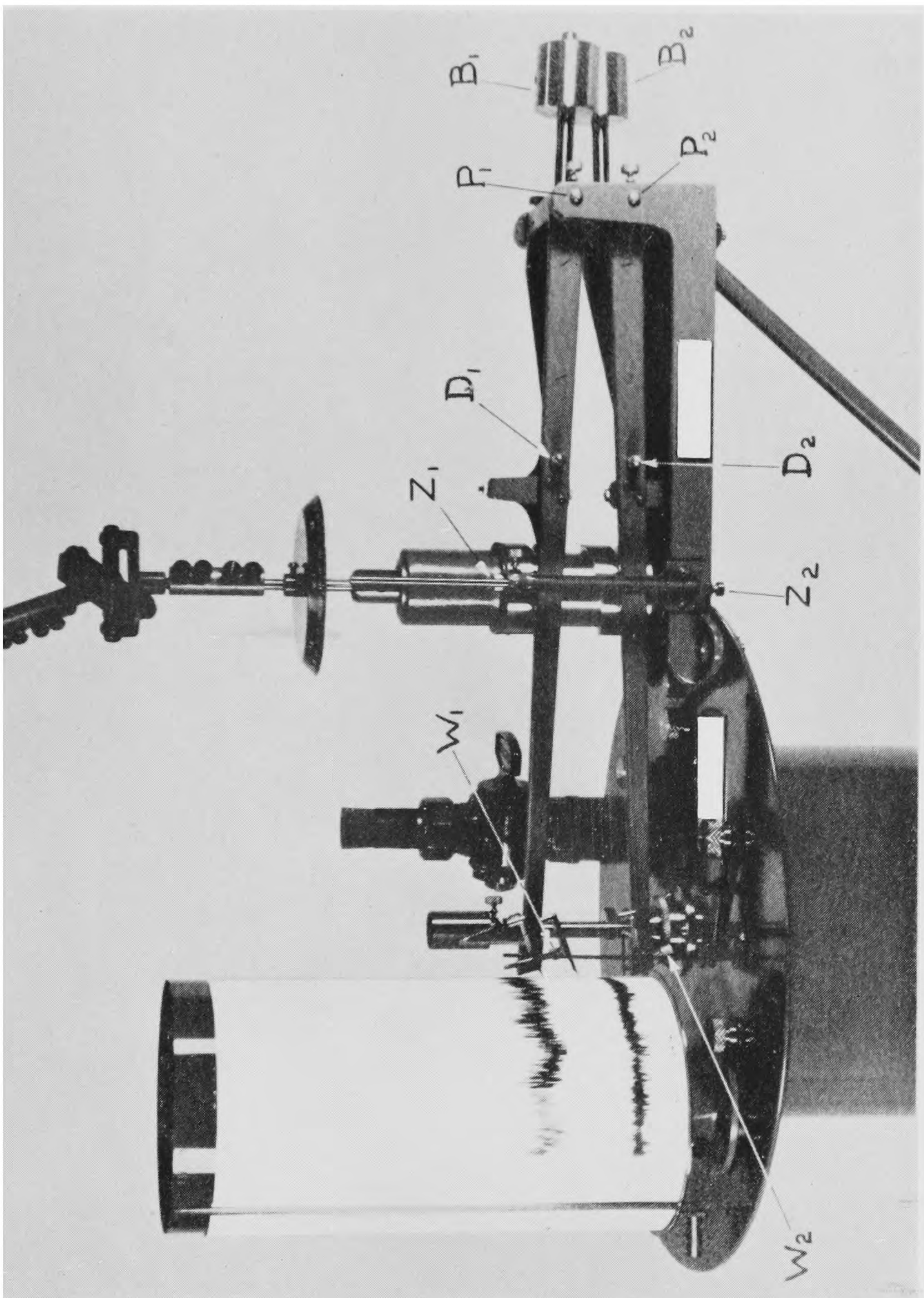
(x) The functioning of the direction recorder should be as follows : the upper pen arm should rise to its stop and coincide with the upper north line at the moment when the lower cam clicks into engagement with the lower helix. Similarly the lower pen arm should fall to its stop and coincide with the lower north line at the moment that the upper cam clicks into engagement with the upper helix. Whenever this has occurred each pen will be on its respective datum line and the slightest turning of the helix should result in one, and one only, of the pens moving, according to the direction of rotation. If neither pen moves, one or both of the zero stops Z_1 and Z_2 (Plate XXXI) must be released. If both pens move, one or both of the stops must be screwed up. This may result in the pens leaving their datum lines, in which case they must be reset by means of the milled pen wire screws W_1 and W_2. These are made free in their sockets by releasing the cheese-head screws at the rear of the pen levers and must be made tight again after adjustment. The two pens should incline slightly downwards to the chart and should be vertically below the speed pen, which can be adjusted by the screws on the shot cup. If the two direction pens are not marking in the same vertical line one or both may be adjusted sideways by releasing the screws which hold the pivot bearings P_1, P_2 and by adjusting these. The screws should be made tight again. As the distance from the pen point to its grip sleeve is important when subsequently fitting new pens, the position of the pen in the sleeve should be such that ink may be applied with the glass filler tube without touching the sleeve. The steel cams should rest upon the helices with about 4 mm. of radial contact. If they rest too deeply they will foul the core of the helices ; if not deep enough there will be excessive wear on the cams. The cams are adjusted by the screws D_1 and D_2. They must be free in their pivots but without shake, so



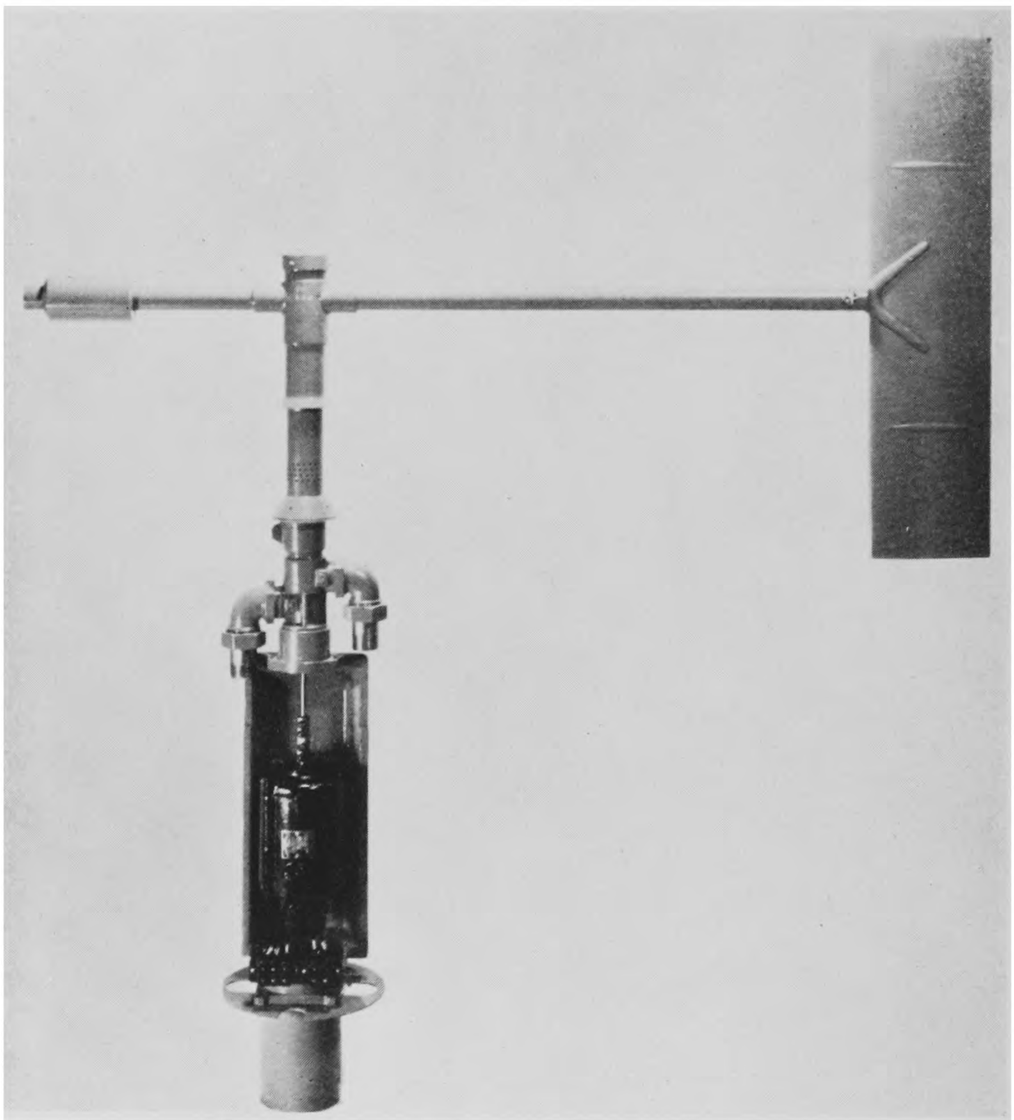
TYPICAL RECORD FROM PRESSURE-TUBE ANEMOGRAPH MK II



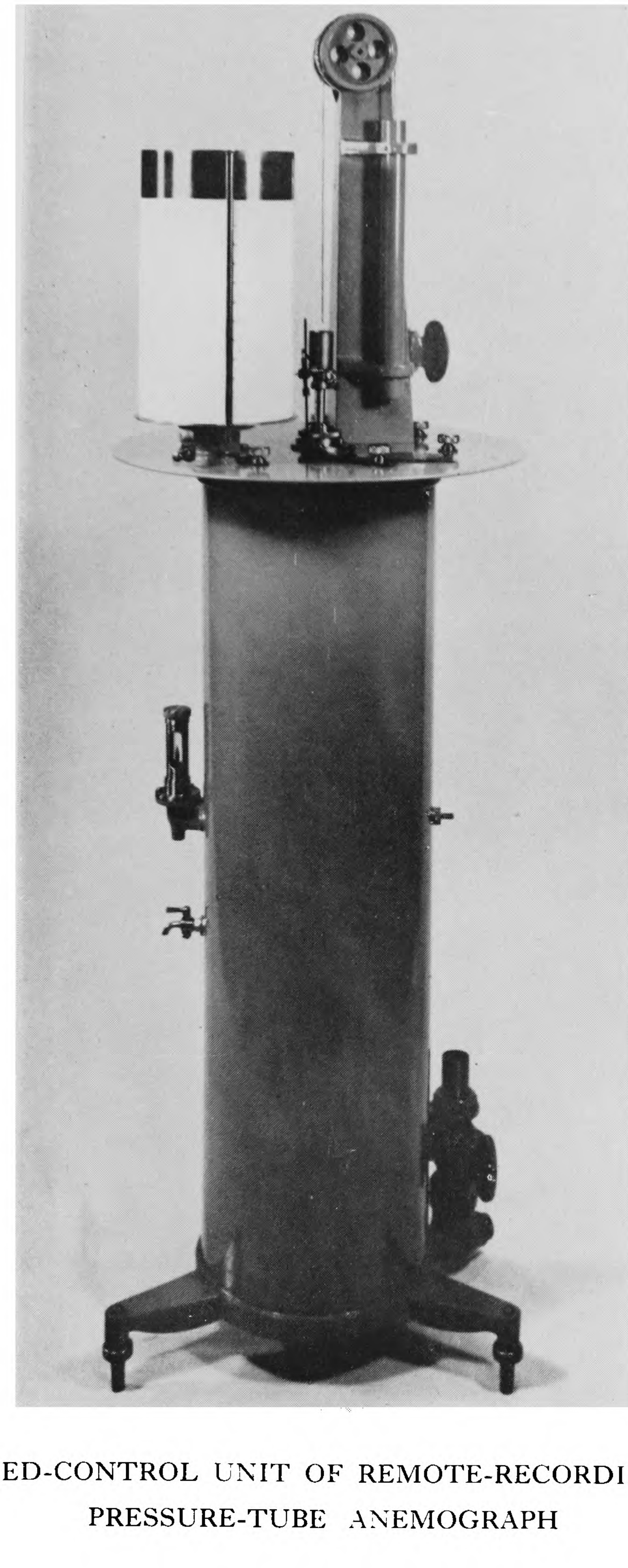
DIRECTION ROD OF PRESSURE-TUBE ANEMOGRAPH MK II



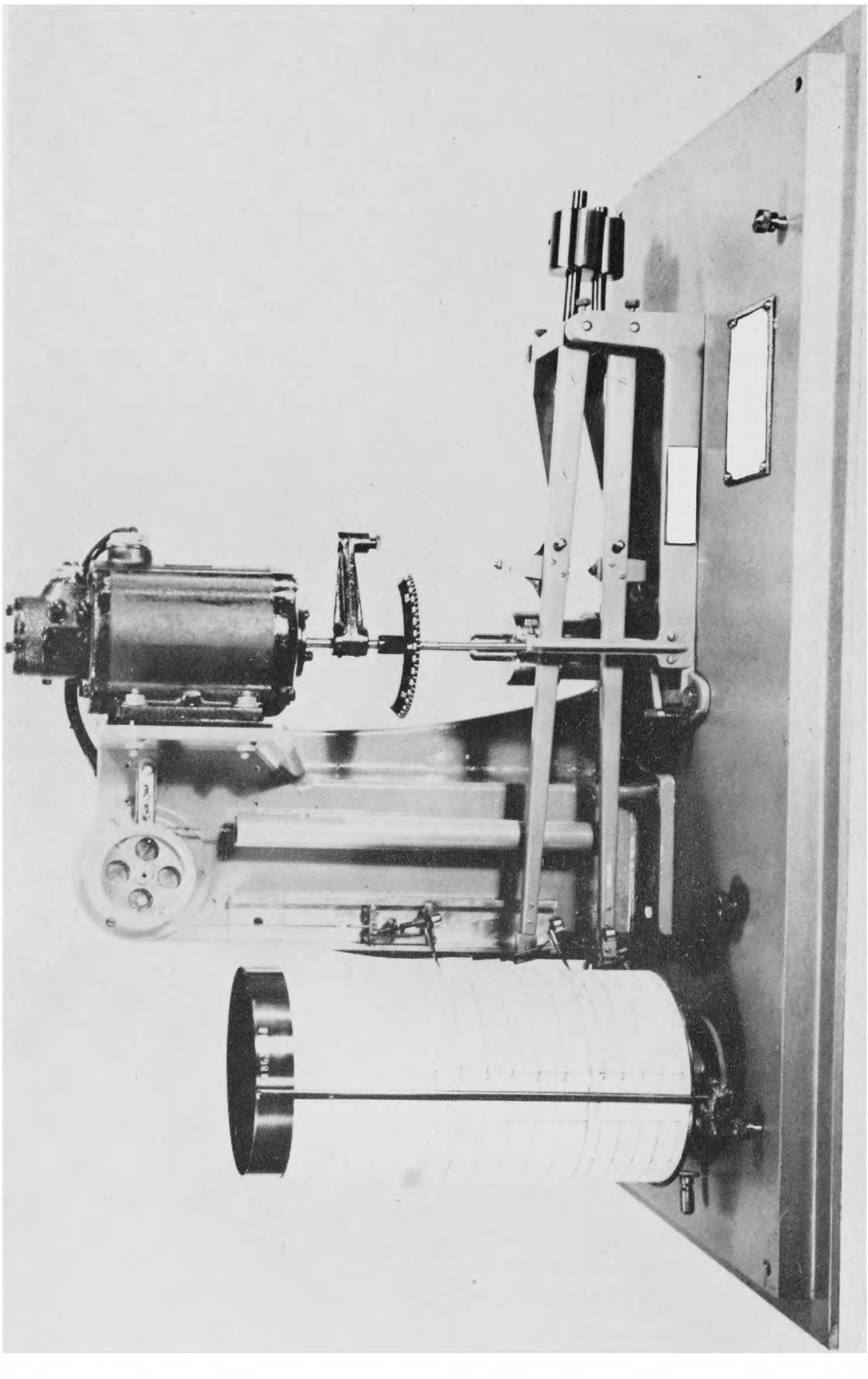
CLOSE-UP OF DIRECTION RECORDER OF PRESSURE-TUBE ANEMOGRAPH MK II



HEAD OF REMOTE-RECORDING PRESSURE-TUBE ANEMOGRAPH



SPEED-CONTROL UNIT OF REMOTE-RECORDING
PRESSURE-TUBE ANEMOGRAPH



RECORDING UNIT OF REMOTE-RECORDING PRESSURE-TUBE ANEMOGRAPH that the light springs will keep them in engagement at the right period of rotation of the helices. The pivot screws are provided with lock nuts to obtain this condition. The pen levers are fitted with balance weights held by set screws B_1, B_2. These should be adjusted so that when the pens are in position the upper and lower pen arms rise and fall respectively without shock to their respective zero stops. If the free vertical movement of the levers is sluggish and not just positive, the cams may become jammed against the ends of the helices when wind directions are oscillating rapidly through north, thus placing a tremendous strain on all grub-screw connexions.

(xi) Orientation of the vane is best done on a calm day. Climb the mast and hang a stout double string over the tail tube of the vane, long enough to reach to the ground with about 15 yd. over. Get an assistant to hold the vane in a desired direction by means of this string. He should also take a bearing of this direction with a prismatic compass or else line up the vane on a distant object whose bearing is known. Loosen the set screws of the coupling sleeve above the flexible coupling, and with the vane thus held the helix should be turned until the direction disc shows the required direction at the fiduciary pointer and one of the pens is at the correct direction on the chart, then tighten the set screws of the coupling sleeve. Detach the string by letting go one end and pulling on the other. If a theodolite is available, the orientation can be done more accurately. One man observes the vane through a theodolite set up three or four hundreds yards from the vane at a point whose bearing is accurately known. A second man climbs the mast and moves the vane until the theodolite observer sees that the vane is pointing directly at the theodolite ; the man up the mast is directed by pre-arranged signals in which direction to move the vane. While it is held correctly pointed, a third man at the instrument sets the helix till the correct direction is indicated, and clamps the direction rod. It is sometimes convenient to disconnect the direction rod from the direction recorder without disturbing the setting. This can be done by unscrewing one pair of steel pivot pins from one of the cross arms of the flexible couplings. Before doing so, one end of the cross arm concerned and the other part of the flexible coupling adjacent to this end should be suitably marked, so that on reassembly an error of 180° cannot be made.

(xii) Ink the pens and the instrument should begin to read correctly.

(xiii) When the instrument has been set up and is running, it should be tested for leaks.

Method of testing for leaks.—The pressure and suction openings in the head should be closed by the methods indicated below and the pipes tested for leaks in the following manner :—With the pressure opening in the head closed both taps of the recorder should be opened to the room and the float raised to 60 or 70 kt. on the chart. (When doing this, great care must be exercised not to raise the float too quickly and draw water over the top of the pressure inlet pipe. The drain plug should be removed after the test is complete and any water drained out, the plug being subsequently screwed firmly home again.) The pressure tap should then be turned to establish communication with the head, the float lowered gently on to the cushion of air in such a way as to avoid violent oscillations and the time of fall from 40 to 10 kt. on the chart noted, the suction tap meanwhile remaining open to the room. The process should then be repeated with the suction holes in the head closed. The float should be raised with both taps open to the room and subsequently allowed to fall with the suction tap turned to establish communication with the head. The time of fall from 40 to 10 kt. on the chart should again be noted, the pressure tap in this case remaining open to the room throughout.

For blocking the pressure and suction openings in the head the following will be required :

(i) rubber bung with diameter tapering from $1\frac{3}{16}$ in. to $1\frac{1}{16}$ in.

(ii) strip of rubber measuring $1\frac{1}{2}$ in. wide by $2\frac{1}{2}$ ft. long cut from a bicycle inner tube—an old tube will serve so long as there are no patches on the strip cut from it.

It will be necessary for some one to climb the mast to place the rubber bung in the pressure opening and to wrap the strip of rubber tightly round the cylindrical part of the head, like a bandage, to cover the suction holes. The " bandage " should be commenced above the holes, clear of the top row, and then continued gradually downwards, the strip of rubber being wrapped tightly over itself until the last turn comes well below the last row of holes and close against the conical shield. It can be held in position by the hand while the test is being made on the recorder below.

Some leakage is unavoidable both on the pressure and suction sides, on the pressure side along the sleeve where the vane fits over the fixed part of the head and on the suction side round the pen rod.

If when the above tests have been carried out the time of fall is found to be less than 50 sec. in either case action is necessary to reduce the leak.

First repeat the tests on the recorder alone with the pressure and suction pipes disconnected and the outlets to the taps blocked by the palm of the hand or otherwise. This will determine whether the leak is in the pipe or in the recorder. If in the pipe, test the unions carefully and examine the compo pipe for damage. If in the recorder, look to the taps and drain plug at the bottom of the pressure pipe and the joint between the top plate and the body of the recorder. The leak round the pen rod would not alone suffice to bring the time of fall below 50 sec. unless the rod were abnormally loose in the collar.

Assembly of direction recorder.—The direction recorder is sent out already assembled, but if it is received damaged it may require reassembling after straightening out damaged parts. The following procedure should then be adopted.

(i) Fix the helices pillar to the top plate with the bolts or screws provided. After lightly smearing the helices thrust race with petroleum jelly place it on top of the pillar between the two washers provided. Lower the helices unit over the pillar and apply a little thin oil to the hole near the top of the unit.

(ii) Examine the direction levers—they may have become bent in transit. Straighten them carefully if necessary. Top and bottom levers may be distinguished by the manner in which their cams engage in the helices. Fix the levers in their bearings on the bracket. The bearings should be adjusted so that the levers are in vertical alignment when viewed from above and so that depth of engagement of the cams in the helices is the same in each case. Lateral play at the bearings should be a minimum consistent with free movement of the levers. Movement of the cams in and out can be made easy or stiff by loosening or tightening the cam pivot screws. The depth of engagement of a cam is adjusted by means of the set screw making contact with the end of the plate carrying the cam. This screw is to be found projecting from the pen arm about the mid position. If the depth is too great the movement of the helix will be stopped at certain points ; if it is not sufficient the cam will not engage in the helix and there will be loss of record. The depth of cam engagement can best be tested after a preliminary setting of the direction-lever balance weights—the word preliminary is used here because the settings will need to be altered slightly when the pen wires and pens are fitted. Apply a little oil to each lever bearing.

(iii) Fix and adjust the balance weight of the top lever, so that when rotating the helix in a counter-clockwise direction (viewed from above) and the cam clears the helix at the end of its downward motion, the free upward movement of the lever is just positive but not such that it " bounces " heavily against its stop. Bouncing will cause ink splashing and may cause the pens to jump in their sockets when operating. Proceed in a similar manner with the bottom lever by rotating the helices unit in a clockwise direction, and check that its fall from its highest point is just positive and not heavy.

(iv) Adjust the depth of engagement of cams such that when the helices unit is rotated fully in either direction there is no perceptible " drag " or " catch ", particularly at those points where the cams slide out of engagement with their helices. It is best to start with the cams engaged to such a depth that there is a perceptible drag or tendency to stick at certain points and then to free the cams until perfectly smooth working is secured. This ensures that they are as fully engaged as possible and that wear of the helices is spread over as large an area as possible. The steel cams should rest upon the helices with approximately 4 mm. of contact measured radially. The cams must be free in their pivots but without shake, so that the light flat springs will keep the cams in engagement at the right period of rotation of the helices.

Method of use.—The daily routine should include :

Changing the chart.—(i) Close the stopcocks and note the exact time (G.M.T.) to nearest minute. Allow the speed pen to come to rest without touching it, but if the air is calm, raise the float (slightly) and allow it to fall so that a vertical time mark is produced by the speed pen.

(ii) Rotate the clock cylinder slightly, so that the speed pen marks its resting position upon the chart, see instances at A, B, and C on Fig. 74.

(iii) Swing the three pens away from the paper by means of the pen lifter. Remove the completed chart from the drum and insert a blank chart in position taking the usual precautions (p. 12).

Adjustment of pens.—(i) Fill the pens with ink after seeing that they are clean. If they are not clean, lift them out of their sockets and wash them, but before removing the direction pen arms from their sockets open the one-point clutch to prevent the cam jamming in the helix. Methylated spirit may be used for removing old ink.

(ii) Swing the two direction pens into contact with the paper, so that they indicate approximately the correct time (G.M.T.), avoiding any splashing of ink. If necessary, raise or lower the clock cylinder by means of the milled headed screw inside the cylinder until the upper or lower pen (as the case may be) rests exactly upon the upper or lower north line of the record. The centre screw is a locking screw, the lower milled head is the one which raises or lowers the cylinder.

(iii) There should be clear evidence upon each chart that both the resting pen and the acting pen will come to rest upon their respective north resting lines—otherwise there may be some doubt as to the accuracy of the record produced by the acting pen. This is secured as follows : having been assured that the pens are marking well, open the one-point clutch or raise the locking ring and turn the helix through a complete circle in such a way that the acting

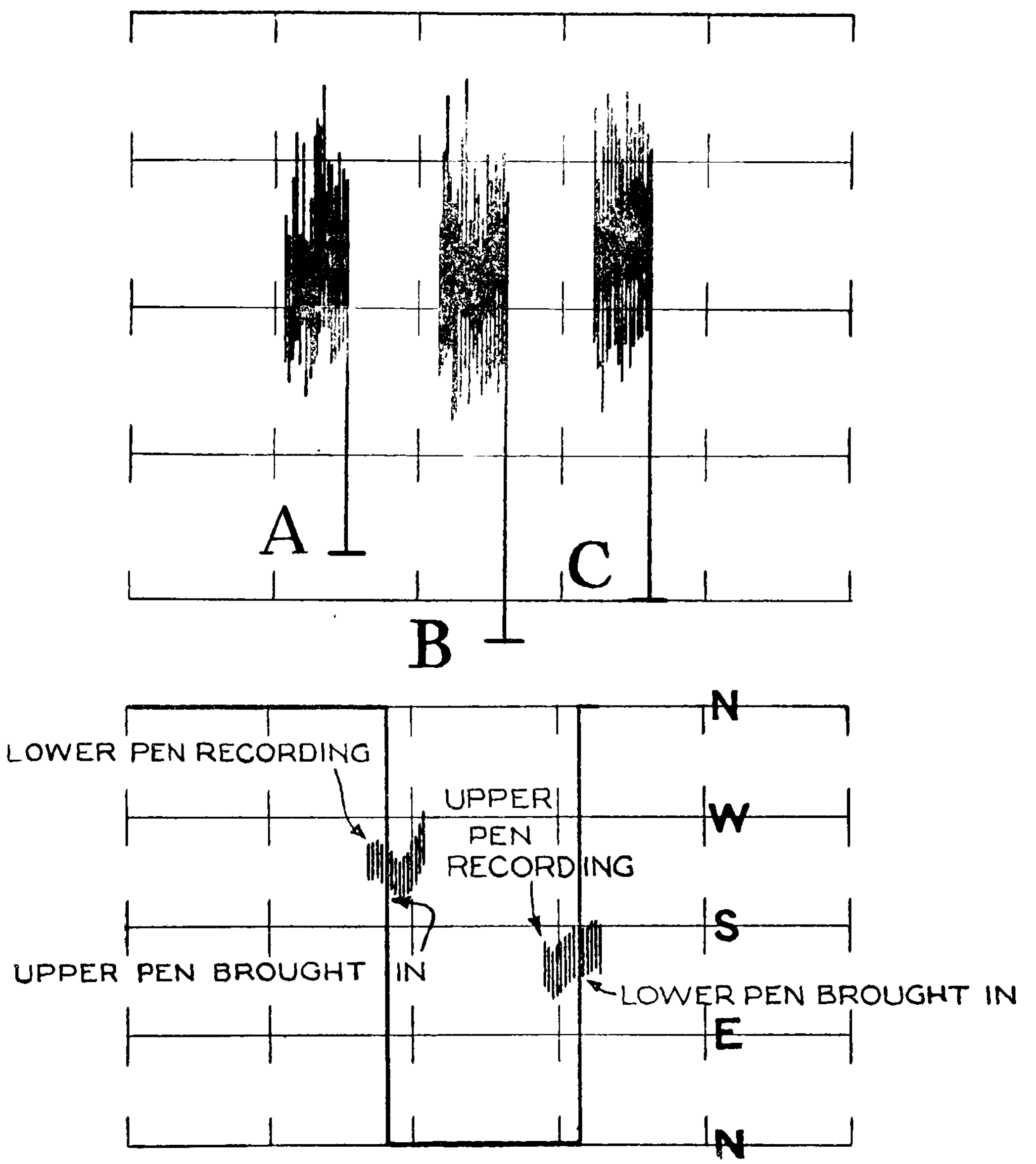


FIG. 74—ADJUSTMENT OF SPEED AND DIRECTION RECORDER

pen rises or falls, as the case may be, to its resting line. If the acting pen is that carried by the upper pen arm, the helix should be turned clockwise when viewed from above. If the acting pen is that carried by the lower pen arm the helix should be turned in the opposite direction. The resting line of the former pen is the upper north line, while that of the latter pen is the lower north line. Close the one-point clutch after the complete rotation has been made. If the acting pen comes to rest on its appropriate line nothing further need be done. If it does not it should be adjusted until it does by means of its socket screw (see p. 228).

(iv) If necessary shot should be added to or removed from the shot cup until the float just falls to the bottom of the float chamber when both stopcocks are closed and the float is raised about ½ in. (see p. 228). Then swing the speed pen into contact with the paper. If necessary, adjust the speed pen to fall exactly upon the zero line of the speed record by means of its socket screw, not by raising or lowering the clock cylinder.

Correction for air density.—If the station is more than 300–500 ft. above sea level or there are extremes of temperature or pressure, it may be necessary to correct the readings of the instrument for variations in the density of the air from the mean value assumed when calibrating the recording unit ; corrections to closer than the nearest 5 per cent. are not normally required except in high winds. Fig. 75 can be used for this purpose, the correction being read from the diagram (to the nearest 5 per cent.) according to the station-level pressure and the dry-bulb temperature in the screen. The correct wind speed, v, when the air density is ρ is related to the indicated wind speed, v_i, by the relation

$$v = v_i \sqrt{\frac{\rho_0}{\rho}} ,$$

where ρ_0 is the standard air density, 1·226 gm./m.³ and ρ is equal to p/RT, where p is the air pressure, R is the gas constant per gramme of air and T is the absolute temperature. Alternatively Table XXXV may be used if greater accuracy is required than is shown in Fig. 75.

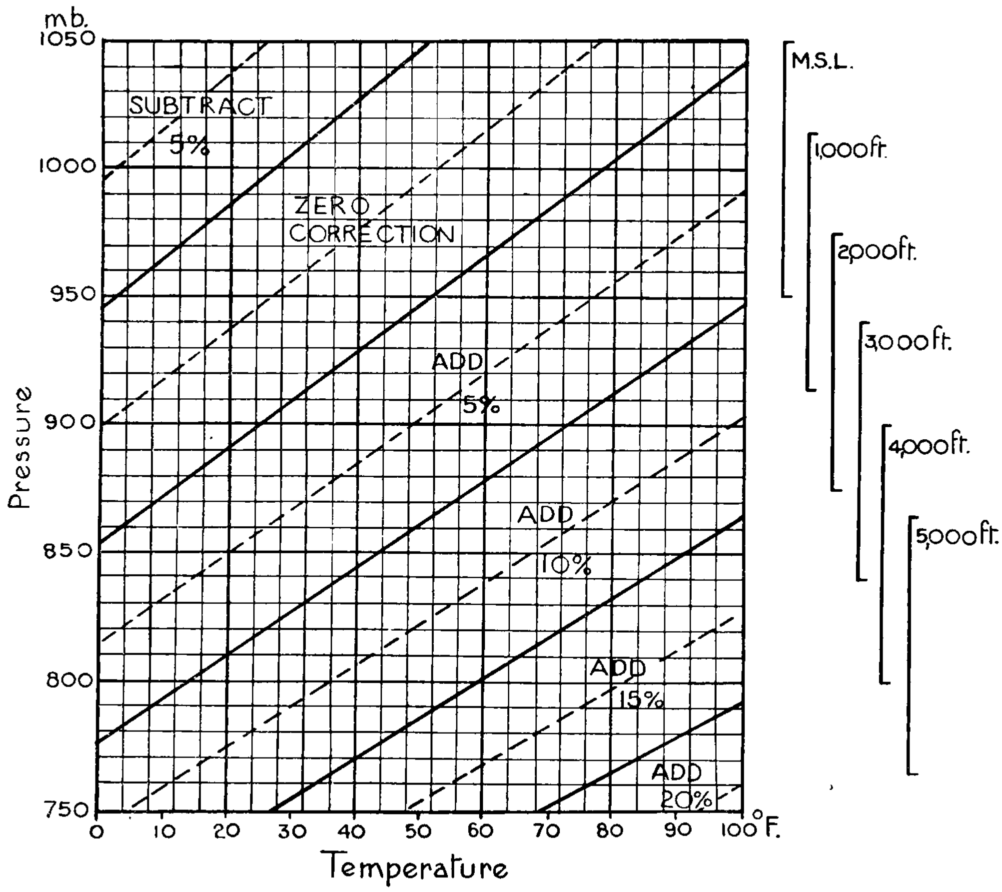


FIG. 75—CORRECTION OF PRESSURE-TUBE ANEMOGRAPH READINGS FOR AIR DENSITY

TABLE XXXV—CORRECTIONS FOR AIR DENSITY TO BE APPLIED TO THE INDICATED SPEED ON THE PRESSURE-TUBE ANEMOGRAM TO OBTAIN TRUE SPEED

	degrees Fahrenheit										
	0	10	20	30	40	50	60	70	80	90	100
mb.	per cent.										
1050	− 7	− 6	− 5	− 5	− 4	− 3	− 2	− 1	0	+ 1	+ 2
1025	− 6	− 5	− 4	− 3	− 2	− 1	0	0	+ 1	+ 2	+ 3
1000	− 5	− 4	− 3	− 2	− 1	0	+ 1	+ 2	+ 3	+ 4	+ 5
975	− 4	− 3	− 2	− 1	0	+ 1	+ 2	+ 3	+ 4	+ 5	+ 6
950	− 3	− 2	− 1	0	+ 1	+ 2	+ 3	+ 4	+ 5	+ 6	+ 7
925	− 1	0	+ 1	+ 2	+ 3	+ 4	+ 5	+ 6	+ 7	+ 8	+ 9
900	0	+ 1	+ 2	+ 3	+ 4	+ 5	+ 6	+ 7	+ 8	+ 9	+10
875	+ 1	+ 2	+ 3	+ 5	+ 6	+ 7	+ 8	+ 9	+10	+11	+12
850	+ 3	+ 4	+ 5	+ 6	+ 7	+ 8	+ 9	+10	+11	+12	+13
825	+ 4	+ 5	+ 7	+ 8	+ 9	+10	+11	+12	+13	+14	+15
800	+ 6	+ 7	+ 8	+ 9	+10	+11	+13	+14	+15	+16	+17
775	+ 8	+ 9	+10	+11	+12	+13	+15	+16	+17	+18	+19
750	+ 9	+11	+12	+13	+14	+15	+16	+17	+18	+20	+21

Starting the record.—Note the correct time, G.M.T., to the nearest minute, and set the clock cylinder so that the pen marks the correct time on the chart. Remove backlash by turning the cylinder on its spindle in a counter-clockwise direction so as to bring the pen back by steady motion to the required time from a point in advance of its proper setting, i.e. from a time on the chart later in the day. A few trials will make this clear and will also show that unless this method is strictly followed, the clock cylinder does not begin to rotate for some minutes, resulting in a loss of time on the record. In the latest pattern clock, however, backlash has been practically eliminated. See that all the pens are marking.

Time marks.—Time marks should be made on the record, as detailed on p. 11. The marks are made by closing the two taps so as to allow the pen to fall to the zero line of the record. The taps should then be opened again. The exact time (G.M.T.), correct to the nearest minute, should be noted at the time the marks are made, and this should be entered on the chart in the space provided after the chart has been removed from the cylinder. If the air is calm a time mark should not be made. In no circumstances should the pen be raised by hand for the purpose of making this mark.

Writing up the chart.—The normal procedure (p. 12) should be followed in writing up the chart.

Maintenance and repair.—*Cleanliness.*—The observer should give the utmost attention to general cleanliness. Ink should not be allowed to solidify upon the underside of the pens or on the pen holders. Drops of ink that may fall upon the top of the tank or trickle down the chart to the clock-cylinder flange should be cleaned off at once with a damp cloth. Older stains should be removed by the application of a small quantity of whitening applied with a damp cloth. Methylated spirit may be used with the whitening if there is no risk of this getting on lacquered brass or polished woodwork. To prevent sticking of the speed pen, the float rod must be kept clean and dry. No metal polish or lubricating oil or cleaning material should be used, but it is beneficial to rub the rod with a piece of blotting paper previously treated with lead pencil.

Water level.—The gauge should be examined about once a fortnight and corrected if necessary. Water may be lost by evaporation, and there is just a possibility of rain finding its way down the air tubes. Distilled water should be added by removing the milled cap of the gauge glass. Any excess should be run off at the little stopcock just below. The level is correct when the top of the pointer is just in the surface of the water, the stopcocks being closed and adjustment (iv) on p. 227 being correct.

Draining plug.—The screwed plug by the lower cock should be removed from time to time by a tommy bar or spanner to allow any trapped water to escape. It will be convenient to see to this at the same time as the water level is examined. The plug must be always screwed firmly back in place after the water has been removed.

Renewing pens.—The speed pen is easily replaced. The distance from the pen point to the little grip sleeve should be as nearly as possible the same as with the old pen to avoid further adjustment. When looked at from above the pen should seem to be at right angles to the paper. The new pen should agree with the direction pens in time—that is they should all fall upon the same vertical hour line at the same time.

Direction pens require a little more attention as they must work in with one another and be in alignment. Assuming that the pen wires have not been strained or damaged in any way it will be found that the point mentioned in regard to the speed pen, namely the distance from pen point to grip sleeve, is of the greatest importance, and much other adjustment can be saved by slight variations in this distance. Repeated trials on the lines indicated in (iii) on p. 231, and with the installation instructions in (x) on p. 228, will enable the observer to detect and remove any error.

Orientation.—The observer should check the record by comparing it with his own reading of the vane. Some instruments have a compass card index fitted, in which case comparison is simple though the readings of the card should occasionally be checked against those of the vane. Any discrepancy should be reported and then corrected. The vane should never be turned from below by means of the direction rod, otherwise the rod may be strained.

Oiling.—The direction mechanism should have a drop of oil about once a month in the hole at the top of the helix, and the bearings of the long levers may need oiling at about the same period. The surfaces of the helices should be wiped over with an oily rag, but free oil there tends to gather dust and grit and should be avoided.

Treatment to avoid stiffness in direction recorder.—To avoid strain on the direction tube it is essential that the helix should rotate freely. The helix is mounted on a central steel spindle which turns in a brass sleeve mounted on the base of the direction recorder. Interposed between the underside of the top of the helix boss and the top of the brass sleeve is a ball thrust race, which takes the weight of the helix assembly. It is possible, owing to the presence of dust and moisture, for the steel helix spindle to become tight in its sleeve ; to avoid this periodical attention should be given as follows. After marking and uncoupling the flexible coupling, open the clutch, hold the direction rod a little to one side and lift out the shaft including the direction disc and groove block. Disengage the helix knives, and lift off the helix complete with spindle. The ball race consists of an upper steel washer, a brass cage containing the balls, and a lower steel washer. When the helix is withdrawn, the ball race may either come off with it or remain on the top of the sleeve. In either case, it should be taken out, cleaned in paraffin and lightly oiled. The spindle should be thoroughly cleaned, and also the inside of the sleeve; this may be done with a paraffin-soaked rag wrapped round a pencil. The spindle should be lubricated with thin oil. In reassembling, be sure that the ball cage has one steel washer above and one below it ; the upper steel washer may adhere to the underside of the helix base. Replace the clutch block and direction disc shaft, and connect up the flexible coupling, being sure to avoid 180° error. The flexible-coupling pivot pins should be lubricated with thin oil frequently.

Removal of vane for cleaning and lubricating.—The vane may be lifted off the head to give access to the ball-bearing which takes the weight of the vane and direction rod. The ball-bearing should be lubricated with thin grease.

While the vane is off, the inside of its central cylindrical portion should be cleaned, first with fine emery cloth and then with a clean rag wrapped round a suitable cylindrical object. The outer surface of the fixed part of the head above the suction holes should also be cleaned, and then left with a slightly greasy surface. If the head has not received attention for some time it may be difficult to lift off the vane, owing to corrosion of the fixed and moving parts. A combined lifting and rotating movement should free the vane. The central spindle also requires lubrication, at the top bearing just below the ball-bearing and at the lower bearing where the spindle emerges from the head. The direction rod should first be disconnected from the direction recorder, and an assistant should then lift the direction rod about 2 in. While it is lifted grease or oil should be applied to the top of the spindle just below the ball-bearing ; and oil should be applied to the spindle so that it runs down the spindle to the lower bearing.

Removal of the head.—This will normally only be required when a new head is to be fitted, or when the head is to be transferred to another mast.

To remove the head, take off the vane, remove the conical nut and lift off the shield. Disconnect the pressure and suction pipes from the head by unscrewing the hexagon union nuts. It may be necessary to loosen the various clamps to the pressure and suction pipes enough to enable the pipes to be lowered slightly, after which the head can be unscrewed from its socket.

The direction rod should be disconnected from the recorder, and as the head is unscrewed an assistant should lift the direction rod from below, until the head is detached and can be lifted high enough to expose the top direction-rod coupling which should be unscrewed. If, however, a " top-fitting " is used, the direction rod should be unscrewed through the inspection door before the head is unscrewed. In either case after the direction rod is detached from the head the assistant should lower it to the ground clear of the direction recorder.

Adjustment of direction recorder (see also p. 230).—When first installed, the direction recorder should be in correct working order. It may subsequently, however, be necessary to make certain adjustments, particulars of which are given below. These adjustments should on no account be attempted unless the recorder is definitely not working properly. If the observer feels in doubt as to the necessity of making adjustments, advice should be sought from the maker, or at Meteorological Office stations from the Instrument Provisioning Branch, specimen charts being forwarded indicating the defect in question.

Adjustment of range of pen arms.—The following procedure should be used to adjust the range of the pen arms. First remove lower pen after having opened the one-point clutch. Then rotate the helix in a counter-clockwise direction (when viewed from above) and adjust the screw holder of the upper pen until this pen just reaches the lower north line on the chart at the lowest point of its travel.

When the pen has reached the top of its travel and its direction arm is resting on the dead stop adjust the stop until the pen is on the upper north line. Then remove the upper pen and replace the lower one. Now rotate the helix in a clockwise direction and adjust the screw holder of the lower pen until the pen just reaches the upper north line at the highest point of its travel. When the pen has reached the bottom of its travel and its direction arm is resting on the dead stop, adjust the stop until the pen is on the lower north line.

After these adjustments have once been made, the correct setting of the pens from day to day will be carried out by lowering or raising the clock drum by the screw provided so as to bring the direction pen which is not giving the record on to the north line of the chart.

Adjustment of alignment of pen arms.—If the pens are not in vertical alignment with the speed pen, the error being small, loosen the two screws that hold the brass sockets of the pen-arm pivots when the arm can be moved bodily forwards or backwards. Tighten up the screws after adjustment.

Adjustment of rate of rise and fall of arms when passing over.—If the top pen rises or the bottom pen falls too rapidly or too slowly when approaching their respective datum lines, the balancing weight should be adjusted to prevent shock or too uncertain a motion.

Adjustment of cams.—This has already been described, see p. 231.

Calibration of the wind-speed recording unit.—The calibration of the wind-speed recording unit should be checked regularly (about once a year if possible). To do this a sensitive and accurate manometer reading to 0·1 mm. of water is required (see p. 257). The Meteorological Office tilting manometer (Stores Ref., Met. 1956) is suitable. The pressure tube (the one leading to the base of the float) is disconnected from the recording unit and the pressure side of the manometer is connected in its place through a glass T-piece, rubber tubing being used to make the joins. The suction tube is connected to the other side of the manometer (or if there is an absence of draughts it suffices simply to open both to the air of the room). A small piece of rubber tubing and a pinch-cock is attached to the open end of the T-tube so that it can be closed as desired.

The pressure beneath the float is raised by blowing down the T-piece until the pen on the chart reaches one of the horizontal lines, and the pressure is measured with the manometer. Table XXXVI gives the standard equivalents of pressure and indicated speed for the head of this anemograph. If alcohol is used in the manometer the pressures must usually be converted to millimetres of alcohol (by dividing each by the specific gravity of alcohol, 0·832).

TABLE XXXVI—RELATION BETWEEN THE WIND SPEED AND THE PRESSURE DIFFERENCE BETWEEN THE PRESSURE AND SUCTION TUBES IN THE PRESSURE-TUBE ANEMOGRAPH MK II

		Speed (kt.)									
v		10	20	30	40	50	60	70	80	90	100
		millimetres									
Pressure of water	Δp	2·5	9·9	22·2	39·3	61·8	89	121	158	200	247
	$\sqrt{\Delta p}$	1·6	3·1	4·7	6·3	7·9	9·4	11·0	12·6	14·1	15·7

		speed (m./sec.)								
v		5	10	15	20	25	30	35	40	45
		millimetres								
Pressure of water	Δp	2·3	9·3	21	37	58	84	114	149	188
	$\sqrt{\Delta p}$	1·5	3·1	4·6	6·1	7·6	9·2	10·7	12·2	13·7

Accuracy and sources of error.—The response of the pressure-tube anemograph to changing wind speeds has already been discussed (p. 198). In a steady wind the record should not be in error by more than 1 kt. at all speeds above about 2–3 kt. The main sources of error that can arise are changes in the weight of the float and errors in the calibration of the recorder. Gold[46] has shown that the total distance the float moves ε, because of an added weight W_1, from its initial position z_1 to its final position z, is given by

$$\alpha\beta W_1 = -\varepsilon + \frac{1}{\beta}\log\left(1 + \frac{\varepsilon\beta}{1+\beta z_1}\right), \qquad \ldots\ldots(79)$$

where $\alpha = 1/2qAg\rho'$ and $\beta = 2(Cq - A)/(C - B)$ (see p. 222). When z_1 is small and comparable with the error ε then

$$\varepsilon = -z_1 + \sqrt{(z_1^2 - 2\alpha W_1)}, \qquad \ldots\ldots(80)$$

i.e. the maximum error is $\sqrt{\pm 2\alpha W_1}$, according to whether W_1 is positive or negative. Table XXXVII shows the errors at different speeds if the float is 10 gm. too light.

TABLE XXXVII—ERROR CAUSED BY TAKING 10 GM. OFF THE FLOAT

Speed (kt.) ..	0	10	20	30	40	60	80
Error (kt.) ..	4·7	1·3	0·7	0·5	0·4	0·3	0·2

For a deficiency of 1 gm. the errors are 1 tenth of these values for speeds above 10 kt., but at zero wind speed the error is 1·5 kt. If the float is too heavy by 10 gm. then zero speed is recorded for a wind of 4·7 kt. The effect of errors of calibration can be seen from Table XXXVIII which shows the speed equivalent of 1 mm. of water pressure difference, for various speeds. Errors in the indicated readings due to changes in air density are not instrumental errors in the strict sense. In extreme cases a correction should be applied.

TABLE XXXVIII—EFFECT OF ERRORS IN THE CALIBRATION OF THE RECORDER

Indicated speed (kt.) ..	10	20	30	40	50	60	70	80	100
Difference in speed corresponding to 1 mm. of water (kt.)	2·0	1·0	0·7	0·5	0·4	0·3	0·3	0·3	0·2

5.5.2. Remote-recording pressure-tube anemograph

Description.—The remote-recording pressure-tube anemograph is a development of the direct-recording pressure-tube anemograph for use when it is desired to have the recording unit at a considerable distance from the head and not directly beneath it. It consists of three main parts :

(i) Mast and head unit
(ii) Speed-control unit
(iii) Recording unit.

The recording unit (consisting of wind speed and direction records) is controlled by the receiving units of two pairs of self-synchronous motors, the transmitting units being operated by the speed-control unit and the wind vane respectively. The self-synchronous motors used are of the " selsyn " and " autosyn " types ; the armatures of these motors are connected to a single-phase a.-c. supply while the three field windings of the receiving motor are connected to the corresponding windings of the transmitting motor. If the armatures of the receiver and transmitter are not in the same relative positions there will be a torque on each tending to bring them into alignment. The armature of the receiving motor thus closely follows the movements of the transmitter armature. This principle is illustrated in Fig. 76.

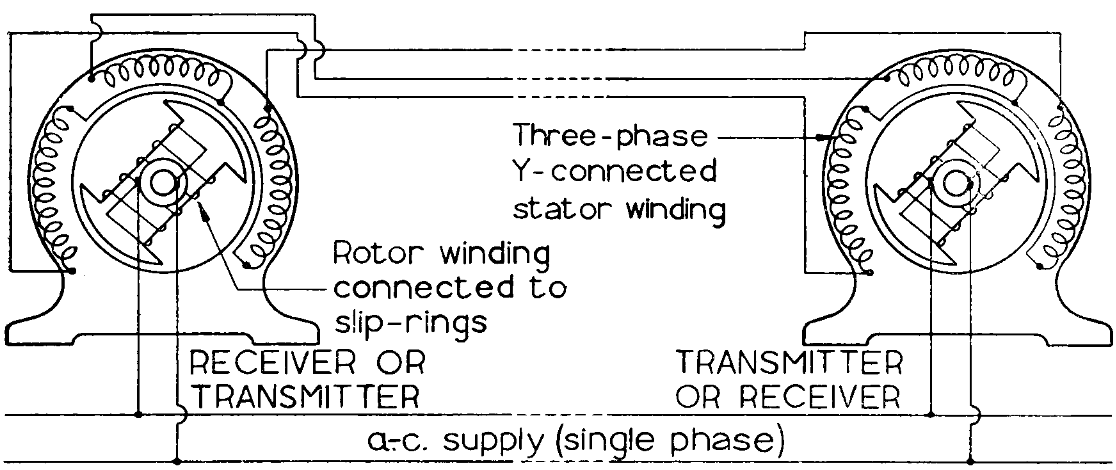


FIG. 76—PRINCIPLE OF AUTOSYN AND SELSYN TRANSMISSION

Head unit.—The head unit (Plate XXXII) is similar in design to that of the direct-reading pressure-tube anemograph Mk II ; the transmitting selsyn for wind direction is, however, mounted in a casting directly beneath the head proper and there is no direction rod. The pressure and suction tubes are connected to the head through unions in a similar way to those in the direct-recording instrument. This head unit is mounted on a mast or pole which carries the pressure and suction tubes down to the speed-control unit which, in turn, is situated near the base of the mast. If necessary a small hut must be built to house it.

Speed-control unit.—The speed-control unit (Plate XXXIII) consists essentially of a speed-recording unit as in the direct-reading instrument, but the movement of the float rod causes a rotation of the transmitting autosyn by means of a fine chain, attached to the shot cup, which passes one and a half times round a pulley attached to the armature of the transmitter motor. The chain is kept taut by means of a small weight.

Recording unit.—The recording unit (Plate XXXIV) consists of two parts. The direction recorder is similar in principle to that of the twin-pen recorder on the direct-reading anemograph. The receiving selsyn is mounted directly above the helix and is connected to it through a clutch. The speed recorder consists of a pen carriage carried by a fine chain passing over a pulley connected to the receiving autosyn, in a similar manner to the speed-control unit. The record is made on a similar chart to the direct-recording instrument. If necessary a speed record may also be made by the speed-control unit.

The direction selsyn runs off 230 V. a.c., but the speed autosyn only requires 32 V. (supplied by a transformer). Sometimes a small selsyn (working off 24 V.) or magslip (working off 50 V.) may be used in place of the autosyn.

The recording unit needs a firm support, and should be placed at a height convenient for observers who have to change the charts and adjust the instrument. It must be accurately levelled. A slight humming sound is emitted by the electrical units, and consideration should be given as to whether this sound will cause annoyance in any particular site where the units are proposed to be placed. Two telephones are usually installed (one at the recording unit and one at the speed-control unit) to facilitate the adjustment and testing of the instrument.

Lists of parts required.—The following is a list of parts supplied by the Instrument Provisioning Branch to Meteorological Office stations.

	Stores Ref.
Head unit, consisting of head, vane, conical shield, large selsyn transmitter, and housing*	Met. 592A
Speed-control unit, consisting of float chamber, float, and small selsyn (or autosyn) transmitter	Met. 592B
Recording unit, consisting of speed recorder with small selsyn (or autosyn) receiver, direction recorder with large selsyn receiver, transformer and terminal block, mounted on an instrument base	Met. 592C
Dust cover for speed-control unit	Met. 611
Dust cover for recording unit	Met. 610
Terminal block and transformer on a board (for use with speed-control unit)*	...
Clock and short clock drum for speed-control unit*	Met. 679
Clock and long clock drum for recording unit*	Met. 519
Pressure and suction piping consisting of 10-ft. lengths of 1-in. gas piping with screwed sockets. One socket is issued for each length of gas piping (total length of gas piping required is approximately double the length of the pole)*	Met. 2392
Two lengths of 1-in. bore compo piping, each 15 ft. long*	...
Two "plumber's unions" for connecting pressure and suction piping to compo piping*	...
Instructions for erection and maintenance	...
Box of small accessories	...
Initial supply of recording charts	...
Field telephones	Met. 491
Safety belt	Met. 327

The box of accessories† should contain the following :—

Speed-control pen arm and holder	Glass rod for ease in inking pens
Upper direction pen arm and holder	Two tommy bars for direction adjustment
Lower direction pen arm and holder	Bottle of lubricating oil
Recording unit speed pen arm and holder	Tin of petroleum jelly
Box spanner	Bottle of recording ink
Flat spanner	Tin of lead shot
Shot tweezers	Tin of spare pens and angle ink reservoirs

* In the case of Meteorological Office stations items marked with an asterisk will be fitted as a Works Service, and the remainder of the items by the instrument mechanic sent by the Instrument Provisioning Branch.

† In certain cases the float-rod collar and shot clip may be packed in this small accessories box.

In addition 5 gallons of distilled water will be required.

The following is a list of parts to be supplied as Works Services at Meteorological Office stations.

Suitable pole or mast with steps evenly spaced up the whole length or with a ladder attached, brackets and clips for the pressure and suction pipes, and suitable earthing arrangements.
Hut supplied with shelves for charts and telephone and a sub-base for the speed-control unit ; unless otherwise specified the hut should be about 6 ft. × 4 ft. × 6½ ft. high.
Suitable table or shelf for the recording unit.
Fittings for heating and lighting the hut.
Cable with all necessary switches, fuses and fittings, including 60 yd. of twin lead-covered rubber insulated cable (1/0·044) for connecting the head to the hut.

Structural installation work.—At Meteorological Office stations the main structural and electrical work has to be arranged as a Works Service. The structural work is briefly outlined below.

Erection of mast and hut.—A suitable pole or mast has to be erected and the head unit mounted at the top. The requirements as to exposure are similar to those for any anemometer, and the principles outlined on p. 201 should be followed in deciding on the site. The head and speed-control unit can be any distance from the recording unit provided the resistance of each of the cores of the cable connecting them does not exceed 5 ohms (see also p. 243). A hut has also to be erected near the base of the pole. When the hut and mast are being erected reference should be made to Fig. 77, copies of which at Meteorological Office stations are obtainable from the General Instruments Branch or from the Works Service.*

Inside the hut the following have to be fitted :

(i) The board carrying the transformer and terminal block (see p. 243)

(ii) A shelf roughly 2 ft. × 1 ft., and 3 ft.–3½ ft. above the floor level for the storage of charts and accessories

(iii) A small shelf for the telephone

(iv) A suitable sub-base for the speed-control unit.

The base of the control unit is mounted on three legs, two of which have levelling screws, evenly spaced on a circle $15\frac{3}{16}$ in. in diameter. The sub-base should raise the legs high enough above the floor level to allow a small tube heater to be placed on the floor beneath the instrument to prevent freezing in cold weather.

Connexion of pressure and suction pipes.—The pressure and suction pipes have to be connected to the head and led down the pole to within about 5 ft. of the instrument base. Compo tubing is connected to the unions attached to the foot of the pipes and led into the hut, the entries being made weatherproof. The pipes should enter the hut with a continuous downward slope so that water cannot be trapped.

Lightning protection.—Suitable earth connexions to the pipes and mast for protection against lightning have to be fitted (see Fig. 77).

Shelf for recording unit.—A suitable shelf or table for the recording unit has to be fitted. This should be 2 ft. 6 in. × 1 ft. 3 in. with a small shelf beneath for the telephone. The height and position of the shelves should be decided by the meteorological officer concerned.

* Director-General of Works drawing M & E 4728/43.

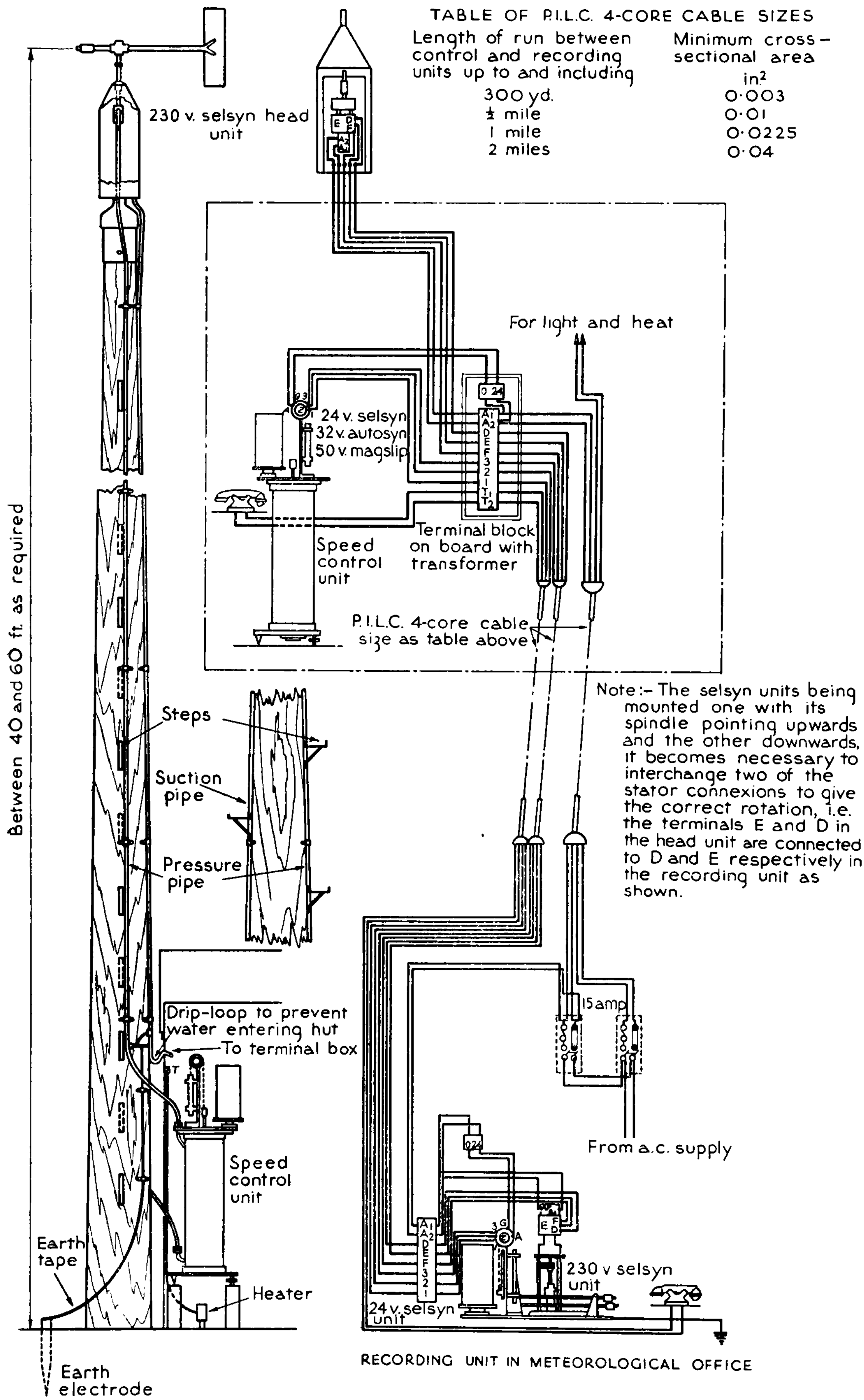


FIG. 77—WIRING DIAGRAM AND GENERAL VIEW OF REMOTE-RECORDING PRESSURE-TUBE ANEMOGRAPH

Electrical installation work.—The electrical work consists of :

(i) Connexion of the terminal block on the head unit to the terminal block on the board in the hut with three lengths of twin lead-covered rubber insulated cable (1/0·044), one wire of which will not be required. The hut ends should be marked clearly as coming from A_1, A_2, D, E and F as appropriate.

(ii) Laying the cables from the hut to the recording unit. All wires should be marked clearly at each end and connected to the hut terminal block at the speed-control unit end. The wiring should be checked by means of the wiring diagram (Fig. 77).

(iii) Supply and connexion of two double-pole single throw switches for the mains supply. Two switches are required so that the lighting and heating of the hut may be independent of the working of the instrument. The mains supply is connected to the terminals A_1 and A_2 and thence to the selsyns and autosyns (but through a step-down transformer for the autosyns or small selsyns).

(iv) Connexion and testing of the telephones.

(v) Supply and fitting of the lighting and heating equipment of the hut. The mains supply at the recording unit should be 220–240 V. 50 c./sec. single phase a.c.

The following notes are for general guidance. The necessary connecting cable consists of 12 wires ; 4 of these carry the mains current, of which 2 are for the instrument and 2 for the hut lighting and heating equipment. Of the other 8 wires, 2 are for telephones, 3 for the field connexions of the direction selsyn (230 V.), and 3 for the field connexions of the autosyn (32 V.) or small selsyn (24 V.) units. The 4 wires of the mains should preferably be separate from the other 8, though they may be buried in the same trench. All must be lead-covered and suitable for burying (unless overhead wires are installed). The resistance of each of the 8 instrument wires must not exceed 5 ohms. The minimum sizes for various distances between hut and recording unit are given in Table XXXIX ; it is better to exceed these sizes.

TABLE XXXIX—MINIMUM SIZES OF CONNECTING WIRES BETWEEN THE HEAD AND RECORDER, AND CONTROL UNIT AND RECORDER

Distance	Number of conductors with diameter of one	Approximate area of cross-section
yd.	in.	sq. in.
100	1/0·036	0·001
150	1/0·044	0·0015
200	3/0·029	0·002
300	3/0·036	0·003
440	7/0·029	0·0044
miles		
½	7/0·044	0·01
1	7/0·052	0·0225
1½	19/0·044	0·03
2	19/0·052	0·04

In districts where frost is liable to occur, provision should be made for heating the speed-control unit in cold weather, such as by a small tube heater placed below the tank of the unit connected to the mains supply.

Final installation of the instrument.—When the preliminary electrical and structural installation is complete the instrument mechanic (from the Instrument Provisioning Branch for Meteorological Office stations) should proceed as follows :

(i) Check over with the Works Services representative and the Meteorological Officer the work already completed.

(ii) Unpack the remaining items of the instrument.

(iii) Set up the speed-control unit, level it, connect up the pressure and suction pipes by means of the compo tubing (blow lamp, solder and flux will be needed), fill up to the mark with distilled water and generally prepare the instrument for use.

(iv) Connect the speed-control unit to the terminal block (25–30 yd. of 40/0·0076 flex required) ; see Fig. 77 for connecting wires G, A, 1, 2 and 3. In order to make the connexions in the autosyn or small selsyn units the cylindrical covers, which are fixed with 3 screws, must first be removed. The wires are then taken through the bushes at the end of the covers and the covers replaced after the connexions have been made. On later models, terminal blocks are provided both on the speed-control unit and the recording units to facilitate connecting up.

(v) Set up the recording unit on the shelf and connect the mains double-pole switch to the recording unit. Connect wires A_1, A_2, D, E and F to the terminal block, noting however that wires D and E must be connected to the terminals E and D respectively. This ensures that the recording selsyn will turn in the correct direction.

Adjustment with respect to the recording selsyn.—After the instrument has been set up, the direction recorder must be adjusted with respect to the recording selsyn by means of one of the two clutch arms, which can be rotated and afterwards fixed by a grub screw. This can best be done on a calm day. The procedure is as follows :

(i) A stout double string should be hung over the tail tube just in front of the vane tail, long enough for its two ends to reach to the ground with about 15 yd. to spare. By means of this string the vane can be held in any desired direction by an assistant who can also take the bearing of the direction in which it is pointing by means of a prismatic compass, or by lining the vane up on a distant object whose bearing is known.

(ii) While the vane is thus held, the current is turned on and the clutch engaged with its upper arm free to revolve about the recording selsyn spindle ; the helix is then turned until one of the pens comes to the correct position on the chart, and the upper clutch arm is now fixed by its grub screw.

(iii) While the string is still on the vane, the assistant should walk round in an agreed direction to rotate the vane, while the pen arms are watched to see that the recorded sequence of directions is the same as the actual one. If not, the wiring of D, E and F between the hut and the recording unit has been wrongly connected up.

(iv) The string is finally detached by letting go one end and pulling on the other.

Zero adjustments of the speed-control unit and speed-recording unit.—These are carried out as follows :

(i) With pressure and suction taps open to the hut and current off, add shot to the cup until the float is felt just, and only just, to touch the bottom when it is raised $\frac{1}{2}$ in. and then let go. The setting line on the float rod should then be level with the top of the collar.

(ii) With the current off, place the pen of the recording unit in position and balance with shot in the cup until it has no tendency to rise or fall when placed on the 20-kt. line.

(iii) Clamp the pulley of the recording unit by pressing the hinged lever into its slots. With the current on and the float of the control unit resting on the bottom of the tank, rotate the recording autosyn by means of the arm projecting from the case until the pen is on the zero line. Disengage the clutch lever.

(iv) It is essential that, with current on and float at zero as in (iii) the hinged lever should fall exactly into the slot without requiring any rotation of the recording autosyn pulley. This adjustment is made before the instrument is sent out, and should not need to be altered. If, however, any movement occurs when the lever is raised, it must be corrected by rotating one of the autosyn pulleys with respect to its spindle ; otherwise the pulleys must never be moved on their spindles.

Testing the instrument.—The following tests are carried out on new instruments before delivery from the manufacturers and need not normally be done again on installation unless it is suspected that the instrument has been damaged in transit. These tests should, however, be carried out (by the mechanic from the Instrument Provisioning Branch for Meteorological Office stations) when an instrument is being re-installed in a new position and on all instruments during subsequent inspections or overhaul.

Direction mechanism.—The following procedure should be used to test the mechanical parts of the direction mechanism :

(i) Adjust the lower datum stop so that the lower cam knife engages in the helix just as the upper arm reaches its limit of travel and drops back to its rest position. Then similarly adjust the upper datum stop.

(ii) Remove the top pen and turn the lower penholder, adjusting the screw until the pen just reaches the upper north line at its limit of travel. Then similarly adjust the upper pen so that it just reaches the lower north line at its limit of travel.

(iii) The rod carrying the direction disc should be adjusted vertically, by the two grub screws above the helix, so that the point engages without play in the recess at the end of the selsyn spindle, but without actually taking the weight of the rotor off its own bearings. If the instrument is mechanically perfect it should now be in adjustment.

(iv) Check the range of the lower helix by adjusting the direction disc to read 90° when the lower pen is on the east line. Then turn the disc to 0°, 180°, 270° and 360°, and note if the pen rests on the corresponding line in each case by rotating the clock drum. If it does so to within 2° the range of the helix is within the tolerance allowed. Similarly check the range of the upper helix with the direction disc in the same position as before. If the upper pen lies on the corresponding lines at 0°, 90°, 180°, 270° and 360° the range of the upper helix is correct, and the helices are correctly placed relative to each other. If the pen lies below or above the line, but with a constant error in either case, the helices are incorrectly placed, the ends of the two scrolls not being in vertical alignment.

(v) It may be found that in the zero position of either pen, i.e. with the arm actually resting on the stop, the pen does not lie on the corresponding datum line when the above adjustments have been made. This may be due to slightly inaccurate placing of the helices, a small error in the range, or both. In this case a compromise between the correct timing of the knives and the correct range has to be adopted. By raising or lowering the stop the pen can be brought nearer the line, but the timing of the two knives will be faulty. The error in the timing of the knives should not exceed 2°, i.e. it should not be possible, when both cam knives are engaged in the helices, for the two pens to rest on their north lines simultaneously (lost motion) during a rotation of more than 2°, and similarly, any overlapping motion should not exceed 2°.

(vi) The points of both pens should be in the same vertical line as the speed pen. They should be adjusted if necessary by moving the bearings of the arms.

(vii) It should be verified that the recesses for the grub screws on the direction rod are so placed that the transmitting selsyn rotor is pulled up slightly when the screws are tightened, so that the whole weight of the head and rotor is taken by the ball-race in the head itself.

The following procedure should be followed to test the electrical parts of the direction mechanism :

(i) Connect the rotor windings of the two selsyn units to the mains in parallel, A_1 to A_1 and A_2 to A_2, and then connect the two sets of field windings to each other in the following manner : D to E, E to D, and F to F (Fig. 77). Release the clutch under the receiving selsyn by withdrawing the screw on the end of the arm, and withdraw the grub screw clamping the lower clutch arm to the spindle.

(ii) Turn the helix so that both pens rest on their datum lines, and then fix a direction disc to the spindle of the transmitting selsyn so that the pointer is at 0°. Hold the transmitting selsyn in this position and switch on the current. While holding the helix in position so that both pens are on their datum lines turn the lower clutch arm until it corresponds exactly with the upper clutch arm when the dial on the transmitting selsyn indicates 0°. Clamp the lower clutch arm in that position and engage the clutch.

(iii) Turn the transmitting selsyn to 90°, 180°, 270° and 360°, care being taken not to overshoot the settings so that the dial must be turned back. The lower pen will take up corresponding positions which should be marked by rotating the clock drum. Turn the transmitting selsyn slightly past 360°, and then back to 360°, 270°, 180° and 90°, marking the positions of the pen again. The up and down readings should not differ by more than 2° or 3°, and the mean of the two readings should be within 2° of the true values of the chart.

Speed mechanism.—The following is the test procedure for the mechanical parts of the speed mechanism :

(i) Level the tank carefully and fill to approximately the correct level with water and then fill the shot cup with shot until the float rests lightly on the bottom, and just, but only just, returns to the bottom when raised ½ in. by hand.

(ii) Disconnect the compo piping from the pressure and suction sides of the float unit and connect to them a sensitive manometer as in the calibration of the direct-reading pressure-tube anemograph (p. 237).

(iii) Adjust the pen to the zero line on the chart and blow up the float until the pressure corresponds to 40 kt. (see Table XXXV, p. 234).

(iv) Adjust the water level to bring the float to the 40-kt. line, and then release the pressure and adjust the weight of shot in the cup again as in (i).

(v) Increase the pressure to 10, 20, 30 . . . . 90 kt. and mark the position of the pen at each point by rotating the drum. Decrease the pressure to the values for 70, 40 and 10 kt. and mark the position of the pen again. The pen should be within 2 kt. of the correct value at any point, and there should be no appreciable difference between the rising and falling positions at 10, 40 and 70 kt.

(vi) It may be found that raising or lowering the water level slightly would give a better distribution of error. Blow up the float to 40 kt. again, adjust the water level to the new value, and repeat the test after re-adjusting the weight of the float. It should be noted that the full effect of the change of level will be felt from 20 kt. upwards, and at 10 kt. the effect will not be so great. When a satisfactory level has been found the pointer in the water gauge should be set after the pressure has been released.

(vii) Blow up the float to approximately 60 kt., turn off the suction tap and place a finger over the hole in the barrel of the tap. Turn off the pressure tap and mark the levels to which the float falls in 60 and 120 sec., timing from the 40-kt. line. The float should not fall from 40 to 10 kt. in less than 60 sec.

(viii) Remove the float collar and blow the float up to 40 kt. after replacing the shot cup and pen. The float should show no tendency to fall over to one side or the other, the trace made on the paper being approximately a vertical line. Measure the diameter of the float rod and the internal diameter of the float collar. They should differ by at least 0·005 in., i.e. 0·0025 in. clearance all round.

The following is the test procedure for the electrical parts of the speed mechanism:

(i) Level the base of the recorder and connect the rotor windings of the two autosyns to the mains in parallel, A to A and G to G. Connect the field windings to each other, 1 to 1, 2 to 2, and 3 to 3.

(ii) Place the pen in the pen carriage of the receiving unit, clamp the pulley by means of the locking arm and rotate the autosyn by means of the adjusting lever until the pen is on the zero line of the chart. Unclamp the pulley and add shot to the shot cup until the pen carriage is balanced at the 20-kt. line. Clamp the pulley again in its zero position and switch on the current.

(iii) Place the pulley of the transmitting autosyn on its spindle, without rotating the spindle, so that the chain is taut with the float resting on the bottom of the tank. Clamp the pulley in position. If this has been correctly done the recording pen should remain on its zero line if the float is held down and the receiving pulley unclamped. If not, a slight further adjustment of one of the pulleys on its spindle may be necessary.

(iv) Switch off the current and adjust the shot in the float shot cup as in (viii) (p. 228).

(v) Blow the float up to 10 kt., open the pressure tap and allow it to fall slowly. If the transmitting autosyn is free from friction and the float rod and collar clean it should fall to within 1 kt. of its zero position, and only 2 or 3 extra shot should be required to bring it back to the correct zero.

(vi) With both pens at zero switch on the current. Blow up the float to 10, 20, 30, ... 90 kt. and mark the position of the recording pen in each case by rotating the clock drum. Lower the float again to 70, 40 and 10 kt. and mark the positions of the recording pen again. The rising and falling readings should not differ by more than $\frac{1}{2}$ or at most 1 kt., and the mean should be within 1 kt. of the value shown by the speed-control unit.

(vii) When the pressure is released both pens should fall gently to their zero lines without any tapping of the tank or recording unit.

Method of testing for leaks.—A similar procedure to that described on p. 229 on the direct-recording pressure-tube anemograph should be followed.

Daily routine.—*Changing the chart.*—In the course of normal routine the chart at the receiving unit will be changed and any necessary adjustments made without any collaboration at the speed control end. The procedure should be as follows :

(i) Switch off the current, placing one finger lightly on the pulley of the speed-recording unit to prevent it rotating.

(ii) Rotate the pulley by hand until the catch on its circumference is opposite the small drop lever on the frame of the speed unit and clamp in that position by dropping the lever into the catch. If the previous chart has been put on correctly the pen should now be on the zero line and the vertical mark made by the pen will serve as a time mark.

(iii) Lift the pens off the chart by means of the pen lifter, and remove the completed chart from the clock drum.

(iv) Insert a blank chart in position taking the usual precautions (see p. 12).

(v) Lower the pens on to the paper.

(vi) The clock should be raised or lowered until the non-recording direction pen is on its corresponding north line.

(vii) The speed-recording motor and pulley should then be rotated together if necessary, by means of the lever projecting from the casing of the motor until the speed pen is on its zero line. As in most charts the distance between the speed and direction scales is constant this adjustment will normally be unnecessary, but will be required if the speed pen is changed or any alteration made to it. The instrument is so set that the relative positions of the recording pulley and motor, when locked together, correspond to the positions they would take up if they were free, the current was on, and the speed-control unit was in its position corresponding to zero wind speed. Thus by switching off the current and locking them together it is possible to set the speed pen to its correct zero position without direct reference to the control unit.

Adjustment of the pen of the speed-control unit.—(i) If necessary, the amount of shot in the shot cup should be adjusted as in (viii) (p. 228).

(ii) Swing the speed pen into contact with the paper.

(iii) If necessary adjust the speed pen to fall exactly upon the zero line of the speed record by means of its socket screw.

(iv) Return pressure and suction taps to normal position.

Adjustment of the pens of the recording unit.—(i) Follow the procedure described in (i)–(iii) on p. 231. A clutch is provided for disconnecting the helix from the direction motor, but if the current is switched off, as in the present case, the whole system of helix and motor can, if necessary, be rotated easily without using the clutch. The clutch should always be released, however, if any adjustments are being made to the direction recorder while the current is still on.

(ii) Swing the speed pen into contact with the paper, so that it indicates approximately 0 kt., avoiding any splashing of the ink, and, if necessary, adjust it to fall exactly upon the zero line of the speed record by means of the handle on the motor.

(iii) The penholder is designed to lift readily from the pen carriage when it is desired to clean or adjust the pen. Great care must however be taken to prevent ink getting on the pen carriage, or it will clog the bearings of the small wheels and cause sticking ; the current should always be switched off first and the speed pulley clamped. If this last is not done, the excessive counterweight, caused by the removal of the pen, will pull the receiving unit out of phase with the control unit and give rise to heating and vibrating.

(iv) The angle which the speed pen makes with the horizontal depends upon the length of pen projecting from the sleeve of the pen wire. This angle should be as small as possible to reduce pen friction, but it must be sufficient to clear the upper direction pen when both are in their zero position.

Correction for air density.—If the place of observation is more than 300–500 ft. above sea level or there are extremes of temperature or pressure it may be necessary to correct the reading for variations in the air density. The procedure outlined on p. 233 should be followed.

Starting the record.—(i) Note the correct time G.M.T. to the nearest minute and set the clock cylinder, so that the pen marks the correct time on the chart.

(ii) See that all pens are marking.

(iii) Unlock the speed pen and raise it to the estimated wind speed by rotating the pulley by hand. Between 0 and 40 kt. the pen will stay in any set position if correctly balanced (see p. 245).

(iv) Turn the direction-recorder helix until the estimated wind direction is recorded. Place a finger on the direction helix so as to check any sudden swing of the recorder and switch on the current. This damping by the finger is necessary as any large error in the estimated direction will cause the recorder to kick round violently when the current is switched on, with the result that one of the cam knives may be caught and bent.

Time marks.—Time marks should be made by switching off the current and lowering the speed pen to its zero line as in (i) on p. 231. When switching on again the precautions (iii) and (iv) detailed above should be taken. The making of the time mark can be combined with control adjustment (see p. 249) when this is done. Care should be taken in this case not to obscure the lower end of the mark made by the pen when sinking to its "working zero". Time marks should if possible be made twice a day as outlined on p. 11.

Writing up the chart.—This should be done in the standard manner (p. 12).

General maintenance of the recording unit.—The general maintenance of the recording unit should follow closely that given for the direct-recording instrument under the following headings :

Cleanliness

Renewing pens

Oiling.

Adjustment of direction recorder (see also p. 245).

The instructions given on p. 234 should be carefully followed.

The weight of the speed-pen carriage and pen is counterbalanced by a small brass cup to which shot may be added. The amount of shot should be adjusted until, with the current off, the carriage is balanced when the pen is recording approximately 20 kt. Once this adjustment is made it should require no further alteration.

When the speed-recording unit is in action one chain winds round the pulley while the other unwinds so that the balance will not be perfect in all positions. When the pen has reached the 40-kt. line this lack of balance tends to pull the pen further up the chart, but the maximum error due to this cause at 90 kt. is less than 1 kt.

In the normal course of events the movements of the recording units follow those of the control units very closely. On no account should either of the recording units be held in one position while the current is on and the control units are functioning, as this will cause excessive heating and vibration in the units. In particular the speed-recording pen should not be forced down to its zero line in these circumstances as this will slacken the chain at the control end, with the result that the chain may leave its groove. This will also happen if the current is switched on while the speed-receiving pulley is clamped, and the speed-control unit is in operation. Should this occur the control unit should be inspected as soon as possible to check that everything is functioning correctly and that the chain has not left its groove.

The selsyn, autosyn and magslip units give out a slight hum in normal working. If this changes to a definite vibration it will probably be found that some abnormal resistance in turning has been introduced, so that the unit has to overcome an appreciable force to reach its equilibrium position ; the cause should be investigated, and rectified if possible.

Instructions for the three-monthly overhaul of the self-synchronous motor units.—The selsyn and autosyn units have to be overhauled every three months and, at Meteorological Office stations, this should be undertaken by the station staff. Magslip units do not need a three-monthly overhaul. The following procedure should be adopted :

24-V. selsyn units.—(i) Switch off power supply to anemometer. If the selsyn is enclosed in a cylindrical case, remove the screws which hold on the case, and slide the case back to expose the terminals at the rear end of the selsyn.

(ii) Disconnect the five wires from the rear end of the selsyn, marking them clearly A, G, 1, 2 and 3 as they are detached.

(iii) Remove the pulley from spindle by undoing the set-screw in the hub.

(iv) Take out the screws which hold the selsyn in its pillar and remove the selsyn from the pillar.

(v) Take out the three screws which hold on the end cover at the emerging spindle end and pull off the cover. Remove the armature with or without its ball-bearings, being careful not to lose any thin skin washers from the bearing housing. If the ball-bearings come out with the armature, take them off the spindle leaving the two stepped washers in position. If they remain in the end covers, extract them by cutting a piece of hard wood down to a diameter which will just pass through the end cover holes but not enter the inner race of the ball-bearings, and tap the bearings out. To get at the rear bearing, remove the triangular piece of insulating sheet which protects the spindle and contact brush, loosen the nut holding the brush which sticks out of a hole in the side of the centre hole of the rear end cover and normally leans on the side of the spindle.

(vi) Wash the ball-bearings in petrol or paraffin and make certain that they are clean, free from grit or dust, and revolve freely. Lubricate them with a little clock oil. If the bearings cannot be cleaned or are mis-shapen, they should be replaced by new ones (R.A.F. Stores Ref., No. 27S/80).

(vii) Replace the bearings in the end cover.

(viii) Insert the rear end of the spindle into the rear bearing, first making sure that one of the stepped washers is on the spindle, between the bearing and the rear end of the armature, with its flat side away from the bearing ; take care not to damage the spring-loaded brush.

(ix) Replace the second stepped washer on the front end of the spindle with its flat side towards the armature, then replace the ball-bearings on the spindle.

(x) Replace the front cover. The three screws which hold it in place should be tightened gradually until the cover is fully home ; but, should this result in the spindle binding, the screws should be relaxed slightly until the spindle revolves freely.

(xi) Replace the spindle rear end contact brush and tighten the nut which holds it in position.

(xii) Replace the triangular insulating sheet and put the selsyn back on its pillar.

(xiii) Re-connect the wires A, G, 1, 2 and 3 (Fig. 77) to the correct terminals and replace the selsyn cover, if any, and then replace pulley on shaft.

(xiv) When both the selsyn units have been overhauled in this manner and re-connected, set them relatively to each other in accordance with the instructions on p. 246 and p. 247.

32-V. autosyn units.—The instructions given for the 24-V. selsyn units should be followed with 32-V. autosyn units, but with the following differences :

(i) The brush which bears on the side of the spindle is contained in a small circular housing held to the outside of the front cover by two screws. This housing, complete with brush, should be taken off before the cover is removed. Great care must be exercised not to lose the brush and its spring, which are very small and easily lost.

(ii) The ball-bearings are smaller in autosyn units and a smaller wooden push rod will be needed to facilitate their removal. For replacement purposes the R.A.F. Stores Ref. No. is 275/40.

(iii) In reassembling, the brush housing is replaced after the front cover has been replaced. On some units the triangular insulating sheet has not been fitted.

230-V. large selsyn units.—The overhaul of these units involves removing them from the head or recording units ; and in both cases the selsyn unit will have to be re-aligned after overhaul.

These large units should not be overhauled locally ; any trouble at Meteorological Office stations in their behaviour should be reported to the Instruments Provisioning Branch who will arrange for them to be overhauled.

It has been found that the large selsyn unit will normally run for a year or more without giving trouble, and the unit at Meteorological Office stations will be overhauled at the time of the annual inspection of the instrument by the instrument mechanic from the Instrument Provisioning Branch.

Maintenance of the speed-control unit.—The general maintenance of the recording unit should follow closely that given for the direct-recording instrument under the headings below :

Cleanliness
Water level
Draining plug.

It is unnecessary to obtain a continuous record of speed from the control unit ; a record should be obtained only when required for test purposes. The pen and pen arm will normally not be in position on the pen rod.

When a record is not being obtained the control unit should be visited about once a week, or on any occasion when the record obtained from the recording unit suggests that the control unit may be in need of adjustment. The unit should then be inspected to see that everything is functioning correctly and to adjust the amount of shot in the cup. The water level will also require occasional checking and adjusting.

The procedure should be as follows :

(i) Ring up the home station and inform the observer in charge of the receiving unit that the adjustments are about to be made.

(ii) Close the stopcocks and allow the float to sink to its equilibrium position without touching it.

(iii) The observer at the home station will see that the recording pen has marked down to its equilibrium position ; he will then lift the pens off the paper by means of the pen lifter, clamp the speed pen in its zero position and switch off the current. The point to which the recording pen falls should be marked by the observer at the home station and the remark "control adjustment" written beside it later when the chart is removed.

(iv) If necessary the amount of shot and the water level should be adjusted in the normal manner. This adjustment should always be made with the current switched off.

(v) The observer at the receiving unit should then be instructed to switch on the current and unclamp the speed pen. While switching on the current he should check the movement of the direction-recording mechanism by holding a finger lightly on the helix. The pens should then be allowed to fall on the paper again.

(vi) Open the stopcocks.

If a record is being obtained from the control unit the chart should be changed in the usual way when the adjustment (iv) above is being made.

From time to time opportunity can be taken to check the setting of the direction recorder by asking the operator at the control end to report the wind direction over the telephone.

Removal of vane for cleaning and lubricating.—The vane is removed simply by lifting it off the head, no preliminary work being necessary before this operation. If it does not lift readily the resistance will be due to corrosion, and it should be lifted and rotated at the same time until it comes away. The brass spindle on which it is mounted should then be rubbed smooth with a piece of very fine emery cloth and the small cup at the top filled with petroleum jelly. A piece of the same emery cloth should be wrapped round a stick or small piece of tube, and used to rub smooth the inside of the upright tube which forms part of the vane which fits over the upright spindle when the vane is in position. Finally the parts should be cleaned with a rag to remove all grit left by the emery cloth. The outer surface of the fixed part of the head above the suction holes should also be cleaned, and then left with a slightly greasy surface, but no oil or grease should be applied to the brass rubbing surfaces. A little petroleum jelly applied as stated above is the only lubricant required. The vane can then be replaced.

Removal of head.—To remove the fixed part of the head, lift off the vane, take off the conical nut and remove the conical shield. Disconnect the vane spindle from the selsyn motor spindle by loosening the screws of the coupling sleeve, and then disconnect the pressure and suction pipes below the elbow by unscrewing the union. The head can then be unscrewed from the casting.

This will normally be required only when a new head is to be fitted, or when the head is to be transferred to another mast.

Accuracy and sources of error.—The remote-recording pressure-tube anemograph has similar characteristics to the direct-recording instrument, and the accuracy in steady winds should be almost as good (see p. 238) ; the error caused by the selsyn and autosyn units should not exceed $\frac{1}{2}$ kt. or 2° in the speed and direction records respectively, provided the units are overhauled regularly. The extra lag introduced into the system is small compared with the lag of the direct-reading instrument.

5.5.3. Special floats for the pressure-tube anemograph

The standard float for the pressure-tube anemograph is designed so that the speed scale on the chart is 6·91 in./100 kt. (6·0 in./100 m.p.h.). A few special floats have, however, been manufactured whose shape is based on a value of $q = 0 \cdot 320$ (see p. 223) giving a speed scale of 3·46 in./100 kt. (3·0 in./100 m.p.h.). If a float of this shape, and of length about the same as a normal float, is used in a normal float chamber it will record up to 120–130 kt. ; but at higher wind speeds air bubbles out from beneath the bottom of the float. To extend the range a longer float and float chamber are required.

It is also possible to design a float which has a scale of 0·691 in./10 kt. up to, say, 40 kt., and then 0·346 in./10 kt. up to about 170 kt. The upper part of the float trumpet would then be identical with that of the normal float, but at about 12 cm. below the zero water level there would be a horizontal shoulder and from then on the trumpet would be of a similar shape to that described above. Its total length would be about 20–22 in. more than the normal float.

5.5.4. Effect of icing on pressure-tube anemographs

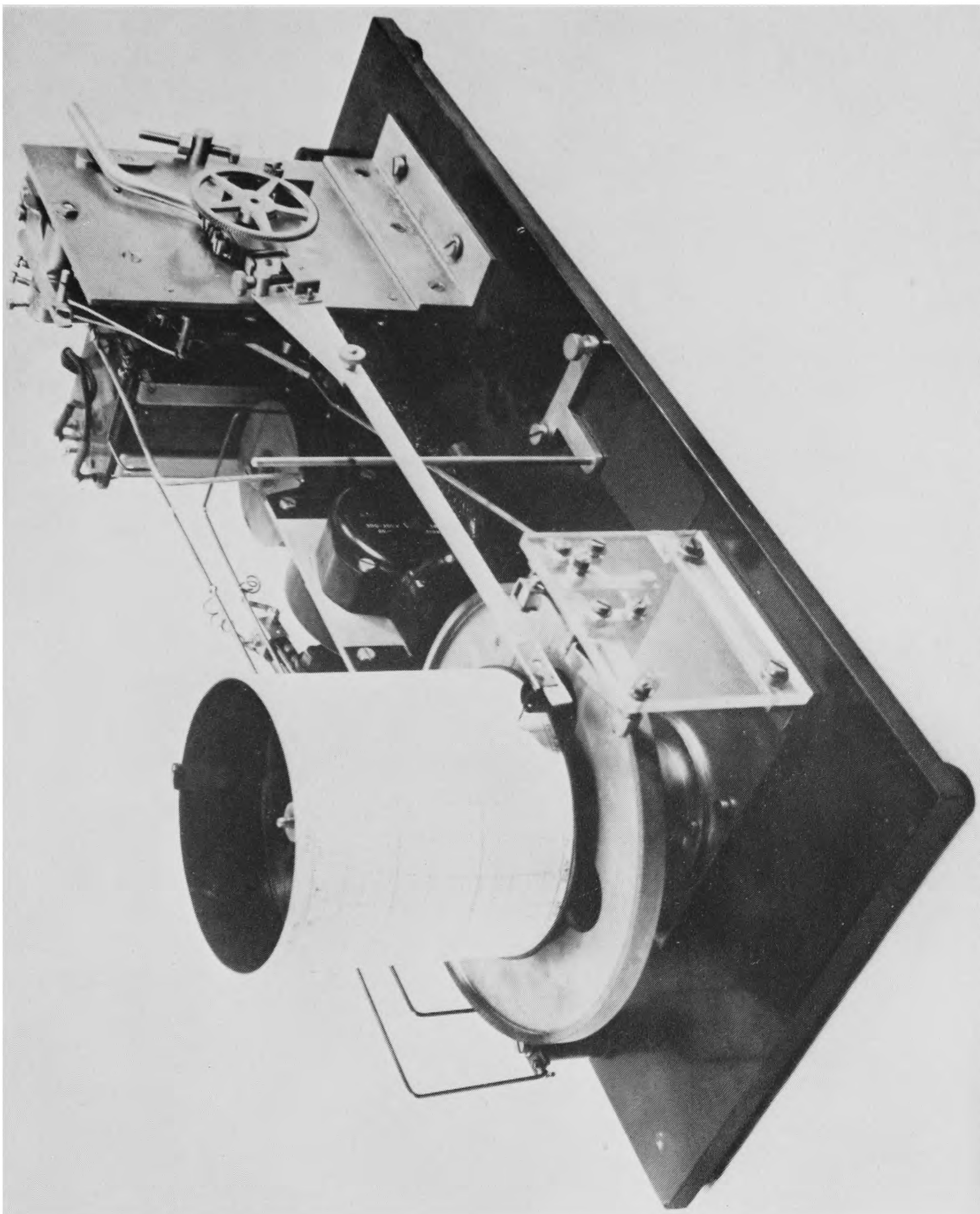
If the head of a pressure-tube anemograph is exposed to snow, or rain, or cloud composed of supercooled water drops it is liable to become blocked by the packing of the snow or the formation of ice in the entrance tube or the static holes. This is not often experienced in the British Isles but is more common in countries which have colder winters.

This can be alleviated to a certain extent by a well designed electric heating system on the anemograph head, but it is difficult to ensure complete immunity in the severest conditions.

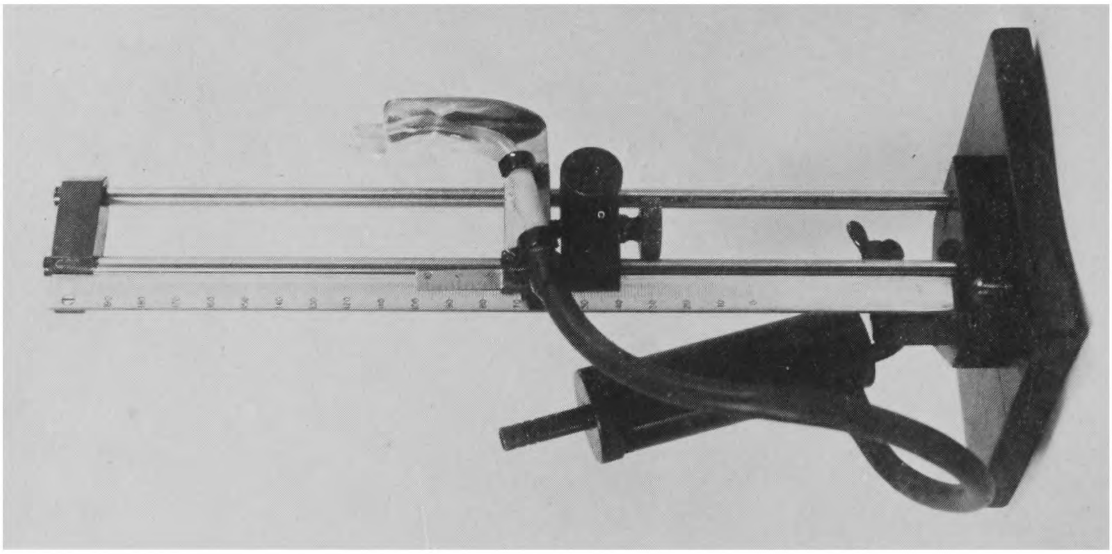
5.6. CUP ANEMOGRAPHS

5.6.1. Cup contact anemograph Mk II

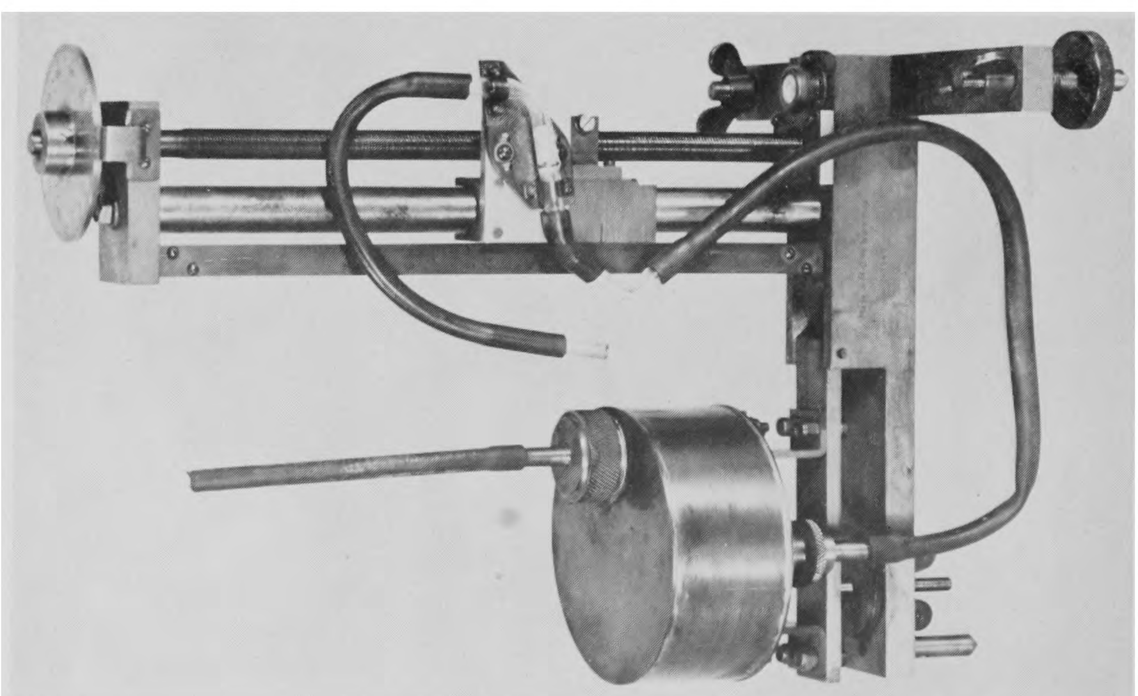
The Meteorological Office electrical impulse recorder Mk II (Stores Ref., Met. 985) is designed to record the number of electrical contacts made in successive small intervals of time (Plate XXXV). If the contacts are made by a cup contact anemometer, the number of contacts in a given interval is a measure of the mean wind speed over the interval, and the complete instrument is called the cup contact anemograph Mk II. The pen arm is connected to a modified electric impulse clock movement, and at each contact it is rotated through a small fixed angle. A time switch, governed by a small synchronous motor, closes another contact at fixed intervals and brings the pen back to its zero position and at the same time moves the drum round by a discrete amount. The record on the chart thus consists of a series of parallel curves whose lengths correspond to the mean wind speeds. The time interval over which the mean speed is obtained can be either 3 min. or 1 min. The drum-movement mechanism and the impulse mechanism are supplied with 6 V. d.c. from the 230-V. a.-c. mains via a transformer and metal rectifier (full wave), while the synchronous motor operates directly from the a.-c. mains. Full-scale deflection is obtained for 76 contacts, so that, with a time interval of 3 min. between successive movements of the pen back to zero, mean wind speeds over this interval of up to 65 kt. can be recorded. If the 1-min. interval is used the maximum speed is 195 kt.



METEOROLOGICAL OFFICE ELECTRICAL IMPULSE RECORDER MK II



METEOROLOGICAL OFFICE TILTING MANOMETER



STANDARD FORM OF MANOMETER

The time scale on the chart depends on the time interval selected, as the drum is rotated through the same small angle each time the pen returns to zero. The drum is of the same external dimensions as the standard S type, and the standard time scale of 11·4 mm./hr. for daily charts is obtained with the 3-min. interval. With the 1-min. interval the time scale is 34·2 mm./hr., and the chart only lasts just over 8 hr. instead of just over 24 hr.

Installation.—The recorder should be mounted on a convenient shelf or table where it will be free from vibration, and the two leads from the contact anemometer should be connected to the two terminals marked " input ". The other two terminals marked " 230 V. a.c." should be connected to the 230-V. a.-c. mains supply. Any standard Meteorological Office cup anemometer giving one contact for every $\frac{1}{20}$th of a mile of wind can be used.

The only adjustment which is likely to be required is to set the pen correctly on the zero line. This can be done by adjusting the milled headed screw on the pen arm, after slackening the locking nut.

Method of use.—There are no special features in the operation of this recorder. The normal daily routine for recording instruments should be followed.

Accuracy.—The instrument should record accurately the contacts made by the anemometer. As the speed recorded is the mean speed over a period the trace obtained differs considerably from that of the pressure-tube anemograph. The gusts and lulls are very much smoothed out. The response of the cup anemometer has already been discussed (p. 194).

5.7. CALIBRATION OF ANEMOMETERS

Anemometers were originally calibrated by mounting them on a large arm which could be rotated in a horizontal plane at known speeds, in a place where the natural air speed was zero or negligible. At the present time, however, almost all testing and calibration is performed in a wind tunnel, in which the air speed can be varied and controlled. The measurement of the actual wind speed in the tunnel is usually carried out (either directly or indirectly) by some type of pitot-static tube whose calibration depends, in turn, on the calibration of a standard form of pitot-static tube carried out on a whirling arm apparatus.

5.7.1. Manometers

The manometers used in measuring wind speed have to be able to measure pressure differences to an accuracy better than 0·05 mm. of water if air speeds below 5 kt. are to be measured. A simple instrument is the Krell inclined-tube manometer (Fig. 78). The sources of pressure are connected to the two arms of what is virtually a U-tube containing a quantity of liquid, one arm of which, A, is inclined at a small angle to the horizontal ; the liquid in this arm will move a considerable distance along the tube for a small amount of vertical motion (i.e. for a small applied pressure difference). The other arm, B, is a large reservoir having an area several hundred times that of the inside of the inclined tube ; in this way the liquid level in the reservoir remains practically constant and the motion occurs only in the inclined tube. A scale along the glass tube enables the movement of the liquid meniscus to be measured. The glass tube is normally mounted on a frame which is hinged at one end so that its inclination to the horizontal can be altered. In this way the sensitivity and range of the manometer can be varied. It is usual to calibrate this manometer for two separate positions of the inclined tube ; e.g. with the tube at an inclination of 11° to the horizontal a 12-in. scale enables wind speeds up to 48 kt. to be measured, while if the tube is inclined at $2\frac{1}{2}$° wind speeds up to 23 kt. can be measured, assuming that alcohol is the liquid used in the manometer (as is normally the case).

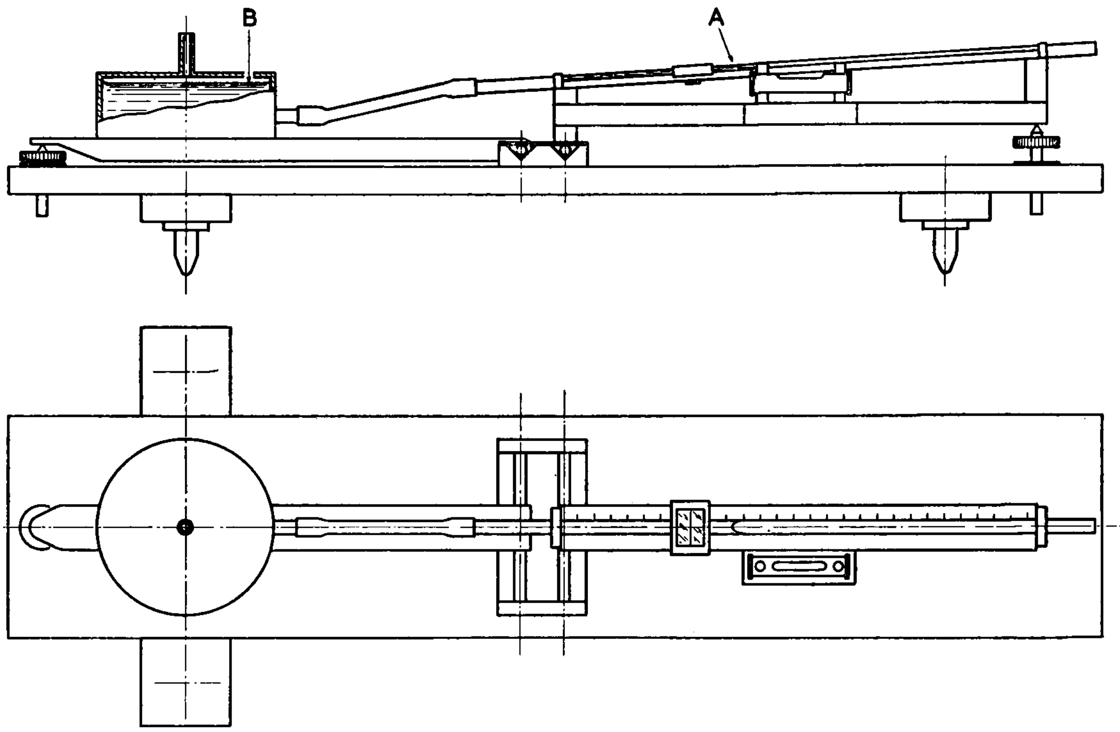


FIG. 78—KRELL MANOMETER

A more accurate manometer, suitable for use with a standard pitot-static tube, is shown in Plate XXXVI. This consists of a U-tube with one short limb inclined at a small angle to the horizontal and connected to the other, much larger, limb by means of a length of rubber tubing. The short inclined limb is mounted on a platform which can be raised or lowered by turning a micrometer screw, and in this way the liquid meniscus in the inclined tube can always be brought to a fixed mark. The movement of the platform carrying the inclined tube, between the zero position with no pressure difference between the two limbs and the final position, can be determined accurately by means of the graduated head of the micrometer screw and a fixed scale by the side of the platform.

The fixed limb consists of a reservoir of large cross-section, so that changes in the level of the liquid in it due to changes in the volume of the connecting tubing can be neglected. The change in height of the platform together with a knowledge of the density of the liquid used enables the applied pressure difference to be calculated.

This instrument is not so simple or rapid in use as the plain inclined-tube manometer, but it has the great advantage that it does not require calibration once the accuracy of the screw thread has been checked.

The Meteorological Office tilting manometer (Stores Ref., Met. 1956) is a simple portable manometer of a similar form (Plate XXXVI). The height of the small inclined tube is read on a millimetre scale with a vernier for readings to 0·1 mm. An adjusting screw enables the final setting to be made accurately, but the main movement is obtained by slackening the clamping screw and lifting the platform carrying the glass tube. The platform moves along the two guide rails. This manometer is used chiefly for checking the calibration of pressure-tube anemographs at speeds above 5 kt. Alcohol is the liquid used, and the accuracy of the manometer is about $\pm$ 0·1 mm. of alcohol. See p. 237 for details of the method used in calibrating the anemographs.

CHAPTER 6

MEASUREMENT OF PRECIPITATION

6.1. GENERAL

6.1.1. Purpose of measurement

Water falls on the surface of the earth in the form of rain, snow, sleet, drizzle, hail and is deposited on it in the form of dew and hoar-frost. The purpose of precipitation measurements is to obtain as much information as possible about the amount and distribution, in time and space, of this precipitation. The simplest and most usual way of doing this is to set up gauges with a horizontal circular aperture of known diameter, and to collect and measure at regular intervals the precipitation which falls through the aperture. It is assumed that the amount collected per unit area of the aperture of the gauge is the same as the amount per unit area which falls on the surrounding surface.

The earliest known actual measurements of rainfall were made by Castelli in Italy in 1639. His gauge consisted simply of a glass cylinder about 5 in. in diameter and 9 in. deep. The first measurements in the British Isles of which records are in existence are those made by a Mr. Townley, of Townley near Burnley, in 1677. No particulars are available about his gauge except that it was exposed on a roof and the water was conducted down through a pipe before it was measured.

The standard types of rain-gauge now in use in the British Isles are the result of gradual development from these earlier patterns, but the principles of the instrument are unchanged from those of the instrument said to have been devised by Castelli. Many different designs of gauges were devised during the nineteenth century, and in 1859 G. J. Symons took up the task of systematizing rainfall measurements in this country. He undertook several series of experiments into the design and size of the instrument, the materials of construction and the methods of exposure, and, as a result, was able to recommend the first steps towards standardization.

There are probably few regions of any size which have a denser network of gauges than one to every ten square miles, so that, with a gauge diameter of 5 in., the area from which water is actually collected and measured is under one thousand millionth part of the area for which the measurements are taken to be representative. In most regions the fraction is much smaller. It is thus necessary to ensure that the exposure of the gauge is such that local sources of error are reduced as much as possible.

6.1.2. Units of measurement

Precipitation is measured on the basis of the depth to which a flat horizontal impermeable surface would have been covered if no water were lost by run-off or evaporation. A measurement is made of the total precipitation, whether of rain, hail or snow, in the form of liquid water ; that is, any snow or hail is melted and added to any rain that has already fallen. In addition, in heavy falls of snow, a measurement is taken of the depth of snow which has fallen since the last observation. As an approximation 1 ft. of snow is taken to give 1 in. of liquid water, and this is used as a check on the readings recorded in the gauge itself by melting the snow collected. The details of the methods to be used in this case are dealt with more fully later.

The units of depth in current use in the British Isles are millimetres and inches. In the Meteorological Office all observations are made in millimetres but other observers frequently use inches (25·4 mm. = 1 in.).

6.2. NON-RECORDING RAIN-GAUGES

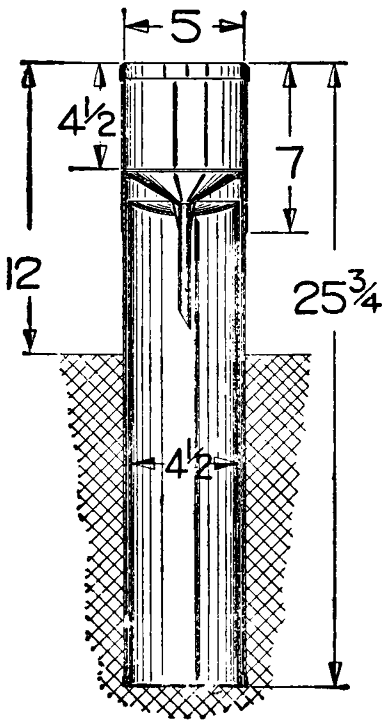
Non-recording rain-gauges may be divided into two main classes, those which are read at daily intervals and those which are only read at intervals of a week or month.

6.2.1. Daily rain-gauges

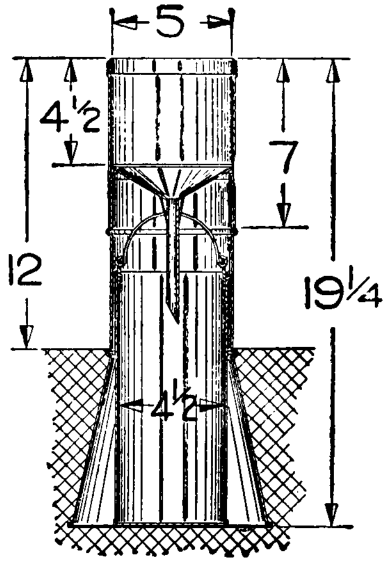
Meteorological Office rain-gauge Mk II.—The upper part of the Meteorological Office gauge Mk II (Stores Ref., Met. 2840) consists of a cylindrical portion with an accurately turned and bevelled brass rim, to which the funnel is attached (Fig. 79). This fits closely on top of an outer case with a splayed base. Inside the outer case is a cylindrical inner can with a handle of brass wire, and inside the inner can is placed a glass bottle (Stores Ref., Met. 492) with a narrow neck. The cylindrical portion and inner can are made from seamless drawn copper tubing, but the remainder of the gauge, apart from the brass fittings and the bottle, is made from sheet copper with soldered seams. The use of copper tubing in the construction of the cylindrical portion ensures the interchangeability of the funnels among different gauges.

The brass ring should have a mean diameter which is accurately 5 in. and should not be deformed in any way. The cylindrical section is made over 4 in. deep to minimize the amount of rain lost by splashing from the sides of the funnel and to hold a reasonable quantity of snow or hail. This deep rim is a feature common to all types of gauge approved by the Meteorological Office. The rain is collected in the glass bottle or exceptionally it may overflow into the inner can. On rare occasions the inner can may be filled as well and the water overflow into the outer case. When this occurs the outer case has to be dug up and the water transferred to a suitable vessel before measuring.

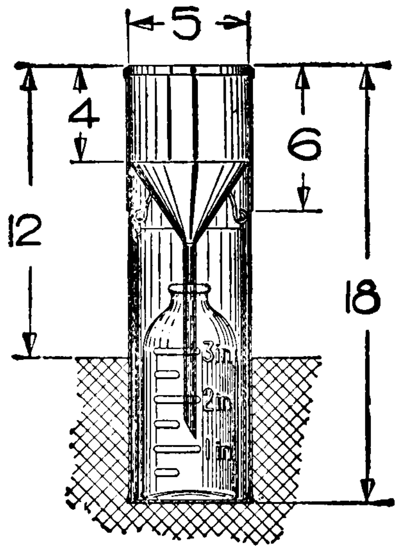
Meteorological Office rain-gauge Mk I.—The Mk I rain-gauge (Stores Ref., Met. 182) is an earlier pattern of the Mk II and is similar in operation, dimensions and lay-out. The main difference is that the cylindrical portion of the funnel and the inner can are manufactured from sheet copper with soldered seams and of a thinner gauge than the copper tubing of the Mk II. The funnels are not so strong, and their interchangeability among different gauges cannot be guaranteed owing to slight variations in the diameters of the cylindrical portions. If a funnel is damaged it is necessary to return the whole gauge.



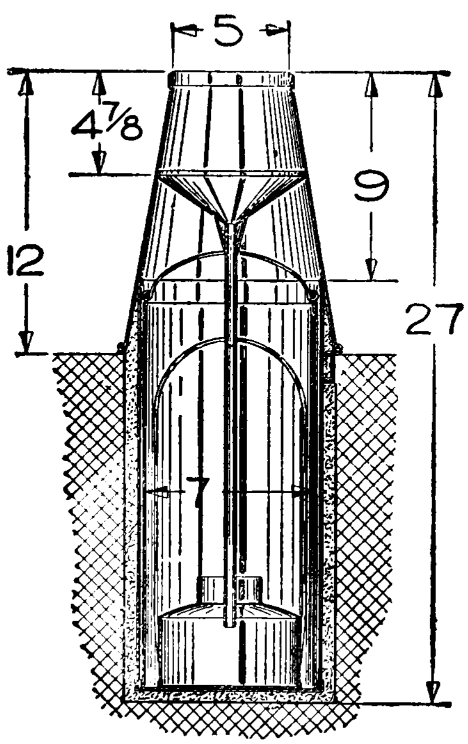
Bradford rain-gauge Mk IV



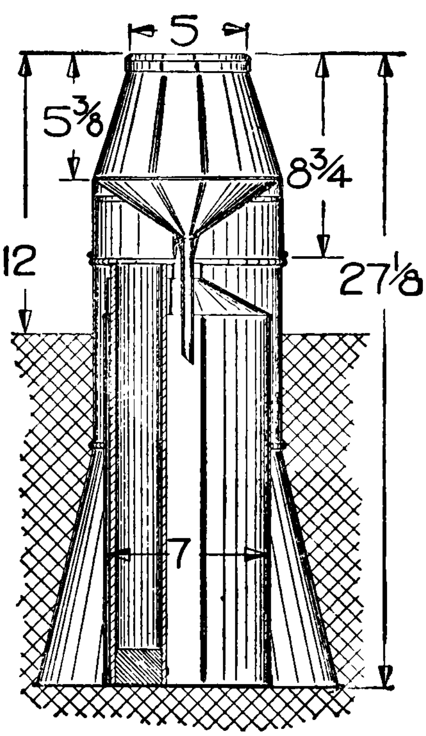
Meteorological Office rain-gauge Mk II



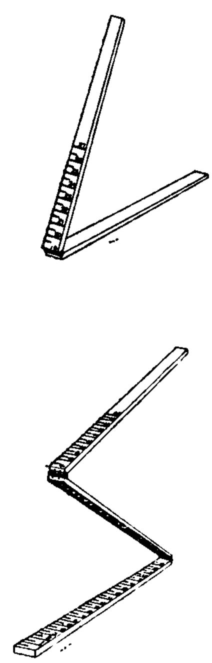
Snowdon rain-gauge



Seathwaite rain-gauge



Octapent rain-gauge Mk IIA



Dip-rods

FIG. 79—APPROVED TYPES OF RAIN-GAUGES AND DIP-RODS

Dimensions are given in inches

Snowdon rain-gauge.—The general arrangement, operation and dimensions of the Snowdon gauge are similar to the Meteorological Office gauge, but with the main difference that it has not a splayed base (Fig. 79). The diameter of the aperture is 5 in., but the spout of the funnel is longer than that of the Meteorological Office gauge. Another difference is that it is sometimes made of zinc instead of copper.

The name " Snowdon " was originally given to the type of funnel in use in the Snowdon and Meteorological Office gauges. It is distinguished from earlier types of funnel by the deep cylindrical section above the funnel proper. The necessity for this was not always recognized, and many funnels in use had only a very shallow rim with a consequent loss by outsplashing.

6.2.2. Monthly rain-gauges

Monthly gauges are for use on mountains, moors and other isolated localities where readings can only be taken at weekly or monthly intervals. The main differences between these and the daily types just described are their larger capacity and stronger construction.

The types of gauge described in this section are the Octapent Mk I, Mk IIA and Mk IIB, the Bradford Mk I and Mk IV and the Seathwaite. The Bradford and Seathwaite were the earliest types, the Bradford being designed originally for use at the moorland stations of the Bradford Corporation Waterworks in Yorkshire, and the Seathwaite by Dr. H. R. Mill for use in mountainous regions with exceptional rainfall, such as Seathwaite in Cumberland. The Octapent was designed by the Meteorological Office, and consists essentially of a funnel from a 5-in. gauge fitted on to the base of an 8-in. gauge (hence Octa-pent).

Octapent rain-gauges Mk IIA and Mk IIB.—The Octapent rain-gauge Mk IIA (Stores Ref., Met. 82) consists of the funnel with the usual accurately turned and bevelled brass rim 5 in. in diameter which fits on top of the outer case consisting of a cylindrical portion soldered to a splayed base (Fig. 79). Inside the outer case is an inner collecting can. This has a narrow opening at the top for the entry of the funnel tube, and a larger circular opening to one side of the funnel entry for the insertion of a " frost protector ". The can is provided with a handle at the top and also a pair of handles at the side to assist in pouring the water out. These handles fold closely to the sides of the inner can when it is inserted in the outer case. The inner can is made from seamless drawn copper tubing of as uniform a diameter as is obtainable. The dip-rod provided for use with the gauge can thus be used with any other gauge of the same type.

The Mk IIB (Stores Ref., Met. 83) is similar to the Mk IIA except that it has a longer central cylindrical portion and a correspondingly longer inner can giving it a maximum capacity of 50 in. of rain as opposed to the 27 in. of the Mk IIA. The Mk IIB is intended for use in regions of high rainfall, where, owing to the inaccessibility of the gauge and possible inclemency of the weather, it may have to be left occasionally for as long as two months or more without a visit.

The remainder of both the gauges is constructed of copper with brass fittings. The use of copper tubing for the cylindrical parts of the gauges ensures interchangeability. The dip-rod (Fig. 79) is made either from cedar wood or from laminated plastic, and is graduated in $\frac{1}{2}$ in. of rain up to a maximum of 27 in. or

50 in. according to the model of the gauge for which it is intended. For convenience in carrying and storing it is hinged (one hinge in the Mk IIA and two hinges in the Mk IIB). The surface of the plastic dip-rods may be improved, if necessary, by treatment with a fine emery cloth using a circular motion or a motion across the width of the rods rather than one parallel to the length of the rods. The inner cans should always be carefully handled to avoid any dents which may impair the accuracy of the measurements with a dip-rod or which may cause damage.

The frost protector (Stores Ref., Met. 599) consists of a length of stout rubber hose weighted and closed at the lower end with a piece of lead, and it is just long enough to come to the top of the inner can when placed upright therein. It operates by collapsing slightly under the pressure due to the expansion of the water when it freezes into ice, and thus relieves the walls of the inner can from excessive pressure. Care should be taken when inserting the protector not to drop it violently on to the base of the inner can because the lead weight at the end may then cause damage. It should be removed before a measurement is made with the dip-rod.

When measuring the rain the dip-rod should be inserted into the inner can until the metal tip touches the base. The rod is then withdrawn and the amount of rain is given by the length of the rod which is damp ; it can be estimated to the nearest 0·1 in. As the diameter of the inner can is 7 in., an inch of rain gives a depth of only 0·51 in. of water in the can, and this is the actual distance apart of the inch graduations on the dip-rod. The amount of rain as measured by the dip-rod should be noted, and then the water should be measured accurately by means of a rain measure (see p. 266). Both readings should be entered in the observation book. When not in use the dip-rod should be stored in a cool dry place.

Octapent rain-gauge Mk I.—This earlier pattern of the Octapent rain-gauge is of the same size and shape as the Mk IIA but differs in details of construction. The inner can and the remainder of the gauge, apart from fittings, are constructed from copper sheet, and, as a result, the dip-rod and the inner can have to be matched together. In the event of damage to the dip-rod it is necessary to return the inner can so that the new dip-rod can be calibrated with the inner can with which it is going to be used. The dip-rod is made of cedar wood with graduation marks for every ½ in. of rain. It is not provided with a hinge. The method of operation of the gauge is similar to the later patterns.

Bradford rain-gauge Mk IV.—The Bradford rain-gauge Mk IV (Stores Ref., Met. 2839) has a 5-in. diameter aperture and is constructed mainly of copper ; seamless copper tubing is used for the inner can, the cylindrical portion of the funnel and, in some instruments, for the outer case (Fig. 79). In general arrangement it is similar to the Snowdon gauge (in particular it has not a splayed base) but is much deeper. To minimize evaporation the inner can is fitted with a diaphragm at the top which is perforated only (*a*) for the admission of the funnel tubing and the dip-rod and (*b*) at one side to pour out the water. The dip-rod and funnel are interchangeable among different gauges as copper tubing is used in the construction of the inner can and the cylindrical portion of the funnel. The dip-rod is made of cedar wood or laminated plastic with graduation marks every tenth of an inch of rain up to a maximum of 15 in., and is hinged in the centre for convenience in carriage and storing. In its method of operation and use the gauge is similar to the Octapent gauges.

Bradford rain-gauges Mk I, Mk II and Mk III.—The Bradford gauge Mk I (Stores Ref., Met. 523) is an earlier pattern of the Mk IV. The main difference is that no seamless copper tubing is used in its construction ; all the copper parts are made from copper sheet. As a consequence the dip-rod can be used only with the inner can with which it was issued, and the funnel, in general, cannot be used with any other gauge. A few models have been made which are longer than normal and can hold up to 27 or 40 in. of rain (Mk II and Mk III) (Stores Ref., Met. 409 and Met. 410 respectively). The dip-rods are made of cedar wood and graduated as the Mk IV dip-rods. They are not hinged.

Seathwaite rain-gauge.—The Seathwaite gauge (Fig. 79) is of a similar size to the Octapent Mk IIA, and may be used as an alternative to this gauge. It has not a splayed base and the depth of the top of the funnel beneath the rim is ½ in. less than in the octapent gauges. The diameter of the aperture is 5 in. and the inner can has a similar capacity to the Octapent Mk IIA (i.e. 27 in.). Surrounding the outer can is an annular space filled with pitch to serve as a precaution against damage by frost. Unlike the previously described monthly gauges, it is not always made of copper, galvanized iron being used in some models.

The main difference in its operation is the use of a copper dipper for measuring the amount of rain. This has a narrow neck, and has a long handle attached ; when filled to the lip it holds exactly 5 in. of rain. A measurement of the contents is first made by means of a dip-rod, and then the dipper is carefully inserted in the inner can and pressed down to the bottom so that it becomes filled with water. It is then withdrawn bringing out 5 in. of rain ; the amount is noted and the dipper emptied and re-inserted. This is continued until the dipper at last comes out only partially filled. The water is then poured from the dipper into a measuring glass and measured. The measurement is completed by pouring the remaining water in the inner can into a measuring glass, measuring it and then adding together all the partial measurements. The measurements by dip-rod and by dipper and measuring glass are noted separately.

6.2.3. Accuracy required

The amount of the total precipitation is measured to the nearest 0·1 mm. or 0·01 in., and the depth of snow to the nearest whole millimetre or 0·1 in.

The accuracy with which the catch of the gauge represents the amount of rain which has fallen in its vicinity depends on (i) the multiple factors which may be summed up as due to the " exposure of the gauge " which are dealt with later, and (ii) the accuracy of the constituent parts of the gauge itself, e.g. the accuracy of the measuring glass, how close the aperture of the gauge is to its nominal diameter, and the accuracy of the dip-rods and inner can combined.

The Meteorological Office types of gauge have a specified maximum error of ± 0·01 in. in the mean of any four equally spaced diameters of the aperture of the gauge, with a tolerance of ± 0·02 in. in any one diameter. This is equivalent to a possible error of ± 0·4 per cent. in the area of the aperture of the 5-in. gauges. The maximum errors allowed in the rain measures are different for different types of measure (see p. 267). In a taper measure for a 5-in. gauge graduated every 0·01 in., and of total capacity 0·50 in., the tolerance at each graduation mark up to 0·09 in. is ± 0·002 in. (± 20 per cent. of the interval between graduations), and above that ± 0·004 in. (± 40 per cent.). All measurements refer to inches of rainfall.

In the earlier monthly gauges the maximum errors allowed on the combined inner cans and dip-rods was $\pm$ 0·1 in. of rain or $\pm$ 1 per cent. of the rainfall, whichever was the greater. In the later Octapent type the dip-rods themselves have a maximum tolerance of $\pm$ 0·02 in. of rain, while the uncertainty in the diameter of the inner can leads to a possible error of $\pm$ 0·3 per cent. In the Bradford type (latest model) the corresponding figures are $\pm$ 0·02 in. of rain and $\pm$ 0·4 per cent.

The combined accuracy of the instrument (collecting aperture, inner can, rain measure and dip-rod) is well within the uncertainty caused by the varying exposures of different gauges and the losses occurring due to the technique of the measurement (pouring from one vessel to another).

6.2.4. Effect of exposure

The quantity of water collected in a gauge has been found to depend on the exposure of the gauge to the wind and also on the disposition and height of surrounding objects. The variation caused by the wind is mainly due to wind eddies around the gauge in a vertical plane, up-currents reducing the catch and down-currents increasing the catch; the more frequent and stronger the eddies, the less is the total catch. The strength and frequency of these eddies depend on the force of the wind, the general contour of the ground surrounding the gauge, the distance away and the height above the gauge of the surrounding objects, and the height of the gauge itself above the surrounding ground level. It is important that the observations at different stations should be comparable, and thus that their exposures should be similar. With this object in view the site of a rain-gauge should be chosen so that the vertical eddies are a minimum, without at the same time losing any of the catch due to direct shading by surrounding objects. The following rules for the siting of gauges have been formulated using these principles.

The gauge should be on level ground, not upon a slope or terrace and certainly not on a wall or roof. It should on no account be placed where the ground falls away steeply on the side from which the prevailing wind blows. Its distance away from every surrounding object should be not less than twice the height of the object above the rim of the gauge and preferably four times. Provided these conditions are satisfied a position as sheltered from the wind as possible is preferable to an exposed one, especially on mountain, moorland or coast stations. At these stations great care should be taken to avoid over-exposing the gauge to the sweep of the wind.

Where it is impossible to secure an exposure with some natural shelter it is often desirable to build a turf wall around the gauge after selecting the most suitable site. The recommended wall (see Fig. 80) has an inside diameter of 10 ft. with its crest

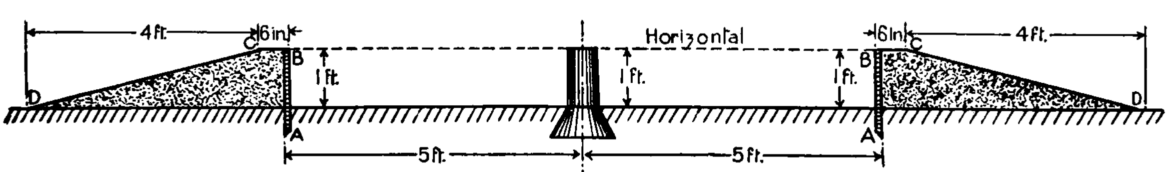


FIG. 80—TURF WALL FOR USE AT EXPOSED RAIN-GAUGE SITES

horizontal and in the same plane as the rim of the gauge. Its inside should be vertical and the outside sloping down gradually, preferably by about 1 in 4, and its crest should be about 6 in. thick. To avoid changes in the height of the turf wall and thus in the exposure of the gauge the inside should be supported by wooden palings driven into the ground with their tops level with the rim of the gauge and the crest of the wall. A drain-pipe should be fitted to drain off the water which collects inside the turf wall.

The main eddies formed in very open situations, such as those which require a turf wall, are due to the obstruction of the gauge itself. If however the rim of the gauge were placed close to the ground level to reduce these eddies, there would be an increasing amount of rain splashing into the gauge from the surrounding surface of the earth. As a compromise between the two factors the standard height of the rim of a rain-gauge above the surrounding ground is fixed at 12 in., and this should always be adhered to.

Another method of attempting to eliminate the effect of wind on the catch of a rain-gauge is to fit shields to the gauge itself. These are designed to modify the wind flow around the gauge so that the resultant flow across the mouth of the gauge is strictly horizontal. If the shield is efficient the catch of the gauge would be independent of the wind speed and the gauge could be mounted at any height above the ground. The type of shield recommended by C. F. Brooks[48] is a development of the original idea of F. E. Nipher in 1879. Fig. 81 shows the general shape. The outer 5 in. or so slopes inward at only 10° to the horizontal and joins on to a more steeply sloping part (at 60°). This steeper portion is then joined to a vertical section ; the shield is symmetrical about the central vertical axis . On the outer rim is fixed a raised, fine-wire screening to minimize splashing, and there is space between the shield and the gauge itself to allow rain and snow which is caught in this area to drain away. The shield illustrated is for a gauge

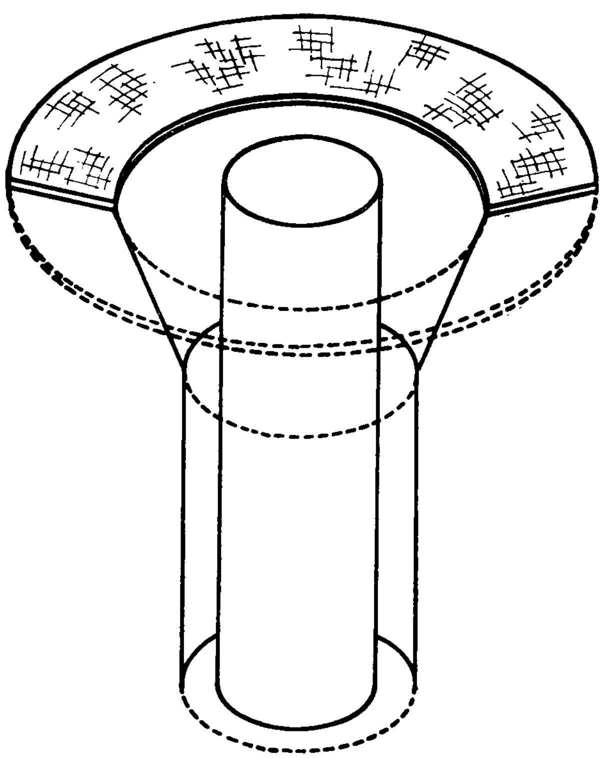


FIG. 81—SHIELD FOR RAIN-GAUGE

8 in. in diameter ; for other gauges with different diameters the proportions might have to be altered. These shields are not used by the Meteorological Office.

6.2.5. Installation and use of rain-gauges

The gauge should be planted in the earth, or set in an earthenware drain-pipe fixed in the ground, and fixed firmly so that it will not be blown over or tilted by the strongest winds. The best surrounding surface is short grass, but if this is not possible the gauge may be set up in gravel or shingle or the like. A hard smooth surface such as concrete should be avoided because of the increased risk of rain splashing into the gauge. The soil should be pressed firmly around the outer case but not rammed down excessively, as there is otherwise a risk of starting the seams. The rim of the gauge should be exactly 12 in. above the surrounding ground and set horizontal. It is advisable to check this with a spirit-level laid across the rim. If the gauge is surrounded by grass this should be kept cut short. The height above mean sea level on which the rain-gauge stands is used as the official height of the station, and should be determined, to the nearest foot if possible, by levelling from the nearest Ordnance Survey bench mark or by other means (see p. 25).

The object in using the glass bottle in the daily gauges is to facilitate the measurement of the rainfall in windy weather. It is easier to pour water from the bottle into the measure without spilling any than it is from the inner can itself. A careful watch should be kept for cracks in the bottle, and any cracked bottle should be immediately replaced because of the risk of leakage. To keep the bottle clean it should be washed out occasionally (and thoroughly dried afterwards). It is an advantage to have two bottles and to use them on alternate days.

The gauge should be tested at each seam for leaks at occasional intervals, and especially after any spell of severe frost. This should be done by filling each part with water and observing whether water escapes at any point ; the funnel would have to be closed at the end by some means. An alternative method of testing the funnel is to close the end of the delivery tube, invert the funnel and press it vertically downwards into a butt of water. The presence of a leak will be shown by the escape of bubbles of air.

If water is found in the outer case without the inner can being full, a leak in the inner can is possible, but if water is found in the outer case without the bottle being filled and with no water in the inner can the outer case should be tested. In either case the funnel may be leaking as well. All leaks should be repaired as soon as detected.

A daily rain-gauge should be examined every day even in dry weather as a fall of dew may give rise to measurable precipitation.

6.2.6. Rain measures

The amount of rain collected by a gauge is measured with the aid of glass vessels known as rain measures. These are made of flint glass, and are graduated to indicate directly the amount of rain which has fallen. They are of various sizes depending on the diameter of the aperture of the gauge with which they are being used, and whether it is a monthly or daily gauge. Rain measures can be obtained reading in millimetres or in inches.

Rain measures can be classified broadly into tapered and flat-based models (Fig. 82). Both have a main cylindrical body, but the tapered model decreases in diameter in the lower part and is rounded off at the base, while the flat-based models have a flat horizontal base with a flange, so that they can be stood in an upright position on a horizontal surface. The Camden model (Fig. 82) has a flat horizontal base and a vertical cylindrical outer surface, but the inner surface, while being a vertical cylinder at the top, tapers at the base in a similar manner to the tapered models. There is thus a greater thickness of glass at the base of the measure than there is at the top. The name is derived from the fact that it was designed for the British Rainfall Organization whose headquarters were in Camden Square, London.

There are 11 main types of rain measures in use for various combinations of units and apertures of gauges.

For 5-in. diameter gauges there are :

Type 1. A taper measure graduated in millimetres with graduation marks every 0·1 mm. and with the graduation mark for 0·05 mm. added. It has a total capacity of 10 mm. (Stores Ref., Met. 146).

Type 2. A taper measure graduated in inches with graduation marks every 0·01 in. and with the mark for 0·005 in. added. Total capacity 0·50 in. (Stores Ref., Met. 145).

Type 3. A flat-based measure graduated similarly to Type 1 without the graduation mark for 0·05 mm.

Type 4. A flat-based measure graduated similarly to Type 2 without the graduation mark for 0·005 in.

Type 5. A flat-based measure graduated in millimetres with graduation marks every 0·5 mm. and with a total capacity of 25 or 50 mm. It is used in conjunction with a gauge that is read at weekly or monthly intervals.

Type 6. A flat-based measure used in the same way as Type 5 graduated in inches with graduation marks every 0·05 in. and a total capacity of 1 or 2 in.

Type 7. The Camden measure graduated in inches with graduation marks every 0·01 in. with the mark for 0·005 in. added. Its total capacity is 0·50 in.

For 8-in. diameter gauges :—

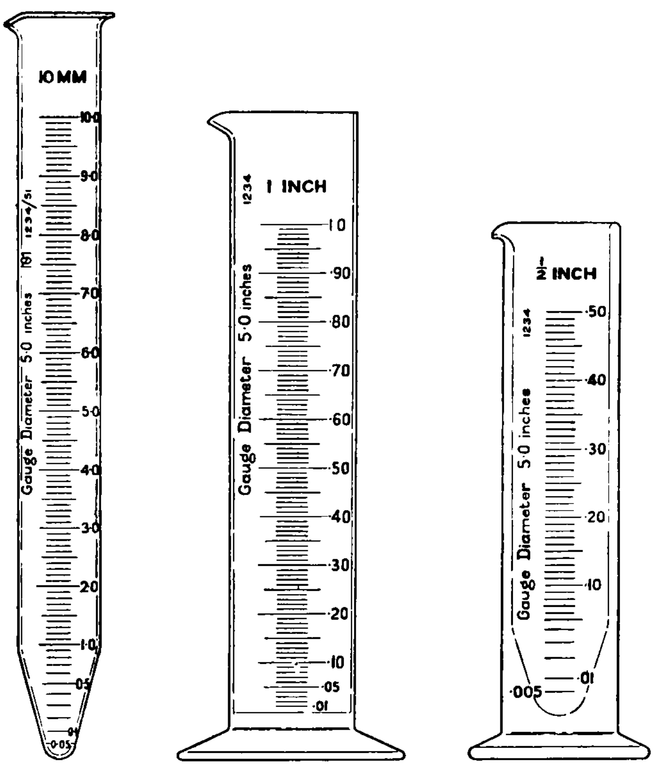
Types 8 to 11 corresponding in graduations, capacity and shape to Types 1 to 4. (Type 8 Stores Ref., Met. 147 ; Type 9 Stores Ref., Met. 148).

Types 3, 4, 10 and 11 are not recommended for routine use, as they are not as accurate as the tapered measures for measuring small amounts of rain.

The maximum errors allowed in the graduations of the rain measures are :

Type	Position	Maximum error
1 and 8	At or above the 2·0-mm. graduation mark ..	± 0·05 mm.
	Below the 2·0-mm. graduation mark ..	± 0·02 mm.
2	At or above the 0·10-in. graduation mark ..	± 0·004 in.
	Below the 0·10-in. graduation mark	± 0·002 in.
9	At or above the 0·10-in. graduation mark ..	± 0·003 in.
	Below the 0·10-in. graduation mark	± 0·001 in.
4 and 11	At any graduation mark	± 0·003 in.
6	At any graduation mark	± 0·01 in.

The tolerances in each case refer to inches or millimetres of rainfall.



Tapered model Flat-based model Camden model

FIG. 82—RAIN MEASURES

When the amount of water is equivalent to 0·05 mm. or 0·005 in. or above, the measurement is recorded to the nearest 0·1 mm. or 0·01 in., but a special record of a " trace " is made whenever either of the two following conditions hold :

(i) When there is less than 0·05 mm. or 0·005 in. of rain in the gauge and the observer knows that this is not the result of a drop or two draining from the sides of the can or bottle after emptying out the rainfall at the preceding observation, i.e. the observer must be reasonably sure that there has actually been precipitation since the preceding measurement. If the precipitation has been in the form of dew or wet fog this should be noted.

(ii) When no water is observed in the gauge but the observer knows from his own observation that some rain or other precipitation (snow, hail, sleet or drizzle) has fallen since the last observation. This sometimes happens, especially in warm dry weather, without the gauge being even damp, because the water has evaporated before it reached the receiving can. It is to assist in distinguishing between a trace and 0·1 mm. and 0·01 in. that the taper and Camden measures have a graduation mark at 0·05 mm. or 0·005 in. The reading of 0·05 mm. or 0·005 in. should never be recorded in the observation book ; only a trace or 0·1 mm. or 0·01 in.

When reading the amount of rainfall the measure should be held vertically between the thumb and first finger ; flat-based measures may be placed on a horizontal surface. The eye should then be brought to the same level as the water meniscus and the reading of the bottom of the meniscus taken to the nearest 0·1 mm. or 0·01 in. The main graduation marks which are repeated on the back of the taper measures will be found useful in ensuring that the eye is at the correct level to avoid parallax errors. Fig. 83 shows various amounts of rain in rain measures and the correct readings that should be made from them.

If the water in the gauge exceeds the capacity of the measure, the measure should be nearly filled to the top mark, the reading taken, and then the contents of the measure poured into a jug. This should be repeated as often as necessary and the readings then totalled, e.g. 9·7 mm. + 9·8 mm. + 2·3 mm. = 21·8 mm. The reading can then be checked by re-measuring the contents in the jug. It should always be remembered that measuring glasses are fragile, and they should be treated carefully at all times, kept clean, and stored in a safe place when not in use.

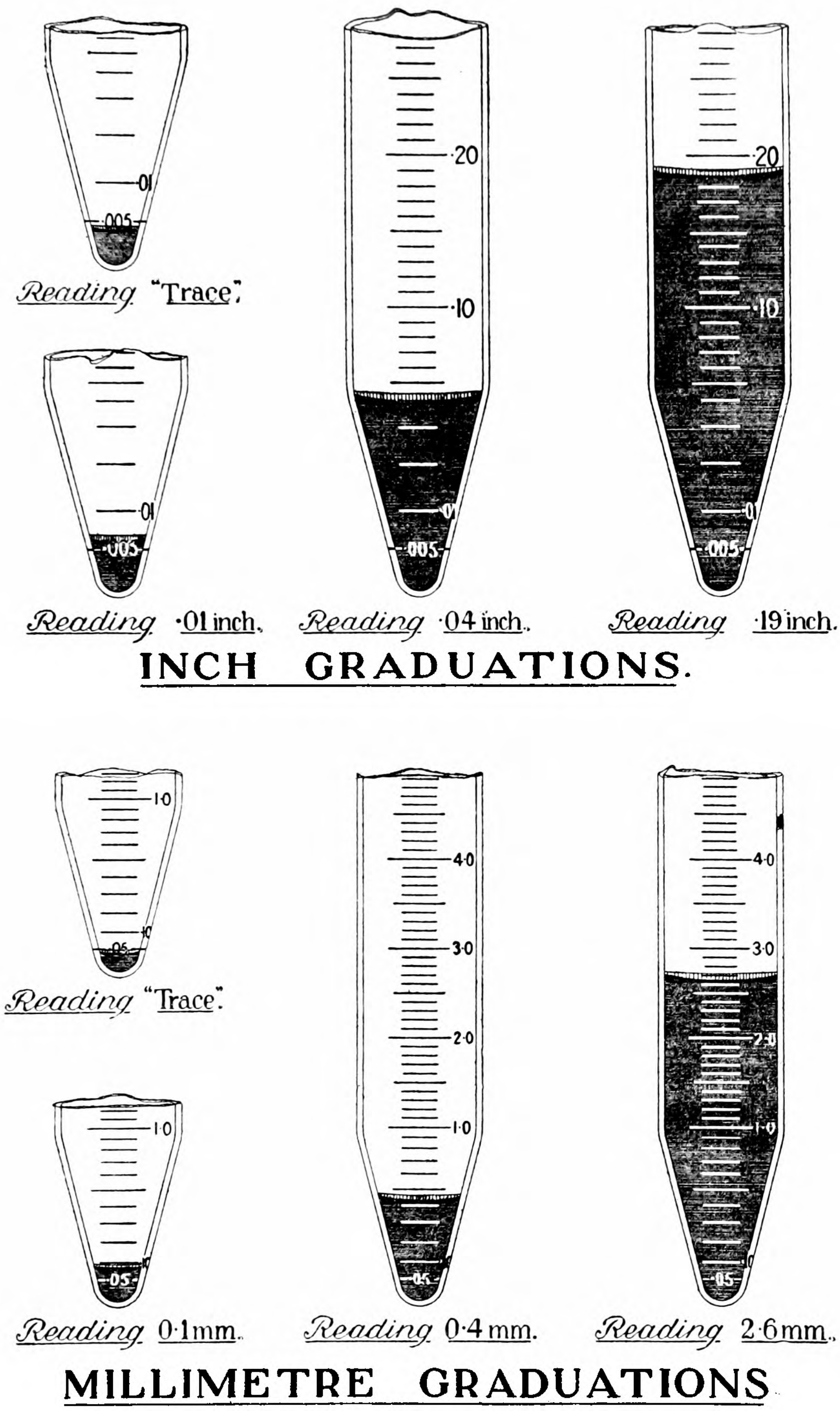


FIG. 83—READING THE RAIN MEASURE

The reading " trace " is also applicable when rain is known to have fallen, even if the gauge is dry.

In cold weather it is advisable to store the rain measure indoors when not in use. If it is stored in the Stevenson screen by placing it upside down over a short vertical rod as is sometimes done there is a risk that it may become frozen to the stand by any residual water left adhering to it after emptying. It is then very easy to break by careless handling. If it cannot be stored indoors it should be dried carefully after use.

6.3. RECORDING RAIN-GAUGES

Recording rain-gauges are used to keep a continuous record of the rainfall. They may be divided roughly into two main classes :

(i) Those which record the total amount of rainfall which has fallen since the record was started

(ii) Those which record the rate of rainfall.

The rate of rainfall at any given time may be determined from the first class of instrument, with varying accuracy according to the instrument used, by measuring the amount of rain which has fallen in a short period centred about the given time. It is not as easy to determine the amount of rain which has fallen in any time by the use of a rate-of-rainfall recorder.

The main use of recording rain-gauges is the determination of the times of onset and cessation of rain and the rate of rainfall during those periods. It is essential to have an ordinary rain-gauge exposed close by for use as a standard by which the readings can be checked and if necessary adjusted.

Rain recorders of the first class mentioned above can be classified into four main types :

Type 1 Float gauges without automatic siphoning arrangements

Type 2 Float gauges with automatic siphoning arrangements

Type 3 Tipping-bucket gauges

Type 4 Weight gauges.

Float gauges record the movement of a light metal float in a float chamber into which the rain is led. In general these gauges suffer from the disadvantage that once the float chamber is filled the record must cease or some means must be provided for emptying the float chamber. In the hyetograph, the only gauge of Type 1 which is described here, the float chamber is emptied by starting a siphon manually. The instrument is so designed that its scale value is sufficiently open to record light rain, and yet the float chamber is of reasonable capacity and the recording chart is of convenient size.

Two gauges of Type 2 are described, the natural-siphon rain-gauge and the Meteorological Office tilting-siphon rain-recorder.

The tipping-bucket gauge does not keep a strictly continuous record of rainfall but shows on the record the intervals of time which have elapsed between the falling of successive amounts of 0·01 in. of rain or some other small amount of the same order of magnitude, i.e. the record goes up in steps and not continuously.

The weight gauge operates by recording the total weight of precipitation in the receiving can. The receiving can usually descends against the compression of a spring or the displacement of a weight.

The second class of rain recorders is represented by the Jardi and Meteorological Office rate-of-rainfall recorders.

6.3.1. Meteorological Office tilting-siphon rain recorder

In the Meteorological Office tilting-siphon rain recorder (Stores Ref., Met. 562), water collected in a circular funnel is led into a cylindrical vessel containing a light metal float (Plate XXXVII and Fig. 84). The vertical motion of this float B, as the water level rises, is communicated by means of a float rod to a pen which records on a chart on a revolving drum. The details of the design are mainly concerned with the method of emptying the cylindrical float chamber after it has been filled with water and so keeping the record continuous.

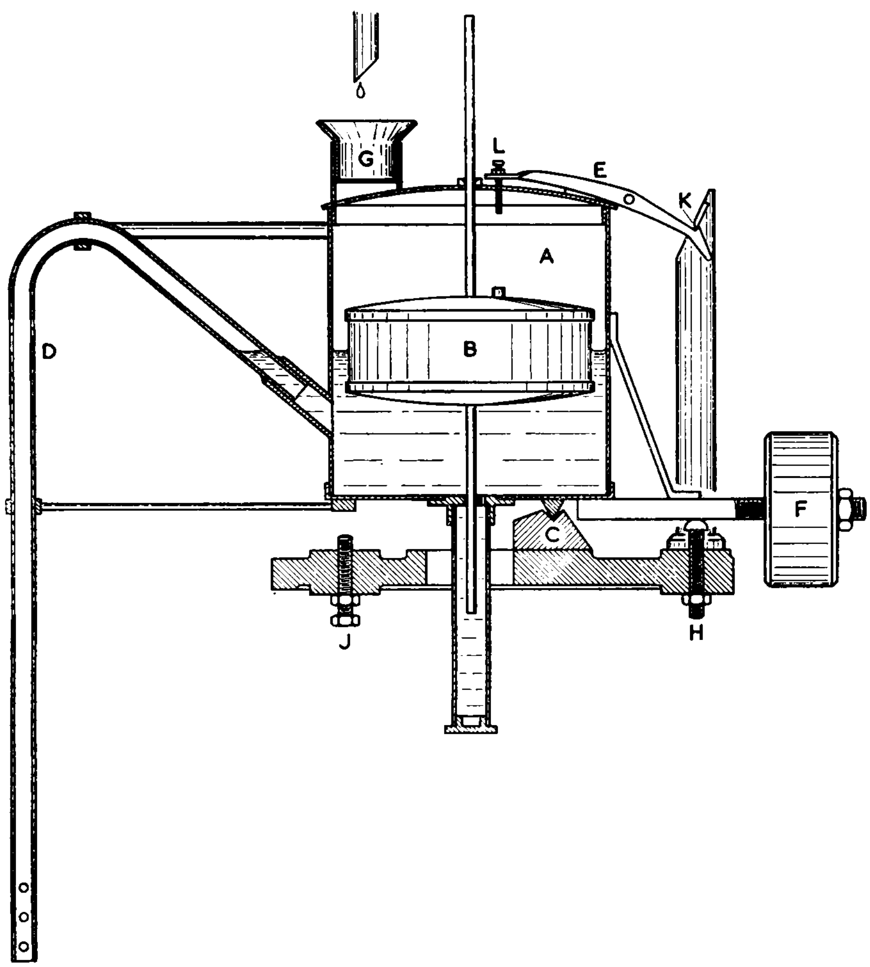


FIG. 84—FLOAT CHAMBER OF TILTING-SIPHON RAIN RECORDER

The recording mechanism is set up inside the container which consists of three main parts, namely the funnel, the base casting and the base itself. The funnel has an aperture defined by a turned brass rim of diameter 11·31 in. A hinged celluloid window, capable of being locked by means of a hasp, staple and padlock, is fitted in the lower half to give access to the pen and recording chart when the instrument is in use. The whole funnel is hinged on to the base casting and carries a hasp which can be engaged with a staple on the base casting and padlocked if desired.

The base casting supports the recording mechanism and consists of a circular gun-metal casting flanged to take the funnel and the base. The base itself is splayed and robustly made of copper sheet, forming a support for the whole instrument. The float chamber, clock and drum, the trigger catch and the pen lifter arm are mounted on a special sub-base plate which is screwed on to the main base casting. By means of the screws the sub-base can be accurately levelled independently of the main instrument.

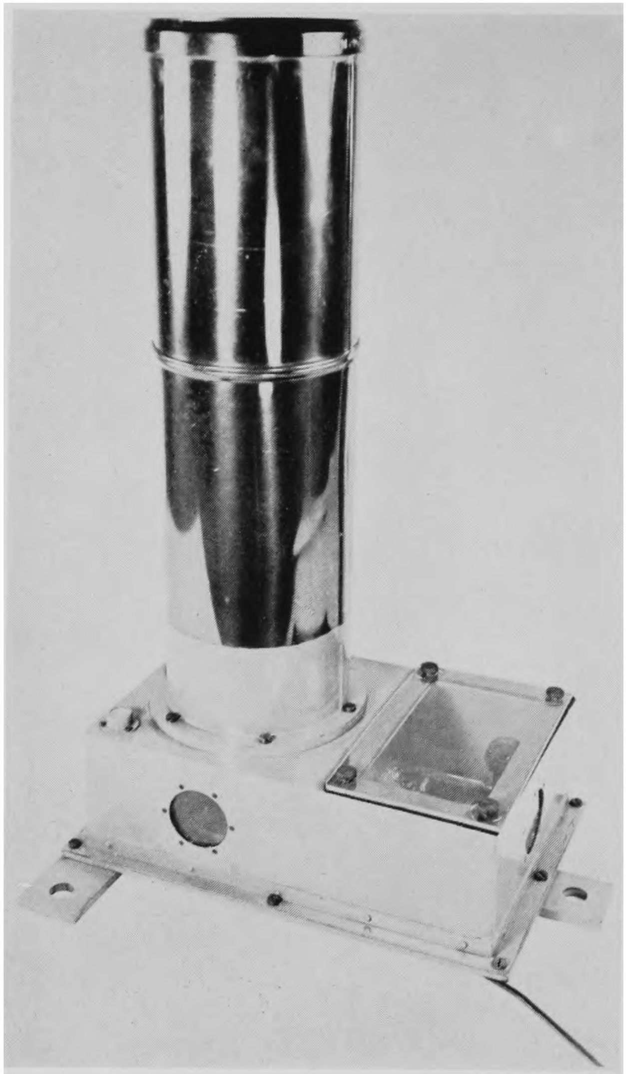
In Fig. 84 the float chamber and its supports are shown alone for the sake of simplicity. After collection the water is led into the main float chamber A via a filter of wire gauze G and a small opening in the top of the chamber. The float B is made of phosphor bronze sheet and is absolutely watertight. The float rod moves up and down between two guides, one in the top and one in the base of the float chamber. To prevent the float from turning about its axis a fork-shaped member is attached to the base of the float and this engages loosely with a projection formed up the side of the float chamber (not shown in the diagram). A balance weight is fixed to the float to balance the turning moment of the pen arm so that with the pen attached and in its normal position the float rests naturally in an upright position.

To the side of the float chamber is attached the siphoning tube D arranged so that the top of the bend in the tube is level with the top of the float chamber. The whole float chamber is mounted on a knife edge C and is counterbalanced by the weight F so that when the chamber is empty or only contains up to the equivalent of 4 mm. of rain the system rests on the knife edge and a back stop H. With more than 4 mm. of rain and up to the maximum of 5 mm. the weight F is insufficient to hold the chamber on the back stop but the chamber is prevented from over-balancing by means of the trigger E which engages with the trigger catch K. When the 5 mm. of rain have been collected a stop on the top of the float pushes against the screw L, at the other end of the trigger to the trigger catch, and releases the trigger from the catch. The float chamber then tilts over until stopped by the front stop J, the water flows over the top of the bend in the siphon tube and a siphoning action is started in a positive manner. Water flows out of the float chamber until the level falls to the top of the exit hole of the float chamber when the siphoning action ceases. In the meantime, when the total weight of the float chamber and contents has decreased sufficiently, the system resumes its vertical position, the whole assembly resting again on the knife edge and the back stop H ready for the process to be repeated.

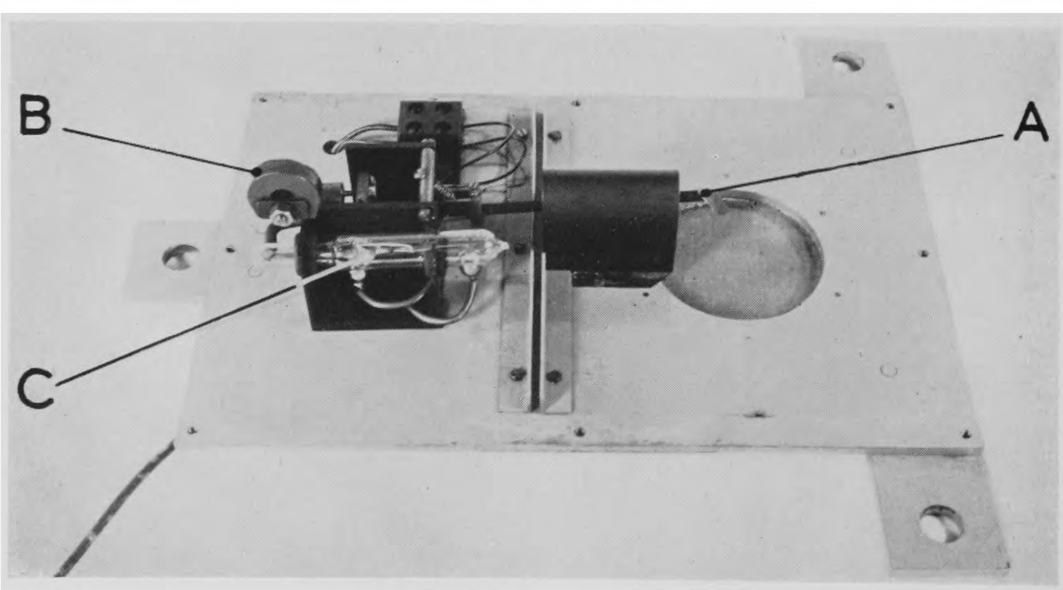
The pen arm is attached to the float rod by means of a gate suspension which is set at a small angle to the vertical to provide just sufficient pressure to keep the pen in contact with the chart. At the moment of siphoning the pen arm is lifted from the chart by the pen-lifter arm, and it does not come into contact with the chart again until the float chamber resumes its vertical position. This happens before the siphoning has completely finished so that the pen returns to the chart above the zero line as siphoning finishes.

The clock is the Meteorological Office standard daily pattern or similar type with an " S " drum, and is mounted slightly higher than the float chamber. The relative positions of the float chamber and clock and drum can be seen from the plan view, Fig. 85. It should be noted that in addition to its function of lifting the pen from the drum when siphoning occurs the pen-lifter arm is used for

METEOROLOGICAL OFFICE TILTING-SIPHON RAIN RECORDER



General view



Details of the mechanism

METEOROLOGICAL OFFICE RATE-OF-RAINFALL RECORDER removing the pen from the chart when changing the chart each day. This is done by moving the lever attached to the base of the pen-lifter arm. If it is to continue to perform the first function properly the pen-lifter arm must not be set very far back from the pen arm.

Installation and adjustment.—The site of the instrument should be carefully chosen in accordance with the principles outlined on p. 264. The site should, however, also be well drained, and such that the free water level never rises to within 4 in. of the surface of the ground. If this is not so the bottom of the siphon tube may dip into water and consequently the instrument may cease to function properly. The base should be sunk into the ground so that the top of the splayed portion is level with the surrounding ground ; the rim is then 1 ft. 9 in. above the ground level. The bottom of the hole should be covered with large stones or rubble for easy drainage of the rain-water collected, and the instrument itself may with advantage be mounted on two slabs of concrete to prevent it tilting due to subsidence.

A spirit-level should be used to check that the rim is horizontal. The sub-base plate can be levelled, if necessary, by means of the three levelling screws provided, but normally with the rim of the funnel horizontal this should not be required. A chart should then be put on the drum, care being taken to see that corresponding horizontal lines on the overlapping portions are coincident and that the bottom of chart is as near to the flange at the bottom of the drum as possible. It should be touching the flange in at least one place. Water should then be poured into the float chamber until siphoning takes place, and when the float chamber returns to the vertical it should be checked that the pen returns to the chart well above the zero line and that it falls to the zero line as siphoning finishes. If the pen does not fall exactly to the zero it should be made to do so by raising or lowering the pen arm on the float rod.

Water should then be poured into the float chamber again to verify that the float chamber would tilt with the pen well below the 5-mm. line were it not for the trigger, and that the trigger would be released at the correct point. An adjustment can be made at this point if necessary by means of the screw L (Fig. 84). When received from the Meteorological Office the gauge should not require any adjustment, except perhaps in the zero reading, provided the rim is horizontal, but if a gauge has become greatly out of adjustment the following procedure should be used to bring it back into adjustment.

Level the sub-base plate and, with the float chamber resting correctly on the knife edge, adjust the back stop H until there is only a little play between the trigger and the trigger catch (about the thickness of a visiting card is sufficient). Next set the counterweight as far from the float chamber as possible. Put on a chart and adjust the pen to read zero after siphoning, after having made sure that the gate bearings of the pen arm are neither stiff nor unduly loose. Now, after setting the front stop as high as possible, pour water into the float chamber until the pen rises a little above 4 mm., release the trigger and tilt the float chamber by hand on to the front stop. Lower the front stop until siphoning begins and then lock it into position. Having poured water in the float chamber again to a little over 4 mm., move the counterweight nearer to the float chamber until the gauge would tilt if the trigger were released. Continue pouring water until the gauge automatically tilts and siphons, and note the point at which the pen returns to the chart when the float chamber returns to the vertical. The best position for the counterweight is such that the pen returns to the chart at a distance above the zero line equal to the greatest distance below the 5-mm. line at which the float chamber will tilt when the trigger is released by hand ; e.g. if the float chamber will tilt when the pen has risen to 4 mm. and the pen returns to the chart at 1·0 mm. after siphoning has taken place the adjustment can be considered satisfactory. The counterweight is

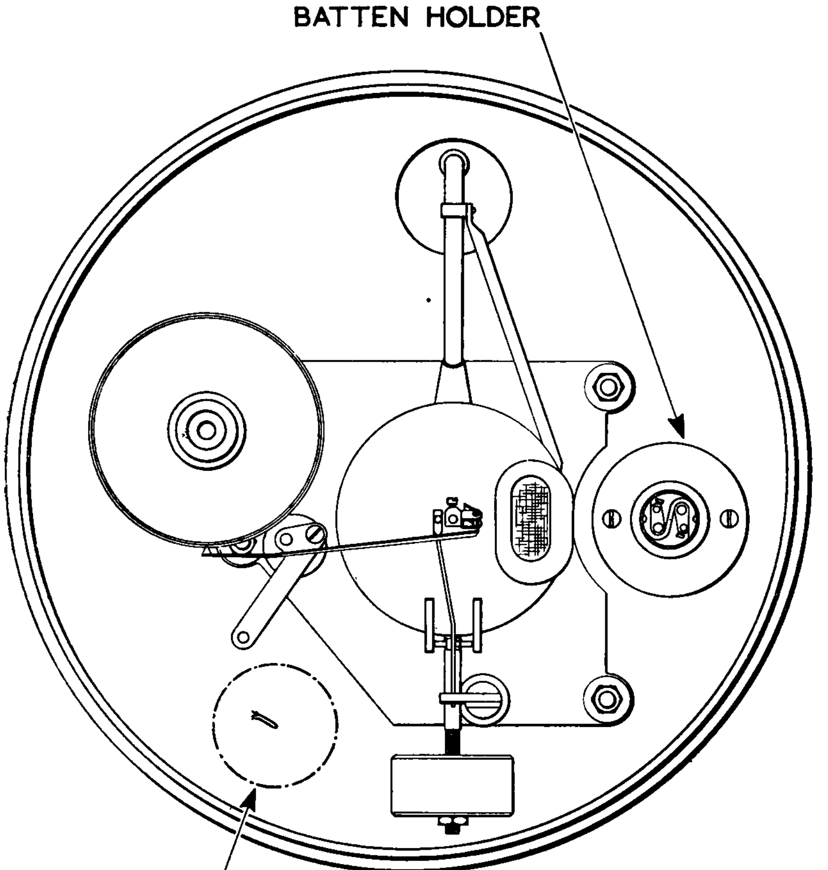


FIG. 85—FROST PROTECTION FOR TILTING-SIPHON RAIN RECORDER

then locked in position. The adjusting screw on the trigger is then set so that the trigger releases the float chamber when the pen shows exactly 5 mm. Finally, the pen lifter should be tested by pouring water into the float chamber until the pen reaches 2 mm. and releasing the trigger and tilting the float chamber by hand ; the pen should be lifted from the chart automatically. If this does not happen the pen arm or the pen-lifter rod has become bent. When the float chamber is vertical the pen arm should be close to, but not touching, the pen-lifter rod.

Some instruments may be fitted with charts which record in inches instead of millimetres. In this case the gauge collects 0·20 in. before it siphons, and in the above instructions where indications on the chart are given in millimetres they can be converted to inches in the same proportions, i.e. for 4 mm. read 0·16 in., and so on.

Method of use and maintenance.—The chart is changed daily at the same time each day (usually 0900 G.M.T.). It should be noted that, after any rain, water collects in the joint between the funnel and the base. If the funnel is opened rapidly this water may be drawn in with the rush of air and wet the chart and working parts of the gauge. To avoid this the funnel should always be opened gently. The general instructions with regard to the care of autographic instruments, care of pens, time marking, headings of charts, etc. (p. 11) should be carried out. In particular the readings for the total rainfall for each day should be regularly and systematically compared with the readings of a standard type rain-gauge exposed near by, and any large errors in the readings of the recording instrument investigated immediately.

Trouble is sometimes experienced with the wire gauze filter over the lead-in to the float chamber. The passage of water through it tends to be impeded by a combination of surface tension effects and the accumulation of solid matter washed through the funnel. The water may even overflow the small collecting vessel in which the filter is fitted and thus be lost. To prevent this the filter should be regularly cleaned with petrol or methylated spirits, but if this does not cure the trouble a few strands of wire should be removed.

Precautions should be taken to prevent damage to the instrument during periods of frost. If the water in the float chamber is allowed to freeze the float is often fixed in position by the first ice which forms on the top of the water surface, and the high pressures set up by the subsequent freezing of the remainder of the water causes damage to the float.

If mains electric supply is available or can conveniently be installed, a standard lampholder (batten type) should be fitted to the base at one side of the float chamber (see Fig. 85) and connected to the mains. A 25-W. lamp so fitted should prevent freezing with temperatures down to 20°F. This work should be carried out by a competent electrician (as a Works Service at Meteorological Office stations).

If the mains supply is not available one or two night-lights (Stores Ref., Met. 573) standing in the special brass holders (Stores Ref., Met. 568) may be installed, in the positions indicated in Fig. 85.

If temperatures below 20°F. (or 25°F. if only night-lights are being used) are expected, the float-chamber unit should be removed and brought indoors, being replaced as soon as practicable. The clock and drum may also be taken in at the same time ; care should be taken when replacing the clock (attached to the adaption plate) ; the plate should only be screwed into the pillar until a moderate resistance is felt, otherwise it can easily be broken off its threaded spindle.

The instrument should be tested at regular intervals, especially when no rain has fallen for some time. This can be accomplished by pouring into the funnel successively equal quantities of water, corresponding to some specific interval on the chart. This quantity is best measured out in a rain measure, but it has to be carefully calculated by taking into account the relative diameters of the apertures of the tilting-siphon gauge and the gauge for which the measure was graduated, e.g. using a rain measure graduated for a 5-in. rain-gauge the amount in the measure which would give a reading of 1 mm. on the tilting-siphon gauge would be $(11{\cdot}31/5)^2 = 5{\cdot}1$ mm.

The time of siphoning should be checked occasionally, in case the outlet tube is becoming choked. The time taken should be about 15 sec., and in any case not more than 20 sec.

It should be noted that special packing cases are provided for the Meteorological Office tilting-siphon rain recorders. In packing a recorder care should be taken to place it in the case the right way round, so that the sliding collar sits easily on it, and will not have to be forced down to make its top edge flush with the top edge of the case.

Sources of error.—If the trace recorded when no rain falls is not horizontal on the chart there may be faults in (i) the setting of the chart on the drum, (ii) in the drum itself, or (iii) in the alignment of the axis of the clock and drum. Faults (ii) and (iii) usually cannot be rectified except by repair or replacement of the drum and clock. Fault (i) can be prevented by taking care when putting the charts on the drum.

It is important to keep the pen-lifter arm in its correct position because, if the pen arm is not lifted off the chart when the float chamber begins to tilt, instead of immediately starting to fall it is liable to move upwards and sideways for a short distance first, thus recording a trace above the 5-mm. line and causing uncertainty of the record.

If the float chamber becomes badly punctured the instrument will stop working, but with a slight puncture the siphoning will only occur after more than 5 mm. of rain have fallen owing to the lower position of the float in the water. This fault will be shown up after siphoning as the pen will fall below the zero line, and should be looked for especially after a period of frost. If a leak occurs it should be located and repaired by soldering, after first removing all the water.

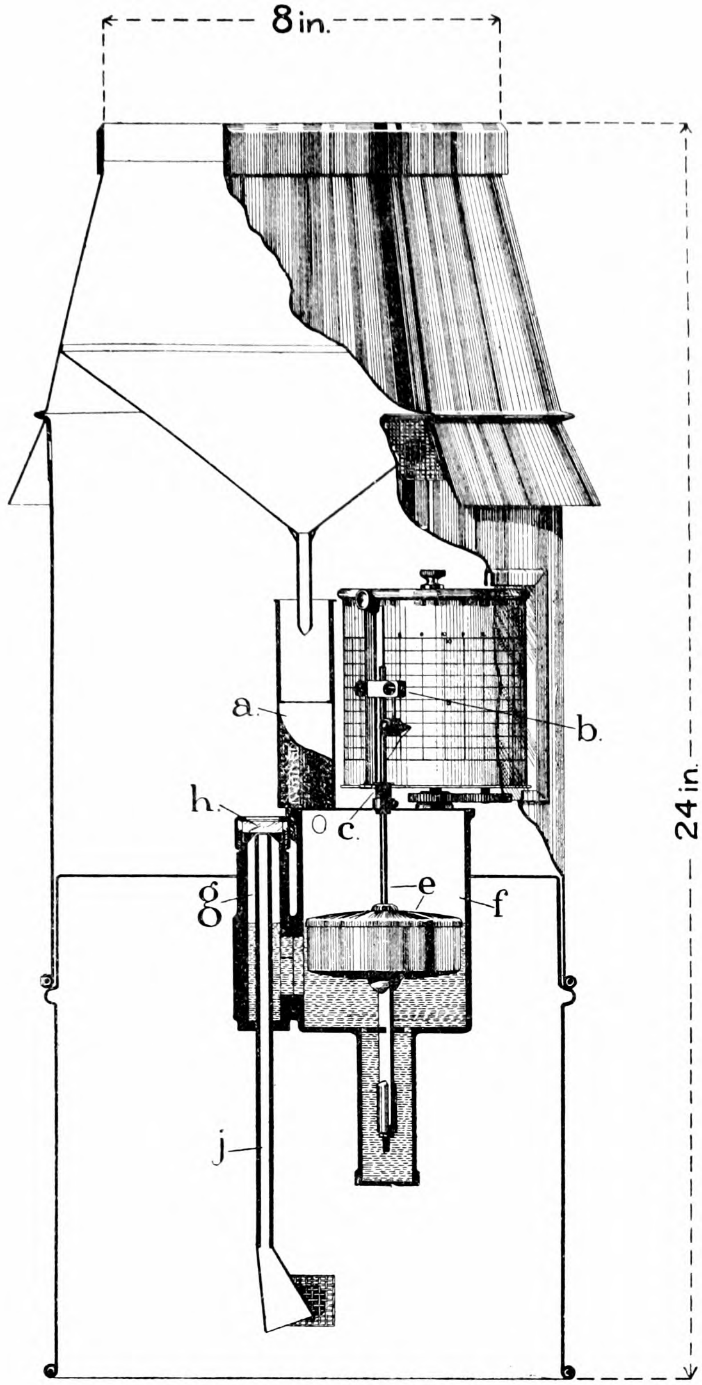
Unavoidable errors arising from the design of the instrument are the loss to the record of rain which enters the gauge whilst siphoning is taking place, and the crowding together during periods of very heavy rain of the series of traces on the chart. The first type of error is small except during periods of heavy rain, but the crowding of traces, so that they are indistinguishable, can be a serious fault. Corrections for both these errors can be obtained by comparison of the records of the instrument with the readings of the ordinary rain-gauge exposed close by.

If other faults develop, the general adjustment of the instrument should be checked over ; it will usually be possible to find the cause and rectify it, if due to maladjustment, by going through the procedure outlined earlier.

6.3.2. Natural-siphon rain recorder

The method of operation of the natural-siphon rain recorder (Stores Ref., Met. 1996) differs from the Meteorological Office tilting-siphon rain recorder in the manner in which the water is siphoned out of the float chamber when it has become full (Fig. 86). The discharge tube of the siphon is inside and coaxal with the tube connecting with the float chamber. The top of this outer tube is a polished glass cap and the discharge tube comes up to within a very short distance of this. When the water in the outer tube rises to the top and flows over the bend, capillary action causes all the air to be pushed out and down the delivery tube so that a full flow is started at once. Similarly at the end of the siphoning, once air gets to the top of the tube the siphoning action is stopped immediately.

To ensure an efficient capillary action, the depth, h, of the annular space between the glass cap and the discharge tube (Fig. 87) must be small. Against this, the speed of siphoning will be reduced if h is so small that a constriction is introduced into the flow of water through the system. The speed of siphoning is a maximum when the



a. ENTRANCE TUBE.
b. PEN CARRIER.
c. THREADED COLLAR.
e. FLOAT & FLOAT ROD.
f. FLOAT CHAMBER.
g. SIPHON CHAMBER.
h. GLASS COVER.
j. DISCHARGE PIPE.

FIG. 86—NATURAL-SIPHON RAIN RECORDER

area of the annular ring is equal to the area of the top of the discharge tube ; increasing further the area of the ring has little or no effect on the rate of flow. Hence, for optimum conditions of operation, the area of the ring need be no greater than the area of the tube. If a is the diameter of the discharge tube, this condition gives

$$\pi a h \text{ need be no greater than } \frac{\pi a^2}{4}$$

$$\text{or, } h \text{ need be no greater than } \frac{a}{2}.$$

If a is $\frac{3}{8}$ in., h need not be greater than $\frac{3}{32}$ in.

The brass rim at the top of the cover and funnel is 8 in. in diameter, and the rain is led from there via the funnel to a float chamber containing a light metal float. This float has a float rod which runs in guides in the top and bottom of the float chamber and, protruding through the top of the float chamber, carries the pen which records on a chart fixed on a revolving drum.

When siphoning occurs the pen falls vertically to the zero line and does not come off the chart. The upper part, comprising the brass rim, funnel and cover, lifts off the base, and the instrument is usually installed so that the base of the upper part when in position is level with the surrounding ground. The rim is then $16\frac{1}{2}$ in. above ground level.

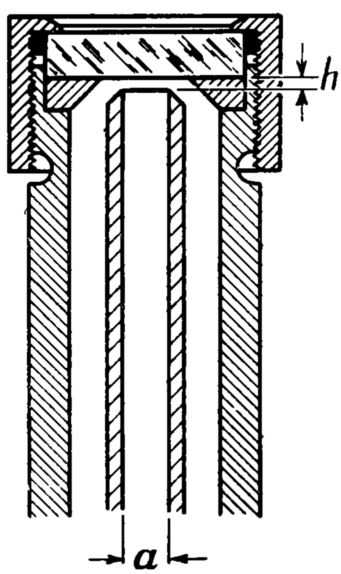


FIG. 87—DETAILS OF SIPHONING TUBE OF NATURAL-SIPHON RAIN RECORDER

The routine care of the pens, chart changing and time marking, etc. are similar to those for the Meteorological Office instrument, and similar precautions should be taken in cold weather.

When first installed the position of the pen on the chart should be checked and, if necessary, adjusted as follows :—Pour water into the inlet tube in the float chamber ; while the bottom of the float chamber is filling nothing will happen but presently the float will begin to rise. Continue pouring water in until the pen nearly reaches the top line of the chart, and then reduce the rate of pouring to single drops at a time until the instrument siphons. Note the reading of the pen at the moment siphoning begins and after siphoning has finished. The readings should be on the top and bottom lines of the chart and any necessary adjustment can be made by altering the position of the pen on the float rod.

The gauge collects 10 mm. of rain before it siphons as opposed to the 5 mm. of the Meteorological Office instrument. It is important that the inside of the glass top of the siphon should be kept clean as this is essential for proper siphoning. The cap can be removed for cleaning by undoing the screw cap which holds it in position. A soft dry cloth without any grease or oil should be used.

6.3.3. Hyetograph

The hyetograph (Fig. 88) is one of the simplest and earliest of the float-type gauges giving a record of the total amount of rain which has fallen since a given time.

On the float rod B connected to the float A are a number of studs C at equal intervals. As the float rises owing to the water entering the float chamber via the funnel D and delivery tube E, one of the studs engages with a pallet F attached to the pen arm G and moves the pen arm upwards causing a trace to be made on the

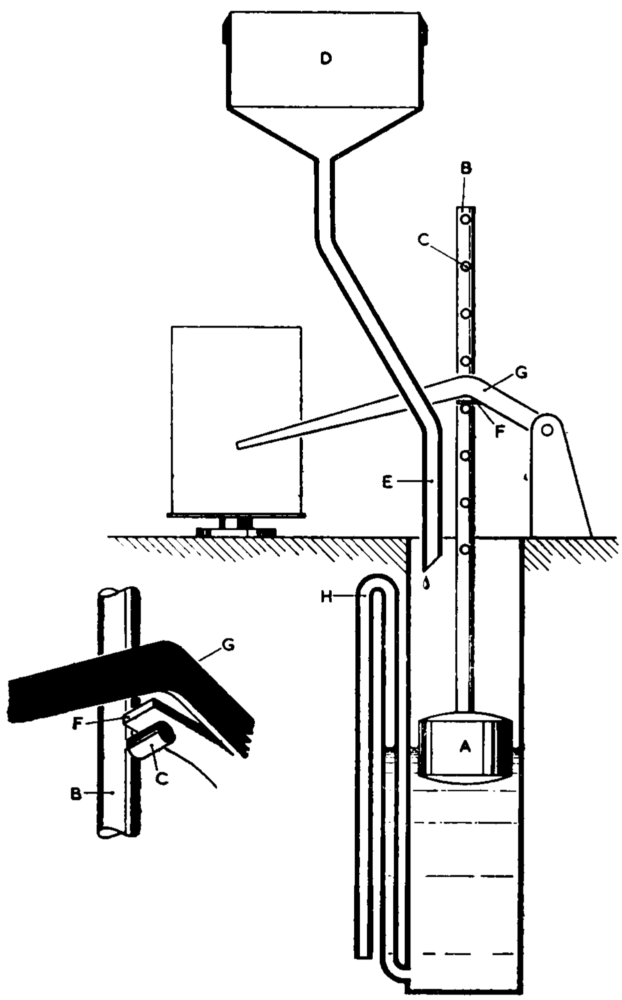


FIG. 88——HYETOGRAPH

recording drum. The pallet is of such dimensions that when the pen reaches the top of the scale the pallet disengages itself from the stud and drops on to the next stud below, causing the pen to fall to zero at the same time. In this way the pen arm traverses the scale several times for the total capacity of 4 in. of rain. The pen arm is prevented from falling too quickly by means of a damping system working in oil. This must be kept supplied with clean thick oil.

When the float chamber is full or nearly full it can be emptied by depressing the float sharply by hand, after disengaging the pen arm and pallet. This starts a siphon H which empties the float chamber. The main advantages of the instrument are its simplicity of mechanism and its non-dependence on the working of any automatic siphon for the continuity of record.

6.3.4. Jardi rate-of-rainfall recorder

The essential parts of the mechanism of the Jardi rate-of-rainfall recorder (Stores Ref., Met. 1383), Fig. 89, are shown in the diagram. A cylindrical metal float chamber A about 4 cm. in diameter has a bottomless extension B about 2 cm. in diameter attached to the base with a circular opening C in the partition separating the two. Resting on the partition when no rain is falling is a light circular metal float D which has a tapered spindle E attached to its base and extending down into the extension B. The diameter of this spindle where it is attached to the float is the same as that of the opening in the partition so that the spindle closes the partition when the float rests on it but not otherwise. The float and spindle are attached to one end of a pivoted arm by means of a strip of German silver F ; a weight on the other end of the arm is not quite sufficient to balance the weight of the float, spindle and strip. Any rain is led into one side of the float chamber so that it does not fall on the float itself.

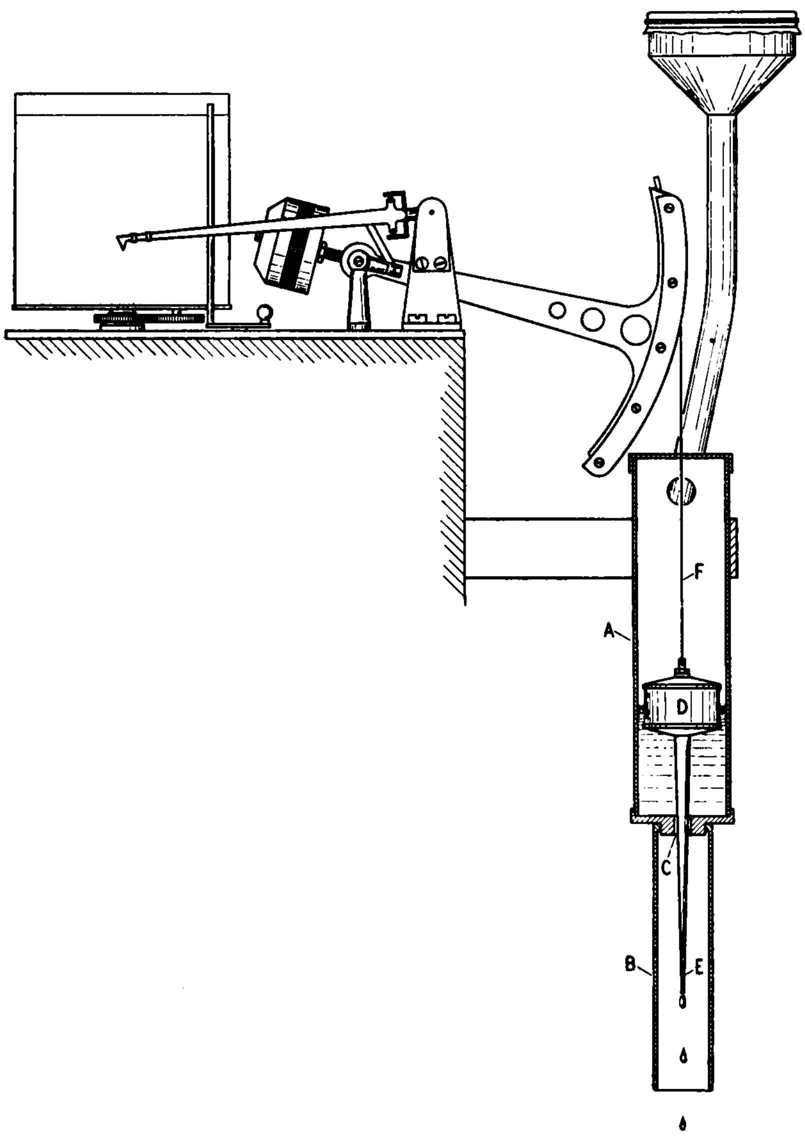


FIG. 89—JARDI RATE-OF-RAINFALL RECORDER

When rain falls it can only escape through the annular space between the spindle and the opening in the partition, hence the level of water in the float chamber, and consequently the float, rises until the rate of flow through this annular space equals the rate of inflow of the water, which in turn is proportional to the rate of rainfall. The angular motion of the pivoted arm from which the float is suspended, caused by the rising of the float, is magnified by a system of levers and transferred to a pen arm which causes a pen to record on a revolving drum. In order that the strip F may be kept in the same vertical plane throughout, the end of the pivoted arm is in the form of an arc of a circle with the centre at the pivot.

The rate at which the rain escapes through the annular space is proportional to the area of the opening and to the square root of the depth of water in the float chamber. This rate is directly proportional to the rate of rainfall, w. Let h be the height the float has risen above its zero position. Then the depth of water $= (h+a)$ where a is a small constant. Let R be the radius of the opening in the partition and r the radius of the spindle at a distance h from the float (it is of course a function of h).

If a linear scale is required on the instrument then $w = bh$ where b is a constant. Also

$$w = c\,(R^2 - r^2)\sqrt{(h + a)}\,,$$

where c is a constant. Which leads to

$$r = \sqrt{\left(R^2 - \frac{Ah}{\sqrt{(h + a)}}\right)}\,, \qquad \ldots\ldots(81)$$

where $A = b/c$. If by wear and tear R increases slightly to $R + \Delta R$, ΔR being small, then

$$w = c\,[(R + \Delta R)^2 - r^2]\sqrt{(h + a)}$$
$$\simeq c\,[R^2 - r^2 + 2R\Delta R]\sqrt{(h + a)}$$

neglecting the term containing $(\Delta R)^2$. If r is given by equation (81) so as to give a linear scale when the instrument is in order then

$$w = c\left[R^2 - \left(R^2 - \frac{Ah}{\sqrt{(h + a)}}\right) + 2R\Delta R\right]\sqrt{(h + a)}$$
$$= bh + 2cR\Delta R\sqrt{(h + a)}. \qquad \ldots\ldots(82)$$

When h is zero then

$$w = 2cR\Delta R\sqrt{a}$$
$$= w_0\,,$$

i.e. falls up to the rate of w_0 will not register on the instrument. In practice, w_0 is normally of the order of 3–5 mm./hr.

The procedure which can be adopted to allow for this initial lag is to set the pen so that it records the minimum rate of flow, w_0, when no rain is falling. When rain falls at rates not far above the minimum value the pen will then indicate approximately the true reading. For larger rates of fall the second term on the right-hand side of equation (82) will become significantly larger than the value w_0, and corrections to the indicated values become necessary. These are best found by calibrating the instrument periodically. An apparatus is set up so that water can be run into the funnel at a constant rate, and the observed readings of the instrument are correlated with the calculated equivalent rate of rainfall. The value of the minimum rate which registers is found in this way as well.

The instrument is very sensitive to the entry of solid matter into the float chamber, and this should be kept clean by periodic flushing out. Some kind of filter in the funnel also helps to keep out solid matter. It should not of course be so fine that it obstructs the flow of rain. This is a delicate instrument, and attention is required to reduce to a minimum the friction in the moving parts if reliable records of small rates of rainfall are to be measured. The range of rainfall rates which can be measured with the usual funnels is from about 5 mm./hr. to 150 mm./hr., but larger rates could be measured if a smaller funnel were used.

6.3.5. Meteorological Office rate-of-rainfall recorder

The Meteorological Office electrical impulse recorder Mk II (see p. 254) has been used in the construction of a rate-of-rainfall recorder (Stores Ref., Met. 772) (Plate XXXVIII). The delivery tube from a funnel of the normal type of rain-gauge has its opening constricted so that the rain falls out in a series of drops of uniform size. Each drop falls on to a very light " paddle " A which is at one end of a balanced arm ; the arm tilts under the impulse of the falling drop and then returns to its normal position as the drop falls off. A small magnet B on the other end of the arm causes a mercury switch C to be closed and then opened again and an electrical signal to be sent to the recording mechanism. Each drop is recorded in a similar manner to each signal from the anemometer in the wind recorder. In this way the rainfall in a period of 1 or 3 min. is recorded on the chart and thus the average rate over this period is known.

With a 5-in. diameter collecting aperture and with an opening giving drops 0·13 $cm.^3$ in volume (equivalent to 0·01 mm. of rain), rates of rainfall up to 16 mm./hr. can be measured if a 3-min. period is used, but up to 48 mm./hr. if a 1-min. period is used. In the first case the chart covers a period of 24 hr., but in the second the time scale is three times as long and the same chart covers a period of 8 hr. This size of drop is nearly the largest which can be obtained with any degree of uniformity using the present type of orifice, and consequently if higher rates of fall have to be measured the diameter of the rain-gauge would have to be cut down.

A great advantage of this recorder is that it is distant recording. The accuracy of the instrument depends on the uniformity of the size of drops formed at the orifice. Notes on the operation and adjustment of the recorder will be found in the section dealing with the Meteorological Office electrical impulse wind-speed recorder (p. 254).

Installation.—Having selected a site for the rain detector using the principles outlined on p. 264 a hole should be dug sufficiently large to take the tripod support with its feet in the hole and the flat strips roughly at ground level. The earth should now be replaced and beaten as firm as possible. Before putting the rain detector on the tripod the mercury in the switch should be so divided between the two cups (by tipping and shaking the whole instrument) that the moving contact is about 1 mm. above the mercury surface. A nut should be placed about half way down each of the three brass screws on the tripod and the rain detector rested on them, the three screws passing through the three holes in the base plate. The nuts should then be adjusted until the spirit-level shows the base to be horizontal, and the remaining three nuts screwed on so as to hold the instrument firmly, taking care not to upset the levelling.

The recorder is installed indoors in any convenient position. Its distance from the rain detector is immaterial provided the total resistance of the cable joining them is less than 10 ohms. One end of this cable should be passed through the hole in the base of the rain detector and connected to the terminal block ; the other end should be connected to the recorder input terminals. The installation is then completed by connecting the other terminal block on the recorder to 230-V. a.-c. mains.

Method of use.—Little attention is required except to change the chart and keep the ink reservoir about two thirds full. The latter is important, for if the ink is ever allowed to dry up completely it is difficult to clean the glass pen to restore the flow. To replace a glass pen, the old one should be removed and the short arm of the new one pressed into the spring clip in the reservoir, pressing it down until the longer arm of the pen fits into the slot in the side of the reservoir. If ink is now put in the reservoir it will flow into and completely fill the glass pen by capillary attraction. If the zero position of the pen is not on the zero line of the chart this may be rectified by means of the adjusting screws of the pen arm.

To change over from 1-min. to 3-min. time intervals (or *vice versa*) the two screws holding down the timing switch should be loosened, and the latter moved so as to bring the appropriate toothed wheel (large for 3 min., small for 1 min.) into engagement with the pinion on the motor. The screws should then be tightened again.

Maintenance.—The levelling of the rain detector should be checked periodically, and the orifice examined to ensure that it is not blocked. No grease must be allowed on the orifice, but otherwise there is no need to clean it. The perspex panel should also be removed periodically and the paddle lever checked for freedom of movement ; a drop of thin oil should be applied to each of its pivots. Two other adjustments may be needed at longer intervals :

(i) If, despite accurate levelling, the drops fail to hit the centre of the paddle, the position of the latter should be adjusted. The perspex panel should be removed and the screw holding the switch mechanism to the base plate loosened. The paddle can now be moved until it is vertically below the orifice, as judged by watching water drops hitting it. After making sure that the paddle lever passes freely through the slot in the perspex screen the screw should be carefully tightened again, and the perspex panel replaced.

(ii) The balance of the paddle may need adjusting. This can be judged from the sound made by the recorder as each drop is recorded. The making and breaking of the circuit should be distinctly audible as two ticks which should be separated by about $\frac{1}{5}$ of a second, i.e. one tick of a watch. If the interval is much shorter there is a risk of some contacts being missed, while if it is much longer there is a risk of occasional double contacts, causing the pen to move twice for one drop from the funnel. The interval can be adjusted by removing the perspex panel from the rain detector and screwing the knurled counterweight slightly towards (away from) the paddle to lengthen (shorten) the contact.

6.3.6. Storm gauge or minute-by-minute gauge

Another type of rate-of-rainfall recorder, installed at Kew Observatory, is the storm gauge or minute-by-minute gauge. The main use of this instrument is to record the peak rate of rainfall measured as the mean rate over an interval of 1 min. during a period of up to 24 hr. The rain is collected by a funnel and falls into a float chamber, and as the float rises it causes a drum to rotate. A fixed pen traces out a line on the drum, and once every minute it receives an impulse from an electromagnet which causes a small deflection or kick in the trace. The distance between successive kicks is therefore proportional to the mean rate of rainfall over that minute. When no rain is falling the deflections in the trace are not separated but fall on top of each other, so that it is not possible to assign the time at which any given kick in the record occurred.

One revolution of the drum gives a trace about 40 cm. long and corresponds to 45 mm. of rain, and by arranging for the drum spindle to be threaded it is possible for the drum to revolve completely several times. An ordinary 8-in. funnel is used, but the orifice is enlarged so that hailstones can fall through at once. The rain-water (and hail) falls into a side tube which is in connexion with the main float chamber and is recorded immediately ; in this way the float is not disturbed, and any hail can float freely on the surface of the water until it melts.

6.3.7. Tipping-bucket gauges

In the tipping-bucket gauge a bucket, as shown in the diagram (Fig. 90), is balanced in unstable equilibrium about a horizontal axis and is divided into two equal compartments by a partition. In its normal position it is thus tilted, with one side resting against a stop. The rain is led into the upper compartment and when a certain definite small amount has fallen (usually about 0·01 in.) the bucket overbalances and tilts the opposite way so that the compartment containing the rain comes to rest against a stop on the opposite side. The rain in this side is thus emptied out, and the rain which falls is led into the other compartment. Each movement of the bucket is recorded either by a mechanism in the gauge itself or, electrically, on a record at a distance.

Records are made in steps of 0·01 in. or some other interval of the same order of magnitude, and thus the gauge is not suitable for use in light rain and drizzle.

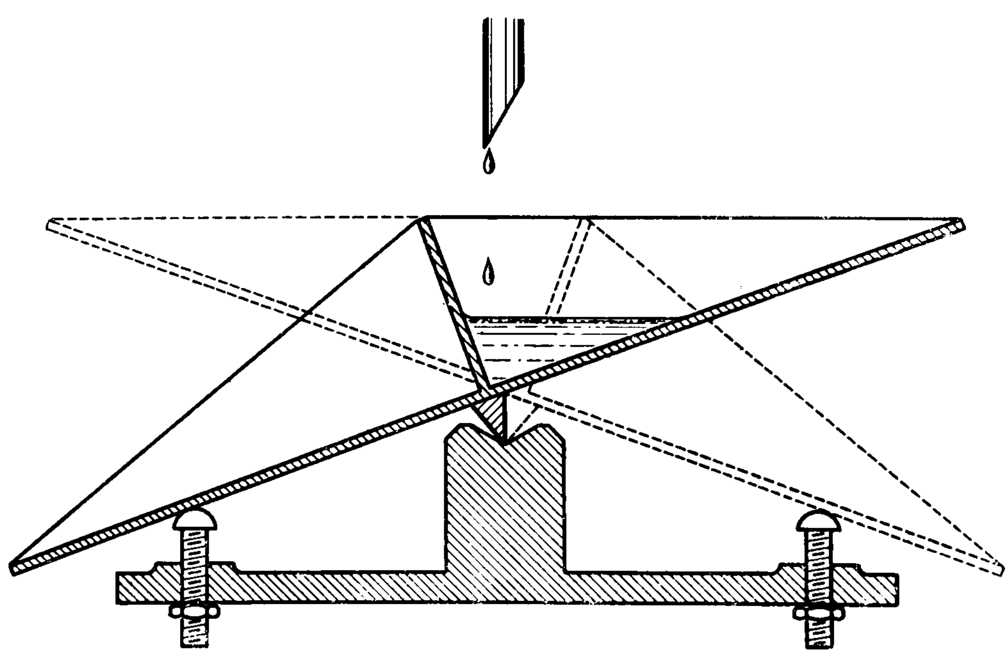


FIG 90—PRINCIPLE OF TIPPING-BUCKET RAIN-GAUGE

Another disadvantage is that the tipping motion takes a finite time, and for the first half of that time rain is still being led into the compartment already containing 0·01 in. Thus in very heavy rain each tipping motion represents rather more than the assumed amount of 0·01 in. By careful design this source of error can be minimized ; for instance, in the pattern used by the Meteorological Service of Canada, when the rate of rainfall is 2 in./hr. (very heavy rain) the error is 1 per cent.[5]

The water surfaces exposed to the air are relatively large so that evaporation errors, in light rain at any rate, are also likely to be comparatively large. Against these disadvantages must be placed the general reliability of the instrument (it can be made very strong and yet light and sensitive) and its ability to record at a distance, which saves the record from possible damage, due to exposure to rain, which can occur with any recording gauge when the charts are being changed in the open.

6.3.8. Weight gauges

For continuous recording of precipitation in cold climates, where the major type of precipitation in winter is snow, a weighing gauge is often used. A receiving can is supported on a platform carried by a form of balance, and all precipitation collected by the receiver is weighed and recorded as soon as it falls into the gauge.

Hellman-Fuess snow-gauge.—The Hellman-Fuess snow-gauge (Fig. 91) is an instrument of the weighing type which can be used to record all forms of precipitation. A cylindrical receiving can is carried on a horizontal platform which is supported by one arm of a balance mechanism. As the weight of the can and its contents increases, the platform descends and the movement of the platform is magnified and recorded by means of a pen on a chart on a revolving drum. A continuous record is therefore made of the amount of precipitation which has fallen (in the equivalent number of millimetres of liquid water) since the record was begun.

Fig. 92 shows details of the counterweight mechanism. The knife-edge B forms the main balance point ; the second knife-edge AA′ carries a frame C, into the top of which is screwed the scale pan and the bottom of which carries the lever EF which forms the link to the recording mechanism. As the weight on the pan increases, the frame descends because the counterweights have to move further from the knife-edge B.

The drum revolves once in 24 hr., and the chart covers a range of 35 mm. of water or its equivalent in solid precipitation. No funnel is provided for the gauge ; a cylindrical housing surmounted by a detachable knife-edge rim surrounds the receiving can. Snow can thus enter without obstruction, but evaporation losses in hot weather are increased.

Assembly of the balance mechanism.—The assembly of the balance mechanism should be carried out as follows. Swing the small square plate on one side of the spindle down out of the way ; see that the two knife-edges of the counterweight are clean and free from dirt, apply a little clock oil to them, and then insert the knife-edge AA′ into the two recesses in the vertical spindle by first passing the end A through the opening exposed by the removal of the plate D, and then pushing A′ back into its recess. The knife-edge B can be gently lowered on to its seating on the main frame. When all works smoothly the plate D can be replaced, and

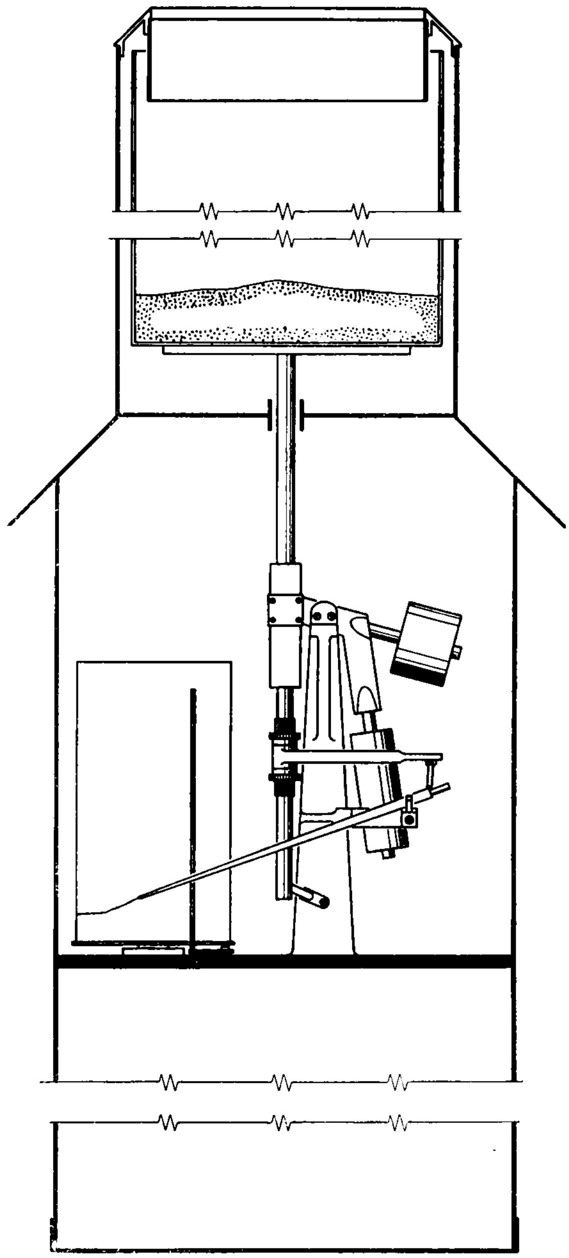


FIG. 91—HELLMAN-FUESS SNOW-GAUGE

the scale pan inserted through the hole in the upper part of the gauge and then screwed home into the top of the spindle, taking care not to grate the knife-edges in the process.

Method of use.—The receiving can is emptied every day before the next record is started. As a check on the accuracy of the record the contents of the can can be measured in a rain measure (making due allowance for any difference between the aperture of the Fuess gauge and the aperture for which the rain measure is calibrated). Any zero error of the pen may be corrected by adjusting the two knurled nuts above and below E. At intervals of a period of a year or so it is advisable to calibrate the instrument afresh by putting known volumes of water in the receiving can and noting the readings on the chart. The scale value of the instrument can be altered if necessary by adjusting the position of the lower of the two counterweights. If exceptionally heavy rain or snow occurs it may be necessary to empty the receiving can before the end of the 24-hr. period to prevent any loss of record owing to the amount of precipitation exceeding 35 mm.

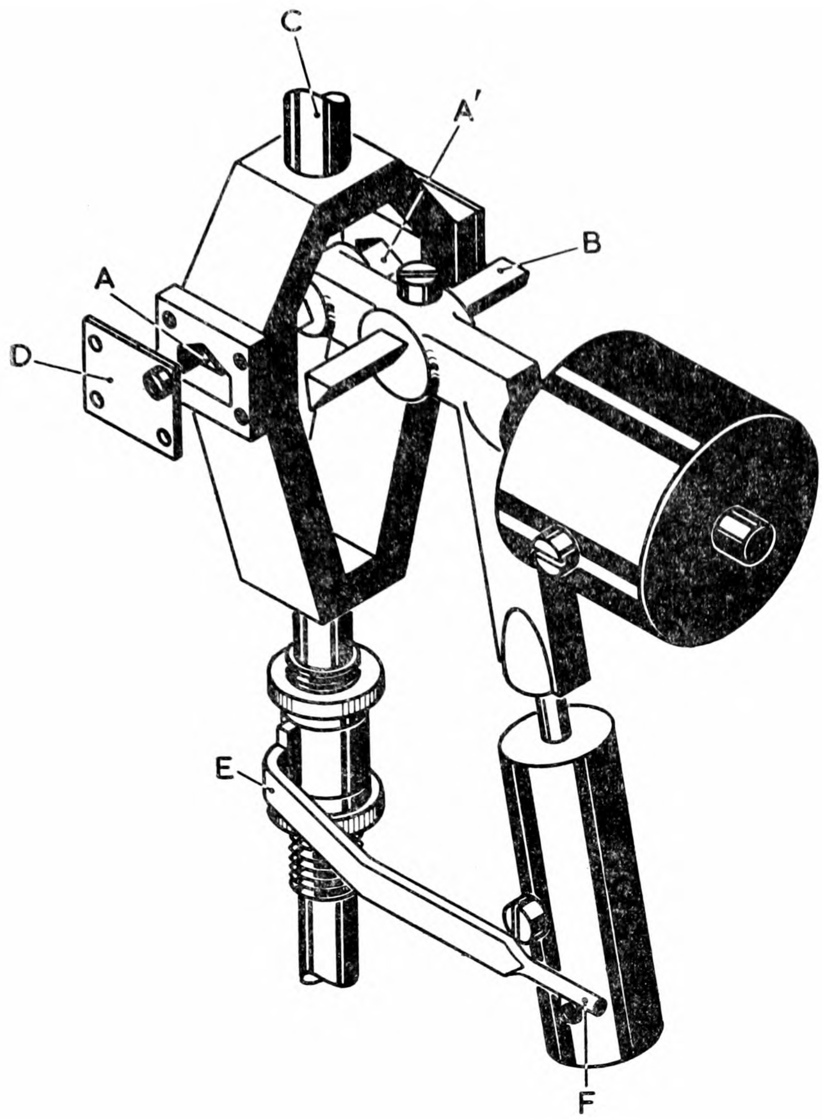


FIG. 92—BALANCE MECHANISM OF THE HELLMAN-FUESS SNOW-GAUGE

Although the instrument's main use is intended to be as a snow-gauge it can be exposed throughout the year and used for all precipitation. By measuring the slope of the trace a measure of the intensity of the precipitation can be found, but in this respect it should be noted that a compromise has had to be made between an adequate total capacity (as no provision is made for emptying the receiver) and the scale value, as the size of the chart is fixed within certain limits by other considerations. The record cannot be read as accurately as that of the Meteorological Office tilting-siphon rain recorder.

A disadvantage of the instrument is that in winds of Beaufort force 4 or more there is a broadening of the trace due to oscillations of the receiving can.

Other weight gauges.—Another form of weight gauge is that of Fergusson[49]. The depression of the receiver against a spring is recorded on a drum, and by a system of links and levers the pen traverses the chart four times, alternately up and down, before its maximum capacity is reached. In the Fergusson gauge a large oil damper is fitted to reduce oscillation due to the wind. A funnel is dispensed with during periods when snow is possible, but at other times one is fitted to reduce evaporation losses.

6.3.9. Other recording rain-gauges

An ingenious combination of the weight-type gauge and the tipping-bucket type is that due to Nilsson[50]. This gauge uses the weighing principle basically, but overcomes the difficulty of the restricted range by emptying the receiver as necessary by a modification of the tipping-bucket principle. A greatly magnified record can therefore be obtained.

The rate-of-rainfall recorder designed by Sil[51] has three identical float chambers, each with a float, but the three float rods are connected to a common lever system such that the position of a pen on a revolving drum is determined by the height of the highest of the three floats. The rain is collected in a funnel, and is led to a distributing system so that it flows into each float chamber in turn for a period of exactly 60 sec. After this period of 60 sec. the water level in the float chamber which has just received the rain remains unchanged for a period of 55 sec., and then a mechanism allows the float chamber to empty itself. This takes 40 sec. or less so that the float chamber is completely empty by the time the rain is led into it in the next cycle of operations. In a period of steady rain the record will consist of a straight line with a series of slight notches of 5-sec. duration every minute. In a period of increasing rainfall intensity the record will be a sloping line, linked with short horizontal steps. The intervals between the steps and the notches are so short however that for practical purposes the line is continuous. The rate of rainfall recorded is the average rate over a period of 1 min. The minimum rate which can be recorded is about 0·02 in./hr.

6.4. MEASUREMENT OF SNOW

To ensure that reliable measurements of precipitation are obtained during periods of snow it is essential to take special precautions. With slight falls no especial difficulty is encountered ; all that is necessary is to melt the snow in the funnel by warming it and to measure the resultant water as if it were rain. There are three ways of doing this :

(i) If snow or rain is not falling at the hour of observation the funnel and inner can may be brought indoors and their contents warmed and melted and then measured in the normal way. The top of the funnel should be covered by a flat plate to minimize the loss by evaporation. Excessive heat should never be applied, as otherwise there is risk of melting the solder on the funnel besides having a loss by evaporation even if the funnel is covered.

(ii) A cloth dipped in hot water may be applied to the outside of the funnel and receiver to melt the snow and ice. Care is required to ensure that no water enters the gauge from the cloth.

(iii) A definite amount of warm water may be accurately measured in the rain measure (the water should not be so hot as to crack the rain measure) and then poured into the gauge. Only sufficient warm water to melt the snow and ice should be used. The amount of water added is subtracted from the total measured. About two rain measures full of very warm water will be required if the funnel is full of snow.

If snow is falling at the time of observation method (ii) or (iii) must be used. The measurement obtained by one of these can be checked if all the precipitation since the last observation has been in the form of snow. The funnel of the gauge should be inverted over the snow in a place where the depth seems to be uniform and of the average amount and the cylinder of snow thus cut out collected and melted. Care must be taken that only the snow which has fallen since the last observation is collected. At some stations a small wooden or stone floor is provided for this purpose.

When heavy snow falls have occurred more elaborate precautions must be taken to ensure that the values finally adopted are representative. The amount of water (i.e. rain or thawed snow) should first be measured, and then the amount of unmelted snow, including any snow immediately above the funnel. This last should be pressed into the funnel and then one of the procedures for melting the snow, mentioned above, should be carried out. The sum of these two readings gives the total precipitation recorded by the gauge. In addition to this, the average depth of snow which has fallen since the last observation should be measured. Measurements should be made over a considerable area to allow for drifting, and care must be taken to measure only the freshly fallen snow for each day. This may be ensured by clearing the snow away from selected areas each morning or by covering small areas of snow with newspaper or a light cloth, pegged down. If possible, additional observations of the depth of undrifted snow, with corresponding readings of the gauge, should be made at times between the regular observations to ascertain as far as possible what the depth would have been if none had melted. This applies more particularly to days where the temperature is not well below freezing point.

If, after changing the depth of snow into the equivalent depth of liquid water (using the ratio 1 : 12), there is a large discrepancy between the two results it is probable that it was due to wind. This would tend to blow the snow out of the funnel of the gauge, and also, by causing drifts, make it harder to give an accurate estimate of the depth which had fallen. Both results should be noted on returns.

Recording rain-gauges of the float type are not usually much use in recording snow. If sufficient heat is supplied to melt the snow quickly losses are encountered due to evaporation. The most useful type of gauge for this purpose is the weighing gauge (e.g. the Hellmann-Fuess snow-gauge p. 285).

The " depth of snow lying " should be distinguished from the depth of fresh snow as measured above. The " depth of snow lying " is the average total depth of snow on the ground surrounding the station. It is determined by plunging a scale vertically into the snow where it lies evenly distributed without drifts. A mean value of several observations should be taken.

The precautions against frost outlined in the description of the Meteorological Office tilting-siphon rain-gauge should be taken with all recording gauges that are liable to suffer damage by frost.

In the case of gauges read monthly every endeavour should be made to secure a reading, even if the gauge is buried in snow or the contents of the receiver frozen. The snow immediately above the funnel should be pressed into the funnel. The best way of melting the contents of the gauge is method (iii) with the hot water measured beforehand and carried in a vacuum flask. Failing this, or methods (ii) and (i), tarred rope may be burnt against the side of the funnel and receiver. After taking the measurement and subtracting the amount of water, if any, which had been added the inner can should be examined for leaks. If it is possible to provide a spare inner can this can be used to replace the one containing the precipitation, to which any snow in the funnel has been added, and the reading can then be made under shelter.

If it is found impossible to visit every gauge in a group owing to very severe weather, efforts should be concentrated on getting a reading from one or two representative gauges. Arrangements should also be made if possible to supplement the readings of the gauges with records of the depth of fresh undrifted snow each morning (made as described above) at certain other convenient places, to represent the area covered by the remaining gauges. This, together with the nearest stations with daily records, enables the best possible estimate to be made of the amount of precipitation which has fallen.

6.5. MEASUREMENT OF DEW

In some parts of the world dew is an important part of the total precipitation. The amount of dew deposited on any given occasion depends on the meteorological conditions and on the properties of the underlying surface (e.g. the type of soil and the type and amount of vegetation) with the important additional qualification that the type of underlying surface determines in part the meteorological conditions. There are thus comparatively great variations, within short distances, in the amount of dew deposited on a given area, and the measurements at any particular spot have correspondingly less significance.

One method of dew measurement is to expose dry weighed plates of hygroscopic material (e.g. gypsum and silica) from sunset to sunrise and to weigh the plates again at sunrise ; the increase in weight gives the amount of dew deposited. The second weighing must be done at sunrise exactly to avoid evaporation losses[52]. A great difficulty is to understand the exact significance of the results, i.e. to find the relationship between the amount of dew deposited on the small plate and the amount deposited on the various different natural surfaces at the same time. Up to the present time the uncertainty of this relation has made the applicability of the absolute values recorded by dew-measuring instruments (or drosometers) very suspect.

6.5.1. Duvdevani dew-gauge

The method outlined above is not suitable for general or routine use because a certain degree of skill is required in operating the balance ; it is also inconvenient or impossible in many places to make an observation exactly at sunrise. A more simple instrument has been devised by Duvdevani[53]. This consists of a rectangular wooden block coated with a special red paint exposed at a standard height above the ground at sunset. The size, form and distribution of the drops of dew on the upper surface of the block the next morning are compared with a series of standard, full-scale photographs of the surface of the block covered with a known weight of dew, and thus a dew-scale number can be assigned for the amount of dew actually present. It is claimed that the appearance of the dew does not change appreciably for some time after sunrise (although evaporation takes place) so that some latitude in the time of observation can be allowed. It is also claimed that it is easy to distinguish rain from dew. The average values of the amounts of dew corresponding to each dew-scale number were found by exposing gypsum and terra silica plates under similar conditions to the dew-gauge. These equivalents cannot be used for each individual night as each dew-scale number corresponds, in effect, to a range of values, but they can be applied for monthly or yearly totals.

The chief merits of the instrument are its simplicity and robustness. It suffers from the drawback of other dew-measuring instruments, that the relation between the amount of dew recorded by the instrument and the amount of dew deposited on natural surfaces is uncertain.

6.5.2. Continuous recording of dew

An instrument which attempts to give a continuous indication of the rate at which dew or hoar-frost is being deposited has been designed by Kyriazopoulos[54]. A long strip of highly glazed paper, coated with a thin layer of soot, is wound by a clock-work mechanism from one drum to another, but only a short horizontal portion of the paper between the drums is exposed to the atmosphere at any one time. It is found that drops of dew, particles of hoar-frost or drops of rain each leave distinct traces on the layer of soot, which can be identified even after the water has evaporated. Time marks are made on the record so that the time of commencement or cessation of the dew, hoar-frost or rain can be found from the record. The formation of the dew or hoar-frost on the paper depends on its emissive properties, but it is stated that dew forms at the same rate, and at the same time, on the top of short blades of grass as on the strip if it is exposed about 15 cm. above the ground.

One advantage of the instrument is that the formation of hoar-frost after dew, dew followed by rain, or all three phenomena one after the other can be shown clearly, and the traces of the first phenomenon are not obscured by the subsequent ones. It can, however, only give a rough indication of the intensity of the dew fall or its total amount.

A good estimate of the amount of dew can, however, be obtained by the methods used for measuring evaporation described on p. 292 where the formation of dew appears as negative evaporation. These methods are however not, as yet, simple enough for routine use.

CHAPTER 7

MEASUREMENT OF EVAPORATION

7.1. GENERAL

Water is lost from the earth's surface by the evaporation of liquid water or ice into water vapour. This occurs both from the surface of sheets of water and ice and also from the moisture absorbed in solid surfaces such as soil and vegetation. It is obvious that over a time interval that is not too short, and considering the surface of the earth as a whole, as much water must be evaporated from the surface as falls on to it as precipitation. The object of attempting to measure rates of evaporation is to obtain knowledge of the details of these processes. The rate of evaporation is defined as the amount of water lost by evaporation from a unit area of surface in unit time.

The measurement of evaporation is much more difficult than the measurement of precipitation, and reliable absolute values of the loss from the surface of the earth over areas of any appreciable size have not yet been obtained. The following factors affect the rate of evaporation, sometimes indirectly, from any body or surface :

(i) Wind at the surface

(ii) Humidity of the air at the surface

(iii) Temperature of the air at the surface

(iv) Temperature of the evaporating surface

(v) Amount of moisture in the surface available for evaporation.

(vi) Nature of the surface.

It should be noted that (iv) depends on (vi) as well as on the meteorological conditions. In addition to the surface values of (i), (ii) and (iii) their variation with height in the lowest layers is also important. The rate of evaporation therefore varies greatly over comparatively small areas. It should be noted also that conditions do arise in which there is a net condensation of water vapour on the surface, i.e. dew is deposited.

7.1.1. Units

The rate of evaporation from a surface can be expressed as the volume of liquid water evaporated per unit area per unit time. This is equivalent to a certain depth of liquid water lost per unit time from the whole area and evaporation is usually expressed in this way. The unit of time may be either a day or an hour and the unit of depth may be centimetres, millimetres or inches. Records from the Meteorological Office evaporation tank are usually expressed in inches per day.

7.1.2. General principle of evaporimeters

Instruments at present used for the measurement of evaporation may be divided into four classes :

(i) Large evaporation tanks sunk into the ground or floating on pontoons in lakes, and so arranged that the surface of the water in the tank is very close to the surrounding surface level. The depth of water in the tank is measured accurately at regular intervals (usually once a day), and after allowing for any precipitation which has fallen, using a rain-gauge exposed near by, the depth of water lost by evaporation since the last measurement can be calculated.

(ii) Small evaporation pans. Either the variation in the amount of water in the pan is measured by eye readings, or the variation in the depth, or the weight of water is recorded automatically.

(iii) Porous porcelain bodies. These measure the amount of water lost by a porous sphere, cylinder or plate kept saturated with water.

(iv) Instruments using wet paper surfaces. These measure the water lost by an exposed filter paper which is kept saturated.

Evaporation from any natural solid surface can be considered as taking place in two separate stages : the diffusion of water, either as liquid or vapour, through the solid to the surface, and the removal of the vapour from the surface. The first stage depends on the factors (v) and (vi), mentioned on p. 292, which are complicated functions of the type and condition of the vegetation (e.g. the species, maturity and extent), the type of soil, and the condition of the soil and subsoil (dependent on the past weather). The second stage depends on the wind speed near the surface, its variation with height, and the vertical distribution of the specific humidity. Only the second stage occurs with water surfaces such as lakes or reservoirs.

As far as the second stage is concerned there is now good reason to believe that measurements made with any small instrument which cannot be regarded as an indistinguishable part of the surface under observation should not be accepted as a reliable indication of the rate of remóval of the vapour from the surface[55]. Measurement of evaporation from small plates exposed to the atmosphere at ground level show no significant change in the rate of evaporation with variation of the vertical temperature gradient, such as would be expected to occur over large water surfaces. It seems therefore that it would be very unsound to use the results from the usual evaporation instruments to deduce the rate of evaporation from large free water surfaces. They are even more unlikely to give the correct result for the evaporation from the ground, where the first stage of evaporation further complicates the process.

7.2. METEOROLOGICAL OFFICE STANDARD EVAPORATION TANK

7.2.1. Description and installation

The standard evaporation tank (Fig. 93) is square with sides 6 ft. long and 2 ft. deep, and is constructed of wrought-iron plates, overlapped and rivetted together. Around the outside, 3 in. from the top, is rivetted a horizontal flange 1 in. wide, and the tank is sunk into the soil up to the level of the flange ; the top of the tank is thus 3 in. above the surrounding ground. In siting the tank four factors have to be taken into account :

(i) Outsplashing of water from the tank in high winds.

(ii) Insplashing of rain from the surrounding ground.

(iii) The necessity of ensuring similar exposures of the rain-gauge and evaporation tank, so that the amount of precipitation caught by the tank may be accurately represented by the amount caught by the rain-gauge.

(iv) The amount of exposure necessary to make the reading representative of the surroundings. If the exposure is too sheltered the instrument would not record the variations in evaporation which would take place in more exposed areas due to the variations in wind strength.

Items (i), (iii) and (iv) have to be balanced against one another and a satisfactory compromise made. A fairly sheltered position has to be chosen as the rain-gauge

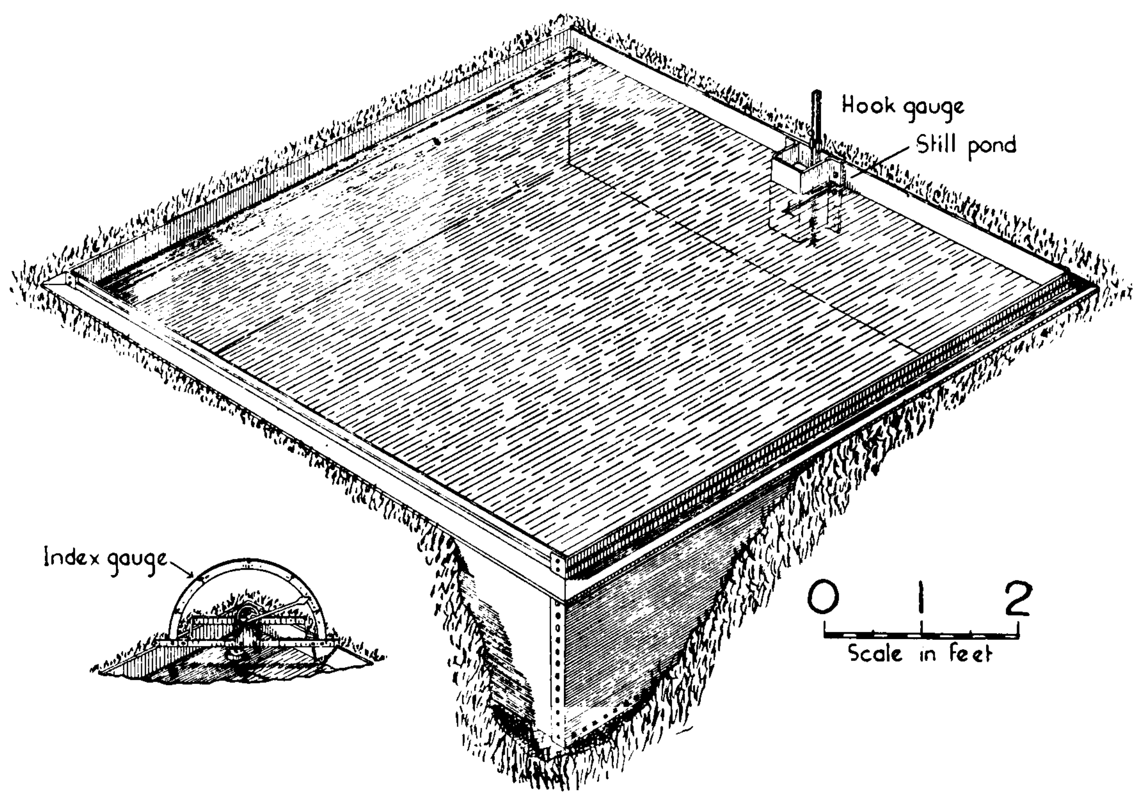


FIG. 93—EVAPORATION TANK

must be sited in accordance with the principles laid down on p. 264, and must also be close to the tank itself. A distance of from 3 to 10 ft. away from the tank is desirable. Item (ii) is kept to a minimum by growing grass on the tank surrounds. The grass should be kept cut short, so that the top of the tank is at least 2 in. above the tops of the blades of grass.

To avoid trouble due to ripples on the surface of the water the measurement of the depth of water is made inside a still-water pond. This is box-shaped without a top and made of galvanized iron. It measures 4 in. square by 12 in. deep, with a round hole in the centre of the base. It is suspended in the tank at the centre of one side, by two flat metal hooks which are soldered on to one of its sides so that, when in position, its top is level with the top of the tank.

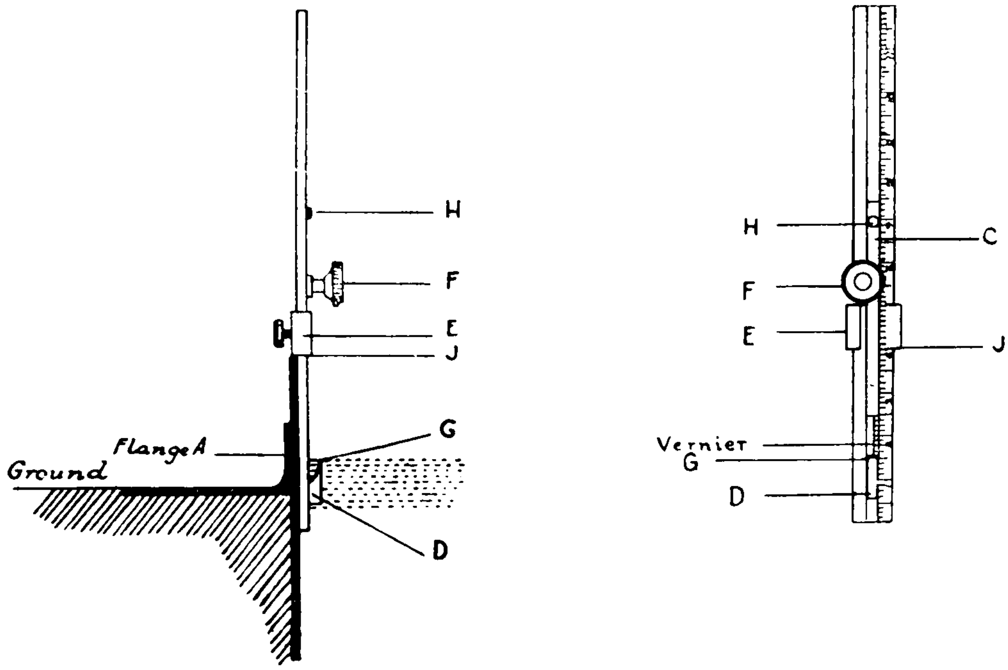


FIG. 94—HOOK GAUGE

The depth of water is measured with a hook gauge (Stores Ref., Met. 2813) (Fig. 94). This consists of a graduated brass rule with a channel in its face in which a slide C, which has a vernier engraved on it, can be moved by a rack and pinion movement controlled by the knob F. The hook is a piece of brass D attached to the slide with a straight horizontal indicating edge G on the same horizontal level as the lowest vernier graduation. The front edge of the slide is kept flush with the graduated face of the channel by means of a spring whose tension can be adjusted by means of a small screw H. A movable clamp E provides support by which the gauge rests on the side of the tank. It is usually set so that its lower edge J is 4 in. above the end of the rule. The height of the indicating edge of the hook above the base of the rule is read by means of the vernier to the nearest 0·01 in. It is obvious that the position of the movable clamp E should not be changed between the daily observations.

7.2.2. Method of use

The level of the water should be kept 2–3 in. below the top of the tank by adding or removing water as required. Readings of the depth of water are taken immediately before and after either operation to measure the depth of water added or removed. If the water freezes all the ice should be broken away from the sides of the tank and the measurement of the water level made while the ice is floating. Provided this is carried out the fact that some of the water is frozen does not affect the level. If the ice is too thick for this to be done the measurement should be held over until a subsequent morning and the evaporation over the extended period determined.

Readings are made daily (normally at 0900 G.M.T.) and the rain-gauge should be read at the same time. The hook gauge is inserted in the water inside the still-water pond with the lower edge of the clamp resting on the side of the tank. The hook is then adjusted by the pinion until it just cuts the surface of the water ; it is usually found that moving the hook upwards from beneath the surface is the most satisfactory way. The reading of the scale and the vernier will then give the height of the surface of the water above the base of the rule to the nearest 0·01 in. Provided the movable clamp has not been altered since the last reading the change in depth can be obtained by subtracting the present reading from the previous one, and, after allowing for the depth of any precipitation, the evaporation or condensation can be found. If water has to be added or subtracted to keep the water level within the required limits, the ordinary reading should be made before the operation, and the second reading used to form the basis of comparison with the subsequent readings.

An alternative method of measuring the depth of water is by the use of an index evaporation gauge (Fig. 93), set up across one corner of the tank. A copper float rises and falls with the level of the water in a copper cylinder, which acts as a still pond, and a brass chain attached to the float moves over a pulley wheel vertically above the float. The float is suitably counterpoised so that its motion represents the changes in level of the water surface in the tank. An index hand is attached to the axis of the pulley wheel and moves over a graduated semicircle, $9\frac{1}{2}$ in. in radius, enabling the depth of water above a fixed point to be read directly. The scale is from 0 to 4·00 in., subdivided to 0·02 in. When both methods are in use a mutual check is provided on the results obtained.

A recorder has been designed for use with the evaporation tank ; it records continuously on a drum the level of a float resting in a float chamber connected to the main tank.

7.2.3. Maintenance

The hook gauge must be kept clean and oiled at intervals so that the rack and pinion movement is smooth in operation. The top 3 in. of the tank and the flange should be kept free from rust, and if necessary a coat of good quality white paint should be applied.

7.2.4. Accuracy and sources of error

The significance of the measurements made with the evaporation tank is a subject of controversy. The temperature variations of the water in the tank are likely to be far greater than those of any large expanse of water such as a lake or the sea ; in addition the wind structure is very different, so that the evaporation from each will not be comparable[55]. On the other hand Wadsworth[56] and Penman[57] have found results obtained from the instrument useful in assessing evaporation from natural surfaces.

A better approximation to the evaporation from the surface of a lake would be obtained by floating the tank on pontoons on the surface so that the water level in the tank was nearly that of the lake. The wind structure over the tank and its surface temperature would then be much closer to that obtaining for the free surface.

7.3. PORTABLE EVAPORIMETERS

The use of portable evaporimeters for measuring evaporation from natural surfaces is, for reasons already mentioned on p. 293, not recommended by the

Meteorological Office. The following brief descriptions should suffice to distinguish between some of the instruments of this type.

7.3.1. Piché evaporimeter

The Piché evaporimeter consists of a long narrow glass tube, graduated in cubic centimetres, one end of which is closed and the other open and ground flat. The flat end is covered with a circular filter paper held in position with a small disc and a metal clip. In use the tube is filled with distilled water, closed with the filter paper and disc and then inverted. Water soaks the filter paper and then evaporates from it ; the amount of water which evaporates in any given time can be measured by making two consecutive readings of the level of water in the tube. The difference will give the volume of water evaporated.

This type of evaporimeter is used for making comparisons over a given area, but it does not give absolute results. It is very sensitive to wind speed, and in making observations in different places similar exposures must be used.

7.3.2. Small evaporation pans

The water lost from the pan can be measured in numerous ways ; a pointed wire soldered to the bottom of the pan and standing vertical is sometimes used to provide a reference point for the depth of water. Each instrument has to be exactly similar in all details, with a similar exposure, if comparable results are to be obtained. The numerical results obtained bear little relation to those obtained by other instruments.

7.3.3. Porous porcelain evaporimeters

Livingston's sphere is an example of the porous porcelain evaporimeter. The evaporating element consists of a sphere about 5 cm. in diameter and of the order of 3 mm. thick. To it is attached a glass or metal tube dipping into a reservoir bottle. Atmospheric pressure on the surface of the water in the reservoir bottle keeps the tube and sphere filled with water. As with the Piché evaporimeter successive measurements of the volume of water remaining will give the amount lost by evaporation in any given time. The sphere is easily broken by frost.

Neither the Piché nor the porous porcelain evaporimeters measure condensation ; this is not a great drawback as the amounts are generally small. It is necessary that the water used should be at the same temperature as the outside air or false results will be obtained before the temperatures become equalized.

7.4. ABSOLUTE EVAPORATION MEASUREMENTS

All the instruments described earlier in the chapter suffer from the criticisms given on p. 293. The results obtained from them cannot be related to the actual evaporation from land or water surfaces. There is however another, more indirect, method of approach. The transport of water vapour away from the surface in a vertical direction depends largely on the turbulence of the air flow, and if no water vapour is being added or subtracted from the air at the surface a state is soon set up in which the specific humidity is everywhere uniform (in the lower layers of the atmosphere). When, however, water vapour is being evaporated from the ground the specific humidity near the ground rises and a gradient of specific humidity in the vertical is set up. The turbulent transfer of water vapour will then result in a net flow of water vapour upwards ; this flow will increase as the specific humidity gradient increases until the rate of transfer upwards of the water vapour by turbulence is equal to the rate of evaporation. Similarly when condensation takes place a specific humidity gradient in the opposite direction is set up whose value depends on the rate of condensation.

The method of measuring the evaporation (or condensation) at any particular time consists of measuring the rate of transfer of water vapour above the surface in question in a vertical direction and equating it to the rate of evaporation or condensation. To do this it is necessary to measure the vertical gradients of specific humidity and wind speed ; the instruments used can be standard types, but great accuracy is required as it is the difference in wind speed and specific humidity between two or more heights which is required. Precision cup anemometers and wet- and dry-bulb thermo-couples, suitably aspirated, can be used provided the lag of the thermo-couples is made a convenient value.

It is possible in this way to measure the changes in evaporation from hour to hour throughout the day. Further details are given by Pasquill[58].

CHAPTER 8

MEASUREMENT OF THE DURATION OF SUNSHINE AND STARSHINE AND OF THE INTENSITY OF SOLAR RADIATION

8.1. MEASUREMENT OF THE DURATION OF SUNSHINE AND STARSHINE

Sunshine recorders as used by the Meteorological Office and in most other countries are designed to measure the duration of " bright " sunshine. There is, however, no very strict definition of " bright " sunshine that can easily be related to all methods of measurement, as different types of instrument respond to different wave-lengths in the sun's radiation. The instruments fall into two main classes :

(i) Those that utilize the heating power of the sun's radiation

(ii) Those that utilize the chemical action produced by the visible and ultra-violet rays.

The duration of starshine is defined as the length of time for which a given circumpolar star is visible during the period while the sun is 10° or more below the horizon. In practice it is taken as being proportional to the length of the visible record produced by an image of the star on a photographic plate or film exposed in a recorder under standard conditions.

8.1.1. General principles and historical development of sunshine recorders

The chief type of sunshine recorder in the first class is the Campbell-Stokes instrument. This was first developed by Campbell in 1853 ; in its original form it consisted of a spherical glass bulb filled with water and placed at the centre of a hemispherical wooden bowl. The sun's rays were focussed by the bulb on the inner surface of the bowl and charred the wood. As the declination of the sun varied from day to day the burns for different days did not exactly coincide, and the amount of sunshine over a period of 6 months between the solstices could be roughly estimated. The instrument was improved in 1879, when Stokes replaced the wooden bowl by a metal bowl in the form of part of a belt cut from a sphere and put flanges on the inside of the bowl to hold specially printed cards, which were charred by the sunlight in the same way as the wood. The water-filled bulb had been, by this time, replaced by a solid glass sphere. In present-day instruments of the Campbell-Stokes type flanges are provided for three sets of cards, one set for the equinoctial periods, one set for the winter and one set for the summer, so that the whole range of the sun's declination can be covered ; the bowl is adjusted so that the plane containing the mid line of the equinoctial card is coincident with the plane of the celestial equator, making the records at the solstices an equal distance above and below this central line. The cards are changed every day, and the total length of the burn (or burns) is compared with the time scale on the card to obtain the duration of sunshine.

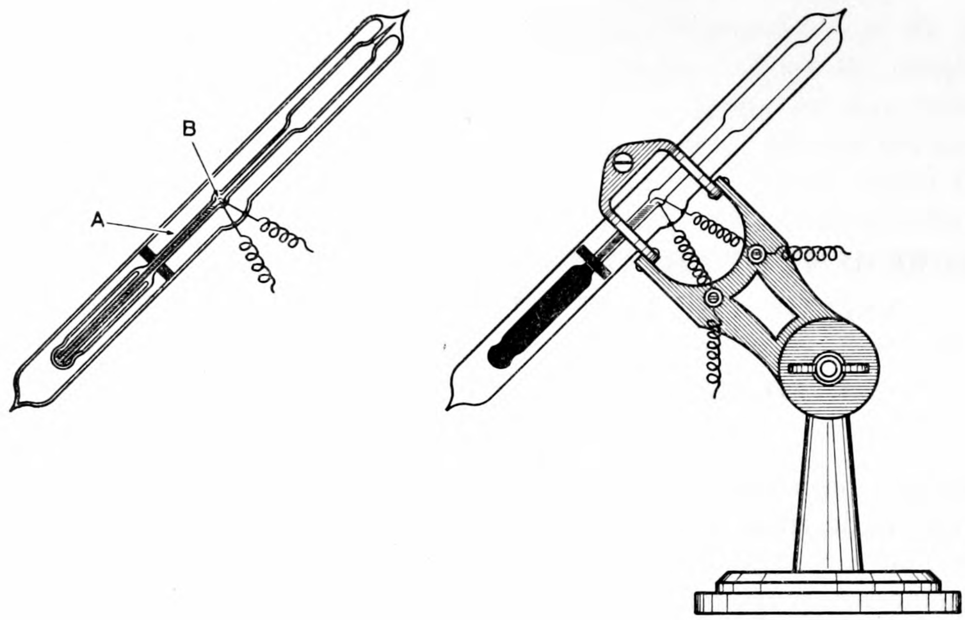


FIG. 95—MARVIN SUNSHINE RECORDER

The other main type of sunshine recorder in the first class is the Marvin recorder (Fig. 95) used in the United States. This is, in effect, a differential air thermometer, with one black bulb and one clear bulb. A record is made whenever there is a certain difference in temperature between the two bulbs, which will occur only when radiation is falling on the instrument. It can be adjusted to respond to radiation corresponding to faint direct sunlight during the middle part of the day.

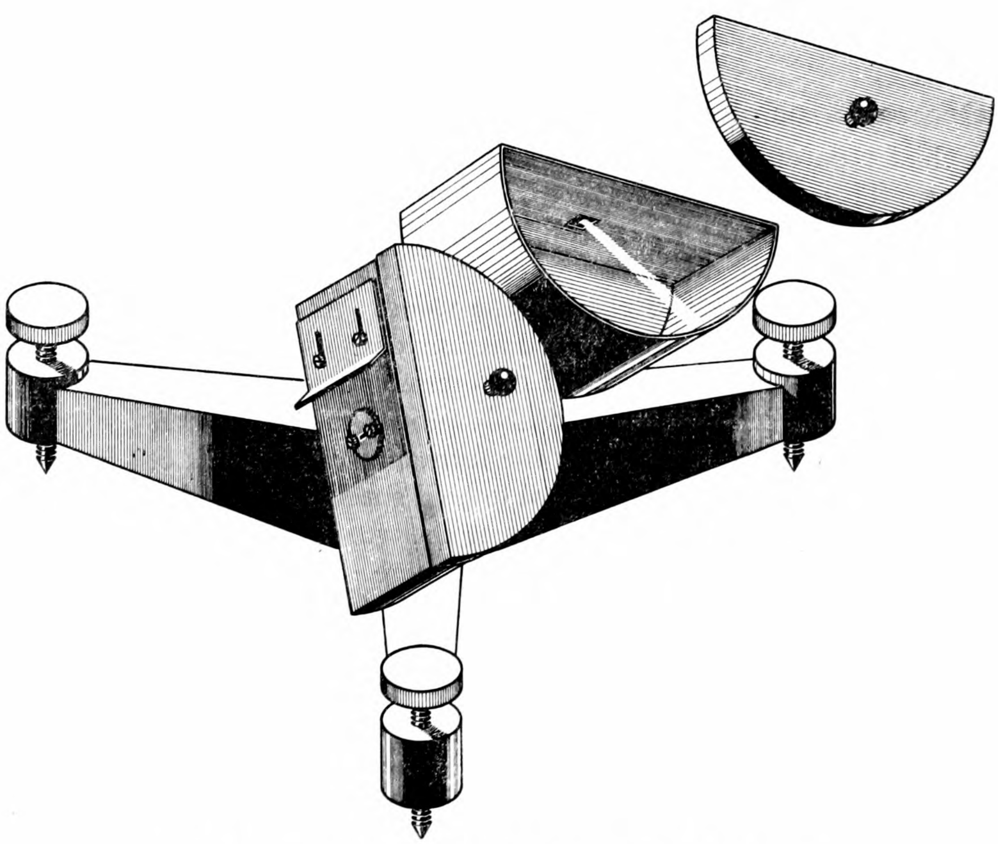


FIG. 96—JORDAN SUNSHINE RECORDER

In the second class of instruments is the Jordan sunshine recorder. When designed by J. B. Jordan in 1838 it consisted of an inner cylinder covered with sensitized paper of the " blue-print " type, around which rotated, once every 24 hr., an outer cylinder with a single slit. When the sun shone, a record was left on the sensitized paper. It was produced in something like its present form by T. B. Jordan in 1885. It now usually consists of two semicylinders (see Fig. 96) each having a short narrow slit in the flat side ; a piece of sensitized paper is fitted into the curved side of each cylinder and the sunshine entering through one or other of the slits makes a trace on this. The instrument is adjusted so that one chart covers the morning hours and one chart the afternoon hours. When the sensitized paper is removed it need only be washed briefly to make the record permanent.

8.1.2. Brief comparison of different types of sunshine recorders

The Campbell-Stokes recorder is a simple robust instrument. By careful specification and testing of the size of the bowl, the focal length of the sphere, the diameter of the sphere, the properties and size of the record cards, and by careful adjustment before and after installation, it has been possible to obtain records which are highly consistent with one another. The card is not burned, however, until the intensity of the direct radiation from the sun reaches a certain minimum value (about 0·2 to 0·4 cal./cm.^{2}/min.), and thus on clear mornings it does not begin recording until some period after the sun has risen, and it ceases recording on clear evenings about the same period before sunset. This period varies with the transparency of the atmosphere, but has a minimum value of about 15–30 min. in temperate latitudes according to season. There is some uncertainty about the measurement of the records, because the image of the sun has a finite diameter and also because of the spreading of the area of burning when the radiation is strong. There is also difficulty in deciding whether a trace has or has not been made if the radiation has been very weak. The possibility of personal errors thus occurs, but this is reduced to a minimum by following instructions on the standard methods of interpreting the records.

The Jordan type of recorder is also a simple robust instrument. If exposed side by side with a Campbell-Stokes instrument the total amount of sunshine recorded over a long period is not greatly different. The Jordan records " afford room for much greater differences of opinion as to what ought to be tabulated and consequently the measurements of the Jordan curves are open to much more uncertainty than are the measurements of the Campbell-Stokes records "[59]. This leads to relatively large day-to-day differences between the two records at times. It is also difficult to keep the sensitivity of the blue-print paper constant from year to year.

The Marvin recorder has the one advantage that it gives an easily deciphered record at a distance, but it has three main defects. It is sensitive to diffuse radiation as well as to the direct radiation from the sun, and thus measures the length of time during which the total insolation (sunshine plus skyshine) exceeds a certain value. It is difficult to standardize and is fragile. The sensitivity depends to some extent on the temperature of the air.

8.1.3. General principles of the starshine recorder

The starshine recorder is essentially a night-sky camera, with a long focus lens, usually mounted with its axis pointing towards one of the celestial poles[60]. A shutter mechanism, controlled by a clock, exposes the film only during the period when the sun is 10° or more below the horizon ; as the earth rotates, images of the stars trace out arcs of concentric circles on the film. This record is interrupted by cloud, fog or thick haze, and serves as a measure of the duration of starshine. The total length recorded will depend on the least difference in density between the image and the background which can be distinguished. This varies with the observer, the type of film and its treatment. For good quantitative agreement between different sets of records the same film material and treatment should be employed.

A starshine recorder was first developed in 1888 by Pickering, based on the same principles as are in use at the present day. The camera in use at present has a field of view of about 18°, so that, if it is accurately aligned, records can be obtained of stars up to 9° from the pole.

8.1.4. Timing the sunshine records

It will be seen that most of the main types of sunshine recorder use the movement of the sun, instead of a clock, to form the time base for their records. It is therefore necessary to know the relation between the position of the sun and the standard of time actually in use. The interval between two successive transits of the sun across the meridian is called a true solar day, and time based on the length of this day is called apparent solar time. Local apparent time is the apparent solar time for any particular place such that the sun passes across the geographical meridian at noon. It is this time which is indicated by a sundial or sunshine recorder when it is correctly adjusted.

The true solar day, however, varies in length throughout the year. For convenience a mean sun is assumed, such that the length of a mean solar day is constant and equal to the average value of the true solar day taken over the whole year. Local time based on the transit of the mean sun is called local mean time. Four times a year, about April 16, June 13, August 31 and December 25, the local apparent time is the same as the local mean time. At other times a certain quantity, known as the equation of time, has to be added algebraically to the local apparent time to obtain the local mean time. Table XL gives the value of the equation of time for every 3 days throughout the year ; it varies a little from year to year, but these values are near enough for most meteorological purposes. Accurate values can be obtained from the *Nautical Almanac* if necessary.

TABLE XL—MEAN VALUE OF THE EQUATION OF TIME FOR EVERY THIRD DAY THROUGHOUT THE YEAR

to the nearest ½ min.

Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	+ 3	+13½	+12½	+4	−3	−2½	+3½	+6	0	−10	−16½	−10
4	+ 4½	+14	+12	+3	−3	−2	+4	+6	−1	−11	−16½	−10
7	+ 6	+14	+11	+2½	−3½	−1½	+4½	+5½	−2	−12	−16½	− 8½
10	+ 7	+14½	+10½	+1½	−3½	−1	+5	+5½	−3	−13	−16	− 7½
13	+ 8½	+14½	+ 9½	+ ½	−3½	0	+5½	+5	−4	−13½	−15½	− 6
16	+ 9½	+14½	+ 9	0	−3½	+ ½	+6	+4½	−5	−14½	−15½	− 4½
19	+10½	+14	+ 8	−1	−3½	+1	+6	+3½	−6	−15	−14½	− 3
22	+11½	+14	+ 7	−1½	−3½	+1½	+6½	+3	−7	−15½	−14	− 1½
25	+12	+13½	+ 6	−2	−3	+2½	+6½	+2	−8	−16	−13	0
28	+13	+13	+ 5½	−2½	−3	+3	+6½	+1½	−9	−16	−12	+ 1½
31	+13½		+ 4½		−2½		+6½	+ ½		−16½		+ 3

The civil or standard time used for everyday purposes (e.g. Greenwich Mean Time or British Summer Time in the British Isles) is the local mean time for some standard meridian of longitude (0° or 15°E. respectively for the times mentioned for the British Isles). To calculate local mean time from standard time it is necessary to know the longitude of the station and the longitude of the meridian used as the basis of standard time. The mean sun revolves about the earth at the rate of 1° in 4 min., so that if the station is $n°$ west of the standard meridian the mean sun will cross the meridian of the station $4n$ min. after it crosses the standard meridian. The following equations then hold :

In the western hemisphere

Local apparent time = Local mean time − equation of time
= Standard time + $4(\lambda_s - \lambda)$ min. − equation of time,

where λ_s is the west longitude of the standard meridian and λ that of the station, in degrees. Note that in Great Britain λ_s is zero or − 15°.

In the eastern hemisphere

Local apparent time = Local mean time − equation of time
= Standard time − $4(\lambda_s - \lambda)$ min. − equation of time,

where λ_s and λ are now east longitudes.

The main use of this data is to calculate the standard time of local apparent noon (i.e. the time when the sun is due south). The equations may then be re-arranged to read as follows :

In the western hemisphere

Standard time of local apparent noon = 1200 + equation of time − $4(\lambda_s - \lambda)$ min.

In the eastern hemisphere

Standard time of local apparent noon = 1200 + equation of time + $4(\lambda_s - \lambda)$ min.

To simplify the calculation of the time of local apparent noon in longitudes near Great Britain, Table XLI is included, which gives this directly in Greenwich Mean Time for each whole degree of longitude from 4°E. to 10°W. for every 5 days throughout the year. The required time for any other day or longitude can then be obtained by interpolation. It should be noted that the standard time equivalent to any other local apparent time can be obtained by applying a correction to the local apparent time equal to the difference between the time given in Table XLI and 1200 and in the same sense. For example local apparent noon at a station with a longitude of 9°W. on March 25 is at 1242 G.M.T. Therefore 0900 local apparent time is at 0942 G.M.T. and so on.

8.2. SUNSHINE RECORDERS

8.2.1. Temperate sunshine recorder Mk II

The principle of the temperate sunshine recorder Mk II is dealt with on p. 299. It is of the Campbell-Stokes type. The whole instrument (frame, Stores Ref., Met. 90, and sphere, Stores Ref., Met. 192) is mounted on a main base of gun-metal, provided with three lugs, drilled to take screws, for fixing purposes (Plate XL). Carried on the main base is a sub-base consisting of a triangular brass plate, which in turn carries the bowl mounting and the sphere seating. The sub-base has three adjusting screws so that it can be levelled accurately, and

TABLE XLI—TIME, G.M.T., (TO NEAREST MINUTE) OF LOCAL NOON

The table is computed from the relationship
local apparent time = G.M.T. + equation of time ± longitude, longitude being reckoned at the rate of plus four minutes for every degree west of Greenwich and minus four minutes for every degree east of Greenwich

		4°E.	3°E.	2°E.	1°E.	0°	1°W.	2°W.	3°W.	4°W.	5°W.	6°W.	7°W.	8°W.	9°W.	10°W.
January	1	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243
	5	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245
	10	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243	1247
	15	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244	1248
	20	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243	1247	1251
	25	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244	1248	1252
	30	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245	1249	1253
February	1	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246	1250	1254
	5	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246	1250	1254
	10	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243	1247	1251	1255
	15	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243	1247	1251	1255
	20	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246	1250	1254
	25	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245	1249	1253
March	1	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245	1249	1253
	5	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244	1248	1252
	10	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243	1247	1251
	15	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245	1249
	20	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244	1248
	25	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
	30	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245
April	1	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244
	5	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243
	10	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241
	15	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240
	20	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239
	25	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238
	30	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
May	1	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
	5	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
	10	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236
	15	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236
	20	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236
	25	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
	30	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
June	1	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238
	5	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238
	10	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239
	15	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240
	20	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241
	25	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242
	30	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243

TABLE XLI—TIME, G.M.T., (TO NEAREST MINUTE) OF LOCAL NOON—*continued*

		4°E.	3°E.	2°E.	1°E.	0°	1°W.	2°W.	3°W.	4°W.	5°W.	6°W.	7°W.	8°W.	9°W.	10°W.
July	1 ..	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243
	5 ..	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244
	10 ..	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245
	15 ..	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
	20 ..	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
	25 ..	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243	1247
	30 ..	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
August	1 ..	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
	5 ..	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
	10 ..	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245
	15 ..	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244
	20 ..	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243
	25 ..	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242
	30 ..	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241
September	1 ..	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240
	5 ..	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239
	10 ..	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
	15 ..	1139	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235
	20 ..	1138	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234
	25 ..	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232
	30 ..	1134	1138	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230
October	1 ..	1133	1137	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229
	5 ..	1132	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228
	10 ..	1131	1135	1139	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227
	15 ..	1130	1134	1138	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226
	20 ..	1129	1133	1137	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225
	25 ..	1128	1132	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224
	30 ..	1128	1132	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224
November	1 ..	1127	1131	1135	1139	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223
	5 ..	1128	1132	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224
	10 ..	1128	1132	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224
	15 ..	1129	1133	1137	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225
	20 ..	1130	1134	1138	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226
	25 ..	1131	1135	1139	1142	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227
	30 ..	1133	1137	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229
December	1 ..	1133	1137	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229
	5 ..	1135	1139	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231
	10 ..	1137	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233
	15 ..	1139	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235
	20 ..	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
	25 ..	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240
	30 ..	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243

provision is made for moving it relative to the main base over a small range in azimuth. The outer surface of the bowl is formed from a belt cut from a sphere by two parallel planes, equidistant from the centre. This is then cut by another plane passing through the centre of the bowl and making an angle of 38° with the other two planes ; this angle is the difference between 90° and the principle latitude, 52°, for which the instrument is designed, and when in use in latitude 52° the plane of this cut is therefore horizontal. The mounting of the bowl on the sub-base consists of a tongue moving in a hinge cheek, so that the bowl may be rotated about an axis through its centre, perpendicular to the hinge cheek. A scale is fixed to the hinge cheek, which gives the inclination of the noon line on the equinoctial card (when in position) to the sub-base. The recorder can be used in any latitude in the range 45° to 65°, and the scale is graduated over this range.

As flat pieces of card cannot be made to fit perfectly into a spherical surface the inner face of the bowl is flanged to take three different types of card, one type for use in the periods about the equinoxes, one type for summer and one type for winter. A cross-section of the bowl is shown in Fig. 97. When in position, the equinoctial card forms part of a cylinder surrounding the sphere, while the summer and winter cards form part of the surface of two cones. The semi-vertical angle of these cones is 16°, and their axes are parallel to the axis of the cylindrical surface. These surfaces are only tangential to the ideal spherical inner surface, but they have the advantage that flat pieces of card can be made to fit them accurately ; they differ nowhere from the ideal surface by more than about 0·02 in. over the parts actually used for recording. The positions occupied by the different sets of cards overlap so that a record can always be obtained without using the extreme edge of the cards.

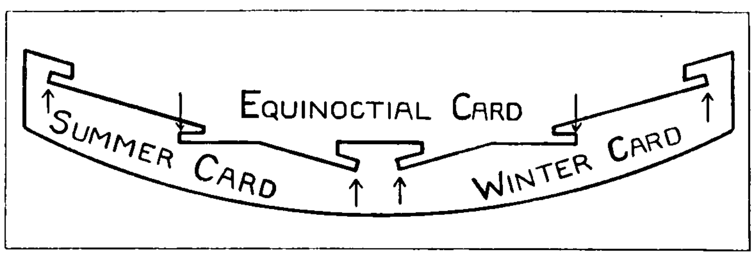


FIG. 97—CROSS-SECTION OF SUNSHINE-RECORDER BOWL

The sphere seating consists simply of a small horizontal cup, with the same radius as the sphere, carried on a short pillar. Its position can be adjusted both horizontally and vertically, after slacking off the appropriate lock-nuts. The cards are kept firmly in position by means of a clamping screw which is screwed into one of three holes in the upper edge of the bowl (according to which type of card is in use). The screw is attached to the sub-base by means of a length of brass chain.

In very exposed situations a retaining clip (Stores Ref., Met. 540) can be fitted to prevent the displacement of the sphere in high winds (Fig. 98). At some stations the sphere is sometimes displaced by sea-gulls or other large birds, and the retaining clip has proved effective in preventing this. It consists of a double length of stout gauge wire fixed to a collar ; when the collar retaining screw is loosened the collar itself can be slid on to the two slotted uprights on the bowl mounting. The wire

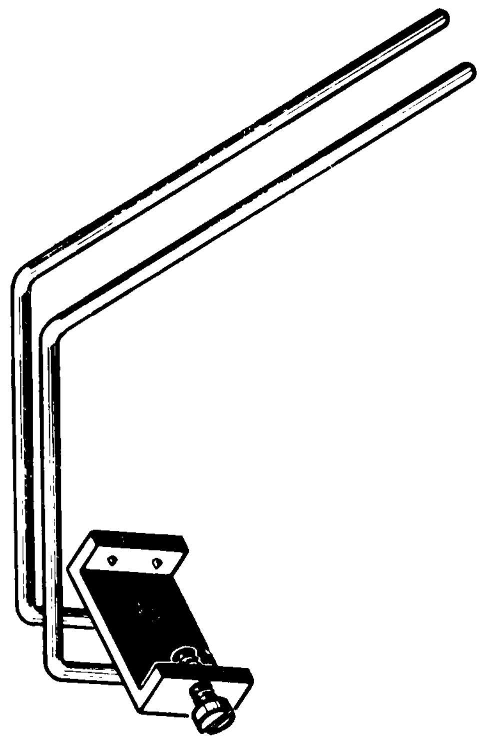


FIG. 98—SPHERE-RETAINING CLIP

should then press lightly on the top of the sphere but it may need to be bent downwards slightly to do so. After it has been adjusted the retaining screw should be tightened.

A fitting has been designed to prevent the deposition of hoar-frost on the sphere during the night. This consists of a wooden box, with portions of two of its sides cut away, which can be placed over the whole instrument after sunset. The record next day from sunrise to about noon can be obtained before the box need be removed. The box reduces the fall in temperature of the sphere on clear nights, and so reduces the risk of hoar-frost being deposited on it.

Sphere.—The sphere is made of uniform well annealed glass ; it should be colourless or of a very pale yellowish green tint. Its mean focal length, defined as the distance from the centre of the sphere to the point at which a narrow pencil of parallel sodium D light is brought to a focus, found from four different measurements in arbitrary directions, should be $2 \cdot 95 \pm 0 \cdot 01$ in. ; any individual measurement should be $2 \cdot 95 \pm 0 \cdot 02$ in. No optical irregularity of the glass which prevents the formation of a sharp image with a narrow pencil of sodium D light is allowed to extend over the whole cross-section of any cylinder of 1-in. diameter whose axis passes through the centre of the lens. The nominal diameter of the lens is 4·00 in., but variations of up to 0·05 in. can occur provided the focal length is correct.

Sunshine cards.—The cards are made from good quality paste board, coloured with a matt finish blue ink. This colour gives a good contrast with the burns, and absorbs freely the radiation which is mainly responsible for the heating effect. A black colour would probably give maximum absorption, but it would then be more difficult to distinguish the burns.

It is important that a standard material should be used for the cards to ensure consistency in the rate of burning. A strict limit has also to be placed on their change in dimensions when wet, and on subsequent drying, to reduce to a minimum the change in scale value, the tendency for the cards to jam in their slots, or the tendency to become too small and thus become displaced. Three types of card are used in the recorder ; the long curved summer cards fit into the bottom set of flanges, the short curved winter cards fit into the upper set of flanges and the straight equinoctial cards fit in the centre flanges. White hour lines are printed on the cards at right angles to the long edges and symmetrically placed about the centre noon mark. The crosses indicate points on the centre line of the card. The time scale of the cards varies from 0·69 in./hr. at the solstices to 0·75 in./hr. at the equinoxes.

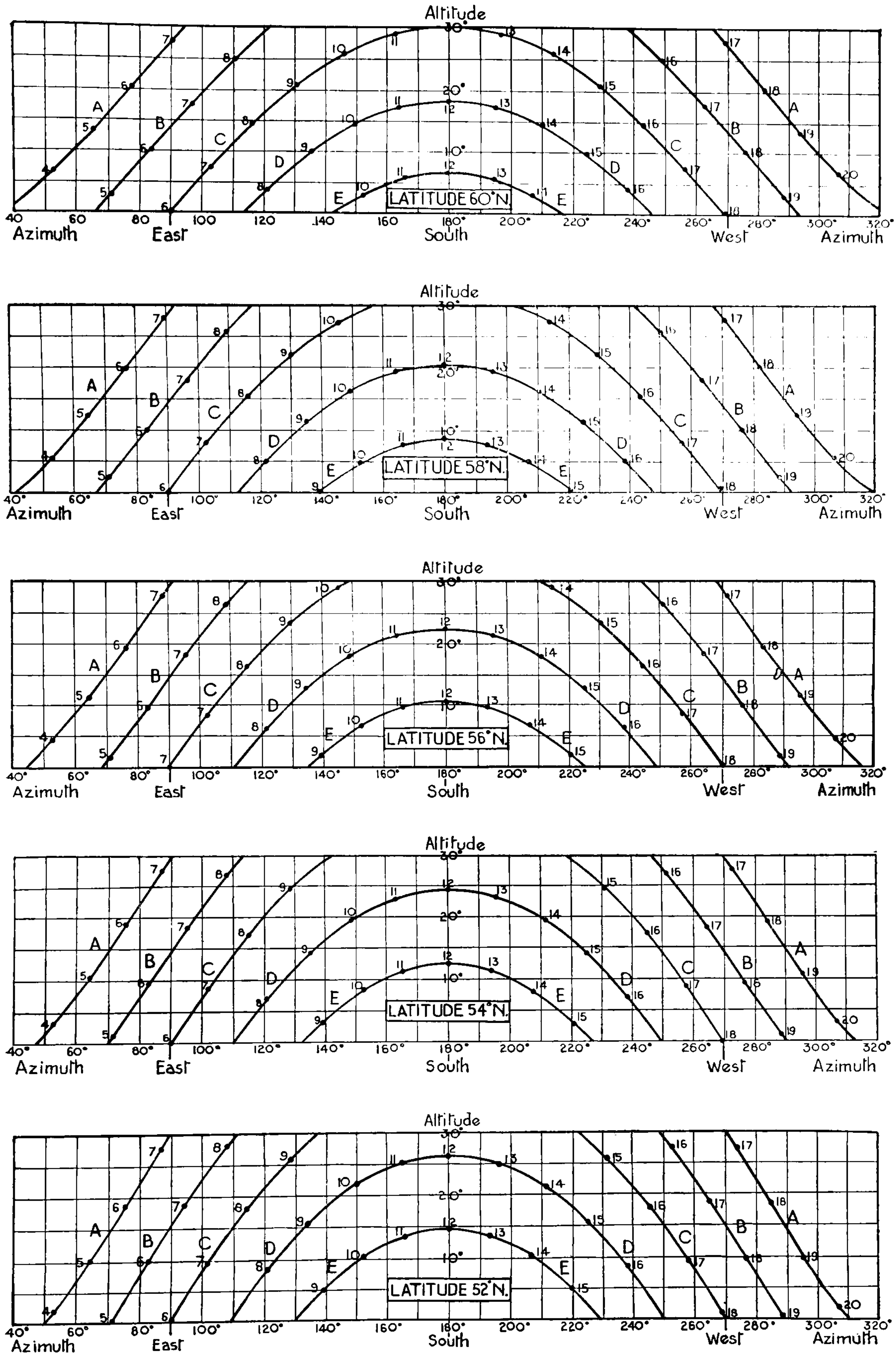
Installation and adjustment.—*Exposure.*—A free horizon is required between the north-east and south-east on the east side, and between north-west and south-west on the west side, these being the approximate limits of the setting sun in the latitudes of the British Isles. To the south no obstruction should have a greater elevation than $6\frac{1}{2}°$ at latitude 60° (an elevation of 1 in 9) or $16\frac{1}{2}°$ at latitude 50° (an elevation of 1 in 3). Between south and south-west and between south and south-east the permissible elevation of an obstacle changes evenly between these limits and zero, but, in general, obstacles whose elevation above the horizon do not exceed 3° may be neglected, as the sunshine is rarely bright enough to record when the sun is at lower elevations than this.

It is not possible in all cases to secure a site for the instrument where it will have an absolutely uninterrupted exposure. In such circumstances it is desirable to estimate how much of the possible sunshine may be cut off by the surrounding obstacles in each month of the year. The diagrams, Fig. 99, show the altitude and azimuth of the sun at each hour (local apparent time) for various latitudes from 60° N. to 30° S. Each of the 5 curves given in the diagrams is for a specific date (or dates) as indicated in the key below ; for any other date a curve must be interpolated which passes through the corresponding value for the sun's noon altitude ; the noon altitude is equal to the co-latitude (90° — latitude) plus the declination of the sun. The sun's declination can be found from the *Nautical Almanac.* To estimate the amount of sunshine cut off by an obstacle the altitude and azimuth of its salient points, as viewed from the sunshine recorder, should be found and plotted on the diagram for the latitude nearest the station ; the length of the curve cut off by the object on any day can then be measured.

The dates corresponding to the five curves are as given in the following key :

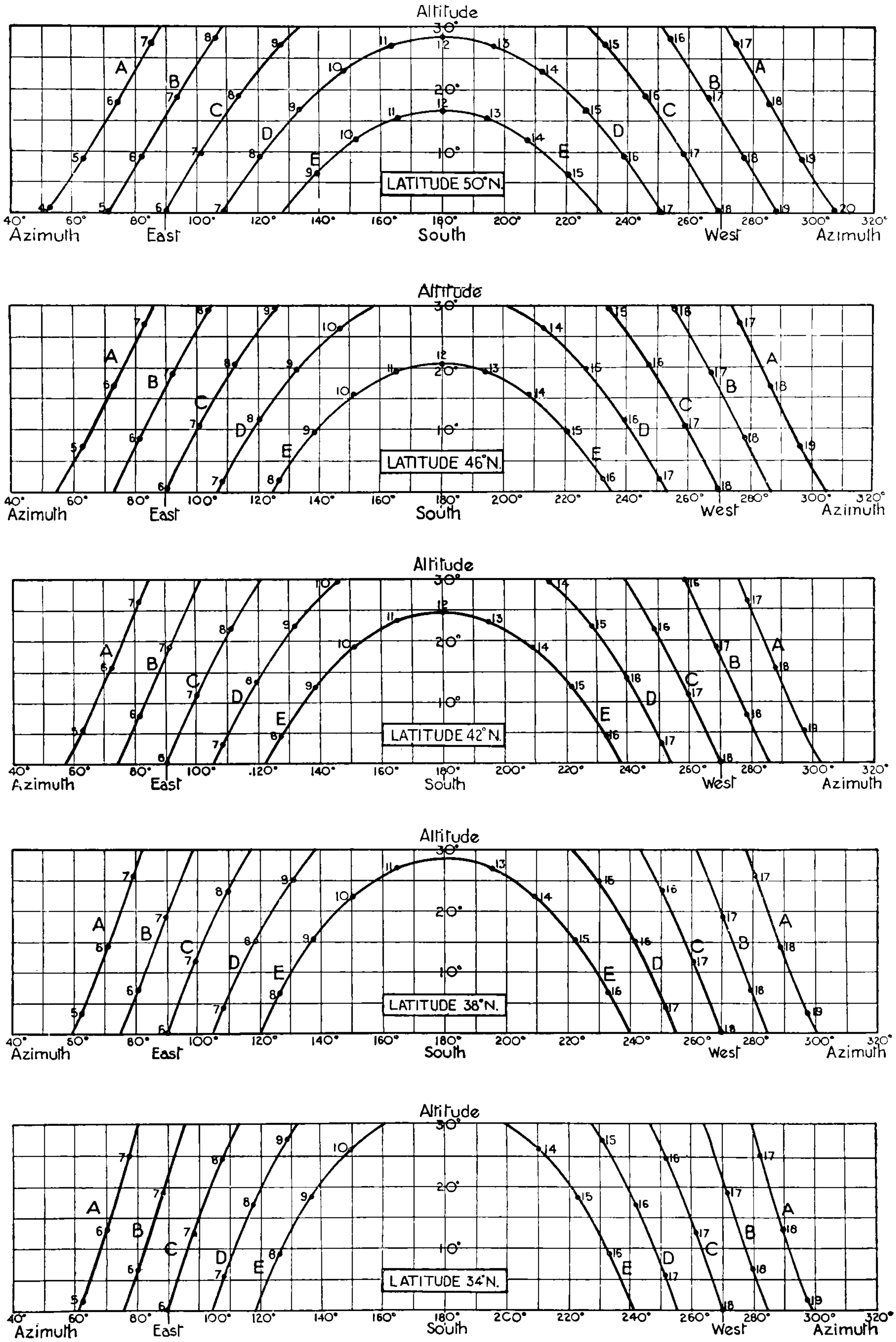
Date	Sun's declination	Hemisphere	
		Northern	Southern
June 22	$23\frac{1}{2}$°N.	A	E
April 21, August 23	$11\frac{3}{4}$°N.	B	D
March 21, September 23	0°	C	C
February 18, October 25	$11\frac{3}{4}$°S.	D	B
December 22	$23\frac{1}{2}$°S.	E	A

A = summer solstice C = equinoxes E = winter solstice



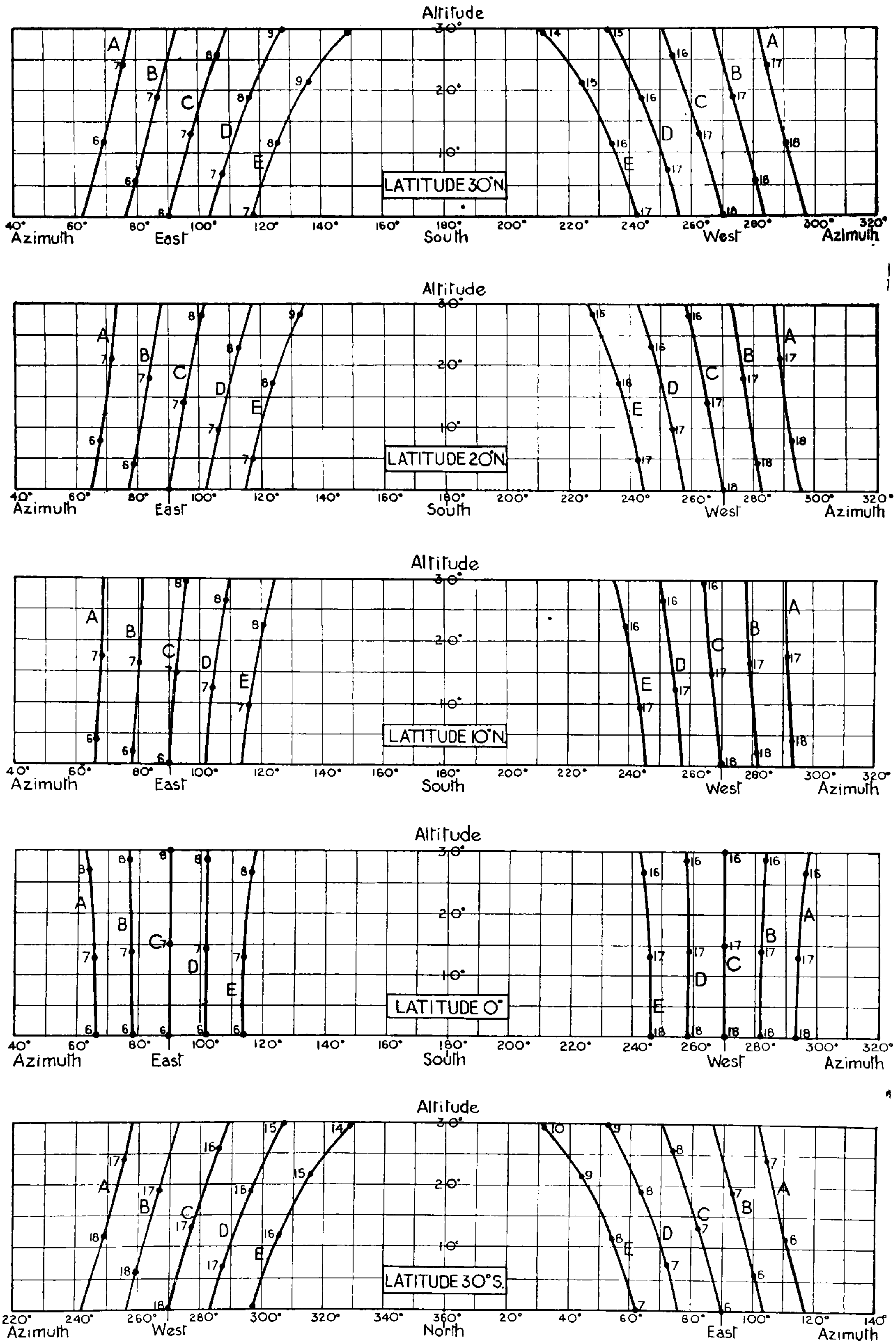
Latitudes 60°–52°N.

FIG. 99—VARIATIONS OF THE SUN'S ALTITUDE AND AZIMUTH



Latitudes 50°–34°N.

FIG. 99—VARIATIONS OF THE SUN'S ALTITUDE AND AZIMUTH (*continued*)



Latitudes 30°N.–30°S.

FIG. 99—VARIATIONS OF THE SUN'S ALTITUDE AND AZIMUTH (*continued*)

When the diagrams are to be used in southern latitudes instead of northern the hours of the day marked on the curves and the azimuths and directions at the foot of the diagrams must also be altered, as well as the interchange of dates. Thus :

Local apparent time		Azimuth (degrees from north)		Direction	
As given for lat. N.	Becomes for lat. S.	As given for lat. N.	Becomes for lat. S.	As given for lat. N.	Becomes for lat. S.
0300	2100	..	..		
0400	2000	60°	240°		
0500	1900	80°	260°		
.	.	.	.		
.	.	.	.	east	west
.	.	.	.		
.	.	.	.		
.	.	.	.		
1100	1300	160°	340°		
Noon	Noon	180°	360°	south	north
1300	1100	200°	20°		
.	.	.	.		
.	.	.	.		
.	.	.	.	west	east
.	.	.	.		
.	.	.	.		
.	.	.	.		
1900	0500	280°	100°		
2000	0400	300°	120°		
2100	0300	..	..		

An example of this simple transformation from the northern to the southern hemisphere is given in the diagram for latitude 30°S.

Support.—The support on which the instrument is fixed should be perfectly rigid, and made of a material which is not liable to warp, or otherwise to become deformed. If necessary a support can be made by laying down a 1-ft. square of cement not less than 2 in. deep, in which three wooden plugs are embedded, positioned suitably for the lugs in the main base of the instrument. If the wooden plugs are tapered, with the broad end downwards, and well painted on the top they should be firm and unaffected by the weather. The front pair of lugs are 7½ in. apart and should lie east-west ; the remaining lug is 7½ in. north (in the northern hemisphere) of the centre of the line joining the other two lugs. Brass wood screws of any size between 8 and 12 can be used to screw the main base in position.

Where a satisfactory exposure is available near ground level a brick or concrete pillar forms a suitable support. To avoid obstruction, however, it is often necessary to install the recorder on a roof of a building.

Adjustment (general).—It will be seen that the instrument must conform to the following conditions if it is to give accurate records :

(i) The centres of the sphere and the bowl must be coincident.

(ii) The plane containing the central longitudinal line of the equinoctial card, when in position in the recorder, must pass through the common centre of the glass sphere and bowl, and must coincide with the celestial equatorial plane.

(iii) The vertical plane through the centre of the sphere which passes symmetrically through the bowl must coincide with the plane of the geographical meridian. This implies, as well, that the bowl must be level in the east-west direction.

(iv) The principal focal length of the glass sphere must be equal to, or slightly greater than, the radius of the bowl measured to the surface of the card.

(v) When a card is in position the hour lines printed across it must lie in meridian planes of the celestial sphere corresponding to hour angles 15°, 30°, 45°, etc. measured from the geographical meridian.

The two last conditions have to be observed by the manufacturers of the instrument and the cards. The distance from the centre of the sphere to the cards is actually made slightly less than the focal length of the sphere for sodium D light (2·87 in. in comparison with 2·95 in.). It is found that the maximum heating effect occurs just inside the visual focus and falls off very quickly outside the focus.

Adjustment for concentricity of sphere and bowl.—This adjustment is made by the manufacturers, and in the case of instruments approved by the Meteorological Office it is tested by the Instrument Provisioning Branch. It can only be satisfactorily checked by the use of a special centring gauge (Stores Ref., Met. 199) and should not be attempted by the observer unless special instructions are received.

The centring gauge (Fig. 100) consists of a curved metal plate which can be fitted into the equinoctial card position in the bowl. Mounted on the plate are two mutually perpendicular metal arcs, with radii about 1 mm. greater than that of the sphere. The gauge is placed in the bowl in the equinoctial card position so that the upright arc is over the noon mark on the bowl ; the distance of the sphere from the two arcs is then noted, and the gauge moved some distance to the left and the right and the observation repeated. If the sphere needs no adjustment

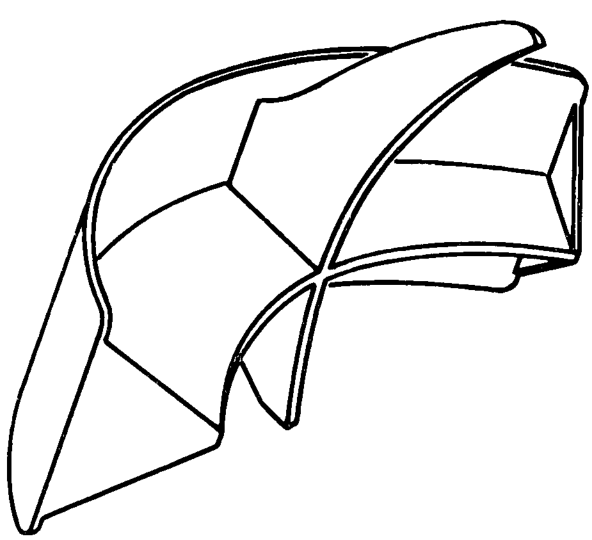


FIG. 100—SUNSHINE-SPHERE CENTRING GAUGE

for concentricity the arcs should be equidistant from the sphere in all places, the distance apart being about 1 mm. If the sphere requires adjustment the seating can be moved in the vertical and horizontal direction, after slackening the lock-nuts which hold it firm. When an adjustment has been made the lock-nuts should be tightened again before the setting is checked by the gauge to prevent any further movement.

Adjustment for latitude.—The position of the bowl relative to the sub-base can be altered by slackening the lock-nut and moving the hinge tongue in the hinge cheek. The bowl should be set so that the reading of the scale on the hinge cheek is the latitude of the station. This ensures that adjustment (ii), p. 312, is correct when the sub-base is levelled.

This adjustment can be roughly checked with the help of Fig. 101 which shows the position on the bowl which the trace should occupy on each day of the year. This can only be regarded as approximate as the positions of the flanges vary slightly on different bowls.

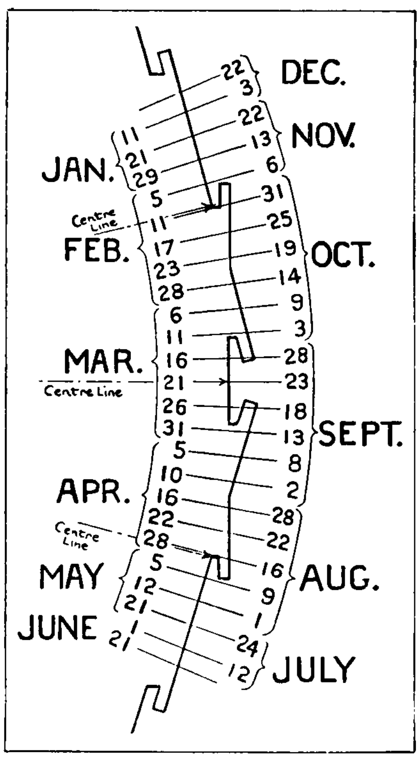


FIG. 101—ADJUSTMENT OF SUNSHINE RECORDER FOR LATITUDE

Adjustment for level.—A spirit level should be placed on the top of the bowl, parallel to the line joining the pair of horns, and the levelling screws supporting the sub-base adjusted until the bubble is central. The level should then be placed on the sub-base in a north–south direction, and the northernmost levelling screw (in the northern hemisphere) adjusted until the sub-base also is level. In both these adjustments the lock-nuts on the top of the sub-base should be slackened before the actual adjustment is performed, by turning the levelling screw underneath the sub-base. The first adjustment should be checked after the second has been made, and if necessary the whole procedure should be repeated until both are correct. A small tommy bar is used to slacken the lock-nuts.

Adjustment for meridian.—This adjustment is made by ensuring that the sun's image crosses an hour line on the sunshine card at the correct local apparent time. It is best done at local apparent noon as defects in the adjustment for level are of least importance at this time. Using the information given above (p. 302) the standard time of local apparent noon should be calculated, and at this time the position of the sub-base should be adjusted so that the image of the sun falls on the noon line of the sunshine card, taking care that the card is inserted properly with its noon line coinciding with the noon line on the bowl. The slots on the sub-base for the three mounting screws and nuts are in the form of short circular arcs with a common centre, so that the sub-base can be rotated through an angle of about 17° in azimuth. It is best to check the adjustment for level after making the adjustment for meridian.

When all the adjustments have been made satisfactorily the lock-nuts should be firmly tightened. The burns should then be parallel to the edges of the card, and along the centre line of the equinoctial card at the equinoxes.

Method of use.—Once the instrument has been set up and properly adjusted it requires little attention beyond changing the cards each day. The glass sphere should be cleaned as required with a chamois leather ; it should not be cleaned with any cloth that would abrade the surface. If snow or hoar-frost settle on the instrument it should be removed as soon as possible.

The cards should normally be changed after sunset each day. If for any reason this is quite impracticable any other hour may be chosen provided it is always strictly adhered to ; there is a risk of having overlapping burns on the card if varying times of changing are employed. If the sun is shining when inserting the card the sphere should be shaded so that a false scorch is not made. If the cards are not changed after sunset the actual time of insertion and withdrawal should be noted on the card.

When inserting the cards care must be taken to ensure that the noon line on the card coincides exactly with the noon mark on the bowl. If, after rain, a card cannot be withdrawn without tearing, it should be cut out by carefully drawing a sharp knife along the edge of one of the flanges which hold it in place.

The long curved summer cards (Form 4511N) should be used from April 12 to September 2 inclusive ; they are inserted with their convex edge uppermost. The short, curved winter cards (Form 4512) should be used from October 15 to February 28 (or 29 in a leap year) inclusive : they are inserted with their concave edges uppermost. The straight cards (Form 4510) are for use during the remainder of the year (about the equinoxes). When inserting the equinoctial card care should be taken to ensure that the hour figures are erect, otherwise the morning sunshine will be recorded on the portion of the card intended to receive the afternoon record and *vice versa*. Before bringing a new set of cards into use it is advisable to clean away any dirt which may have accumulated in the flanges.

Measurement of the cards.—There are two main difficulties that arise in measuring the total length of the trace on a sunshine card. These are (i) when the scorch is very faint, such as is usually the case near sunrise and sunset, or when the sun is shining through haze, and (ii) when the sun has been shining brightly but intermittently, or when a strong burn has abruptly stopped.

In the first of these cases the criterion that should be applied is that the whole of the brown trace, as far as it can be fairly seen, should be measured, the measurement being carried right to its extreme end. Difficulty arises in the second case because the image of the sun has a finite diameter and the area of the burn is further extended by smouldering. A burn caused by the exposure of a few seconds will therefore cover a length of card equal to several minutes. When measuring a strong burn that stops abruptly, the measurement should not therefore be taken to the extreme ends of the burn but an allowance made for the extension of the burn beyond its true position. This is best done by assuming that the end of the burn is at a point halfway between the extreme end of the burn and the centre of curvature of the rounded extremity. The beginning of a strong burn should be treated in a similar way.

A convenient method of evaluating the total trace is to place along it the edge of another sunshine card of similar shape to the one carrying the record and to mark on the card, with a sharp pencil, lengths equal to the lengths of the successive burns. The position of the card should be adjusted so that these lengths form a continuous line. The length of the line can then be read off the hour scale on another sunshine card, care being taken to measure along the same portion of the card as that on which the burn actually fell. If the burns are fairly short a straight piece of paper could be used and the total length measured on a special scale, Form 3092 (Fig. 102), using that part of the scale which corresponds to the date in question. Plate XXXIX shows the principles outlined above applied to the measurement of a typical sunshine record. Readings are made to the nearest 0·1 hr.

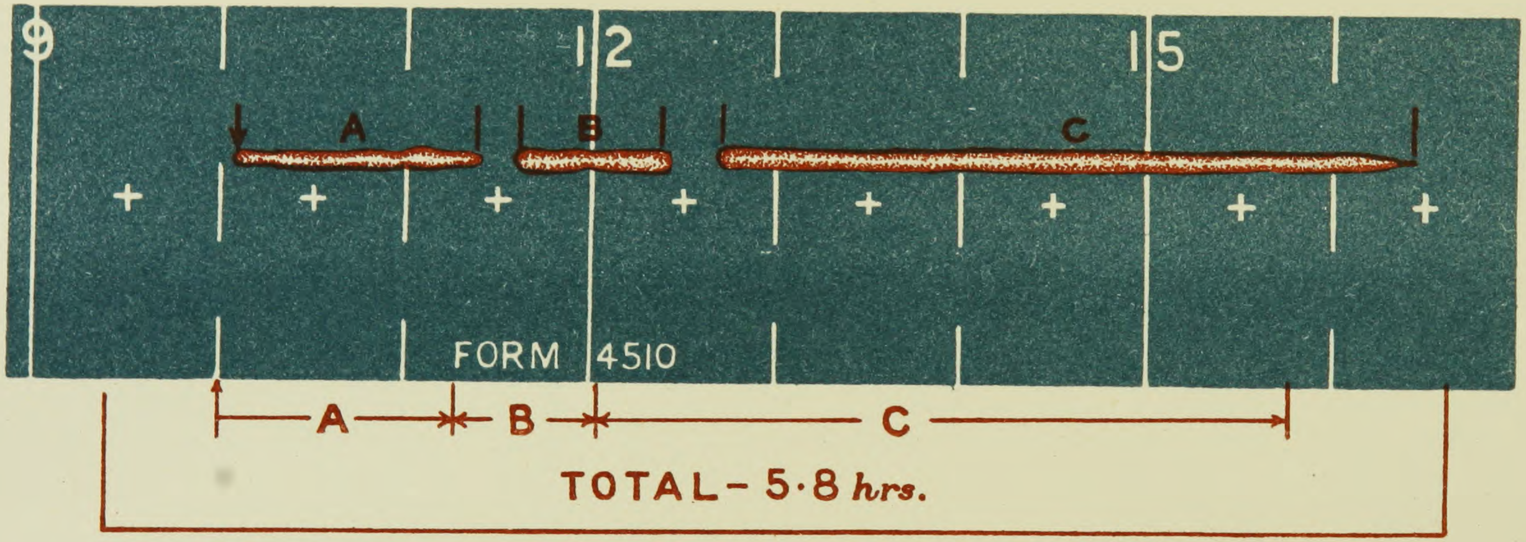
Maintenance and repair.—Provided the support for the instrument is firm and does not warp, little is needed in the way of maintenance apart from keeping the base and bowl clean. Any necessary re-adjustment should be carried out on the lines indicated above ; the necessity for these will be shown by an examination of the records and a consideration of the following section.

Accuracy and sources of error.—The effects of various errors which may be due to faulty adjustment or manufacture are discussed below.

The enumeration of these possible errors in the adjustment of the bowl and sphere shows the necessity of careful testing and installation. The records obtained should be regularly examined to ensure that the adjustment has not changed ; provided this is carried out the instrument should give reliable and consistent records over a long period. The readings of different recorders placed side by side justify the practice of reading the length of the trace to the nearest 0·1 hr.

Errors of concentricity.—A small displacement of the sphere relative to the centre of the bowl can be considered as made up of two components : (i) a displacement in the plane of the celestial equator, and (ii) a displacement in the line through the centre of the bowl perpendicular to the plane of the celestial equator.

In the first case the burns will be in the correct position at the equinoxes but will be slightly displaced and not parallel to the central line of the card at other times. For periods of sunshine covering the whole day the recorded duration will be too large if the displaced centre is nearer the sun than the true centre and too small otherwise. A displacement of 0·1 in. of the centre towards the sun will increase a 12-hr. sunshine record at the equinox by 16 min. It would be slightly less for other declinations.



MEASUREMENT OF SUNSHINE CARDS.

The illustration shows a typical record on part of an equinoctial card. Marks have been made on the card (purely for purposes of illustration) to show between what points the measurements should be taken. The first and second portions A and B, and the beginning of the third portion C of the record have rounded ends and allowance is made for the spread of the burn. The record becomes faint after about 16h.20m. and the measurement is taken as far as the trace can fairly be seen.

To obtain the total duration, the lengths of the separate portions are marked in succession along the edge of a strip of paper, and the total for the day is then read off by applying the marked strip, as shown, to the scale on the card. In the case of a curved card, the edge of another curved card should be used and the measurement may be made by placing the marked edge on a blank curved card, as near as possible in the same position as the actual burn.

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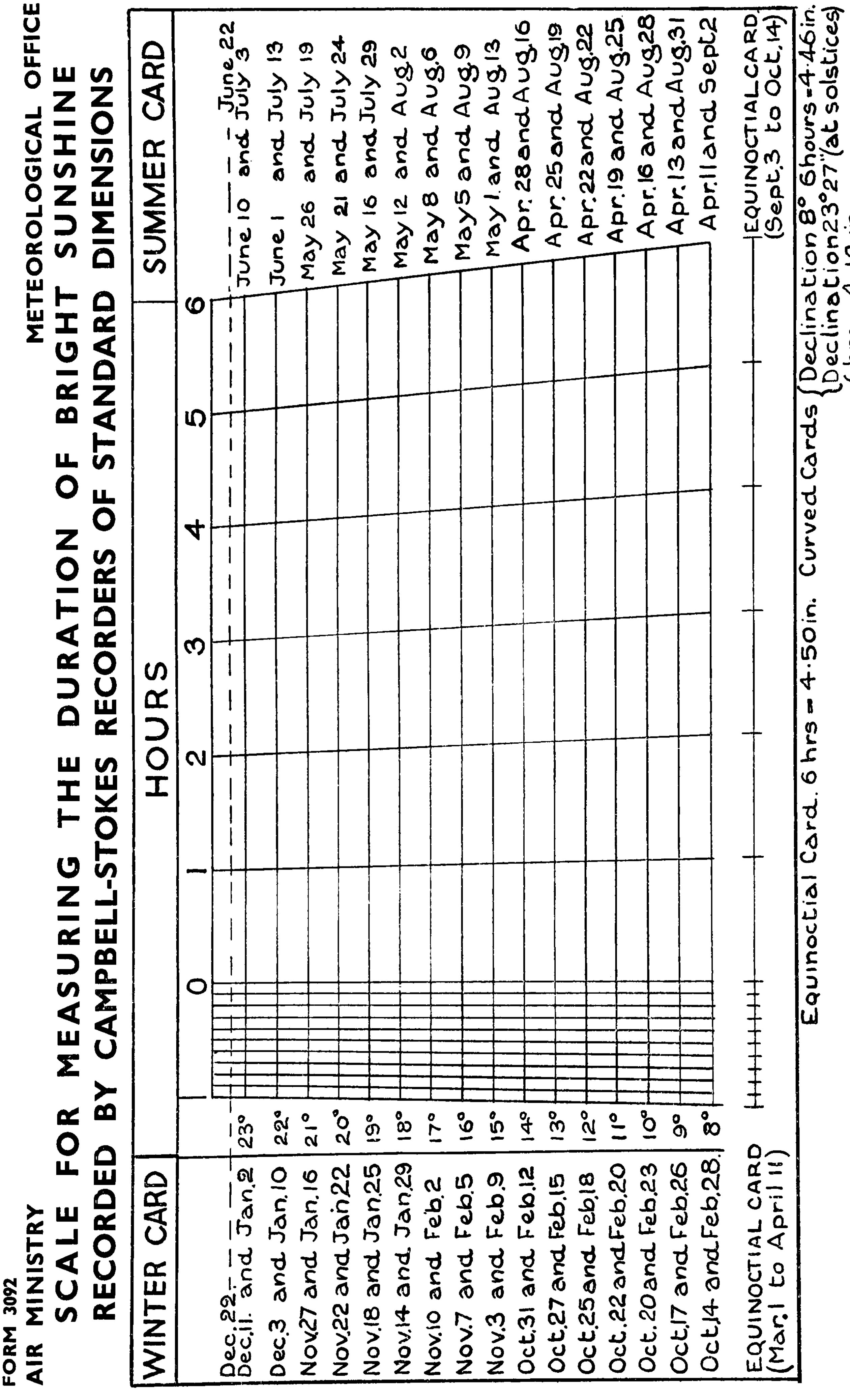


FIG. 102—SCALE FOR MEASURING SUNSHINE RECORDS

In the second case the error in recorded duration is zero on the equinoctial card, and is about 0·6 min./hr. on the summer and winter cards for a displacement of 0·1 in. (the error is positive on the summer cards and negative on the winter cards for an upward displacement). The burns remain parallel to the edges of the card but are displaced a distance x on the equinoctial card, and a distance which varies between $0 \cdot 93x$ and $1 \cdot 04x$ on the summer and winter cards, where x is the small displacement of the centre of the sphere. Thus there is a risk of some records being lost due to the burns falling on the frame.

Latitude and level errors.—If a plane passing through the central line of the equinoctial card and the centre of the bowl does not coincide with the plane of the celestial equator, the error in the direction of the pole of the plane can be resolved into two parts, a small error, $\Delta\phi$, in the plane of the geographical meridian and a small error, Δi, at right angles to the plane of the meridian, giving corresponding errors Δa and Δb in the position of the image on the card as recorded by the time scale. Δa vanishes at noon and at the equinoxes. If $\Delta\phi$ is 2° and δ (sun's declination) is $+ 23\frac{1}{2}°$, then Δa is nearly 4 min. at 0600 or 1800 local apparent time (positive at 1800 and negative at 0600) ; and this is the magnitude of the error in recorded duration of continuous sunshine from 1200 to 1800 or 0600 to 1200. The error would be different in sign in winter from that which was given above (for summer). For a given latitude Δb has a numerical minimum at the equinoxes and at 0600 and 1800, with a maximum at noon. If Δi is 2°, ϕ is 55° and δ is $+ 23\frac{1}{2}°$, Δb is $7\frac{1}{4}$ min. at noon and $4\frac{1}{2}$ min. at 0600 and 1800, giving an error in recorded duration of continuous sunshine from 1200 to 1800 of only $2\frac{3}{4}$ min. The recorded duration of continuous sunshine from 0600 to 1800 will not be affected. The error $\Delta\phi$ affects the curvature of the record, the burns appearing slightly curved on the equinoctial card and not parallel to the edges on the summer and winter cards. The error Δi does not affect the curvature of the records appreciably, but it causes the burn to cross its true position at an angle equal to $\Delta i \sin \phi \sec \delta$. If $\Delta i = 2°$, $\phi = 55°$ and $\delta = 23\frac{1}{2}°$, this angle is $1\frac{3}{4}°$. In both cases there is a risk of the burn passing off the edge of the cards. If the burn is higher on the card in the morning than in the evening the west side is higher than the east side and *vice versa.*

Meridian errors.—If the vertical plane through the centre of the sphere which passes symmetrically through the bowl does not coincide with the geographical meridian the recorded duration of sunshine will be correct but the burns will not be parallel to the edges of the card. The angle between the actual and true course of the burn is given by $\Delta\lambda \cos \phi \sec \delta$. If the error in the direction of the plane $\Delta\lambda$ is 2°, $\phi = 55°$ and $\delta = 23\frac{1}{2}°$, this angle is $1\frac{1}{4}°$. The indicated time will also be incorrect by an amount of 4 min. per degree error. There is a risk of loss of records due to the burn moving off the card. If the burn is higher on the card in the morning than in the evening the bowl faces east of south and *vice versa.*

Errors in the focal length of the sphere.—These are not likely to be serious for spheres approved by the Meteorological Office because of the strict tests mentioned above. Imperfect focussing results in a thicker and less intense burn, and, when the radiation is feeble, the possibility of the loss of some of the record.

Errors in the size of the bowl.—If the bowl is larger than the standard dimension but is used with standard cards the amount of sunshine recorded will be too large. The size of the bowl is usually checked by inserting a brass template, with the hour lines marked on at the correct distances apart, in the place of the equinoctial card and measuring the direct distance apart of the 0600 and 1800 lines. This should be 5·73 in. It can be shown that the true duration of sunshine will be $5{\cdot}73/d$ of the indicated duration, where d is the measured distance between the 0600 and 1800 lines on the template, provided d is not very different from 5·73 in.

Errors in the cards.—Errors in the printing of the cards or change in size with humidity will give corresponding errors in the indicated duration of sunshine (a contraction of the scale will give excessive indicated duration). The Meteorological Office specification for the cards lays down that their length must not change measurably, i.e. more than $\pm$ 0·01 in., after immersion in water for 18 hr. and must not contract by more than 1 per cent. on redrying. The width should not increase by more than 2 per cent. on immersion or decrease on redrying to less than 99 per cent. of the original width. The errors corresponding to these limits are very small, and errors due to printing should also be very small.

Errors due to loss of light in the sphere.—The spheres as at present manufactured are very stable but their transparency does decrease gradually with age. The condition of the sphere determines the minimum value of the intensity of the incident radiation which will give a record on the card. Upon this value depends the time at which the record starts on clear mornings or ceases on clear evenings.

8.2.2. Tropical sunshine recorder Mk II

The general principles of the tropical-latitude Campbell-Stokes sunshine recorder (Stores Ref., Met. 596) are similar to the temperate-latitude model, but the instrument is designed for use in all latitudes less than 45° (Plate XLI and Fig. 103). The pedestal mounting of the sphere cannot be used in tropical latitudes

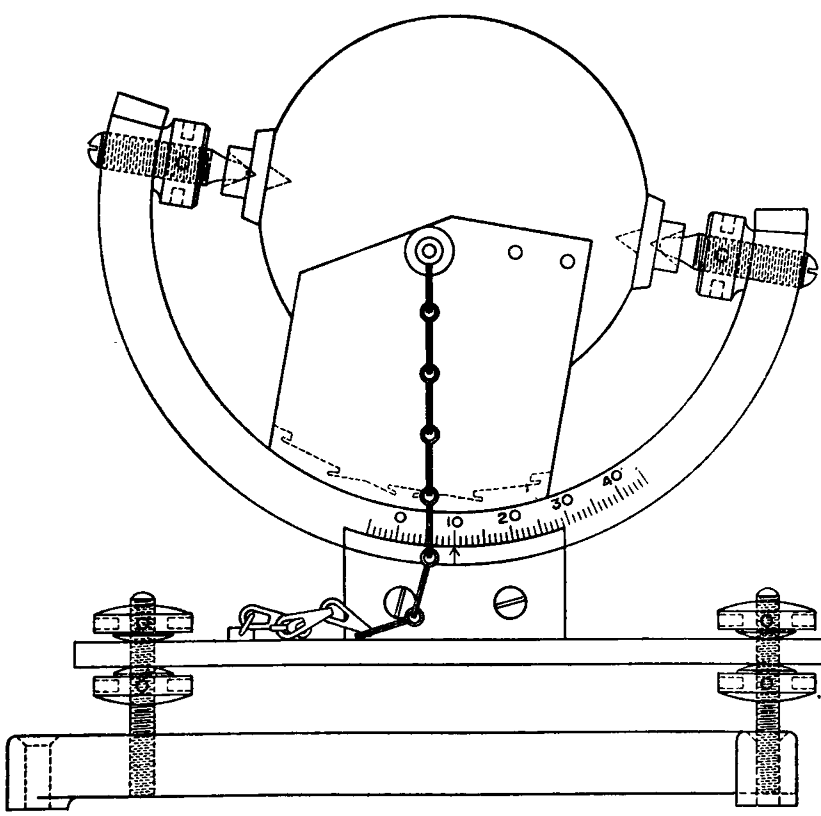


FIG. 103—SECTION VIEW OF TROPICAL SUNSHINE RECORDER MK II

as the elevation of the sun reaches 90° at times. The bowl consists of one half of a belt cut from a sphere, with one pair of corresponding corners symmetrically cut off by a plane passing through the centre of the sphere and making an angle of 60° to the plane of the original cut. Thus when the bowl is adjusted for latitude 30° the plane of this second cut is horizontal. The inner surface of the bowl is flanged to take 3 sets of cards in a similar way to the temperate-latitude model.

A semi-circular brass bar of nearly rectangular cross-section, attached symmetrically to the back of the bowl and concentric with it forms the main support for the sphere. The sphere is held at two ends of a diameter by means of brass screws fitting into cup-shaped attachments fitted on the sphere itself. When the instrument is in position the sphere support lies in the plane of the geographical meridian. The sphere support is clamped into position on the sub-base by means of a well fitting cheek plate held by two screws. It has engraved on it a scale of latitude (+45° to −5°) which indicates the inclination of the noon line on the equinoctial card, when in position, to the sub-base. The sub-base and main base are similar to the temperate-latitude model. The position of the centre of the sphere can only be adjusted along the line joining the two screws which support it in position.

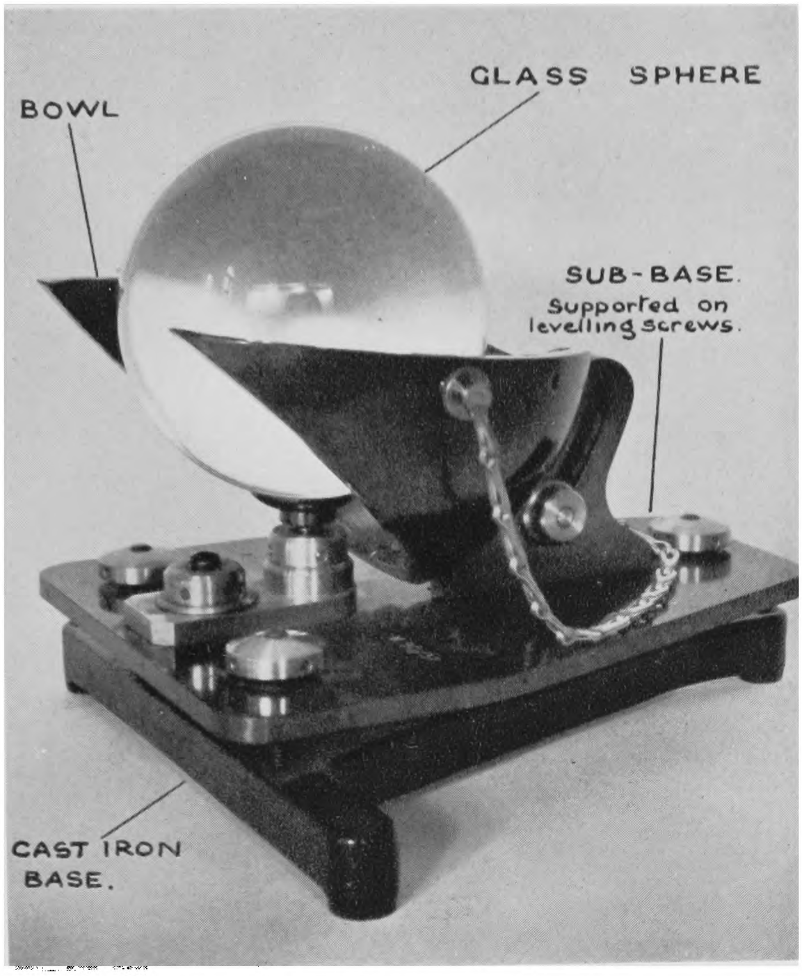
Installation and adjustment.—The instructions for setting up the temperate-latitude model should be followed generally, but certain detailed modifications are required.

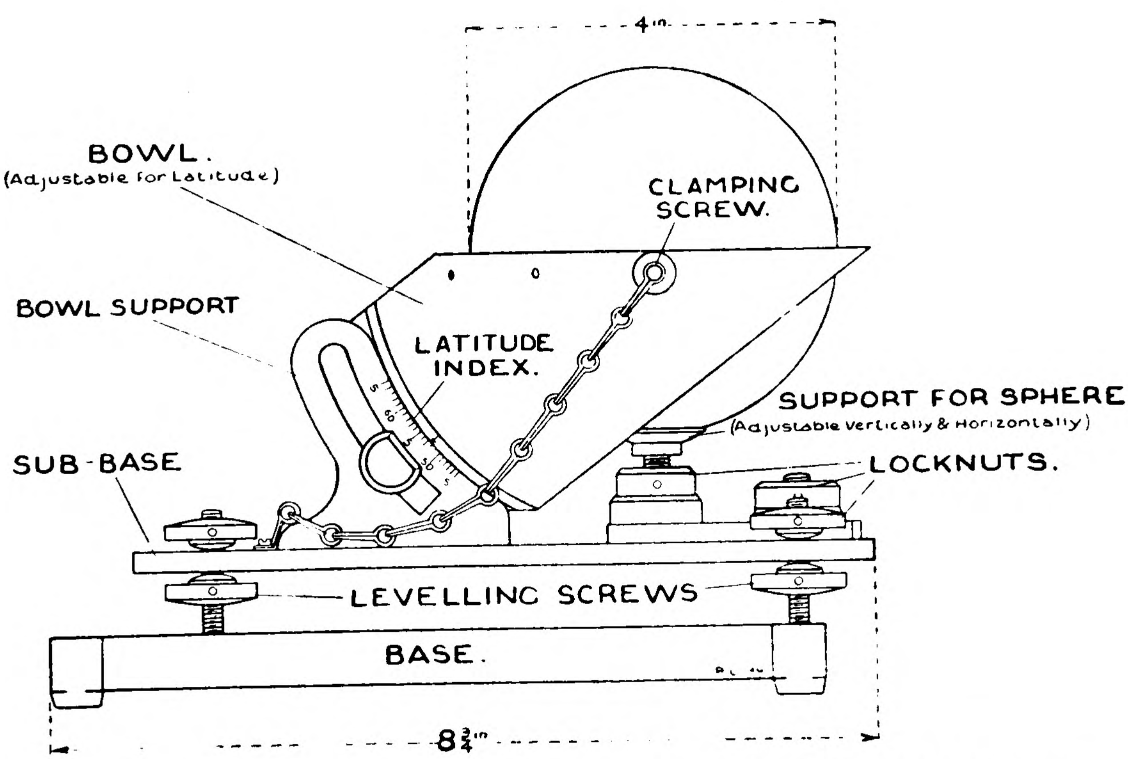
Exposure.—The unobstructed horizon need only be between west-south-west and west-north-west and between east-south-east and east-north-east. Obstructions to the south (or north in the southern hemisphere) should not subtend angles of elevation of more than 21½° at latitude 45°. This limit rises to 66½° at the equator. It should be noted that in latitudes less than 23½° the sun passes the vertical and appears to the north of the instrument (in the northern hemisphere) at certain times. Its elevation at due north and consequently the upper limit for obstruction in this direction does not, however, come below 66½°. Although the latitude scale is nominally engraved for latitudes +45° to −5° it would not need to be used at the extreme setting 0° to −5° as that range is covered by merely reversing the instrument.

Support.—A similar support to that specified for the temperate-latitude model will be required, and the main base should be mounted on it in a similar way.

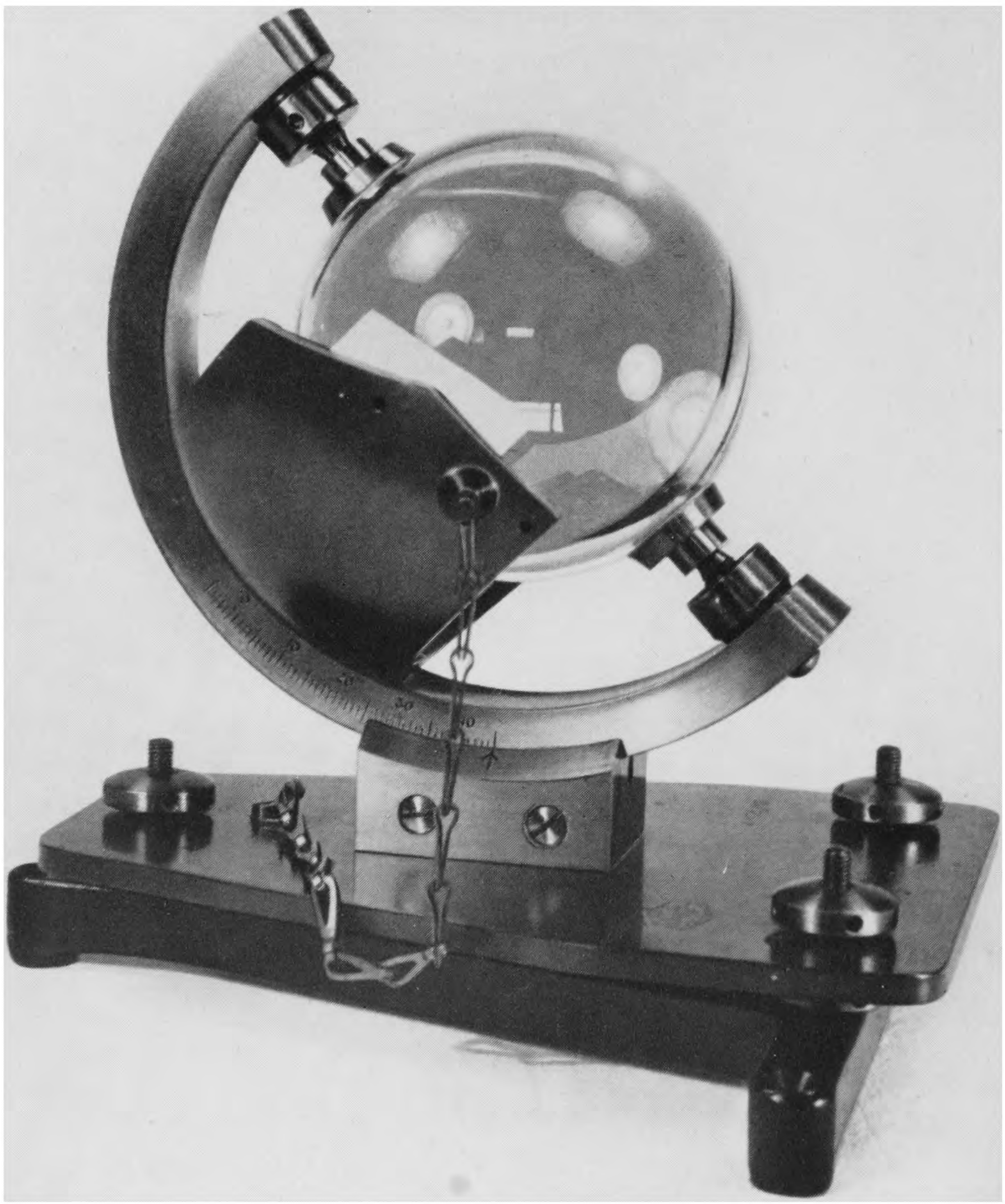
Adjustment for concentricity of sphere and bowl.—This can be checked with a centring gauge, but should only be attempted on the receipt of special instructions. The position of the centre of the sphere can be altered along the line joining the two supporting screws by slackening the lock-nuts with a small tommy bar, unscrewing one screw, and screwing up the other. The lock-nuts should be tightened again after the adjustment. If the sphere has to be removed for any purpose care should be taken to unscrew one screw only. If both screws are loosened the concentricity of the sphere and bowl may be lost.

Adjustment for latitude.—This can be carried out by loosening the two cheese-head screws holding the cheek plate on the bowl support and moving the bowl until the arrow opposite the scale points to the correct reading for the latitude of the station. The screws should then be tightened again.

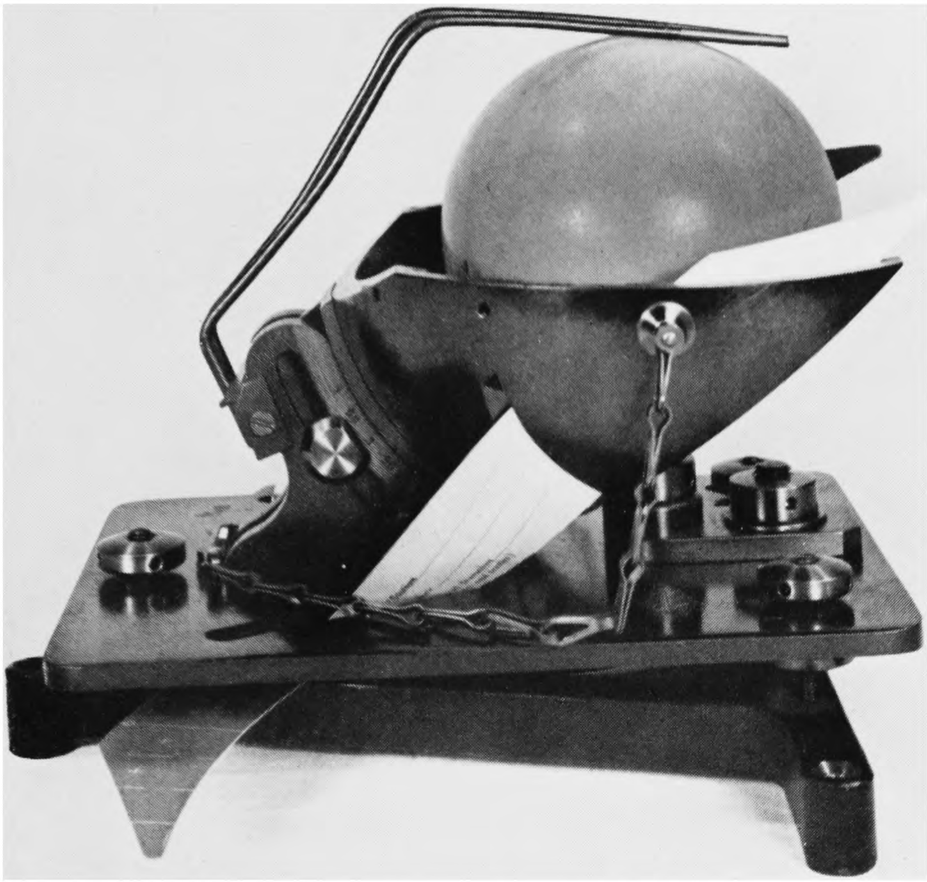




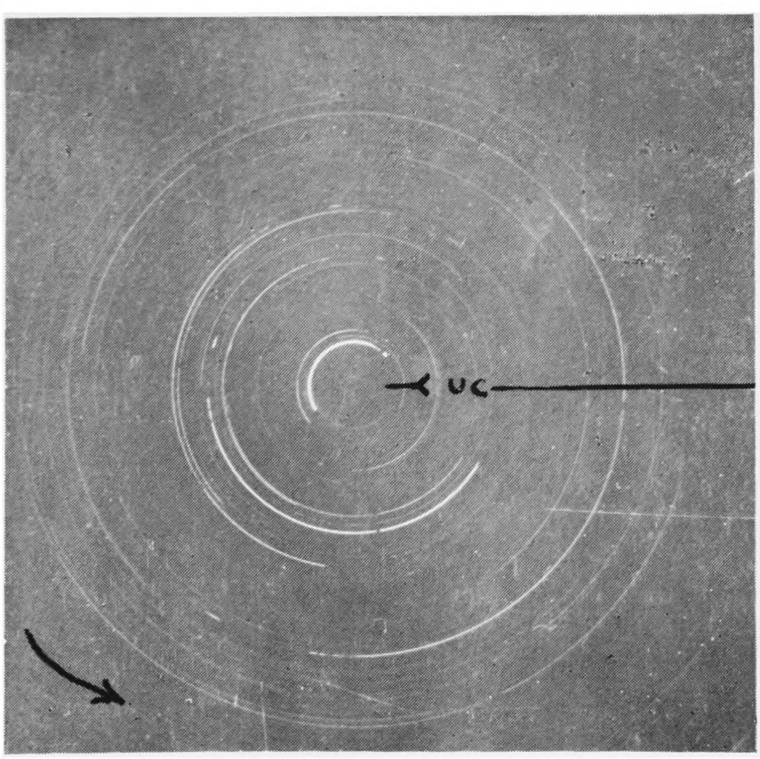
TEMPERATE SUNSHINE RECORDER MK II (CAMPBELL-STOKES)



TROPICAL SUNSHINE RECORDER MK II

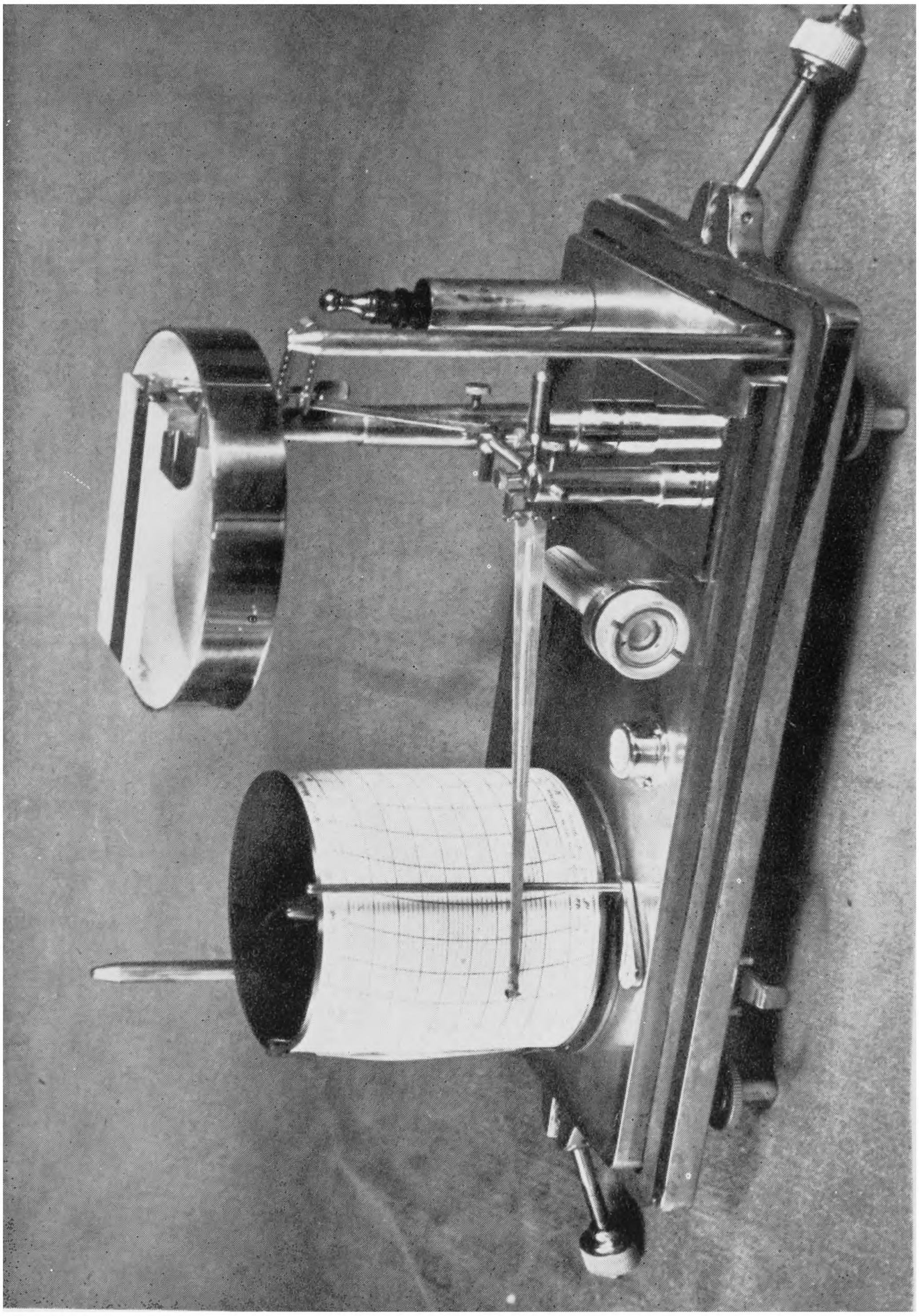


SLOTTED SUNSHINE RECORDER



TYPICAL NIGHT-SKY RECORD

U.C. = Upper culmination



BIMETALLIC RADIATION RECORDER

Adjustment for meridian.—This is not as easy as in the temperate-latitude model because of the greater elevation of the sun at noon. The best method is to align the support of the sphere as accurately as possible in the north–south direction, with the help of a compass (making due allowance for deviation) or bearings from a map, and then insert a card and obtain a trial burn. If the burn is found to travel along the card accurately parallel to the centre line, the adjustment is correct. If not, the recorder should be slightly turned in azimuth until accurate burns are obtained. When the test burn is high on the card in the morning and low on the card in the afternoon and evening the sub-base should be turned in a clockwise direction (when looking down on top of the instrument). For the opposite errors, a counter-clockwise movement should be made. A small movement is sufficient to cause a noticeable difference in the slope of the burn across the card. When the burn runs truly parallel to the centre line of the card the clamping nuts on the sub-base should be finally tightened.

Method of use.—The method of use is generally similar to that of the temperate-latitude model ; in particular the times of changing from one set of cards to the other are the same. There are two series of cards (each composed of equinoctial, summer and winter cards) which can be used with this recorder. One series is suitable for latitudes 0° to 25° and one series is nominally for 20° to 40°. For the latitudes 40° to 45° it is best to use the temperate-latitude cards. These will project some $2\frac{1}{2}$ in. beyond the edge of the bowl, but their use will ensure that no records are lost in the early morning or late evening during midsummer.

The Meteorological Office Form numbers of the series of cards for latitudes 0° to 25°N. are :—equinoctial 4520, summer 4521, winter 4522, and for the series for latitudes 20°N. to 40°N., equinoctial 4524, summer 4525, winter 4526.

Accuracy and sources of error.—The sources of error are the same as for the temperate-latitude model but some differences in magnitude occur. For the classes of errors that do not depend on latitude similar considerations (see p. 316) apply to the tropical-latitude model.

Errors of concentricity.—These errors will produce a similar effect to those in the temperate-latitude model. They cannot always be fully corrected because of the method of supporting the sphere, but any residual error should be very small.

Errors of latitude and level.—Δa will be the same as in the temperate-latitude model. The magnitude of Δb varies with the latitude ; its effect on the measured duration of the record decreases with a decrease in latitude. If $\Delta i = 2°$, $\phi = 25°$ and $\delta = +23\frac{1}{2}°$, then Δb is $8\frac{3}{4}$ min. at noon and $7\frac{1}{4}$ min. at 0600 and 1800. The error produced in 6 hr. continuous sunshine from 0600 to 1200 is thus only $1\frac{1}{2}$ min.

Meridian errors.—The magnitude of the effect of this error is slightly greater in the tropical-latitude model. If $\phi = 25°$ and $\delta = +23\frac{1}{2}°$ and the error in the meridian is 2°, the angle between the actual and correct direction of the burn is 2°. This increases to a maximum of $2\frac{1}{4}°$ at the equator.

Errors peculiar to the tropical-latitude model.—It will be seen that the cards in this recorder are not supported by the bowl outside the portion referring to the hours 0600–1800. This is not important in latitudes less than 30° to 40°, as the sun rises and sets close to these hours, but at higher latitudes in summer the sun rises appreciably earlier than this and sets appreciably later. If the lengths of card unsupported by the bowl are exposed to rain and wind they are liable to be bent out of position, and consequently will not lie at the focus of the sphere. This will result in the loss of the record. This difficulty can be overcome by fitting a bowl intermediate in shape between the temperate-latitude and the tropical-latitude models. Such a bowl has recently been introduced for latitudes 25° to 45°.

8.2.3. Modifications of the Campbell-Stokes sunshine recorder

Several modifications have been made to the basic design of this recorder, and it is of interest to list some. One variation consists in having the bowl made in two halves, joined by a hinge along the noon line. During the morning the half nearest the sun is let down so that no part of the sphere is shaded by the bowl ; during the afternoon the other half of the bowl is let down in place of the original half. The cards therefore have to be exposed in two parts and the change-over made at midday. In this way more light can be concentrated on the cards at sunrise and sunset, and the records on that account should begin earlier and end later. The actual increase in sunshine recorded due to this appears to be small however. Measurements over a period of three months suggest it is about 0·4 per cent.[61] The chief disadvantage is that the recorder has to be attended to within a few minutes of midday.

A modification by H. Stade[62] consists in having the sphere supported as in the tropical-latitude model, and having a bowl which supports a card of length equal to only about 8 hr. The bowl can, however, be rotated about an axis lying in the same direction as the celestial pole, and is usually moved at midday. In this way a record can be obtained at any latitude including the poles (by changing the position of the bowl three times throughout the 24 hr.). In this variation also, the record for one day is in more than one portion, but the advantage of an unobstructed sphere is obtained.

The inconvenience, during the summer months, of having to change the sunshine cards after sunset can be avoided by a modification to the temperate-latitude model[63] (Plate XLII). Two slots are cut in the bowl of the recorder at about the 0830 and 1530 position, between the flanges holding the summer card. The card is inserted in the normal position during most of the day, but after 1530 (local apparent time) the card is taken out and re-inserted with the morning portion passing through the slot in the 1530 position and down beneath the bowl, through another slot in the sub-base ; an additional engraving on the bowl at the 1800 position enables the card to be set correctly without reference to the noon mark. At the same time, the next day's card is inserted in the other side of the bowl with the evening portion passing through the slot in the 0830 position and down through another slot in the sub-base ; an engraving on the bowl at the 0600 position enables the card to be set in the correct position. The next morning, before 0830 (local apparent time) the previous day's card is removed, with the complete day's trace, and that day's card taken out from the slot and placed in the normal position. The sphere should be removed during the process of changing the cards to prevent any false scorches.

The main advantage of this method is that the whole day's record is obtained on one card without visiting the recorder at inconvenient hours.

8.2.4. Other forms of sunshine recorder

Jordan sunshine recorder.—The main principles of this instrument were outlined earlier in this chapter (p. 301). Quadrants are used to set the instrument for latitude and, like the Campbell-Stokes instrument, it must be set level and adjusted for the meridian. Further details can be found in the paper by R. H. Curtis[59].

Marvin sunshine recorder.—A diagram illustrating the general principles is shown in Fig. 95. The narrow tube A joining the clear bulb and black bulb extends nearly to the bottom of the black bulb and is filled with mercury. When the temperature of the black bulb rises above that of the clear bulb the mercury will be forced up the tube A so that it closes an electrical circuit at B. The adjustment of the instrument is not easy and requires experience. Further details are given by Marvin[64]. An indication of its main sources of error and its disadvantages was given on p. 301.

Maurer sunshine chronograph.—In this instrument radiation from the sun is focussed by means of a lens on to a card covering a drum and chars it in a similar way to the Campbell-Stokes instrument. A clockwork mechanism is used to rotate the drum once every hour, and to rotate the lens about the drum axis once every 24 hr. A screw carrier shifts the drum upwards by a small amount in each rotation. By arranging the axis of the drum to be parallel to the axis of the earth the lens can follow the sun, and the record for the day consists of a cardboard sheet containing a number of slightly slanting burn marks ; the hour scale is thus much more expanded than in the Campbell-Stokes instrument (nearly 5 in./hr. in one instrument). Further details are given by J. Maurer[65,66]. The total amount of sunshine recorded by such an instrument was found to be slightly less than that recorded by a standard Campbell-Stokes instrument[61].

8.3. NIGHT-SKY (STARSHINE) RECORDER

8.3.1. Camera

The camera (Stores Ref., Met. 1061) consists essentially of a light-tight box (in the front of which is fixed a lens of about 10 in. focal length) mounted so that it is pointing towards the celestial pole (Fig. 104). At the focus of the lens is a film carried in a standard ¼-plate roll-film camera back. A shutter mechanism, controlled by a clock, is arranged to uncover the lens at the beginning of the night and shut it at the end of the night, so that, in the northern hemisphere, the images of the Pole Star and other stars near by are recorded on the film whenever the sky conditions permit.

The shutter is a circular sheet of phosphor bronze from which a portion has been removed to form a shutter opening ; the shutter opening subtends an angle of 60° at the centre of the sheet. It is mounted on a horizontal axis through its centre in a recess in front of the lens, and is balanced to make up for the portion which has been removed. Engaging with the pinion on the shutter axis is a gear wheel which is mounted on the same axis as an eight-pointed star wheel. On the horizontal spindle of the 24-hr. clock are fixed two striker arms which, as they rotate, engage with the star wheel and move it on by one point. The rotation of the shutter caused by the engagement of the first arm causes the opening to appear

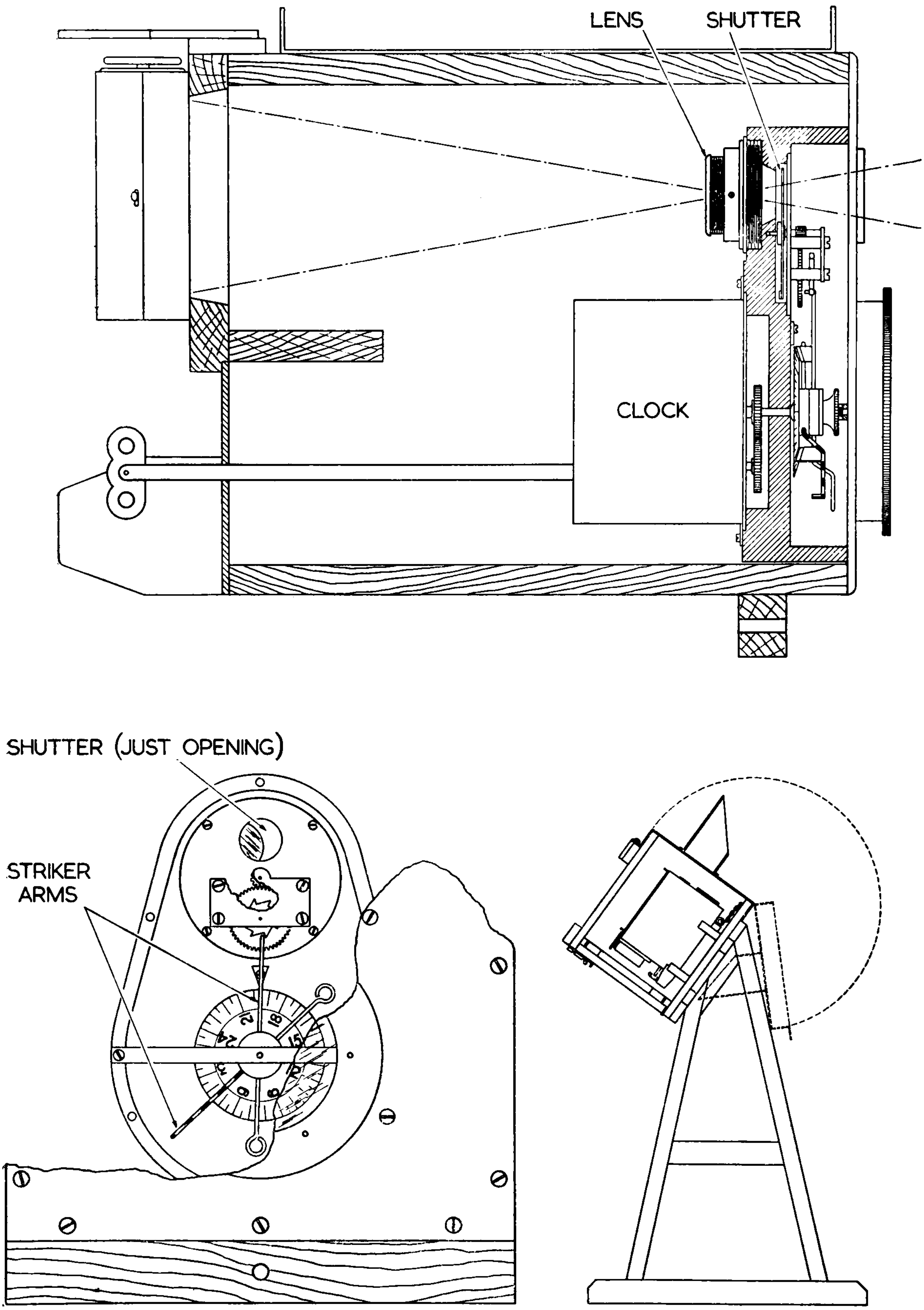


FIG. 104—NIGHT-SKY (STARSHINE) RECORDER

in front of the lens ; the second striker arm causes the shutter to close. When the shutter is fully closed a white spot painted on it appears in front of the lens.

A time-scale disc, engraved for every hour from 0100 to 2400, is also carried on the clock spindle, and this should be set so that it indicates the correct standard time against a white fiducial mark. The shutter assembly and the clock are mounted on the front plate of the box with removable inspection window, to enable the position of the time-scale disc and the striker arms to be adjusted. After the lens has been focussed for infinity on the plane of the film it is fixed in position by means of a grub screw. The back of the film holder is kept in position by means of press clips, and can be removed when necessary. Two elementary sights are fitted to the top of the camera, parallel to the main axis of the instrument, and are used when it is necessary to align the instrument.

8.3.2. Stand and housing

A wooden stand and housing (Stores Ref., Met. 2137) is used to support the camera in position and shield it from the weather. The housing has a door at the back and front, the door in the front being hinged along the bottom and having a circular opening with a cowled hood, which is directly opposite to the lens of the camera when the door is shut. Two horizontal battens are used to support the camera ; it is merely placed in position and rests with the strip of wood across its base against the batten nearest the front door. The housing is supported on a wooden stand about 5 ft. high, at an angle of 54° to the horizontal (when the base of the stand is level). This angle corresponds to the approximate mean latitude of the British Isles, and the small adjustment necessary for other latitudes can be made when fixing the stand in position.

8.3.3. Installation

Site.—The field of the camera (about 18°) should be free from obstruction by fixed objects, and, as far as possible, be away from sources of drifting smoke. The site should be away from lights in general, and in particular there should be no fixed lights within 30° of the axis. It should be in such a position as will reduce to a minimum the risk of fogging from an observer's hand lamp or from the head-lights of road vehicles. Light coloured buildings which may reflect moonlight and artificial light should also be avoided as far as possible. Urban sites are usually less suitable than country sites. As the recorder should not be exposed to vibration, some shelter from the wind is an advantage.

Foundation.—The foundation for the instrument should be a horizontal bed of concrete 3 ft. 6 in. long by 2 ft. wide and about 1 ft. deep with its long sides pointing north and south. Four holes should be made for the foundation bolts ; it is advisable to use the feet of the stand as a template, but they should lie at the corners of a rectangle 31 in. by 12½ in., with the long sides pointing due north and south. The holes should be about 6 in. deep, and wide enough to ensure that some adjustment of the stand in azimuth can be made.

Erection of the stand.—Four foundation bolts 7½ in. long and ⅜ in. in diameter are required. These should be inserted in the feet of the stand, with their heads downward and with nuts and washers in position, so that about 1 in.

of bolt protrudes above the feet. On a clear night the stand should be placed in position with the bolts in the holes provided in the foundation, and the camera in the housing ; the stand should then be adjusted for azimuth by aligning the sights of the camera on *Polaris*, and, if necessary, a preliminary adjustment made for elevation, because of any difference in latitude of the station from the value assumed in designing the housing (54°). If the station is in the range 51° to 57° this adjustment may be made by inserting packing underneath the feet of the stand at the appropriate end, but if the station is outside this range this would leave only about $1\frac{1}{2}$ in. or less of the bolt actually in the foundation at the raised end. In these cases it would be better to make some of the adjustment by fixing an accurately planed strip of wood to one or other of the supporting battens in the camera housing. Having completed the accurate adjustment for azimuth and the preliminary adjustment for elevation, the bolts should be finally grouted in position. A mixture of two parts of sand to one of cement by volume, made with enough water to make it easy to pour, is a suitable filling. After the filling has set and hardened any necessary further adjustments for elevation can be made by loosening the nuts on the foundation bolts, inserting or withdrawing packing under the feet of the stand and tightening the nuts when the adjustment is complete. The alignment of the camera can be checked on a clear moonless night by removing the back of the film holder, putting a piece of ground grass or other suitable material in the plane of the film and noting the position of *Polaris* in the field of view. The star should be as near the centre of the field as possible. Fig. 105 can be used as a help in locating *Polaris*.

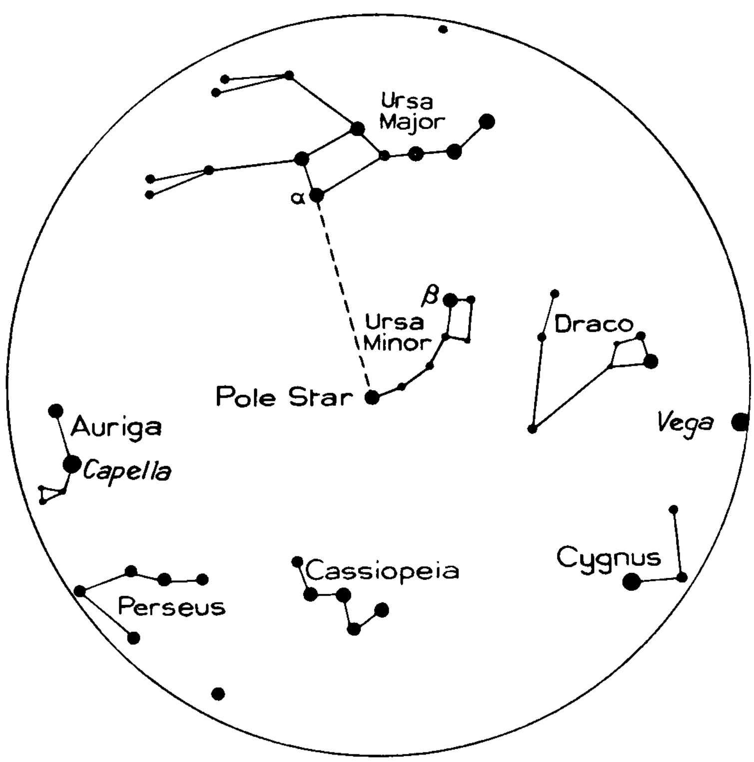


FIG. 105—DIAGRAM SHOWING THE CHIEF CIRCUMPOLAR STARS

The diagram shows the stars which never set, for latitude 52°N. The stars perform a complete rotation round the north pole of the heavens in about 23 hr. 56 min. The Pole Star is very close to this pole. Because of the difference of about 4 min. between this time of rotation (sidereal day) and the ordinary day of 24 hr. the aspect of the diagram changes a little each night if the sky is observed at the same time (G.M.T.) throughout the year. When so viewed at the same moment nightly the stars perform one complete rotation in the year.

8.3.4. Method of use

Shutter and time-scale setting.—The position of the striking arms relative to the time-scale disc can be set to any desired pair of values. There is however a distinct difference between the time at which the shutter commences to admit light and the time on the time-scale disc to which the striking arm is set (assuming the clock to be correct), the shutter being late in opening ; and there is a corresponding difference in the time of closing of the shutter, the shutter again being late. The average values of these two intervals are 20 min. and 10 min. respectively, but different instruments vary in this respect, and they should, if possible, be checked on the instrument being used by actual timing. This correction should be taken into account when setting the striking arms.

Exposure should only be made when the sun is 10° or more below the horizon. Data for the purpose of obtaining the times at which this is so is obtained in the twilight tables in the *Nautical Almanac* ; interpolation should be made between the civil twilight (sun 6° below the horizon) and nautical twilight (sun 12° below the horizon), taking into account the latitude and correcting for the longitude of the station. Settings should normally be rounded off to the nearest quarter of an hour on the safe side, and then the correction made for the lag of the striking arms. Resetting of the striking arms is normally performed once a week ; during the first half of the year the settings should refer to the end of the week during which the exposures are being made, and during the second half of the year they should refer to the beginning of the week.

The time-scale disc should be checked regularly and kept within 0·2 hr. of the correct time.

Management of the film.—The film normally used is a medium-speed orthochromatic film of size No. 18. The backing paper is only numbered 1 to 6, but 7 exposures are required for a week's record. Seven separate windows are therefore provided in the back of the film holder and the routine to be followed in turning on the film is as follows :—on Monday the number 1 on the backing paper is brought into the end window furthest from the winding spool (marked first–Monday) ; on Tuesday the film is wound on until the number 1 comes into the other end window (nearest the winding spool, marked second–Tuesday) ; on Wednesday the film is turned on until the number 2 comes into the second window from the spool (marked third–Wednesday) ; on Thursday the number 3 is brought into the third window from the spool and so on, until finally the number 6 is brought into the sixth window from the spool on the Sunday (marked seventh–Sunday). After the final exposure the film is wound on until all the backing paper is on the new spool. It is then safe to remove the back of the camera, remove the spool of film and seal it up, ready to be developed.

Development of the film.—The following notes are included for those stations which develop their own films ; these notes are supplementary to general instructions about developing, which can be found in any good photographic textbook.

It is best to carry out the development in complete darkness if possible, or failing that with a very dim red or green safe-light. A suitable developer will be recommended by the maker of the film. A large deep dish should be used and the end of the film should be held in bulldog clips or other suitable holders. The motion of the film through the developer should be adjusted so that all portions of the film are equally affected. After development the film should be rinsed in clean water, and then placed in the fixing solution for a period of 10–15 min. After fixing, the film should be washed thoroughly in running water for a period of 1–1½ hr., and then hung up to dry in a place as free from dust as possible. At all stages, until the film is thoroughly dry, it should be handled as little as possible, and then only by the ends.

Fresh developer should always be used whenever necessary ; as a rough guide 40 oz. should develop 6–8 films. The developer should be kept in a well corked container in the dark when not being used. The fixing solution should be renewed regularly and not allowed to get stale.

Measurement of the records.—The records are not normally measured on the station, but the principle adopted is to use a special scale with a number of concentric circles and radial lines, running from the centre of the circles, engraved on it. The circles on the scale are made concentric with the record on the film, and the radial lines then enable the total length of record, expressed in degrees, to be measured. This can be converted into hours on the basis of 1 hr. to 15°. The total duration of the exposure can be found from the shutter striking arm settings, and thus the proportion of the total exposure for which the stars were visible.

If hourly tabulations are required the scale has to be orientated with reference to some fixed point. This is usually provided by calculating the upper culmination time of the star (from astronomical tables) ; this time is shown on the film by the line at right angles to the edges of the film through the centre of the record, provided the recorder was accurately horizontal (see Plate XLII). The ambiguity of 12-hr. if the film is cut up into separate daily records can soon be resolved.

The records which are usually measured are those of δ *Ursae Minoris* and α *Ursae Minoris* (*Polaris*). The traces form circles on the film of radius about 0·6 in. and 0·2 in. respectively, and the circles on the scale are drawn for these radii, so that the film can be accurately centred. A lens is necessary for the examination of the traces if the best accuracy is required.

Recommended routine.—As it is easy to lose records by faulty shutter settings, by errors of the clock or by faulty winding on of the film, a definite routine of checking and setting should be adopted. It is advisable to keep a notebook so that the observers may initial that the routine has in fact been carried out. The recommended routine is given below.

Monday morning.—Take the recorder out of the housing and remove it to where the film is changed ; take out the exposed film (after ensuring that the film has been fully wound on). If it is necessary to regulate the clock, detach the front of the recorder by removing the 12 wood screws and unscrew the clock-winding handle (in the direction opposite to that of winding) ; regulate the clock by means of the adjustment at the back, and then replace the front of the recorder. Adjust the setting of the shutter striking arms for the coming week with the camera still empty ; see that the shutter is closed, insert the new film, wind it on to the correct starting point, wind the clock and replace the recorder in the stand.

Monday afternoon.—Check that the clock is working and showing the correct time, and check that the correct shutter settings have been made.

Other mornings.—Check that the shutter is closed (white spot showing in the shutter window) and that the clock is working and showing the correct time. Adjust the clock if necessary, and then, if the previous checks have been satisfactory, wind on the film.

Other afternoons.—Check that the clock is working and showing the correct time and that the film has been correctly wound on.

8.3.5. Maintenance and repair

The clock should be kept correct to within 0·2 hr. (12 min.). The instrument should only be inspected in daylight, never when the shutter is open.

The interior of the camera should be kept clean and free from dust. This can best be accomplished by only removing the front and back when absolutely essential, and then only in a clean atmosphere. In particular the film holder and the guides over which the film moves must be kept scrupulously clean. The housing and stand should be kept in good condition by renewing the paint whenever necessary and replacing faulty or worn-out members.

The flat piece of glass over the shutter window should also be kept clean. The bearings of the clock and shutter should not require lubricating, but if signs of sticking occur a very sparing application of good clock oil may help.

8.3.6. Accuracy and sources of error

Records can be partially or wholly lost by the fogging of the film, deposition of dew or hoar-frost on the lens or window in front of the lens, bad definition of the traces, faulty operation of the camera (careless insertion of the film causing it to jam, forgetting to wind the film, and thus causing double exposure, or overwinding of the film and thus causing a loss of record at the end of the week) or by incorrect orientation. Fogging of the film can be caused by faulty shutter settings or stoppage of the clock, causing the shutter to be open in daylight, extraneous lights or extreme glare shining in the recorder, or by too much light during the development of the film. Most of these can be avoided by careful handling and siting of the recorder and careful developing.

The camera lens should be correctly focussed when the recorder is received, but if the traces seem to show that they are out of focus a check should be made. This can be done in daylight, when there is no film in the camera, by siting the lens on a very distant object and putting a ground-glass screen in the normal position of the film (ground-glass side nearest the lens) and viewing the image produced. The position of best focus can be found by moving the screen slightly backwards or forwards. If the focus of the lens is markedly in error it can be altered after removing the small grub screw which holds it in position. Faulty operation of the camera can only be overcome by careful attention to detail and full instructions to all concerned.

Errors of orientation in the vertical can be seen from the examination of the developed film. If the records are too low on the film (when the film occupies the same position as in the camera) the elevation of the camera is not enough and should be increased ; $\frac{1}{2}$ in. error on the film corresponds to about $2\frac{1}{2}°$ in elevation.

The accuracy with which the records can be measured depends on the contrast between the records of the star and the background density. This can be increased up to a certain point by prolonging the development of the film, but it is largely determined by the focussing of the camera and the amount of haze in the atmosphere between the recorder and the star. It is probable that with a good record the total angular trace of any star can be obtained to the nearest 2–3° (8–12 min.). The larger the radius of the trace the star makes the smaller will be the density of the record (for a given intensity of light received from the star), but the less the effect on the total time of a given uncertainty on the film.

8.4. MEASUREMENT OF THE INTENSITY OF SOLAR RADIATION

This section deals with the measurement of the intensity of solar radiation at the earth's surface, including both direct radiation from the sun and that which reaches the earth after being scattered or reflected by the atmosphere and its constituents (e.g. clouds, dust, smoke, etc.). Most of this radiation is contained in the range of wave-lengths $0 \cdot 3\mu$ to 4μ. It is not intended to deal with the measurement of the variation of intensity with wave-length, but to restrict the discussion to instruments which measure the total amount of radiation in all wave-lengths. Further, detailed description will be limited to those instruments which can be used in a network of stations, and only a brief description given to those instruments which are less widely used.

The intensity of radiation is expressed as the amount of radiant energy falling on unit area of surface in unit time. The orientation of the surface must obviously be specified, and in practice the intensity of radiation on two plane surfaces only is measured, first, that falling on a horizontal surface, and secondly, that falling on a surface placed normal to the line joining the place of observation to the instantaneous position of the sun. It is usual, also, to restrict the latter observation to radiation coming from directions lying within about 5° of the direction of the centre of the sun, although the various instruments differ slightly among themselves in this respect.

8.4.1. Units

The unit used for solar radiation is the calorie per square centimetre per minute. The solar constant, being the mean value over the whole year of the intensity of solar radiation on a surface placed normal to the sun's rays just outside the earth's atmosphere, is usually assumed to be $1 \cdot 94$ cal./cm.^{2}/min. on the Smithsonian scale (see p. 349). There is, however, some doubt as to the exact value of the solar constant. It may be as much as $2 \cdot 0$ cal./cm.^{2}/min. Radiation intensity is also sometimes expressed in milliwatts per square centimetre; 1 cal./min. equals $69 \cdot 7$ mW.

8.4.2. General principles of radiation measuring instruments

A brief description is given here of the principal types of instruments used for measuring radiation. A more detailed account can be found in "Handbuch der meteorologischen Instrumente"[6].

Thermopile instruments.—In a thermopile a thin blackened surface, supported inside a relatively massive well polished case, is exposed to the radiation, and the difference in temperature between the surface and some reference point or points inside the instrument case is measured by several thermo-junctions arranged in series. The blackened surface rises in temperature until its rate of loss of heat by all causes is equal to the rate of gain of heat by radiation. If this rise in temperature is to be a function only of the intensity of radiation, the rate of loss of heat for a given temperature difference must be independent of the external conditions, such as the ambient temperature or the wind speed past the instrument. It is also desirable that the rise in temperature shall be proportional to the radiation intensity ; this means in practice that convection currents inside the case must be avoided. The time constant or lag coefficient should also be kept conveniently small. By making the case massive and with a polished outer surface the temperature is kept uniform over the instrument and only changes slowly. It is, however, sometimes desirable to shield it from direct solar radiation when the cloud is very broken and the intensity of radiation varies considerably over short periods.

Moll-Gorczynski solarimeter.—These principles may be illustrated by considering the Moll-Gorczynski solarimeter used for measuring the radiation falling on a horizontal surface (Fig. 106). The blackened surface consists of alternate thin strips of manganin and constantan, with one set of junctions along the centre line of the surface (the active junctions) while the remaining junctions are in good thermal contact with the relatively massive supporting posts which are insulated electrically but not thermally from the base plate. If the temperature of the centre of the receiving surface is raised, an electromotive force is set up which can be measured on a suitable galvanometer or potentiometer.

The receiving surface is covered with two concentric hemispherical glass domes and the whole instrument is supported in a solid brass case. The glass domes serve to shield the sensitive surface from the wind and rain and reduce the tendency for convection currents to form. The top surface of the instrument case between the two glass domes is highly polished to reduce the absorption of radiation, and the remainder of the instrument is protected from direct radiation by mounting it in the centre of a circular guard plate, the top surface of which is exactly level with the blackened surface of the thermopile. The temperature of the case is, therefore, kept at, or near, the surrounding air temperature, and is more uniform than it would be if subjected to strong and possibly fluctuating radiation.

Heat can be lost from the blackened surface, mean temperature T_s,

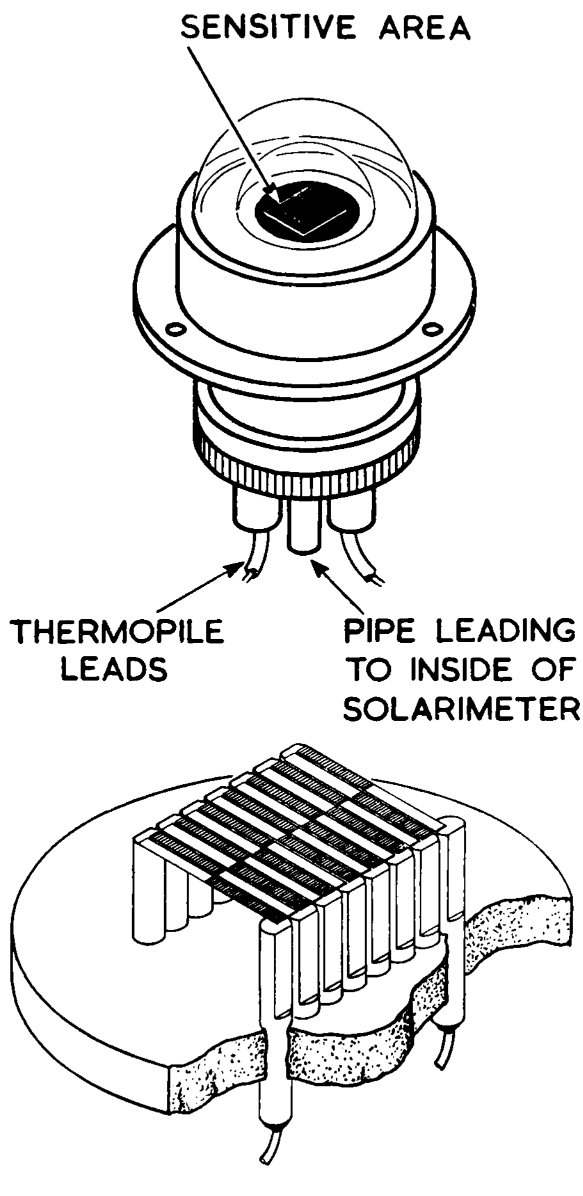
(i) By conduction through the air to the main case of the instrument, temperature T_m. This will be proportional to $T_s - T_m$.

(ii) By conduction to the supporting pillars, temperature T_p (T_p will be very close to T_m).

(iii) By conduction through the air to the glass hemispheres, whose temperature is T_h. The glass hemispheres will in turn lose heat by thermal radiation and will gain by the slight absorption of solar radiation and by conduction from their supports. The glass hemispheres will therefore, in general, rise or fall in temperature until the net rate of gain or loss of heat is made good by conduction to or from the surrounding air. The difference in temperature between the outside air and the hemispheres will thus be a function of the wind speed.

(iv) By radiation to the case and to the glass hemispheres.

In order to obtain a constant and linear relation between the difference in temperature, $T_s - T_p$, and the rate of loss of heat from the blackened surface



ENLARGED VIEW OF SENSITIVE AREA

FIG. 106—MOLL-GORCZYNSKI SOLARIMETER

under all conditions, it is, therefore, necessary to make T_m, T_p and T_h as nearly as possible equal to each other. This is best done by keeping them all equal to the ambient air temperature.

The effect of differences between T_h and T_p can be allowed for if, instead of measuring $T_s - T_p$ the value $T_s - T_s'$ is measured, where T_s' is the temperature that the blackened surface takes up if the glass hemisphere is covered by a shutter. This is equivalent to determining the zero of the recording galvanometer at regular intervals throughout the day instead of using the zero recorded during the night. The differences are, however, slight, and well within the other errors of the observations.

Such a thermopile as this must be calibrated by comparing it with a standard instrument, and this should preferably be done using actual solar radiation under its normal conditions of use. In this way any slight variation with wave-length in the absorption characteristics of the black surface or the glass hemispheres will not matter, whereas if a laboratory source were used, any variation with wavelength of the ratio of the responses of the two instruments would give a wrong result.

Linke-Fuessner actinometer.—The Linke-Fuessner actinometer (Fig. 107) is another thermopile instrument. This, however, can only accept radiation from a cone of semi-angle about 5°, and so it is used for measurements of the direct solar radiation at normal incidence and for radiation from selected parts of the sky. A thermopile of a similar design to that described above but without the glass dome

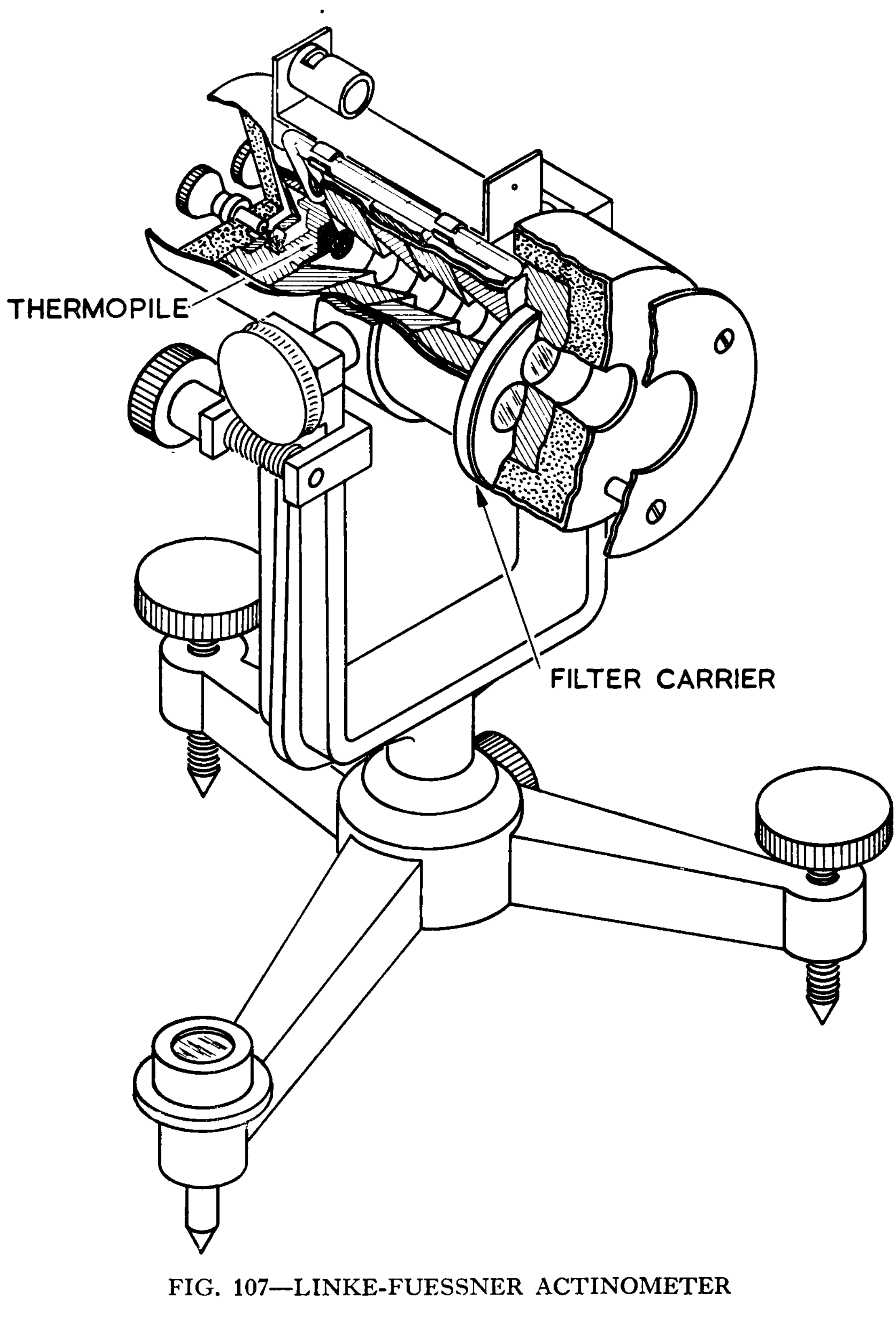


FIG. 107—LINKE-FUESSNER ACTINOMETER

is mounted within a shell made of a series of concentric conical milled rings which are screwed upon one another. This heavy thick copper body, which is highly polished, experiences only a very slow temperature rise when exposed to direct solar radiation, and a uniform temperature is maintained. Filters for the investigation of individual spectral regions can be introduced in a filter carrier.

This instrument can be used for solar radiation measurements, and also for measuring the thermal radiation from the sky at night and from the ground. In the latter cases a more sensitive galvanometer is required.

Silver-disc pyrheliometer.—The silver-disc pyrheliometer (Fig. 108), is an instrument for measuring direct solar radiation. The radiation is allowed to fall on a blackened silver disc supported by fine steel wires inside a copper shell. A mercury-in-glass thermometer is used to measure the temperature of the disc, its bulb being placed in a mercury-filled cavity in the disc. The copper case is, in turn, placed inside a wooden box to reduce temperature changes. Diaphragms are used to limit the angle of acceptance of the instrument to approximately a cone of semi-angle 5°, and a shutter is provided to cut off the radiation altogether. The principle of the apparatus is that the initial rate at which the silver disc is heated by the radiation is found by measuring the rate of change of the disc temperature.

Thus suppose the area of the disc is A, its thermal capacity C and temperature T. Let the radiation intensity be I and the temperature of the inner case be T_c. Then the rate of loss of heat from the disc is $k(T - T_c)$. The temperature of the disc then changes according to the equation

$$C\frac{dT}{dt} = IA - k(T - T_c).$$

Integrating, this becomes

$$T_1 - T_c = \frac{IA}{k}\left\{1 - \exp\left(-\frac{t_1k}{C}\right)\right\} + (T_0 - T_c)\exp\left(-\frac{t_1k}{C}\right),$$

where T_0 is the initial value of T and T_1 is the value of T after a small time t_1. If t_1 is sufficiently small so that t_1 is much less than C/k, then

$$1 - \exp\left(-\frac{t_1k}{C}\right) \simeq \frac{t_1k}{C},$$

and the factor $(T_0 - T_c)\exp(-t_1k/C)$ may be taken as equal to $(T_0 - T_c)$. Therefore

$$T_1 - T_c = IA\frac{t_1}{C} + (T_0 - T_c),$$

$$I = \frac{C}{At_1}(T_1 - T_0).$$

The procedure when using the instrument is usually as follows :

(i) Set the instrument up with the shutter closed.

(ii) Take thermometer readings (1) and (2) 20 sec. and 120 sec. respectively after the commencement of the experiment.

(iii) Open the shutter immediately after reading (2), check the adjustment of the instrument, and take readings (3) and (4) 20 sec. and 120 sec. after the beginning of the 3rd minute.

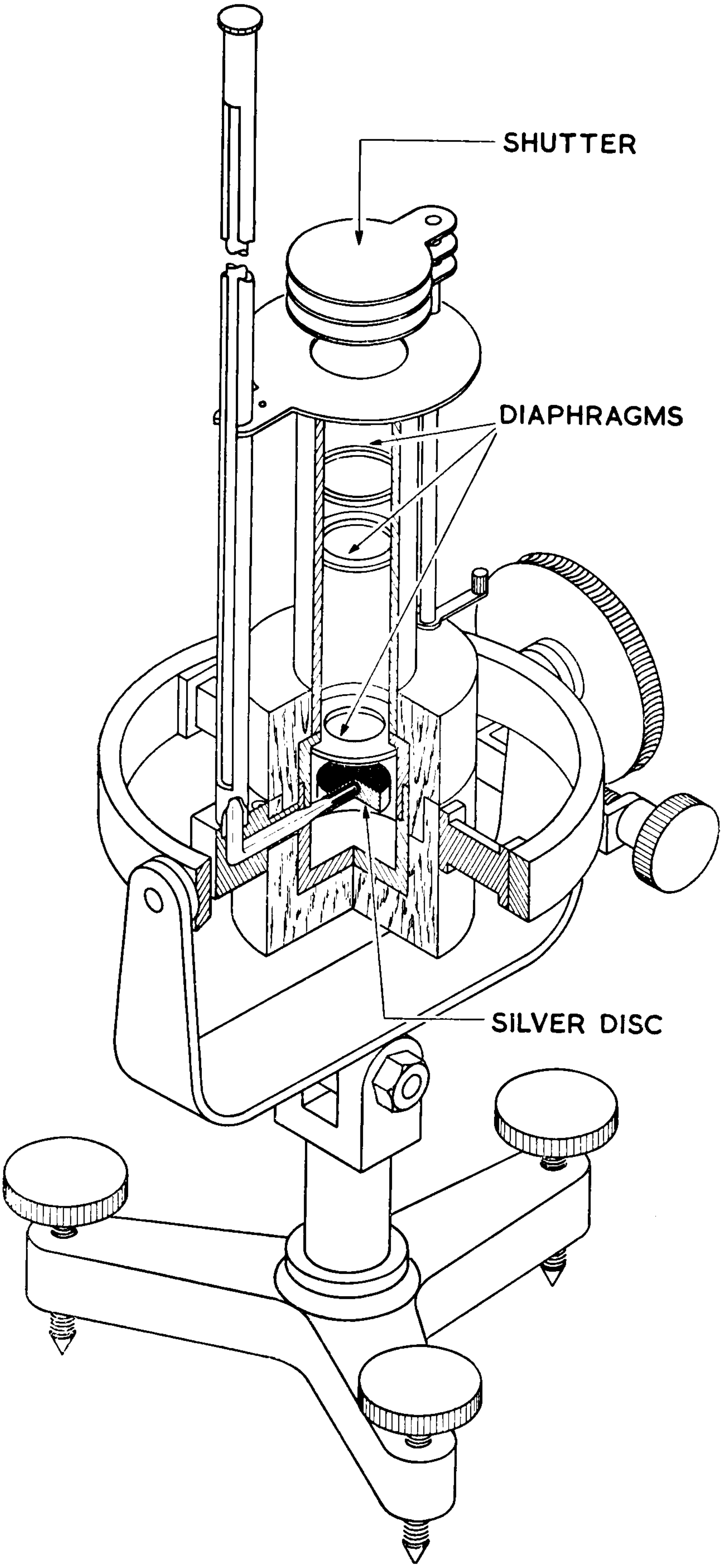


FIG. 108--SILVER-DISC PYRHELIOMETER

(iv) Close the shutter after reading (4), and take readings (5) and (6) after further periods of 20 sec. and 120 sec. respectively.

(v) Repeat the cycle (iii) and (iv).

The rate of rise of temperature, R, is then taken as

$$R_1 = (4) - (3) + \frac{(1) - (2) + (5) - (6)}{2}$$

$$R_2 = (8) - (7) + \frac{(5) - (6) + (9) - (10)}{2}$$

etc.

Corrections must now be applied to each value of R as follows :

(i) The thermal capacity of the disc will vary with its temperature. To correct for this add $K(T - 30)R$ to R, where T is the mean temperature of the disc during the exposure and K is a constant applied with the instrument.

(ii) If the ambient air temperature differs much from 20°C. a correction must be made for the exposed stem : subtract $K'(T_a - 20)R$ from R, where K' is a constant ($= 0{\cdot}00014$) and T_a is the ambient air temperature.

Applying corrections (i) and (ii) reduces the observations to a standard disc temperature of 30°C. and a standard stem temperature of 20°C. The intensity of radiation is then given by

$$I = BR\,[1 + K(T - 30) - K'(T_a - 20)],$$

where B is the instrumental constant.

The silver-disc pyrheliometer is found to keep its calibration virtually unchanged for many years, and is used in America as a secondary standard instrument.

Ångström pyrheliometer.—The Ångström pyrheliometer (Fig. 109) is a standard instrument for the measurement of direct solar radiation at normal incidence. It has two identical strips of platinum coated black, similarly mounted except that one strip is exposed to the radiation while the other is shielded from it. A current of electricity is passed through the shielded strip until the temperatures of the two strips are equal, and then the rate of heat development in the shielded strip by its electrical resistance is equated to the rate of absorption of radiant energy by the unshielded strip. The equivalence or otherwise of the temperatures of the two strips is determined by two fine thermo-couples attached to the back of the strips, connected in series with a sensitive galvanometer. The current through the shielded strip is measured with an accurate milliammeter.

Such an instrument is, in theory, an absolute instrument as all the relevant factors can be measured, but small corrections have to be made for the imperfect absorption of the exposed strip and the slightly different exposure of the shielded strip as compared with the exposed strip, so that in practice each instrument is compared with a standard instrument of the same type, and a calibration figure computed. When making an observation each strip is exposed in turn, and a mean value found for the current required.

The great advantage of the Ångström pyrheliometer is that the equilibrium current through the shielded strip is not affected by changes in the rate of heat loss from the sensitive strip, provided the changes affect both strips equally.

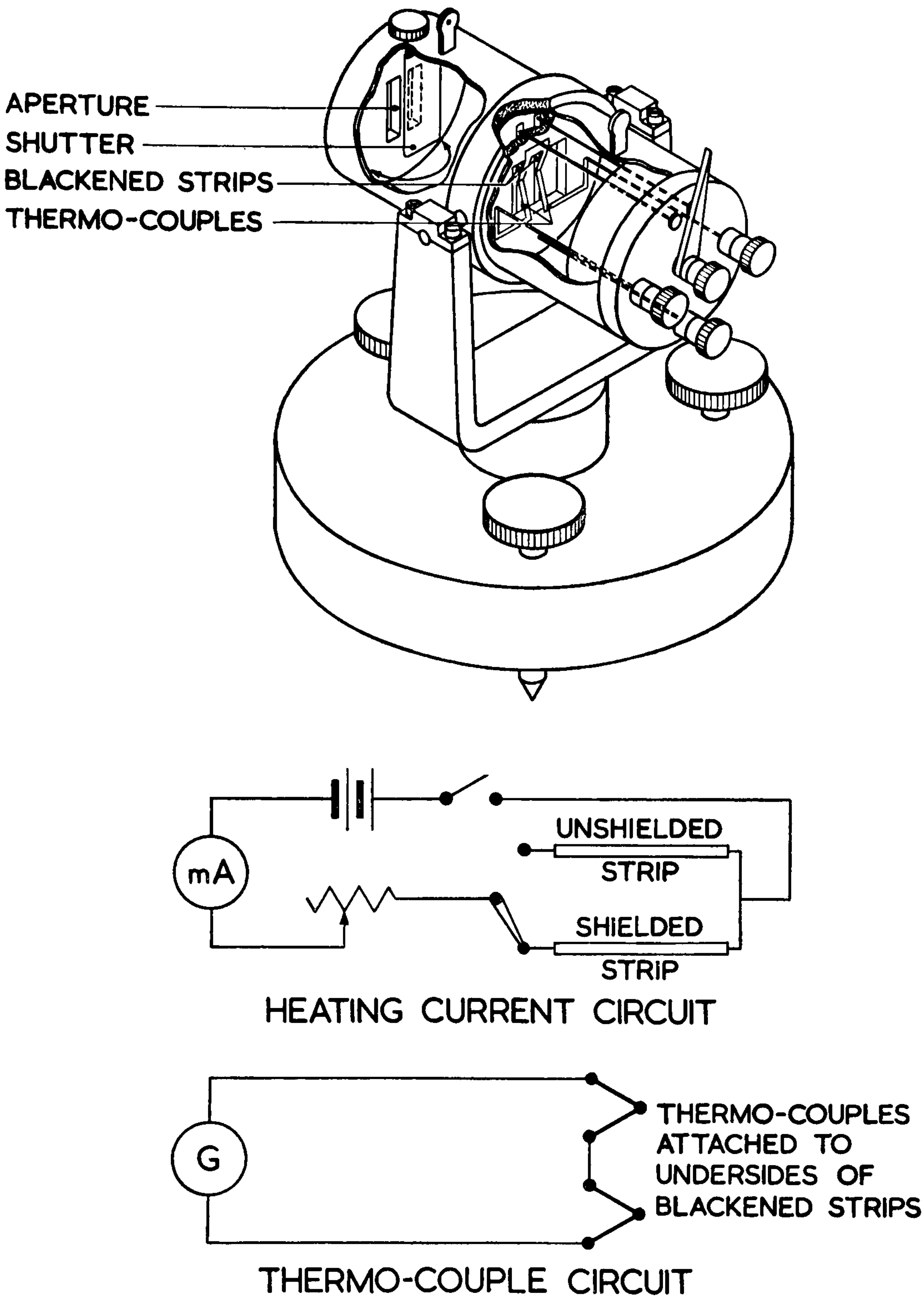


FIG. 109—ÅNGSTRÖM PYRHELIOMETER

Michelson actinometer.—The Michelson actinometer (Fig. 110) is often used as a secondary standard instrument. Like the silver-disc pyrheliometer it is very portable, and needs no external source of power or additional measuring instruments. The radiation is allowed to fall perpendicularly on a thin blackened bimetallic strip which is normally almost flat. This strip is enclosed in a narrow chamber in the metal case, and has attached to an extension a very fine quartz fibre; the other end is fixed to the case. As the temperature of the strip rises, because of the absorption of the radiation falling on it, its curvature changes and the quartz fibre moves. The movement of the fibre is observed by means of a microscope and measured by means of a scale in the eyepiece; a small mirror, illuminated by light coming from a small aperture provides a light background against which to view the fibre.

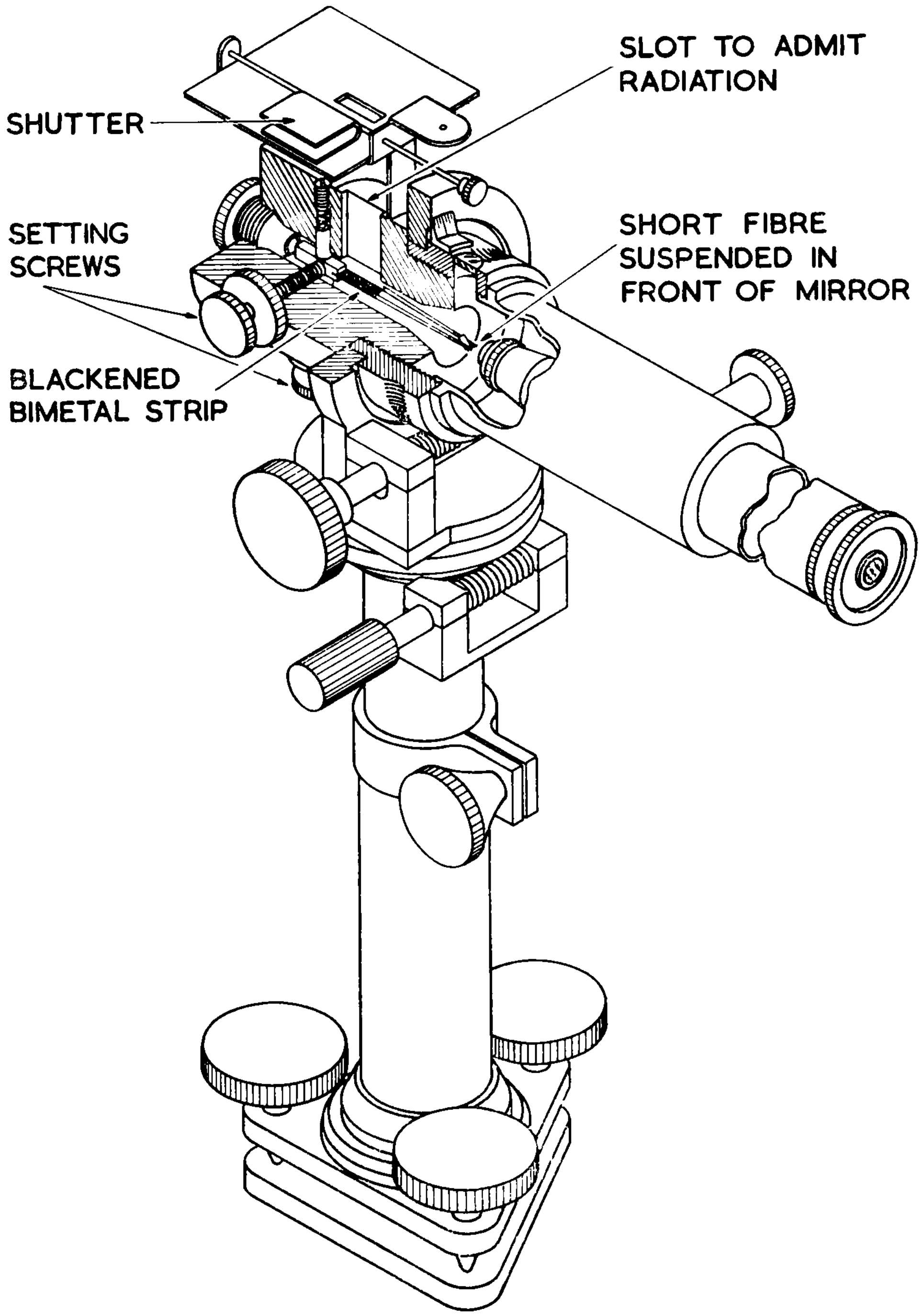


FIG. 110—MICHELSON ACTINOMETER

The radiation falling on the bimetallic strip can be controlled by a shutter, and the angular size of the (rectangular) opening as viewed from the bimetal is 5° × 14°. The strip is made very thin so that its lag is small; the equilibrium position is reached in about 20–30 sec. Air temperature changes of course affect the strip as well as temperature changes caused by radiation so that zero setting screws have to be provided.

In a typical instrument a temperature rise of the strip of about 3° C. would indicate a radiation intensity of 1 cal./cm.^{2}/min., and with a microscope magnification of 60 times a usual deflection in bright sunshine can be read to the nearest 1 per cent.

The observational procedure would be as follows :

(i) Set the instrument on its stand and orientate it so that the solar radiation will fall perpendicularly on to the bimetallic strip when the shutter is opened. A small view-finder is used for this.

(ii) Adjust the position of the quartz fibre in the microscope field of view until it is on a convenient low reading and then note this reading A_1.

(iii) Open the shutter, wait about 45 sec. and then take the reading B_1.

(iv) Close the shutter, wait about 45 sec. and take the reading A_2.

(v) Repeat (iii) and (iv) twice obtaining further readings B_2, B_3 of the reading with radiation and A_3 and A_4 of the zero. The mean deflection is then equal to

$$\frac{1}{3}\left\{B_1 + B_2 + B_3 - \left(A_2 + A_3 + \frac{A_1 + A_4}{2}\right)\right\}.$$

Once this instrument has been calibrated against a standard instrument the radiation intensity can then be found from the calibration factor.

Radiation recorders using black and white surfaces.—Radiation measuring instruments using black and white surfaces are typified by the Epply pyrheliometer and the bimetallic radiation recorder, the latter being based on the Robitzsch actinograph. These instruments are used to measure the total radiation on a horizontal surface. The sensitive surface is divided into two parts, one blackened to absorb as much radiation as possible, the other made white to absorb as little radiation as possible. Because of the different rates at which the two surfaces absorb radiation their temperatures differ, and this difference of temperature is a measure of the incident radiation.

Bimetallic radiation recorder.—The receiving surface of the bimetallic radiation recorder (Plate XLIII) consists of two parallel rectangular white-coated strips of bimetal between which is placed a similar strip of bimetal coated black. At one end the three strips are connected to a common rod, while the other ends of the white strips are fixed to the frame of the instrument. The other end of the black strip is connected to a simple lever mechanism, and its movements are recorded on a chart placed on a normal clock drum. It will be seen that in this way the movements of the pen arm are proportional to the difference in temperature between the strips, and thus to the intensity of radiation, and are independent of ambient temperature changes. The receiving surface is covered by a glass hemisphere.

This instrument is much simpler to operate than a thermopile instrument, but it has, however, a relatively large lag coefficient (5–10 min. as opposed to about 10 sec. for the solarimeter thermopile), and the effect of friction between the recording chart and the pen is somewhat greater than in, say, a bimetallic thermograph, because the control of the instrument is not great. The control could be increased to a certain extent by increasing the thickness of the bimetallic strips, but this would mean an increase in the lag coefficient ; in practice, a compromise has to be reached. As a result of these two effects, the instrument is not considered suitable for measuring the instantaneous value of the radiation intensity, but it can be used for daily totals.

Epply pyrheliometer.—The receiving surfaces in the Epply pyrheliometer (Fig. 111) consist of a central white disc surrounded by a concentric black surface, the whole being placed inside a glass globe. The difference in temperature between the black and white surface is measured with thermo-couples, and can be recorded by a suitable potentiometer or galvanometer recorder.

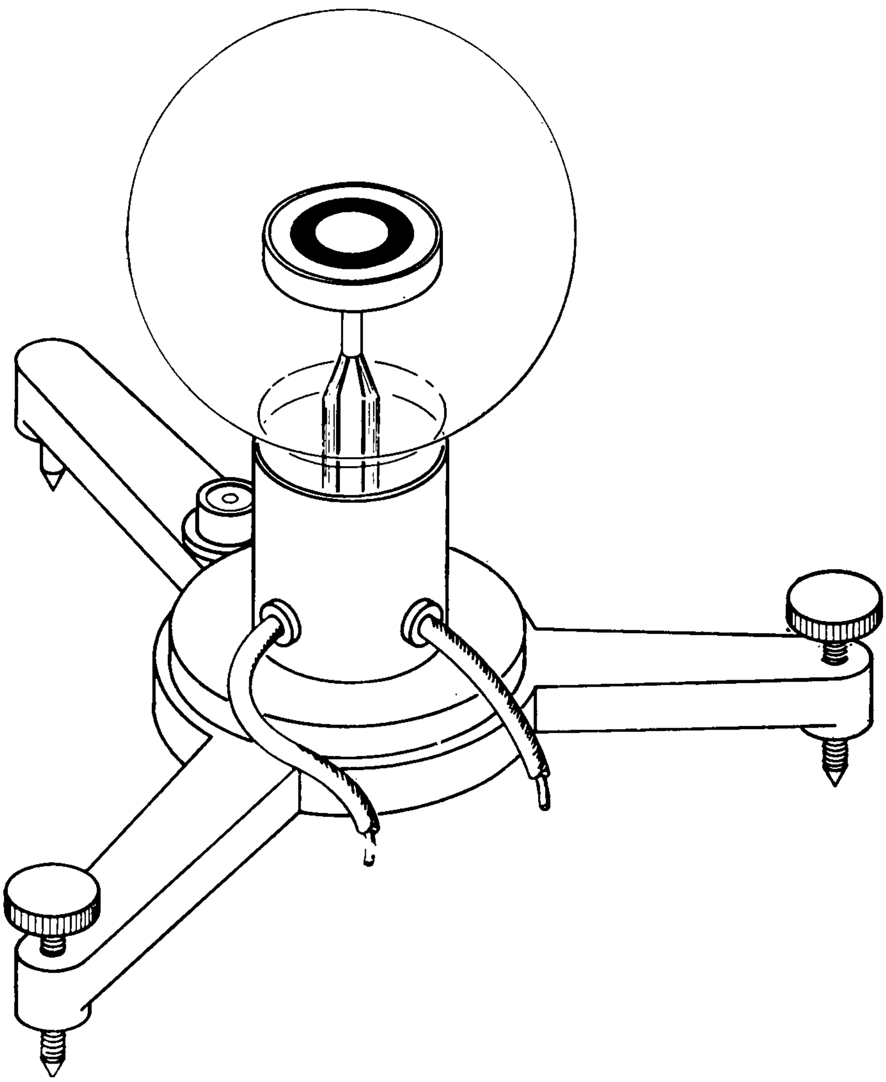
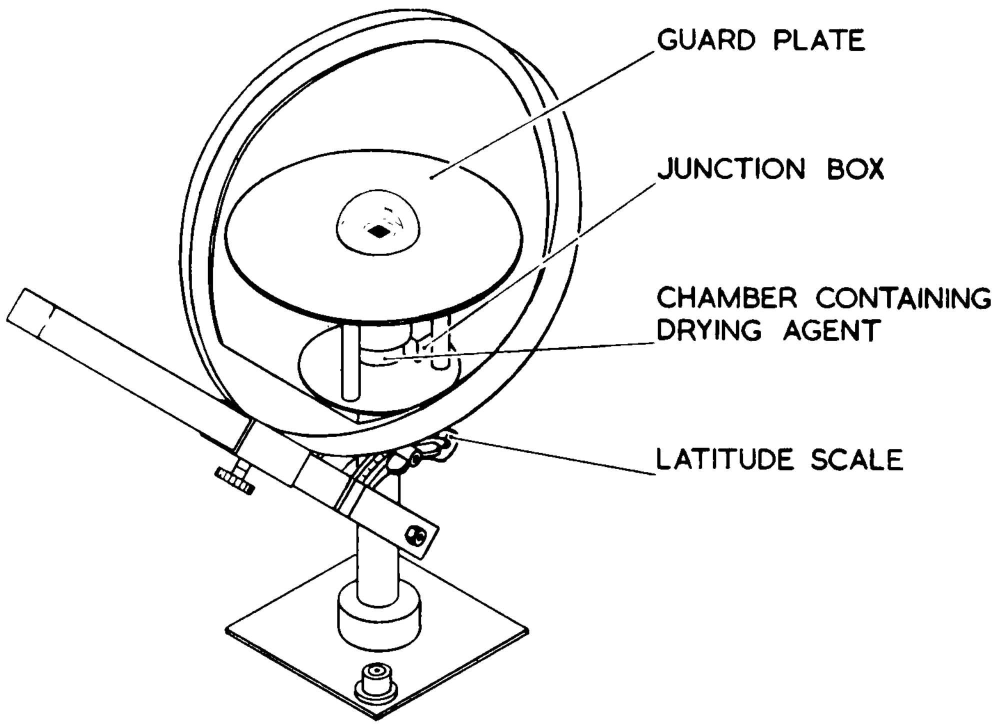


FIG. 111—EPPLY PYRHELIOMETER

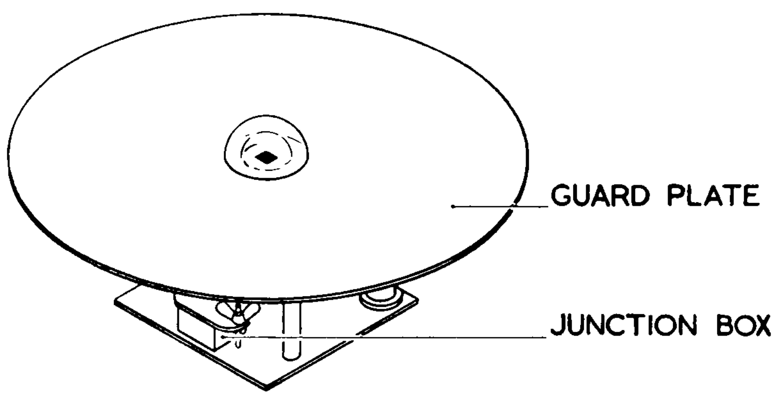
8.4.3. Measurement of the intensity of total and diffuse solar radiation on a horizontal surface

Measurements using Moll-Gorczynski solarimeters.—A description of the Moll-Gorczynski solarimetric thermopile (Stores Ref., Met. 977) has already been given (p. 120). When used for measuring the total radiation intensity it is mounted in as open a position as possible in a mount similar to that shown in Fig. 112. The essential parts of the mount are the chromium-plated guard plate, the top surface of which is co-planar with the sensitive surface of the thermopile, the cylindrical chamber into which the base of the thermopile fits and which carries a drying agent, and the junction box to which the thermopile leads are taken. The base plate carries a circular spirit level.

The diffuse radiation solarimeter mounting is shown in Fig. 112. The direct radiation from the sun is cut off by the shadow band, a circular metal ring carried on an adjustable arm. The arm is pivoted about a horizontal east–west axis which



Mount for measuring diffuse radiation



Mount for measuring total radiation

FIG. 112—MOUNTINGS FOR MOLL-GORCZYNSKI SOLARIMETER

cuts the vertical axis of the solarimeter, and the ring may be moved up and down the arm. The arm is set so that its angle to the horizontal is equal to the latitude of the station ; movements of the ring up and down the arm can then allow for the changes in the sun's declination. The mounting commonly in use at British stations can be used from about latitude 40° to latitude 60°. Besides cutting off the direct radiation, however, the shadow band also cuts off a certain amount of diffuse radiation, and this must be corrected for (see p. 346). The remainder of the mounting is similar to that for the total radiation solarimeter, except that the guard ring is not so large.

The instrument is usually employed with a thread recorder and when both the total and diffuse radiation are being recorded an instrument giving the two records on the same chart is used. This recorder consists of a moving coil galvanometer whose pointer is clamped down on to an inked thread and thence on to the drum, once every minute. The clock mechanism also turns the drum and switches the circuit. In some thread recorders different colour threads are used for each circuit, and then each solarimeter is connected in circuit for 1 min. out of every 2, and the interval between the two dots in any one circuit is 2 min. In other recorders, however, only a single black thread is used, and in this instrument one circuit is connected to the galvanometer for 3 min., while the other is only connected for 1 min. In this way the traces can be distinguished by the frequency of the dots in each trace.

Special instruction booklets are issued by the makers of the thread recorders, and reference should be made to these for detailed instructions for the installation, operation and maintenance of these instruments, but the general outline is given in the next section.

Mechanical details of installation.—It is essential for the solarimeters to be mounted in the open in such a position that there is no obstacle to obstruct the sun's rays in all seasons between sunrise and sunset, and, preferably, no obstruction between the instrument and the sky down to the horizon in all directions. This second requirement will rarely be fully obtained in practice because of the presence of chimney stacks, etc., but the best situation obtainable should be selected, bearing in mind the fact that the instruments must be inspected and adjusted at frequent intervals. A horizontal platform about 8 in. square is required for each solarimeter mounting, with pockets into which can be grouted three vertical bolts. The base of each mounting should be used as a template for placing the holes. The orientation of both solarimeters should be such that the longer line of thermo-couples (supported on eight pillars) is facing north. The shade ring mounting on the diffuse solarimeter should be such that the plane containing the movable arm and the centre of the thermopile lies due north–south. When the bolts have been grouted into place the mounting can be placed on them, and held in position by nuts above and below. In this way the base of the mounting, and thus the sensitive surface of the thermopile, can be made accurately horizontal. It may be found in some instances easier and more economical to build a support for the mountings out of steel strip or angle iron instead of a solid platform. In any case the support must be amply strong enough to hold the mountings in the strongest wind likely to be experienced in that locality.

The recorder must be mounted in a room on a solid wall or shelf so that it is not affected by vibration when people walk about or doors are opened or shut. In addition it should not be close to radiators or other heat sources and the sun must not at any time shine directly upon it. The room, however, should be one that is normally kept at an even temperature ; one with a large diurnal change should be avoided. These precautions are necessary because temperature changes of the recorder affect its sensitivity, and unsymmetrical heating may affect the zero.

The solarimeters should be connected to the recorder by twin-core lead-covered cable (Stores Ref., Met. 328). The distance between the recorder and the solarimeters is immaterial from the electrical point of view, because, as will be seen from the next paragraph, even the resistance of 1,000 yd. of cable, normally used, is not usually excessive. To reduce the cost of the installation, however, the recorder should be as close to the solarimeters as is convenient and practicable. Two lengths of cable will be required, one for each solarimeter.

Electrical Installation.—The solarimeters will be supplied with a calibration certificate from Kew Observatory giving the resistance of the thermopile and its output in millivolts per calorie per square centimetre per minute. The values of the resistance and the current sensitivity of the recorder will also be supplied, the current sensitivity being given as so many micro-amperes per full-scale deflection of the recorder. The full-scale deflection can now be made to correspond to a suitable radiation intensity by connecting a fixed resistance in series with the solarimeter.

If the recorder can make two colour records the full-scale deflection for both solarimeters should be equivalent to 1·5 gm.cal./cm.²/min. If, however, the recorder is one with only a black thread, it is necessary to separate the two traces completely. This is best done by altering the zero of the recorder from one edge of the chart to a convenient division about ⅓ of the total chart width away from the edge. The diffuse record solarimeter can then be connected to the recorder with the polarity of the leads reversed, and its deflection will be in the opposite direction to that of the total record. The sensitivity should be such that for each record the full-scale deflection of the recorder (over the whole chart width) is equivalent to a radiation intensity of 3 gm.cal./cm.²/min.

A double pole two-way switch should be inserted in the leads from each solarimeter, between the series resistors and the solarimeters themselves, so that the recorder can be short-circuited when it is required to make a time mark on the chart. The complete electrical circuit is then as shown in Fig. 113. A suitable switch is a toggle switch (Stores Ref., Met. 221).

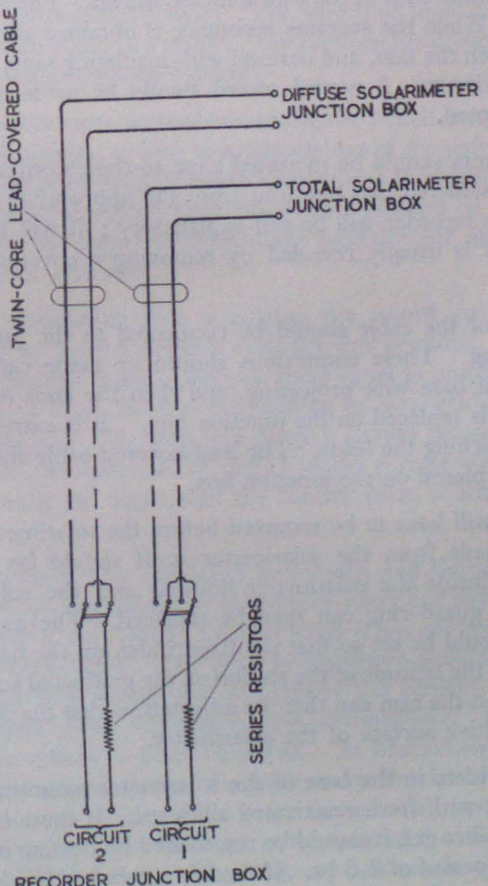


FIG. 113—ELECTRIC CIRCUIT OF SOLARIMETER

When calculating the series resistance required in each circuit allowance must be made for the resistance of the connecting cable. Each core of the lead-covered cable recommended has a resistance of 2·38 ohms/100 yd. An example of the calculation involved is given below.

Solarimeter No. 123 has a resistance of 9·0 ohms and a constant of 7·5 mv./cal/.cm.^{2}/min. This is to be used with recorder No. 123456 which has a resistance of 19·5 ohms and a full-scale deflection for a current of 60 μamp. The length of cable used is, say, 150 yd. making a total lead resistance of 3 × 2·38 ohms which equals 7·1 ohms (the cable has two cores and the resistance of each is included). The total resistance of the circuit is so far 9·0 + 19·5 + 7·1 ohms, i.e. 35·6 ohms.

The full-scale deflection has to be equivalent to 1·5 cal./cm.^{2}/min. This radiation intensity produces an electromotive force of 1·5 × 7·5 mV., i.e. 11·25 mV. This voltage will produce a current of 60 μamp. in a circuit of total resistance 11·25 × 10^3/60 ohms, i.e. 187·5 ohms. It is necessary, therefore, to make the resistance of the solarimeter circuit up to this value ; the additional resistance required is 187·5 — 35·6 ohms, i.e. 151·9 ohms.

A resistor of this value should be wound with constantan or manganin wire on a wooden former with the ends of the wire soldered to tags. The accuracy required is about 1 per cent. When the accurate resistance is obtained the resistor should be varnished, apart from the tags, and covered with insulating tape. A resistor will be required for each circuit. A careful record should be made of the value of the resistors finally adopted.

The series resistors should be mounted close to the recorder (inside its case if possible) and each soldered into one lead from the appropriate solarimeter. The junction box on the recorder will be self-explanatory ; it will have two junctions for each circuit ; it is usually revealed by removing a cover at the base of the instrument.

The other end of the cable should be connected to the junction box on the solarimeter mounting. These connexions should be made carefully leaving the minimum amount of bare wire projecting, and then the ends of the wires waxed over before the cap is replaced on the junction box. It is extremely important to prevent moisture reaching the leads. The lead-covered cable should be supported so that no weight is placed on the junction box.

The guard ring will have to be removed before the solarimeter can be fixed in place. The bare leads from the solarimeter itself should be connected to the two-way connecter inside the solarimeter housing and the solarimeter screwed into position. The guard ring can then be replaced. The movable arm of the diffuse mounting should be set so that the fixed index on the base of the mount is opposite the value of the latitude of the station on the graduated scale. The position of the shadow ring on the arm can then be adjusted so that the shadow of the ring falls across the sensitive surface of the solarimeter.

The silica-gel holders in the base of the solarimeter mounting should then be unscrewed and filled with fresh reactivated silica gel. If there is any doubt as to the freshness of the silica gel, it should be reactivated by heating it to a temperature of 300–400° F. for a period of 2–3 hr. If there is a cobalt chloride indicator mixed with the gel, it will be coloured blue when dry and pink when moist.

Method of use.—The thread recorder used to obtain the records is more delicate than most other meteorological instruments and must be handled with care. The drum and switch mechanism may be driven by clockwork or by an electric motor. The instrument should first be studied carefully and the various parts identified ; the instruction booklet supplied by the manufacturers should be used as a guide. The way in which the drum is to be taken out should be noted as careless removal may damage the instrument. It should be impressed on all concerned that the galvanometer pointer should be clamped except when actual recording is in process.

The normal routine for recording instruments outlined in Chapter 1 should be followed as far as possible. The following hints, however, cover a few of the special characteristics of this type of recorder. When the inked thread is new the galvanometer pointer becomes greasy and sometimes sticks to the thread. The pointer then fails to take up its correct position and may record a straight line sloping gradually up the chart as the inked thread moves on. The remedy is to clamp the galvanometer pointer and then to clean it by rubbing it gently with a match stick. This trouble may also cause an unsteady zero during the night.

The inked thread is moved on automatically each time the clamping lever is depressed, but on some models there is no reversing mechanism. On these instruments, therefore, the thread must be completely re-wound when it is passed completely from one spool to the other. The length of time that elapses between each winding is usually about two weeks. Instructions for doing this will be found in the manufacturer's instruction booklet.

The recorder may be time marked by closing the switch fitted in the leads for a period of 2–3 min. (covering at least two depressions of the galvanometer pointer). The zero of the recorder is found from the trace during the night. It should not be adjusted for every small deviation from the correct position on the chart, but any large changes should be corrected by turning carefully and slowly the adjusting screw on the top of the recorder.

Instructions for tabulating and measuring the record are issued separately, but it is convenient to make a perspex scale for this purpose. This should have engraved on it two parallel lines (a distance apart equal to one hour on the chart), and, at right angles to these, lines corresponding to each graduation on the chart (0–60 in most instances). The zero and every 5 should be emphasized. In this way the zero line on the scale can be placed in the correct position according to the zero reading during the night, and the correct value of the trace read on the scale.

The solarimeters should be inspected frequently, and the shadow ring on the diffuse solarimeter mounting should be adjusted on every fine day. Particular care is needed after a period of dull cloudy weather when it has not been possible to make this adjustment for some time. The glass hemispheres should also be inspected frequently, as it has been found that sometimes the cement used in fixing the glass domes deteriorates so that the hemispheres become loose. If this does happen, the domes should be rcfixed in place with wax. At Meteorological Office stations a suitable wax can be obtained from the Instrument Provisioning Branch. Great care should be taken when doing this to make the wax only just sufficiently hot to enable it to be used easily. The silica gel in the base of the solarimeter should be renewed frequently. Moisture should not on any account be allowed to condense on the inner surface of the glass hemisphere.

Calculation of corrections to be applied to the results.—Corrections have to be applied for two reasons :

(i) Certain permanent obstacles may obscure a small but definite amount of the sky.

(ii) The guard ring obscures part of the sky (as well as the sun) from the diffuse instrument.

Any correction as the result of (i) is a constant fraction, and will apply to both instruments, while that from (ii) varies with time and applies only to the diffuse instrument.

The quantities to be computed are the fractions of the vertical component of radiation which are lost by obstructions. Since the receiver has a cosine law of response, radiation incident at angles less than 5° to the horizon has very little effect, and consequently obstacles of similar elevation are equally ineffective.

To determine the correction accurately it would be necessary to take account of the variation of intensity over the hemisphere. This variation is important, for example, on cloudless days, when the circumsolar diffuse radiation is far greater than in other parts of the hemisphere. However, it is not practicable to do this and it is usually assumed that the intensity of diffuse radiation is uniform over the whole sky. Provided that not more than 10 per cent. of the sky is obscured, observations corrected on this assumption are usually more accurate than uncorrected observations.

If θ stands for elevation and ψ for azimuth then it can be shown that an elementary area at (θ, ψ) will contribute a fraction $\frac{1}{2}\sin 2\theta d\theta d\psi/\pi$ to the total vertical component.

To calculate the loss due to a fixed obstacle of finite size the outline of the obstacle is mapped on a θ–ψ diagram. Its projection on this diagram is divided into component areas over each of which θ does not vary by more than 5°. Then $\Sigma\ (\frac{1}{2}\overline{\sin 2\theta}\Delta\theta\Delta\psi)/\pi$, where $\overline{\sin 2\theta}$ is the mean value of $\sin 2\theta$ over each component area, gives the total loss due to the obstacle.

The loss due to the shade ring is calculated in a similar way. Let the radius of the ring be R and the half width be d ; and let ϕ be the latitude and δ the declination of the sun then the general equation for the projection of the two rims of the ring on to the θ–ψ diagram is :

$$\cos\theta\sin\psi\cos\phi + \sin\theta\sin\phi = \frac{R\tan\delta \pm d}{\sqrt{[(R\tan\delta \pm d)^2 + R^2]}},$$

where ψ is measured positive from east through north. Substitution in this equation, at a series of values of θ ($\theta = 0°$, 10°, etc.), will give pairs of values of ψ representing the two rims of the ring. This procedure is repeated for some five days in the year (summer and winter solstices, the equinoxes and, say, January 15 and May 15). When the outlines of the shade ring have been drawn in for the five typical days, the areas obtained are split into convenient parts (say between $\theta = 0°$ and $\theta = 10°$, etc.) over which values of $\frac{1}{2}\sin 2\theta$ may be conveniently assigned.

The final corrections, $\Sigma\ (\frac{1}{2}\sin 2\theta.\ \Delta\theta\Delta\psi)/\pi$ are then computed, and a curve drawn giving the annual variation of this quantity which is symmetrical about the summer solstice. Typical values at Kew for a shade ring of radius 135 mm. and half width 9 mm. are : midwinter 1 per cent., midsummer 8 per cent. Interpolation through the year to the nearest 1 per cent. is sufficiently accurate to give the corrections to be applied each month. The final corrected diffuse-radiation values are obtained from the equation :

$$D_{\text{corrected}} = \frac{D_{\text{measured}}}{(1 - Z)},$$

where Z is the correction found above.

Maintenance.—The main items of the recorder maintenance are covered by the manufacturer's instrument booklet. This will give instructions about any necessary oiling. The inked threads should be renewed when the traces become faint and difficult to read. If the wiring is exposed to the weather over an appreciable length (over 20 yd. say), it should be tested at intervals of about 12 months, or immediately if any fault is suspected. The best way of doing this is to disconnect the cable from the recorder junction box and from the solarimeter junction box and, keeping the two ends separate, measure the resistance between the two wires and between each core and the lead cover of the cable. A high voltage generator-type resistance meter is suitable for this. The readings should be well over 10 megohms. The two cores should then be joined together at the solarimeter end and the resistance between the two cores at the recorder end measured ; the resistance should now be equal to the calculated cable resistance within fairly close limits ($\pm$ 20 per cent.). A break will be immediately seen.

The calibration of the solarimeters must be checked at regular intervals. This will probably be done by supplying a travelling substandard solarimeter whose calibration has been recently checked against the standard Ångström pyrheliometer at Kew Observatory. This will be exposed alongside the other solarimeters and a series of comparative measurements made, first between the sub-standard and the total solarimeter, and then between the sub-standard and the diffuse solarimeter, all solarimeters measuring the total radiation. A clear day on which the radiation is not fluctuating rapidly should be chosen, if possible, and several hours' record taken for each comparison. When comparing the readings due account must be taken of any difference in a series resistance of the leads.

Mean hourly values of the corresponding deflections should be measured, and the ratio (standard solarimeter deflection/station solarimeter deflection) taken ; call this R_1. Several values will be found (R_1, R_2 . . .) according to the number of hours record taken. The mean value, R, should be found. The corresponding ratio of the output of the two solarimeters in millivolts will be Rr_1/r_2 where r_1 is the resistance of the standard solarimeter circuit and r_2 is the resistance of the station solarimeter circuit. If a radiative intensity of 1 cal./cm.^{2}/min. results in an output from the standard of K mV., then the output of the station solarimeter, with the same intensity, would be Kr_2/Rr_1 mV.

Accuracy.—The largest single source of error in this equipment is in assessing the record. The overall accuracy for hourly totals is estimated to be between 5 and 10 per cent. of the average value. By using an automatic integrator this accuracy can be improved.

The procedure normally used for calibration of the standard solarimeter is discussed on p. 349.

Bimetallic radiation recorder Mk III.—*Installation.*—The general description of this instrument (Stores Ref., Met. 1519) has been given earlier (p. 339). An earlier type used is shown in Plate XLIII with its cover removed. Later instruments are similar in principle, but have various refinements leading to better and more uniform performance. The site of the instrument should be carefully chosen so that as clear a view as possible of the whole sky is obtained, especially in the direction of the rising and setting sun, approximately between north-east and south-east and between north-west and south-west. In these latter directions a view of the horizon should be obtained, if at all possible ; if not, the obstructions should not exceed 3° in elevation. The instrument should be stood on a firm support, and, except in very exposed positions, no further fixing should be required as the instrument has a heavy base. The glass window opposite the drum should face due north (in the northern hemisphere) so that the bimetallic strips lie east–west.

After installation, the instrument should be carefully levelled, using the spirit level on a base as a reference.

Method of Use.—With the bimetallic strips shielded from radiation the pen should read approximately zero, but a small deviation in the positive direction does not matter, as the effective zero can be found from the traces made during the night. Any initial large error should, however, be corrected by using the zero adjusting screw.

The force available to move the pen is very small, so the friction between the pen and the chart must be reduced to a minimum by carefully adjusting the gate suspension of the pen arm. It is not advisable to make a time mark, but the time recorded by the pen on the chart should be noted at a known time once a day, and the reading noted on the chart when it is finally removed from the drum.

The silica-gel drier must be revived by heating whenever it becomes damp ; when dry the indicator colour is blue, but when damp it is pink. The temperature of the drier should not be allowed to exceed 400° F. when it is being heated.

Care needs to be exercised when replacing the instrument cover as the clearance between the rim of the glass hemisphere and the bimetallic strips is very small. Both guide rods should be in their proper sockets before the cover is finally slid home.

Calibration.—These instruments are calibrated at Kew Observatory against a standard solarimeter using a laboratory source of radiation. The calibration factor is supplied in the form of x mm./cal./cm.^{2}/min. There is, however, some variation in the factor with the aximuth and elevation of the radiation source, so that a mean value has to be taken. This value will depend to some extent on the latitude of the station using the instrument.

An improved instrument of this type is being developed that will give a much more uniform response, and which will enable the calibration figure to be given with more confidence. Meanwhile, however, the calibration figure should be treated as the best available. It is desirable that it should be checked at regular intervals (once a year) until more knowledge is obtained of the stability of these instruments.

Any comparison between the results obtained with these instruments and the results obtained from the solarimeter method of measuring radiation will be very useful. The comparison should be made between the daily totals of radiation estimated from both methods. The planimeter should be used to measure the bimetallic recorder charts.

These instruments can be used with either a weekly or a daily clock. The records are, however, much more easily evaluated with a daily chart, and these should be used wherever possible.

Maintenance.—The lever system of the instrument must be kept clean and free from dust, and the glass hemisphere must be cleaned with a soft cloth frequently. The adjustment of the gate suspension should be checked at intervals to ensure that the pressure of the pen on the chart is kept to a minimum. The case of the instrument should be kept clean.

Accuracy and sources of error.—The main sources of error of this instrument are the variation of the calibration constant with the angle (both azimuth and elevation) at which the radiation falls on the bimetallic strips, and the effect of the friction of the pen on the chart. Data on the original instruments suggest that the first effect did not give rise to errors of more than 5–10 per cent. when daily totals were measured. The effect of friction was to make the instrument unreliable for instantaneous values or even hourly means. An improved instrument has, however, been developed in which the mean plane of the bimetallic strips is kept horizontal at all ambient temperatures, and in which radiation is prevented from penetrating beneath the strips. This has given a much more uniform calibration factor, and, together with the use of a thicker bimetallic strip to give more power, has resulted in a more reliable instrument.

8.4.4. Measurement of solar radiation at normal incidence

There are three main methods of measuring solar radiation at normal incidence, i.e., with the Ångström pyrheliometer, with the silver-disc pyrheliometer, and with a thermopile. The first two instruments are suitable only for spot readings, but with the third instrument, in conjunction with a recording galvanometer, continuous recordings can be made. The thermopile normally used is essentially the same as that used in the solarimeter described on p. 340, but with the glass hemispheres replaced by a flat glass plate. The thermopile is fitted in a heliostat, driven either by clockwork or a synchronous electric motor, which rotates the thermopile about an axis perpendicular to the plane of the celestial equator, and at such a rate that the thermopile sensitive surface can be kept perpendicular to the line joining the thermopile to the sun. The axis of rotation needs to be continually adjusted as the sun's declination changes.

The angle of view of the thermopile is restricted by a series of circular diaphragms, so that only a small annulus of sky can be " seen " around the sun. The recording galvanometer used is generally a similar type to that used for recording the intensity of radiation on a horizontal surface using the solarimeter, and the full-scale deflection is adjusted to be a convenient radiation intensity in a similar way to that described on p. 341.

The spot-reading instruments are usually used to check the calibration of the recording instruments. They have to be set up so that their " angle of view " is centred on the sun.

8.4.5. Standard instruments and methods of calibration

Absolute scales.—Meteorological instruments for measuring radiation intensity are calibrated against substandard (or secondary standard) instruments. These substandard instruments are in turn compared with primary standard instruments. In Europe the substandard instruments are mainly Ångström pyrheliometers and are compared with a standard instrument of the same type at Uppsala. In America the silver-disc pyrheliometer is mainly used, and these instruments are compared with an absolute instrument held at the Smithsonian Institution at Washington. These two scales differ however, the unit on the Smithsonian scale being in fact of a higher radiation intensity than the nominally equivalent unit on the Ångström scale.

The exact value of the difference is, however, a matter of some argument. If a silver-disc pyrheliometer and an Ångström pyrheliometer are used to measure the normal intensity of the solar radiation at the same time and at the same place and the results compared, the silver-disc instrument will read about 3·5 per cent. below the value obtained from the Ångström instrument. Part of this difference occurs because the amount of sky radiation from the sky surrounding the sun, which falls on the receiving surface, is not identical in the two instruments. Thus they do not measure the same thing.

This, however, does not account for the whole of the difference between the Smithsonian and Ångström scales. When comparisons are made with laboratory sources so that the radiation from the surrounds is negligible, it is found that the difference between the two scales is about 2·7 per cent. This is the true difference between the magnitudes of the scale units, but if actual measurements of solar radiation at normal incidence with two instruments are being compared, then the probable difference in the results will be, as stated previously, about 3·5 per cent. This latter figure is obviously not constant as the intensity of the sky radiation near the sun will vary from day to day.

The radiation measurements made in the United Kingdom are related to the Ångström scale.

Calibration of solarimeters.—The procedure used at Kew Observatory to calibrate a solarimeter used for measuring the total radiation on a horizontal surface is briefly as follows :

(i) On a clear, cloudless, or near cloudless, day the solarimeter is exposed with its sensitive surface horizontal and a reading, A mV., of its output is obtained on a millivoltmeter or galvanometer.

(ii) Its sensitive surface is then shaded from the direct sunlight by a small obstruction and the new reading of its output, B mV., is taken.

(iii) Meanwhile the Ångström pyrheliometer is sighted on the sun. The first strip is exposed to the radiation and the current through the second one is adjusted until the two strips are at the same temperature. This value of the current is noted.

(iv) The second strip is then exposed to the radiation and the electric current passed through the first strip. When the strips are at the same temperature the value of the current is again noted.

The zero of the galvanometer used to indicate any temperature difference between the strips is taken when the two strips are shaded from the radiation. If the mean of the two current measurements is I mV., then the radiation intensity normal to the direction of the sun is kI^2 where k is the instrumental constant of the Ångström instrument. The intensity of the direct solar radiation on a horizontal surface is thus $kI^2 \sin E$ where E is the elevation of the sun (found from tables). Thus a radiative intensity of 1 cal./cm.²/min. produces an output of $(A - B)/(kI^2 \sin E)$ mV.

Thermopiles used for measuring the intensity of solar radiation at normal incidence can be compared directly with the Ångström pyrheliometer.

8.4.6. Daylight illumination recorders

The intensity of daylight illumination on a horizontal surface is measured, at certain meteorological stations, with photocells exposed below suitable diffusing surfaces. The luminous flux from the sun and sky falls on a horizontal white diffusing surface of pot opal glass, which is protected by a hemispherical dome of clear glass. The dome is mounted on an outer case which is shielded by a white louvered screen.

The opal plate surmounts an inner, airtight box which contains the detecting element. This comprises a selenium barrier-layer photocell, and a glass filter manufactured to a specification of the National Physical Laboratory. The filter matches the mean response curve of the cell used, so that a cell may be replaced with little loss of precision. The spectral response of the instrument is very close to that of the standard eye.

The air within the recorder is kept dry by silica-gel. A restricting diaphragm immediately below the opal plate limits the maximum output current to about 500 μamps. at noon in midsummer.

In a later version of the instrument, the opal glass is mounted slightly proud of the instrumental horizon to give a spatial response in close agreement with that of a perfect receiver. The improved model is thermostatically controlled to 100°F.

For this type of cell the linearity of the response is a function of the load resistance. A nearly linear response is obtained when the load resistance is 200 ohms. Therefore a network of shunt and series resistors is incorporated which permits the use of three sensitivities (for different seasons) while keeping the total resistance constant at 200 ohms.

In deriving final corrected values of daylight illumination, allowance should be made for errors caused by the temperature coefficient of the photocell and thread-recorder, and for errors resulting from deviations from the cosine law of the diffusing surface.

Standardization.—These instruments require recalibrating several times a year. This work is normally carried out at Kew Observatory.

CHAPTER 9

MEASUREMENT OF VISIBILITY

9.1. GENERAL

The visibility is defined as the greatest distance at which an object of specified characteristics can be seen and identified by an observer with normal sight under normal conditions of daylight illumination. It is usually estimated in daylight by an observer noting the furthest object which can be seen and identified out of a series of previously selected objects at known distances from the observing point. The selected objects normally range from close at hand (at about 10–20 yd.) to the furthest distance at which a suitable object is available. When this method cannot be used (e.g. at night or on ships at sea) the visibility may be measured by instruments, or a rough estimate made on the appearance of near objects, or, at night, an estimate made on the basis of the perception or otherwise of lights of known strengths at known distances. The visibility at night is expressed in terms of the equivalent day-time visibility.

Before describing the instruments used it is necessary to consider the factors which affect the appearance of natural objects and the measurement of visibility.

9.1.1. Effect of the atmosphere on the transmission of light

When a beam of light passes through the atmosphere it is diminished in intensity by three factors :

(i) Scattering by molecules of the air, nuclei and small droplets

(ii) Diffuse reflection by larger solid and liquid particles in suspension

(iii) Absorption, which is only appreciable in the case of solid particles.

The total diminution, ΔE, in the flux density* E of a parallel beam in passing through a distance Δd of the atmosphere is proportional to E and to Δd,

i.e. $$\Delta E = -\sigma E \Delta d\,, \qquad \ldots\ldots(83)$$

where σ is the extinction coefficient which varies in a complicated way with the wave-length of the light and the composition of the atmosphere, and is the factor which largely determines the visibility. If σ is constant over the whole path of the light, equation (83) can be integrated to give

$$E = E_0 e^{-\sigma d}\,; \qquad \ldots\ldots(84)$$

σ can be considered as being made up of two parts σ_s and σ_a, σ_s being that part of σ which is due to scattering and diffuse reflection and σ_a being that part which is due to absorption. σ_s is sometimes known as the scatter coefficient. When σ_a is very small (as in air free from smoke particles) $\sigma \simeq \sigma_s$.

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* The strict definitions of the terms flux density, luminous intensity and brightness are given by Middleton[67].

If, instead of a parallel beam, a point source of luminous intensity*, I_0 c.-p., is considered, it is necessary to take into account the diminution due to the inverse square law, and equation (84) becomes

$$E = \frac{I_0}{d^2} e^{-\sigma d}. \qquad \ldots\ldots(85)$$

9.1.2. Visibility of natural objects during daylight

Consider a uniform object of apparent brightness* at the eye, B, surrounded by a background of the same colour and apparent brightness B'. The brightness contrast, K, between the object and the background is then defined as

$$K = \frac{B - B'}{B'},$$

or

$$K = \frac{B' - B}{B'} \text{ when } B' > B.$$

If B approaches B' it is found that at a certain small value of K $(= \varepsilon)$ the eye can no longer distinguish the object from the background, i.e. the object becomes invisible. ε is called the threshold of contrast, and for normal observers in ordinary daylight illumination is about 0·02 to 0·04. ε_t is, however, found to be a function of the colour and angular dimensions of the object viewed (it increases for small objects) and may be greatly increased by bright lights in the field of view (glare). It also increases for very small or very large values of B. The question of colour does not normally arise when viewing distant objects in the atmosphere, as all objects tend to appear grey when nearing the visual range.

The atmosphere affects the total amount of light received by the eye from any object (i.e. from the direction of the object, for the eye cannot distinguish the origin of the light) in two distinct ways : it diminishes the direct rays from the object and it adds to the beam scattered and diffusely reflected light from other sources, e.g. the sun, the sky or the earth.

The first factor does not alter the contrast between the object and the background, but the second factor, because it adds a constant amount to both the background and the object brightness, reduces the contrast between them. If the object and background were to recede from the eye then the apparent contrast would decrease and when it fell to the value of ε (appropriate for the conditions of illumination and object) the object would no longer be distinguished ; i.e. the object would be at the visibility distance.

The maximum distance at which a given object can be seen in any given circumstances depends mainly on the state of the atmosphere (i.e. on the extinction coefficient), but it also depends, usually to a much lesser extent, on the elevation of the sun, the reflecting power of the object, the reflecting power of the background, the cloudiness and general illumination, the angular separation of the sun and the object, the angular size of the object and the eyesight of the observer. It is not, therefore, always possible to interpret visual observations accurately in terms of the extinction coefficient. It is however possible to eliminate the effect of some of these variables, provided certain conditions are observed, and to

* The strict definitions of the terms flux density, luminous intensity and brightness are given by Middleton[67].

standardize others, so that observations at different places and by different observers may be strictly comparable. If a perfectly black object elevated above the horizon is used, the visual range is practically independent of the elevation of the sun and its angular separation from the object, and if, in addition, the angular dimensions of the object as seen by the observer are also specified and the observer has normal eyesight then the visual observations should be comparable. The recommended size of objects is given in 9.1.3.

Koschmieder (see bibliography No. 67) has shown that if the extinction coefficient is uniform throughout the part of the atmosphere under consideration, the apparent brightness, B_s, of a black object at distance *d*, due entirely to scattered light, is related to the brightness of the horizon at the same azimuth, B_h, by the equation

$$B_s = (1 - e^{-\sigma d})B_h. \qquad \ldots\ldots(86)$$

As *d* increases the contrast between the object and the background will eventually fall to ε, and at that distance *d* will be equal to the visibility *V* ;

i.e.

$$\frac{B_h - B_s}{B_h} = e^{-\sigma V}$$

$$= \varepsilon,$$

or

$$V = -\frac{\log \varepsilon}{\sigma}; \qquad \ldots\ldots(87)$$

ε is usually taken to be 0·02, in which case

$$V = \frac{3 \cdot 91}{\sigma}. \qquad \ldots\ldots(88)$$

This theory does not hold strictly if the sky is not uniformly illuminated, e.g. if it is partly clouded, but the errors involved are not large. It follows that *V* can be calculated from a measurement of σ.

If dark-coloured objects are not used or the objects viewed against a terrestrial background, the observed value of *V* will, in general, be less than that given by equation (88), and in some cases very much less, e.g. when the reflecting power of the object is close to that of the background or when light-coloured objects are viewed with a low sun. If however the terrestrial background is at least 50 per cent. further away from the observer than the object is, the error due to not having a sky background is negligible.

9.1.3. Selection of visibility objects for day-time use

The principles which should underly the selection of the objects can be summarized as follows :

(i) The objects should be black or very dark coloured and stand above the horizon when viewed from the normal observing point.

(ii) They should subtend an angle of at least ½° in width and elevation to the observer but nor more than 5° in width. This upper limit can easily be exceeded with near objects, unless care is taken.

The synoptic code for reporting visibility provides for observations of great precision for visibilities up to 10 miles, but it is not expected that observers will achieve this precision over the whole range. Wherever possible, however, enough objects should be selected to enable a careful observer to achieve the following standards in daylight :

nearest 20 yd. for visibilities up to 220 yd.
nearest furlong for visibilities from 220 yd. to 1 mile
nearest $\frac{1}{4}$ mile for visibilities from 1 mile to 2 miles
nearest $\frac{1}{2}$ mile for visibilities from 2 miles to 5 miles
nearest mile for visibilities from 5 miles to 10 miles.

For visibilities above ten miles the objects chosen should as far as possible enable the observer to estimate the visibility to the nearest code figure.

The objects should be well distributed in azimuth from the observing point so that variations in visibility in different directions may be determined. It will probably be found convenient to draw up a table giving the bearing and distance of each selected object. Alternatively a plan may be drawn in which the objects are marked (using perhaps a non-linear scale of distance from the observing point).

Climatological stations are not required to make visibility observations with such precision, and all that is necessary in their case is to determine the furthest object visible out of a set labelled A–M, whose distances are given in Table XLII.

TABLE XLII—DISTANCES OF STANDARD VISIBILITY OBJECTS USED FOR CLIMATOLOGICAL OBSERVATIONS

Object	Standard distance		Permissible variation of object distance
	m.	yd.	yd.
A	20	22	20–24
B	40	44	40–48
C	100	110	100–120
D	200	220	200–240
E	400	440	400–480
F	1,000	1,100	1,000–1,200
	Km.	miles	miles
G	2	$1\frac{1}{4}$	$1\frac{1}{8}$– $1\frac{3}{8}$
H	4	$2\frac{1}{2}$	$2\frac{1}{4}$– $2\frac{3}{4}$
I	7	$4\frac{1}{3}$	4 – $4\frac{3}{4}$
J	10	$6\frac{1}{4}$	$5\frac{5}{8}$– $6\frac{7}{8}$
K	20	$12\frac{1}{2}$	$11\frac{1}{4}$–$13\frac{3}{4}$
L	30	$18\frac{2}{3}$	$16\frac{3}{4}$–$20\frac{1}{2}$
M	40	25	22 –28

9.1.4. Visibility of lights

At night the distance at which a light can be seen depends on five factors :

(i) Brightness of the light
(ii) Sensitivity of the observer's eye
(iii) Presence or absence of other bright lights in the field of view
(iv) Transparency of the atmosphere
(v) General level of illumination.

For meteorological purposes it is desirable that visibility reports at night should indicate the same degree of atmospheric transparency as they do by day, so, in deriving the visibility from observations of fixed lights, it is necessary to eliminate as far as possible the effects due to the other factors mentioned above.

The sensitivity of the eye is expressed in terms of the visual threshold, i.e. the illumination produced at the eye by a light so faint that it can only just be seen. It varies somewhat from one observer to another and for the same observer at different times. For visibility observations at night using direct vision (i.e. looking directly at the light) an average value however is taken to be 0·15 Km. candles ($= 0 \cdot 14 \times 10^{-7}$ ft. candles). This is the illumination produced by a lamp of 0·15 c.-p. at a distance of 1 Km. in perfectly clear air.

Except for red light, the sensitivity of the eye for indirect vision (i.e. looking a little to one side of the light) is greater than for direct vision, after a few minutes have been spent in the dark. This means that if the illumination produced at the eye is between certain limits the observer can see the light if he looks to one side of it but cannot see it if he looks directly at it. The eye's sensitivity for indirect vision (again except for red light) continues to increase for an hour or so after the observer has gone from a lighted room into weak illumination or darkness, whereas adaptation for direct vision in the dark is complete in about two minutes. Indirect vision should therefore not be used for visibility observations, and observers must guard against any tendency to regard any light as visible for this purpose as long as they can see it at all without making sure that they can see it when looking directly at it.

Using the average value of the sensitivity of the eye given above (0·15 Km. candles) and equations (85) and (88) it is possible to calculate the distances at which lights of varying candle-power will just be visible on nights of given visibility and *vice versa*. These relations are exhibited graphically in Fig. 114. It should be emphasized that this diagram holds strictly only for observers in darkness or moonlight with average eyesight and using direct vision, or alternatively who have left a lighted room less than 5 min. ago but more than 2 min. The effect of variations from these conditions can, however, be allowed for when using the diagram by using an " apparent " candle-power of the light instead of the true candle-power.

The corrections to apply to the true candle-power are given in the following procedure, which should be used when it is desired to convert the equivalent daylight visibility into the distance at which a particular light will be visible.

(i) Ascertain from the local engineer, or from the manufacturers, the candle-power of the light when viewed from the direction in question.

(ii) Correct for the background brightness as follows :—

In darkness or moonlight	In weak twilight	In strong twilight or weak daylight	In full summer daylight
No correction	Divide candle-power by 10	Divide candle-power by 100	Divide candle-power by 1,000

(iii) In darkness correct for the state of the observer's eye as follows : No correction is needed if direct vision is used and the eyes are fully adapted for that type of vision (i.e. more than 2 min. spent in darkness) or if indirect

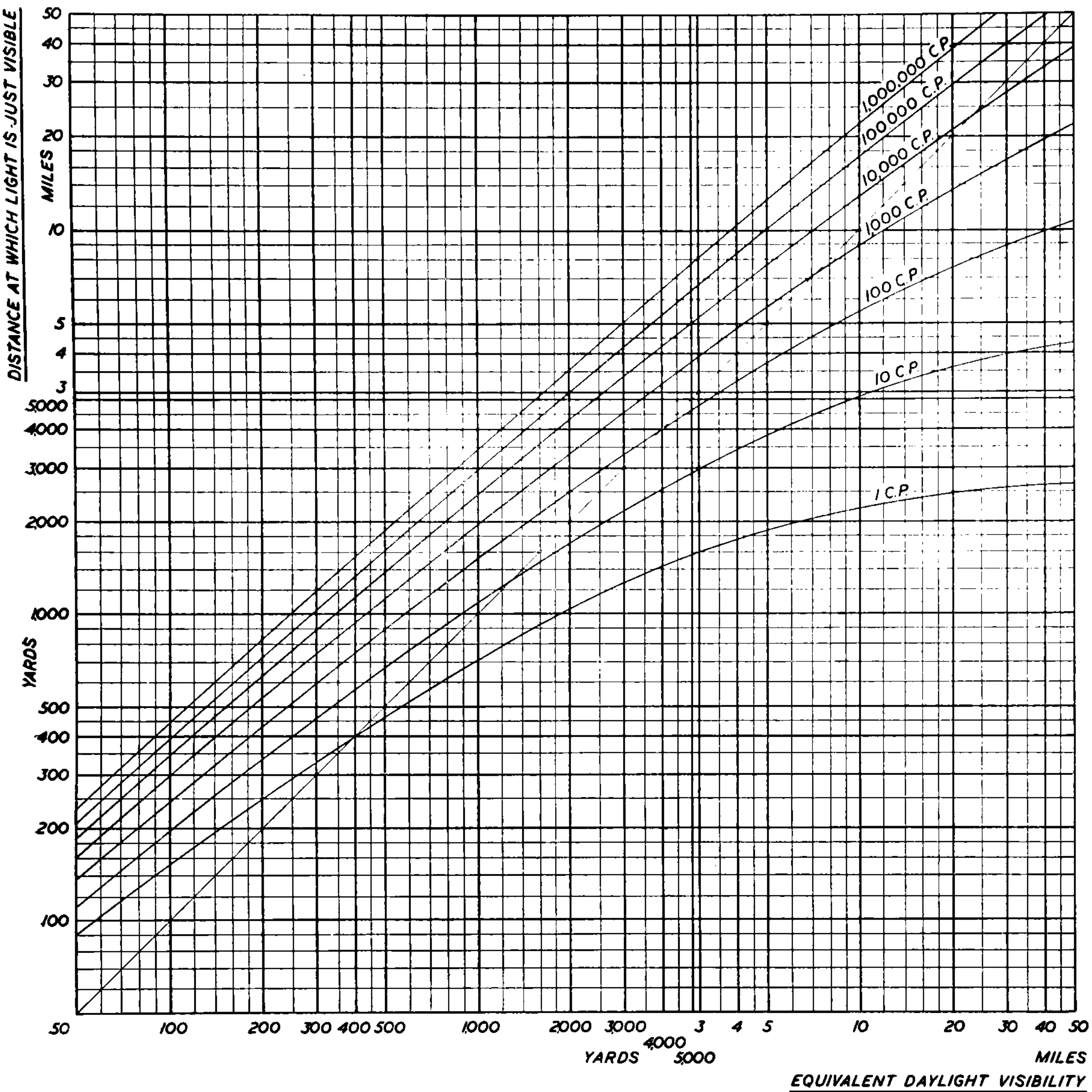


FIG. 114—VISIBILITY OF LIGHTS AT NIGHT

vision is to be used, e.g. in searching for a light to decide where it is or whether it is on, with eyes only partially adapted (i.e. 2–5 min. spent in darkness) ; if indirect vision is to be used with eyes fully adapted (i.e. over ½ hr. in darkness) the correction depends on the colour of the light as follows :

Red light	Orange or yellow light	White light	Green light	Blue light
No correction	Multiply candle-power by 5	Multiply candle-power by 20	Multiply candle-power by 50	Multiply candle-power by 250

If less than two minutes can be spent in the darkness before attempting to observe a light, all that can be said is that reduced candle-power should be used, i.e. the range at which the light can be seen will be less than that obtained using the actual candle-power.

(iv) Use the diagram as follows : Find the vertical line corresponding to the equivalent daylight visibility and follow it until it intersects the curve corresponding to the candle-power of the light, corrected if necessary as described above. The ordinate of this point gives the range at which the light can just be seen.

9.1.5. Oblique or air-to-ground visibility

The discussion of visibility in the preceding sections has been confined to visibility in a horizontal direction, in which conditions are often quasi-homogeneous. The pilot of an aircraft coming in to land, or wishing to identify objects on the ground, is however interested in " oblique visibility " as his line of sight is inclined to the horizontal. The ease with which objects or lights on the ground may be seen from the air, or the furthest distance from which they can be identified, may differ considerably from the horizontal visibility at ground level of similar objects because of two distinct factors. First, the properties of the atmosphere (i.e. the extinction coefficient) may vary with height, and secondly the objects are not viewed against a sky background but against a terrestrial background which may range from an almost perfect reflector (snow field) to an almost perfect absorber. The effect of this second factor depends on the properties of the object being looked at and those of its background and cannot be further discussed in this Handbook (reference should be made to " Vision through the atmosphere " by Middleton[67]). Methods of measuring the variation of the extinction coefficient with height in the lowest layers are under development, and it is expected that these will provide useful additional information.

The differences in the visibility from aircraft that may be caused by such a variation with height can be simply illustrated by considering two cases. In the first, suppose that at night a uniform fog or haze layer extends to half the height of an aircraft with clear air above. An ordinary light on the ground can then be seen by an observer in the aircraft when it is 1·5 to 1·8 times as far from the observer (actual distance not horizontal distance) as the furthest distance at which it is visible to an observer on the ground, the actual ratio depending on the candle-power of the lamp and the visibility at the ground. As a second case consider the air beneath the aircraft divided into two equal layers the lower of which has a horizontal visibility of twice that in the upper layer. When the ground-level visibility is $1\frac{1}{2}$ miles or less the distance at which a light can be seen from the aircraft (again actual distance not horizontal distance) is only 0·7 to 0·8 that at which the same light can be seen on the ground. In each case divergence from the conditions at the surface increases as the candle-power of the light increases and as the surface visibility decreases.

9.1.6. Instrumental measurement of visibility

The use of instruments to measure the visibility is usually confined to places at which there is no suitable set of visibility objects or to night observations. This restriction is made largely because most of the simple instruments depend on some kind of visual photometry requiring a certain amount of skill and training. Ordinary visual measurements in day-time are, moreover, usually accurate enough for most purposes, if a suitable set of observing objects is available.

The Gold visibility meter and the photo-electric visibility meter are or have been in routine use at land stations. The other meters described are mainly experimental models.

The instruments described in this chapter fall into three classes :

(i) Instruments which are used to measure the extinction coefficient

(ii) Instruments which are used to measure the scatter coefficient

(iii) Range meter of Waldrum and visibility meter of Shallenberger and Little.

Instruments which are used to measure the extinction coefficient.—The Gold visibility meter comprises a simple optical wedge and compensating filter by which the apparent intensity of a special light at a known distance from the observer can be reduced to a constant value, namely the least intensity that the eye can appreciate, by altering the density of the wedge between the light and the eye. This meter can therefore only be used at night. By comparing the readings on a perfectly clear night with those on the night in question it is possible to calculate the extinction coefficient and thus the visibility.

In the photo-electric visibility meter a photo-electric cell is used to measure the intensity of a beam of light after it has passed through 200–300 yd. of the atmosphere. By comparing the reading recorded with that which would be obtained on a perfectly clear night it is possible to calculate the extinction coefficient. Its chief advantage over the Gold visibility meter is that the results do not depend on the sensitivity of the observer's eye.

In the Bergmann visibility meter a beam of light which is periodically interrupted by a chopper is projected on to a small triple mirror and the reflected beam focussed on a photo-electric cell. At the same time a portion of the original beam is reflected to a second photo-electric cell connected in opposition to the first. The resultant output from the two photo-electric cells is amplified, rectified and indicated on a meter. A variable density filter in the path of the portion of the original beam is then adjusted until the meter reading is a minimum, indicating that the two beams of light are equal in intensity. In this way the extinction coefficient can be obtained. This instrument has not been used extensively but the principle is sound.

Instruments which are used to measure the scatter coefficient.—In the " loofah " and the Beuttell visibility meters the intensity of the light scattered from a beam when it passes through the atmosphere is measured by means of a visual photometer arrangement. In the first, however, light scattered at one angle only to the original beam is measured, while in the second, light which is scattered over a range of angles is measured. The " loofah " meter is totally enclosed and can be used at all times ; it is a large instrument and was specially designed for use on ships. The Beuttell instrument can be used only at night, but is small and portable.

These instruments can, strictly speaking, only be used to make an estimate of the visual range when absorption of light by the atmosphere can be neglected—i.e. when $\sigma \simeq \sigma_s$. Their main disadvantage is that the visual range is measured on the basis of the properties of the atmosphere over a very short path. This may lead to large errors if this small sample of the atmosphere is not representative of the surrounding area.

Range meter of Waldrum and visibility meter of Shallenberger and Little.—The range meter is based on different principles to those previously mentioned. An object at a known distance is viewed through a telescope (or one side of a pair of binoculars) and the appearance of the object as it would be if it were to be moved away from the observer is simulated by moving a weak prism up in front of the aperture of the objective lens. By noting the position of the prism at which the object just appears to merge with the horizon background it is possible to express the visibility as a multiple of the actual distance of the object. This instrument can only be used in daylight. An advantage of this principle is that the eye is used in its normal state in viewing objects under normal illumination conditions. It was first described by Shallenberger and Little[68].

9.2. MEASUREMENT OF VISIBILITY AT NIGHT

9.2.1. Gold visibility meter Mk II

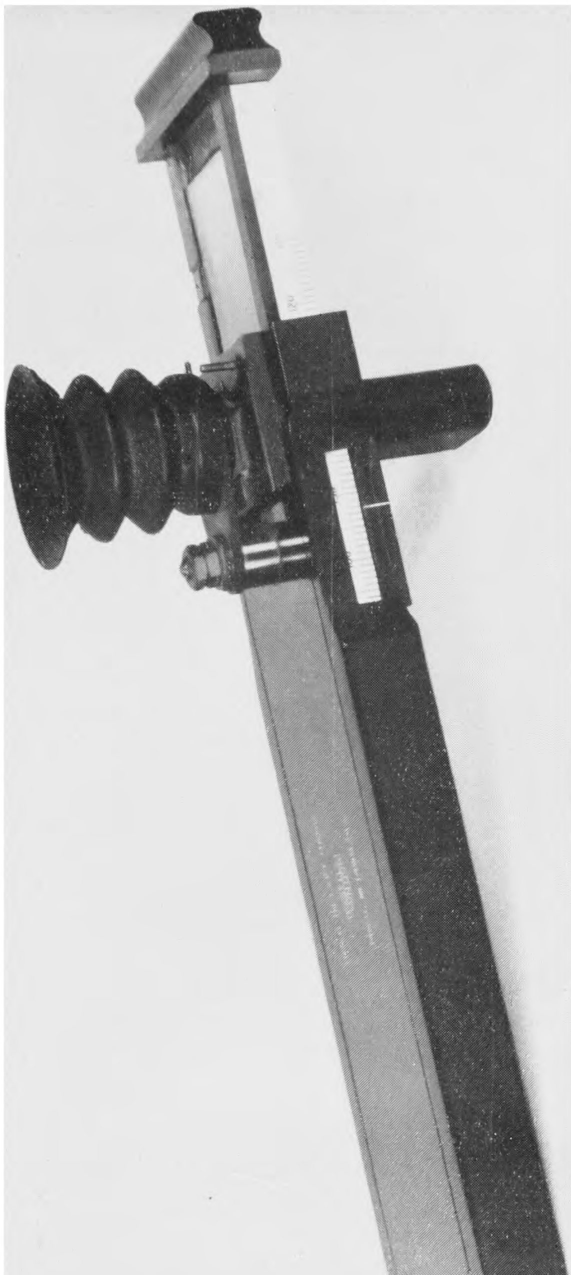
The principle of the Gold visibility meter Mk II (Stores Ref., Met. 647) has been described briefly on p. 359 (Plate XLIV). The main filter is cemented between two glass plates, approximately 20 cm. by 4 cm., and mounted in a frame of plastic material which can slide into the main casing. It is normally prevented from coming completely out by means of a screw. The filter has the following main properties :

(i) It transmits light of all visible wave-lengths equally.

(ii) The variation in density along the filter is uniform in the sense that, if the fraction of light transmitted is measured at a number of equidistant points along the filter, the figures for the adjacent points will always be in the same ratio. It is almost transparent at one end, while at the other it transmits only about 1/4,000 of the incident light.

Two small neutral filters (about 2 cm. square) are mounted close to the open end of the main casing. These have the same uniform gradation of density as the main filter but are fixed so that the change in density is in the opposite direction ; the superposition of one of the small filters over any position of the large filter thus results in an area of uniform density. One small filter is nearly transparent but the other transmits only about 1/1,000 of the incident light. These filters are fixed side by side so that the parts of the main filter which they cover have the same density and a movable eye-shield enables the observer to look entirely through one filter or the other. The fraction of light transmitted by the combination of filters varies from about 1/2·5 to 1/4,000 if the clearer of the small auxiliary filters is used, and between 1/2,500 and 1/4,000,000 if the denser filter is used, the actual value depending on the position of the main filter in relation to the auxiliary filter. Two scales, one on each side of the movable frame carrying the main filter, enable the total opacity of any filter combination in nebules (see p. 361) to be obtained. The scale on the same side of the frame as the filter should be used. A metal shield can be fixed to the main casing on the opposite side to the eyepiece to reduce any glare from other lights.

Visibility lights.—Fixed lights of constant intensity must be used, and it is most convenient to have three lights at approximately 100, 500 and 1,500 yd. from the observer. The lights should be 6–10 ft. from the ground, and should have some form of hood to protect them from the weather (and from theft), but which



GOLD VISIBILITY METER MK II

is easily removable for cleaning and replacing the lamps. The hood should be black inside and no lens or focussing mirror should be used. A 15-W. lamp should preferably be used at 100 yd., 100-W. lamp at 500 yd. and 100-W. lamp (or higher if possible) at 1,500 yd.

On an airfield the lights should be well screened so as to be visible only from near the observation point, and should be sited so as not to shine along any runway. On R.A.F. stations the lights should not be placed within 125 ft. of a taxi-track or within 225 ft. of a runway. It is not essential that the lamps should be switched on and off from near the observation post ; it may often be much cheaper to install a switch on the light itself, leaving it on all night. Alternatively the lights could be wired into a road lighting or obstruction light circuit, provided these are (or can be) switched on all night. Circuits subject to large voltage variations (either deliberate or accidental) should be avoided, however. In all cases where the lights are on for long periods, the lamps must be renewed at regular intervals, e.g. monthly in winter and quarterly in summer. It is desirable that the new lamp should be of exactly the same type as the old, but in any case new calibration figures should be made for each observer.

The observations are greatly facilitated if the lights are observed through fixed tubes, one for each light. These may be lengths of iron pipe about 4 ft. long and $1\frac{1}{2}$ in. in diameter. It is preferable to fix them through the wall of a room, if a suitable room is available, i.e. one from which all the lights can be seen, and which can be darkened for a few minutes before each observation. The advantages of this arrangement are

(i) There is never any doubt as to which light is being observed, as each tube points directly towards its own light.

(ii) The observer can be in complete darkness, and any extraneous lights are shielded from his eye.

(iii) The observations can be made in greater comfort, especially in cold or wet weather, and will therefore be more accurate.

In the absence of these tubes the observations must be made out of doors, in a position well away from any artificial light.

When the installation is complete the distance of each light from the observation point should be carefully measured.

Basic theory of the instrument.—When designing this meter Gold[69] introduced a new unit into the specification of the transmission of light by the atmosphere. Consider a small screen interposed in the path of a beam of light so that the flux density is reduced from E to Ex, where $x < 1$. If there are n similar screens interposed in the beam the final flux density is Ex^n. If now x is chosen so that when there are 100 screens the final flux density is reduced to 1/1,000 of its original value, the unit screen is said to have an opacity of one nebule, and the 100 screens put together have an opacity of 100 nebules.

Therefore $$x^{100} = \frac{1}{1000},$$

i.e. $$x = 0{\cdot}933.$$

Any length of the atmosphere acts in the same way as a number of screens, and so may be said to have an opacity of a certain number of nebules. This opacity may be uniformly distributed or concentrated in certain places. It can be seen that, considering a beam of light traversing a length d of uniform atmosphere, of opacity n nebules :

$$E_0 e^{-\sigma d} = E_0(0{\cdot}933)^n ,$$

i.e.

$$\sigma = \frac{0{\cdot}0691n}{d}$$

$$= 0{\cdot}0691N , \qquad \ldots\ldots(89)$$

where N is the opacity of the atmosphere in nebules per unit distance. The fraction of light transmitted by the wedge and filters can thus be expressed in nebules (from about 14 to 120 and 114 to 220).

From the method of use of the instrument it is seen that, on each occasion that an observation with one particular lamp is made, the total opacity between the eye and the lamp, made up from the opacity of the atmosphere and the opacity of the filter, is the same. If R_0 is the reading of the meter on a night when the atmosphere is perfectly clear (zero opacity), then from equations (88) and (89) on any other night when the visibility is V the reading R is given by

$$R + \frac{3{\cdot}91d}{0{\cdot}0691V} = R_0 ,$$

i.e.

$$V = \frac{56d}{R_0 - R} . \qquad \ldots\ldots(90)$$

This equation is used to obtain the visibility from the meter reading.

Preparation of the conversion diagrams.—The conversion diagrams are a simple method of solving equation (90). A separate diagram will be needed for each light, and they may be conveniently drawn on a sheet of squared paper. A straight line about 12 in. long should first be drawn, and on one side a linear scale of nebules should be marked on a scale of 10 nebules = 1 in. For the nearer lights it may be necessary to extend the scale to 150 or 180 nebules ; the length must be such as to include the highest of the individual calibration figures referred to below, i.e. the value of R_0. On the other side of the line should be marked a scale of visibilities using the relation

$$\text{Nebules} = \frac{56 \times (\text{distance of light in yards})}{\text{visual range in yards}} .$$

The scale marks should be made at the following intervals of visibility :

Every 10 yd. up to 200 yd.
Every 20 yd. from 200 yd. to 300 yd.
Every 50 yd. from 300 yd. to 1,000 yd.
Every 100 yd. from 1,000 yd. to 2,000 yd.
Every 200 yd. from 2,000 yd. to 3,000 yd.
Every 500 yd. above 3,000 yd.

The scale should not be extended below 11 nebules (i.e. visibility of more than five times the distance of the light) unless this is necessary to provide an overlap with the next more distant light. Part of a specimen scale applicable to a light at exactly 100 yd. is given in Fig. 115.

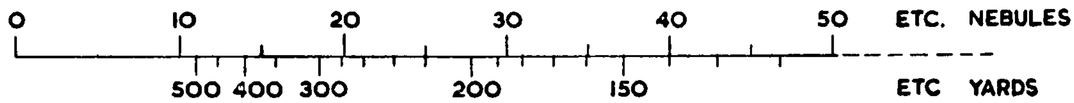


FIG. 115—CONVERSION DIAGRAM, NEBULES TO YARDS

The boundaries of the code figures used for reporting the visibility may be inserted in the diagrams if required (preferably in a different colour).

Individual calibration figures.—Before the meter can be brought into routine use, each observer must determine his calibration figure for each light R_0, which is the meter reading which would be obtained if the atmosphere were perfectly transparent. In practice this should be done immediately after dark, on an evening when the visibility has been observed (during daylight) to be not less than 12 times the distance of the light in question and is not expected to change much, i.e. when there is a cloudy sky, a fresh wind and relative humidity not over 95 per cent. The procedure described in the next section should be carefully followed, and not more than one light should be observed at one time, as the longer time taken would improve the adaptation of the eye to the dark, and thus cause non-representative readings.

The calibration figure is then obtained by adding

$$\frac{3{\cdot}2 \times \text{distance of light in hundreds of yards}}{\text{visibility in miles}}$$

to the actual reading of the meter.

This can conveniently be done by preparing a diagram for each light, similar to the one described on p. 362 ; on top of the line should be marked a linear scale of nebules from 0 to 5 (1 in. = 1 nebule) and below it a scale of visibility in miles.

Instead of drawing the diagrams on squared paper, Form 2812, Conversion diagrams for use with the Gold visibility meter, may be used at Meteorological Office stations, both for these diagrams and those described on p. 362.

A calibration book should be kept, with a page for each observer showing his calibration figure for each light with the date when it was determined. New figures should be determined on every convenient occasion, and comparison with earlier figures will give the best average figure for future use.

Routine use of the meter.—The procedure for making an observation with the meter should be as follows :

(i) Ensure that the glass surfaces of the meter are clean. If not, clean them with the wash leather provided.

(ii) Allow about 2 min. for the eye to accommodate itself to the darkness before beginning to make an observation.

(iii) Observe the most distant light which is visible through the visibility meter, and adjust the sliding filter until the light is only just visible. This should be done by pulling out the slide until the light just disappears, then pushing it in slowly until the light just reappears. Always begin with the eye-shield over the clearer small filter, but if the light is still visible with the slide pulled right out, the eye-shield should be transferred to the dark filter. Look directly at the light during the observation as the sensitivity of the eye is more constant for direct vision. Do not spend a long time trying to improve the observation, as this will make it worse owing to changes in the state of adaptation of the eye to the dark. The observer should aim at always spending exactly 3 min. between leaving a well lighted room and completing the observation. If the observer normally wears spectacles for distant vision he should use them for making observations, but they must be kept clean and free from condensation or rain (as must the meter itself).

(iv) When the sliding filter has been correctly adjusted the scale reading should be noted, care being taken that the slide is not accidently moved before being read. The reading should be taken from the scale on the side where the eye-shield has been used.

(v) This reading should be subtracted from the observer's calibration figure for the light used, and the resulting figure used, in conjunction with the appropriate conversion diagram, to read off the prevailing visibility.

(vi) If the difference between the calibration figure and the observed reading is less than 11 nebules, even for the most distant light, the diagrams cannot be used. The visibility is then known to be over five times the distance of the farthest light and it must be estimated visually.

Maintenance of the instrument.—The glass surfaces of the meter should be kept clean, using the wash leather provided with the instrument ; anything that is liable to scratch the surface of the glass should not be used. The slide carrying the main filter can be withdrawn completely by unscrewing the small screw at the rear of the main frame. The rest of the instrument should be kept clean and it should be returned to its case immediately after use.

Accuracy and sources of error.—The main source of error in the results is the variation in the sensitivity of the eye, but by following the instructions carefully this is reduced to a minimum.

The brightness of the lamps will vary, in a slow and regular manner owing to deterioration in the lamp and as random fluctuations about the mean. The slow and regular changes can be allowed for by repeating the determination of the calibration figures at regular intervals but the random fluctuations cannot be allowed for. Added to these errors is the independent setting error of 1 or 2 nebules. It has been estimated[70] that the probable errors arising from the first two causes are $\pm$ 5 nebules and $\pm$ 3 nebules respectively, so that an overall probable error is about $\pm$ 6 nebules. This corresponds to an error in the visibility of about 11 per cent. when the visibility is the same as the distance of the lamp used, 22 per cent. when it is twice the distance and 55 per cent. when it is five times the distance of the lamp. It is therefore clear that the furthest visibility lamp that can be seen should be used for an observation.

The estimate of the error due to the variation in the sensitivity of the eye can be greatly exceeded if the meter is not handled properly and every possible care is not taken to get an accurate reading.

9.2.2. Meteorological Office photo-electric visibility meter Mk II.—The principle of the Meteorological Office photo-electric visibility meter Mk II has been briefly described on p. 359. The instrument is not in widespread use, and detailed instructions for its installation and setting up are not included in this edition of the Handbook.

The source of light is a small signalling lamp, mounted, with its axis horizontal, on an adjustable base plate (to provide adjustment for the direction of the beam) and fitted with a cylindrical shield to keep the rain off the glass. The intensity of the beam of light from this source after it has travelled through about 300 yd. of the atmosphere is measured by means of a selenium photo-electric cell connected to a sensitive galvanometer. The receiving unit consists of a convex lens placed near the far end of a long tube, with, at the focus of the lens, a stop consisting of a small hole in the centre of an opaque screen. The selenium photo-electric cell is placed 2–3 in. behind the screen and at right angles to the axis of the cylinder. The beam of light from the lamp is brought to a focus by the lens on the centre of the stop ; the beam then diverges and falls on to the photo-electric cell.

The purpose of the long cylindrical shield and the stop is to reduce the intensity of daylight and light from other extraneous sources which can fall on to the cell. The searchlight and receiving unit must of course be aligned so that the line of maximum intensity in the beam passes through the receiving unit, and so that the axis of the lens and of the cylindrical shield are co-incident and pass through the searchlight. The adjustment of the searchlight is not very critical as the beam has a fairly wide spread, but the receiving unit must be accurately adjusted ; the lens is fitted for easy adjustment. It is found that with this instrument the galvanometer deflections in daylight with the searchlight off are quite small and easily allowed for, so that observations may be made at all times.

A sensitive moving-coil mirror galvanometer is used to measure the current produced by the photo-electric cell, and the deflections produced are proportional to the intensity of the light falling on the photo-electric cell. The searchlight lamp is run from the mains supply, and the voltage applied to it can be varied by means of a variable transformer and measured with a voltmeter.

Theory.—The basic equations used are that linking the flux density of the searchlight beam at the receiving unit, E, at a time when the mean extinction coefficient is σ, to the corresponding flux density in perfectly clear conditions, E_0, and that linking the extinction coefficient with the visibility V,

i.e. $$E = E_0 e^{-\sigma d} \text{ and } \sigma V = 3{\cdot}75^* ,$$

where d is the distance from the searchlight to the receiving unit. E can be taken as equal to $k(D - D_0)$ where D is the deflection of the galvanometer with the searchlight beam switched on, D_0 is the deflection with searchlight beam off and k is a constant. D_0 is small and is due to daylight or other light sources ; it can be allowed for by adjusting the zero of the galvanometer scale. The voltage on the lamp is so adjusted that E_0 gives an increase in deflection of 10 divisions,

i.e. $$V = \frac{3{\cdot}75}{\sigma} = \frac{3{\cdot}75d}{\log_e (E_0/E)} = \frac{3{\cdot}75d}{\log_e (10/d)} .$$

After d has been measured a calibration card can be drawn up relating the visibility and the galvanometer deflection D, for every $0{\cdot}1$ of a division of the galvanometer.

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* The constant used is 3·75 instead of the theoretical value 3·91 (see equation (88), p. 354) to make some allowance for the fact that the actual objects used in day-time visibility estimates are often not completely black. The observations at night should then be more homogeneous with the day-time observations. The differences involved are, however, very small.

Method of use.—It is first necessary to find out what voltage applied to the searchlight lamp results in a deflection of 10 divisions in perfectly clear conditions. This is done on a day when the visibility is 15 miles or more in all directions and there are no local concentrations of smoke and dust along the path between the searchlight and the receiver. With the searchlight off, the scale of the galvanometer is adjusted until the line in the centre of the light spot is on the zero graduation. The searchlight is then switched on, and after waiting for about 2 min. for the lamp to settle down the lamp voltage is adjusted until the galvanometer reading is that which is on the calibration card corresponding to the observed visibility. This reading will be very close to 10·0 divisions. The lamp voltage is then noted for future reference.

On subsequent occasions when the visibility has to be measured the galvanometer reading is first adjusted to zero with the searchlight off. The searchlight is then switched on and the voltage adjusted to the standard value determined as above. After about 2 min. the galvanometer reading is noted. The calibration card then gives the visibility.

The standard voltage is determined as often as possible to allow for slow changes in the lamp and photo-electric cells.

Accuracy and sources of error.—The accuracy of the instrument depends on three factors :

(i) The accuracy of the photo-electric measurements as a measure of the extinction coefficient of the atmosphere over the given light path

(ii) The accuracy with which the limited path of the atmosphere may be assumed to be representative of the surrounding atmosphere

(iii) The accuracy of the relation assumed between the visibility and the extinction coefficient.

The first factor depends mainly on the condition and response of the photo-electric cell, and the constancy of the lamp output. It also depends on the accuracy of the standard voltage observations and the change which may have occurred in the lamp and photo-electric cell since the last determination. Frequent and accurate standard readings are necessary to check the normal changes in the photo-electric cell and to detect any abnormal changes as soon as possible. As will be seen from the calibration card, the accuracy falls off rapidly for visibilities over about 5 miles, and changes in visibility above this limit cannot be measured reliably.

Systematic errors caused by non-uniformity of the atmosphere can only be avoided by careful siting of the instrument, but random errors will still occur. The errors will be reduced if the mean of several consecutive observations is used rather than a spot reading, especially when conditions are variable.

The visual theory on which the relationship between the extinction coefficient and the visibility is based only holds strictly in a very limited set of conditions, for a standard observer and for use with perfectly black objects seen against the horizon sky. These conditions are rarely completely met with in practice, so that, while in many cases visual estimates of the visibility in day-time agree well with observations made with this instrument, under some conditions quite large discrepancies may occur. This seems to indicate that, possibly, a more refined theory will be required in the future.

9.2.3. Beuttell visibility meter

The principle of the Beuttell visibility meter[71] has been briefly described on p. 359. It is an experimental instrument and is not in routine use. A 12-V. light bulb (Fig. 116) is housed in a chamber, painted white inside, which has two pieces of opal glass, B and C, in its walls to serve as perfectly diffuse sources of light. The light from B passes along the narrow tube D to another piece of opal glass at E and then on to the lens G after reflection by a piece of plain glass F, while the light from C passes out into the atmosphere. Some of the light scattered from the beam by the atmosphere passes through the aperture H, is reflected from the mirror J, and thence goes to G through the piece of glass F. If the eye is placed above G it sees a field of view divided in half, the light in one half coming from B and in the other half from H. A rotatable diaphragm L enables the area of the surface of B which can be " seen " by the piece of opal glass E to be varied ; i.e. it varies the intensity of light passing from E to the observer's eye. A spherical concave mirror K is fixed below the light chamber, opposite H and J, with its centre of curvature at H. This mirror reflects back to H certain of the light from C which is scattered in a backward direction and also serves to cut down the amount of stray light entering H. This means that the light tracing out the path HJFG includes light scattered in nearly all directions from the incident light.

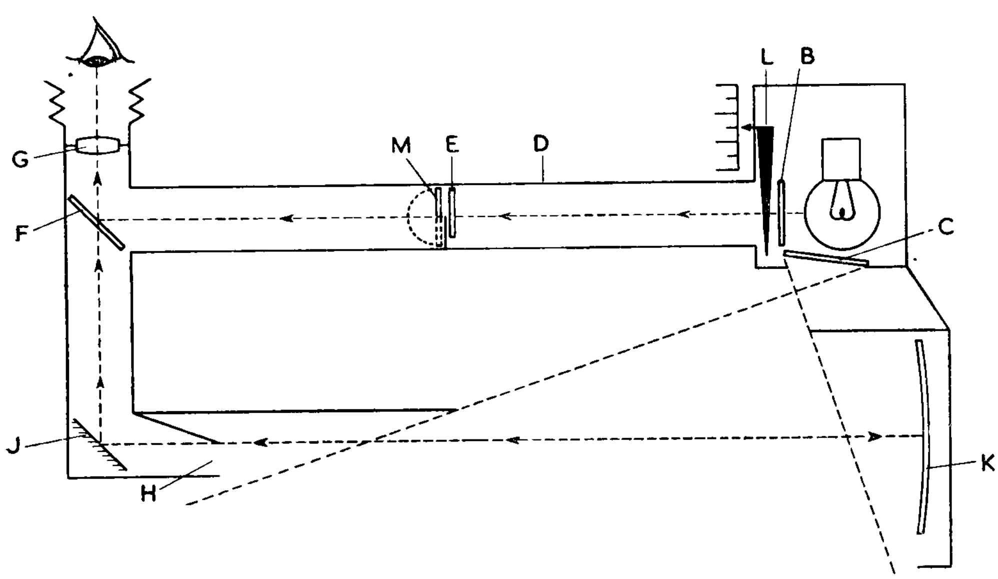

FIG. 116—BEUTTELL VISIBILITY METER

To increase the range of intensities of scattered light which can be measured a filter M, with a transmission factor of 1/17·6, can be switched into the beam of light travelling along D. If the scale on the diaphragm reads in miles when the filter is in position it will read in hundreds of yards when it is not in position. The scale itself was obtained by empirical calibration of the diaphragm.

Installation and method of use.—The light bulb can be connected to a bank of accumulators or a transformer. The observing point should be well exposed and free from local sources of smoke pollution, so that it is as representative as possible of the surrounding atmosphere. It should be away from stray sources of light. The visibility is obtained by balancing the brightness of the two parts of the field of view ; the scale on the rotating diaphragm then gives the visibility.

The instrument is not easy to use because the brightness of the field of view is so low that the eye is not in its most sensitive condition to perceive a brightness contrast. Great care should therefore be taken to ensure that the eye is adapted to the dark.

Little maintenance is required beyond keeping the glasses clean and renewing the bulb if necessary.

Accuracy and sources of error.—The main objection to the instrument is that it is used to obtain the visibility on the basis of an observation on a very small sample of the atmosphere. As the atmosphere is not normally homogeneous this gives rise to errors, which may be large at times. One other source of error is the effect of absorption in the atmosphere ; when this occurs the extinction coefficient is greater than the scattering coefficient and the indicated visibility would be too large. This, however, is only serious in very smoky conditions near large towns and is not normally a great limitation.

This instrument will not give reliable results in rain or other precipitation because of the discontinuous nature of the phenomenon when a very small horizontal area is considered.

9.3. INSTRUMENTS FOR THE MEASUREMENT OF VISIBILITY BY DAY

9.3.1. Loofah hazemeter

The principle of the Loofah hazemeter (Stores Ref., Met. 765) has been briefly described on p. 359. It can be used both day and night.

A 24-V. 240-W. lamp A projects a beam of light, concentrated by means of an ellipsoidal mirror B, through a wide slit C in a screen placed at an angle of 30° to the axis of the beam (Fig. 117). A diffusing glass is placed in front of the lamp to ensure a reasonably uniform beam distribution, and a photometer is placed behind the slit so that it receives light scattered at an angle of 30° to the main beam ; it " looks " through the beam into a perfectly black light trap D. The unscattered portion of the beam is reflected at a polished black surface set at 45° to its incident direction and is finally absorbed in the matt-black interior walls of the instrument. This ensures that the amount of stray light reflected back into the photometer field is a minimum. This is important as the brightnesses to be compared are low. The photometer consists of a cube E made by cementing together a pair of 45° prisms, one having a silver strip down the centre of its diagonal face. A rectangular three-part field is thus obtained, the centre strip being illuminated by the scattered light, while the outer strips are illuminated by light reflected by a prism K from a white flashed opal screen F which is itself illuminated directly by the lamp. Changes in the brightness of the lamp, due to ageing or fluctuations in the electricity supply voltage, therefore affect both sides of the photometer field equally. The brightness of the comparison field can be varied by means of a uniformly graded neutral wedge filter G between the opal screen and the photometer which is coupled to a scale H and the photometer control knob by a copper stranded cable. A blue glass filter is placed in the path of the light in the comparison field to provide a colour match with the scattered light.

The scale is graduated directly in terms of scatter coefficient. The calibration should be checked regularly by the use of two calibration plates J made of white opal glass ; these are lowered well below the beam in normal use, but can be raised into position when necessary by the use of the calibration plate control. The first plate is then nearly normal to the beam, while the second is immediately in front of the light trap facing the photometer. Light is reflected by the first plate to the second plate and thence to the photometer. The calibration plate control also introduces into the photometer line of sight a neutral density filter cemented to a

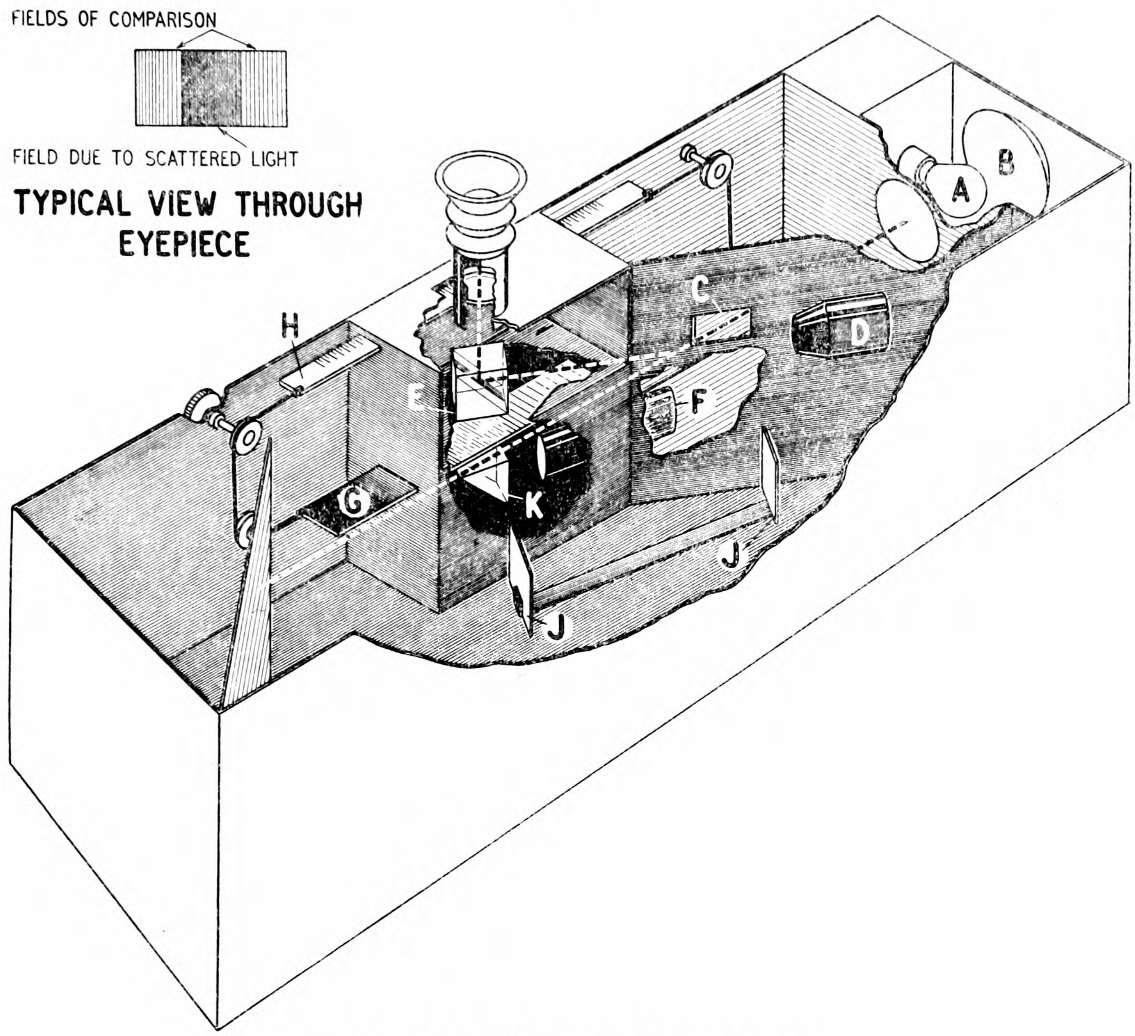

FIG. 117—LOOFAH HAZEMETER

blue glass filter ; in this way the intensity of the light reaching the photometer is reduced to a known value depending on the brightness of the beam, the constants of the instrument and the transmission of the filter. It is then measured by the photometer in the usual way, the correct scale reading being indicated by a red line. Provision is made for adjusting the scale relative to the neutral wedge should this prove necessary. When the calibration plates are only raised to the half-way position a small metal mirror reflects the beam of light directly on to the front face of the photometer cube, so that in this way any condensation which takes place on this surface (the only one likely to " mist " over when the instrument is in use) may be evaporated.

When in normal use, the range of scatter coefficients covered by the scale is 10^{-3} to 10^{-5}/ft. (corresponding to visibilities of 1,300 yd. and 74 miles). An additional neutral filter can, however, be placed in the path of the scattered light ; the range covered is then $(10^{-3}/t)$ to $(10^{-5}/t)$/ft., where t is the transmission factor of the additional filter.

The instrument is housed in a ⅛-in. sheet aluminium box, mounted resiliently on a steel-angle base. The photometer eyepiece, scale, calibration knob, indicator and adjustment are housed under one of the removable covers, and the switch and lamp resistance control knob are under the other. The photometer control knob is recessed into the side of the box, and is convenient to the right hand when looking into the eyepiece.

The heat generated by the lamp causes the air surrounding it to rise and leave the instrument through a baffle above the lamp ; outside air is drawn in through louvers in the sides, and thus a circulation of air is set up. This circulation is essential if a representative sample of air is to be obtained inside the instrument. The light is scattered from air which has just entered the instrument and before there has been time for its temperature to be affected appreciably.

A full description of this instrument and a discussion of the basis of its design is given by the Admiralty Research Laboratory[72].

Installation.—The instrument should be situated in a well exposed position, away from local sources of smoke pollution. The power supply is usually obtained by means of a transformer working from the a.-c. mains, but a 24-V. d.-c. supply can be used if available. A d.-c. voltmeter is incorporated in the circuit, together with a variable resistance, so that the power consumed by the lamp may be adjusted within certain limits. When used on board ship it should be mounted forward of the funnel or other sources of smoke or dust, and should not be so screened as to prevent the air stream, due to the motion of the ship, from entering the louvered openings.

Method of use.—When balancing the photometer the brightness of the two outside rectangles in the field of view is reduced or enhanced by moving the photometer control knob until the brightness of the comparison field is equal to the brightness of the centre rectangle ; the field then appears uniform all the way across. The readings at balance should be obtained after throwing the photometer out of balance, first in one direction and then in the other ; normally about 6 observations in all should be taken and the mean reading found.

The following procedure should be used when determining the visibility :

Obtaining the meter reading.—

(i) Remove the covers from the controls and open the side louvers.

(ii) Switch on the electricity supply and adjust the controlling resistance until the voltmeter reading is 24 V. if d.c. is being used, or until the lamp is operating at its maximum brightness if a.c. is being used.

(iii) Raise the calibration plates to the half-way position (so that the indicator is opposite the mark " warm ") and leave for about 5 min. This will allow time for the air circulation to be established, and to ensure that all moisture is removed from the photometer cube.

(iv) Raise the calibration plates to the full extent and check the calibration by balancing the photometer fields. Note the reading if different from that marked with the red line.

(v) Lower the calibration plates and again balance the field. If the brightness of the centre rectangle is too great to allow a balance to be obtained, the additional neutral filter should be rotated into the beam of scattered light and the field then balanced as before.

The observer should never smoke when making an observation because of the risk that smoke may get into the meter and give rise to erroneous readings.

Calculation of the visibility when balance obtained without the use of the auxiliary filter.—If the scale reading obtained when using the calibration plates was equal to that given by the red line on the scale (or within about 5 per cent.) the visibility V is given by

$$V = \frac{3 \cdot 91}{y \times 10^{-5}} \text{ ft.}$$

$$= \frac{74}{y} \text{ miles ,}$$

where y is the scale reading for balance with the calibration plates down.

If however the scale reading obtained at balance when using the calibration plates was not the correct value x, but some other value z, then the observed reading y with the plates down should be corrected to yx/z,

i.e. $$V = \frac{74z}{xy} \text{ miles.}$$

This correction should, however, only rarely be necessary.

Calculation of the visibility when auxiliary filter necessary for balance.—The transmission factor for the auxiliary filter will be found noted on a card inside the instrument. The visibility should then be calculated as above using the reading obtained with the filter in position, and the result multiplied by the value of the transmission factor.

Maintenance.—It is important that all the optical surfaces should be kept clean and dust free. Since the instrument is normally kept closed there should not be much opportunity for dust to collect inside, but it will probably be necessary to remove the top lid about once a month and wipe over the following surfaces with a clean chamois leather :

Outside of the photometer prisms

Outside surface of the white opal or blue glass disc comparison surface at the end of the tube below the wedge box

Both sides of the diffusing glass screen in front of the lamp

Lamp bulb

Reflecting surface of the mirror

Both white opal test plates (it is particularly important that these should be kept perfectly clean and white—any dirty marks should be dealt with by removing the glass plate and scrubbing with soap and water)

Auxiliary filter.

Other surfaces are either totally enclosed, and therefore unlikely to get dirty, or else are normally exposed during readings (e.g. the cover-glass in the eyepiece) and can be cleaned whenever necessary.

Accuracy and sources of error.—There are several limitations to the use of this instrument. The empirical relationship between the scattering coefficient and the intensity of the light scattered forward at an angle of 30° to the incident beam which is assumed, has been established experimentally for scattering coefficients between 10^{-3} and 10^{-5}/ft. (visibility between 1,300 yd. and 74 miles), but its extension to scattering coefficients of 10^{-2}/ft. (visibility 130 yd.) or above is rather uncertain. Any comparison between the results obtained by the meter and accurate visual observations for visibilities below about 1,000 yd. would be of great use in assessing the accuracy of the relationship used. The instrument is intended to be used only in clean air where absorption can be neglected ; in other conditions the estimate of the visibility obtained from the instrument will be too high. Scattering from precipitation is not measured, so that no estimate of the visibility can be made when precipitation is falling.

There is also the sampling error that may occur because the atmosphere is not normally uniform, while the instrument only measures the scattering coefficient of a very small volume of air. Particular care is necessary in interpreting the observations made on a day when conditions are such that the visibility is very variable ; a mean of several readings over a period of 15 min. or more will give a much more reliable result than a single observation.

Subject to the limitations discussed above the scatter coefficient, and thus the visibility, can be determined with an accuracy of about $\pm$ 20 per cent.

9.3.2. Waldrum range meter

The optical principles of the Waldrum range meter are illustrated in Fig. 118 (see also p. 360). The objective lens is limited by a square aperture so that the exit pupil (which is the image of the aperture) is smaller than the eye pupil and therefore the apparent brightness of the images of distant objects will be proportional to the size of the aperture. A shallow biprism with large vertex angle slides over the aperture so that the light through the two adjacent prism surfaces forms two images, one slightly displaced from the other. The apparent brightness of each image is proportional to the area of the aperture covered by the corresponding prism surface. Moreover the image of the background sky from one surface will be superimposed on the image of the distant object from the other. The effect of this on the appearance of the image of the original object can be shown to be exactly the same as if the object were to be moved farther away from the observer ; if the movement of the prism is continued the contrast between the images of object and background sky will be eventually reduced to the threshold value ε and the object will no longer be seen.

It can be shown that the ratio of the visibility, V, to the distance of the object, d, is then related to the fraction a of the aperture which contributes to the formation of the main image,

$$\frac{V}{d} = \frac{\log (1/\varepsilon)}{\log (a/\varepsilon)} \cdot \qquad \ldots\ldots(91)$$

As the aperture is small a direct scale of the position of the prism (and thus of V/d) is not used; instead the prism is moved by a cam and bezel ring with the scale of V/d (from 1·0 to 4·0) engraved on the outer bezel.

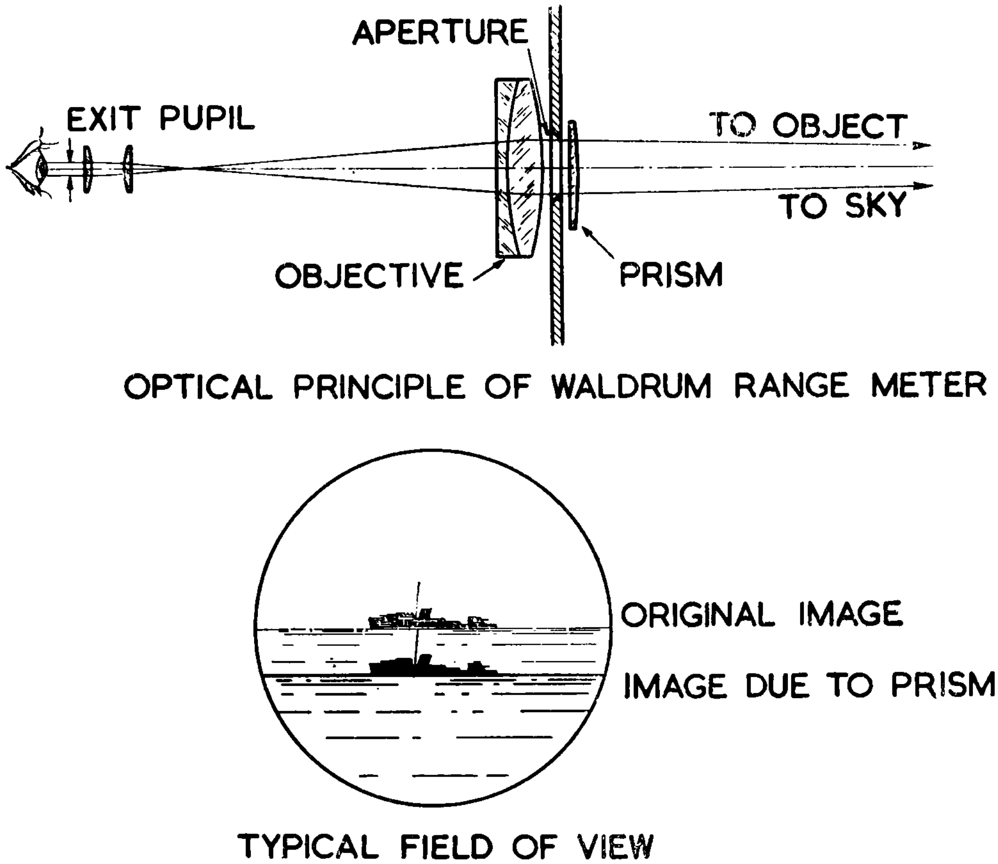

FIG. 118—WALDRUM RANGE METER

Method of use.—The telescope, or binocular, is first focussed on a suitable object, and then the attachment fitted over the object lens (with the base of the small prism horizontal and below the aperture). When the prism is raised by turning the outer bezel a second image will be formed below the original ; the original image will grow brighter and gradually merge with the background. The scale reading at which the image finally disappears will give the ratio of the visibility to the distance of the object.

Accuracy and sources of error.—The chief difficulty is to judge the exact disappearance point, but a great advantage of this type of meter is that the eye is not subjected to considerable changes in brightness when using it.

The values of the ratio of the visibility to the distance of the object for which the meter can be used are limited to less than 4 so that a fairly appreciable portion of the atmosphere has to be used, and errors caused by the non-uniformity of the atmosphere are not large.

CHAPTER 10

CLOUD OBSERVATIONS

10.1. GENERAL

Observations of the physical characteristics of clouds, including their extent (vertical and horizontal), height above the ground or sea surface, structure and form, are of great importance. The classification of the clouds is essentially a non-instrumental observation, and is described in " Cloud forms "[73] and the "Observer's handbook "[74].

The height of the cloud base at any land observing station is measured (or estimated) above the ground level in the vicinity of the observer. When the visibility is poor, because of haze or mist, the cloud base is often ill defined and no rigid criterion can be laid down as to where the haze ends and the cloud begins. The definition given by the International Meteorological Organization[8] is :— " The base of the cloud is the lowest zone in which the type of obscuration perceptibly changes from that corresponding to clear air or haze to that corresponding to water droplets or ice crystals. In the air below the cloud those particles which are responsible for obscuration show some spectral selectivity while in the cloud there is virtually no selectivity (due to the different droplet sizes involved). It is realized that the extent of this zone will depend on the method of observation used." This definition is complicated, and not very suitable for practical measurements. The methods by which the height of the cloud base may be determined are detailed on p. 375 of this chapter.

The extent of the cloud can only be measured at present by visual observation roughly from the ground. The horizontal extent is usually estimated separately for the three main groups of clouds used in synoptic meteorology (see p. 375) in oktas (eighths) of the total sky area. A conical cardboard tube whose aperture subtends at the eye a solid angle equal to one eighth of a hemisphere can be of help when estimating cloud amounts especially when the cloud is scattered. The length of the tube should be 1·07 times the diameter of the open end, and it should be covered at the other end by a disc with a small peep-hole in the centre (see Fig. 119).

The structure of the cloud (i.e. droplet or ice-crystal sizes and concentrations) can be investigated with instruments operated from an aircraft, but this aspect will be dealt with in another part of this Handbook.

The direction of the motion of the clouds and their apparent speed is also important in that it usually gives information about the wind at the cloud level. There are, however, exceptions in the case of clouds formed in connexion with standing waves to the lee of mountains. Instruments for measuring the direction of cloud motion and the apparent speed are described later in this chapter.

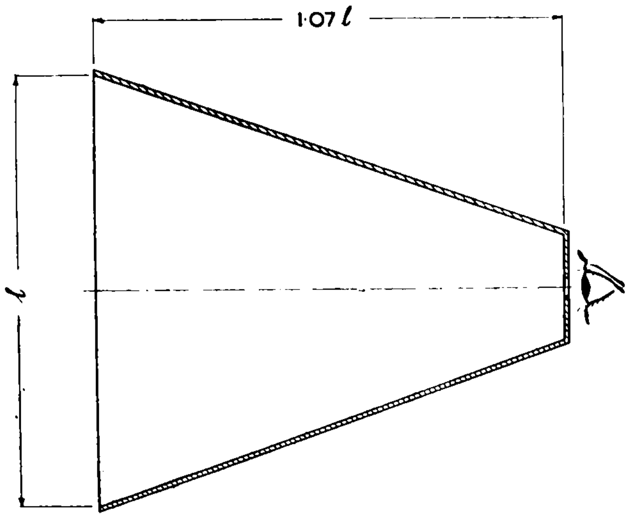

FIG. 119—CARDBOARD TUBE OF AID IN ESTIMATING CLOUD AMOUNTS

Eye observations of the form and shape of the clouds provide evidence of the method of their formation. Clouds are classified into three main groups. In the first are clouds of the stratocumulus, stratus, nimbostratus, cumulus and cumulonimbus types ; these are known as " low " clouds because their bases usually lie below 8,000 ft. above the surface. The second group comprises the altocumulus and altostratus clouds ; these are known as " medium " clouds because their bases are usually between 6,500 and 20,000 ft. The third group comprises the cirrus, cirrostratus and cirrocumulus clouds, known as " high " clouds because their bases are usually above 20,000 ft. In general it may be assumed that the suffix " stratus " implies a sheet cloud, while the suffix " cumulus " implies a cloud whose vertical thickness is comparable with its horizontal extent. Fuller and more precise information about the classification of clouds can be obtained from the " International cloud atlas "[75], the " Observer's handbook "[74], " Cloud forms "[73] and, for synoptic purposes, the " Handbook of weather messages "[31, 76].

10.2. MEASUREMENT OF CLOUD HEIGHT

10.2.1. General principles

Searchlight methods.—One of the most accurate and convenient methods of measuring the cloud height is by means of a searchlight. A narrow parallel beam of light is projected in a known direction from a small searchlight, and the elevation of the spot of light produced on the base of the cloud is measured from the other end of a base-line (Fig. 120). If h is the height of the cloud above the observer, E is the angle of elevation of the spot of light and l is the length of the base-line, then, when the searchlight beam is projected vertically upwards,

$$h = l \tan E \, . \qquad \ldots\ldots(92)$$

The searchlight beam need not however be vertical. If its angle of elevation in the vertical plane containing the searchlight and the observing point is E', then

$$h = \frac{l}{\cot E + \cot E'} \, . \qquad \ldots\ldots(93)$$

The accuracy of the measurement of h is limited by the accuracy with which the angle E can be measured (which may vary with the magnitude of E). From equation (93) it is seen that

$$\frac{\partial h}{\partial E} = \frac{l}{(\cot E + \cot E')^2 \sin^2 E}$$

$$= \frac{h^2}{l \sin^2 E},$$

i.e. at a constant height $\partial h/\partial E$ is a minimum when E is 90° and the spot is overhead. For a vertical beam E can never become 90° and $\partial h/\partial E$ becomes equal to $(h^2 + l^2)/l$.

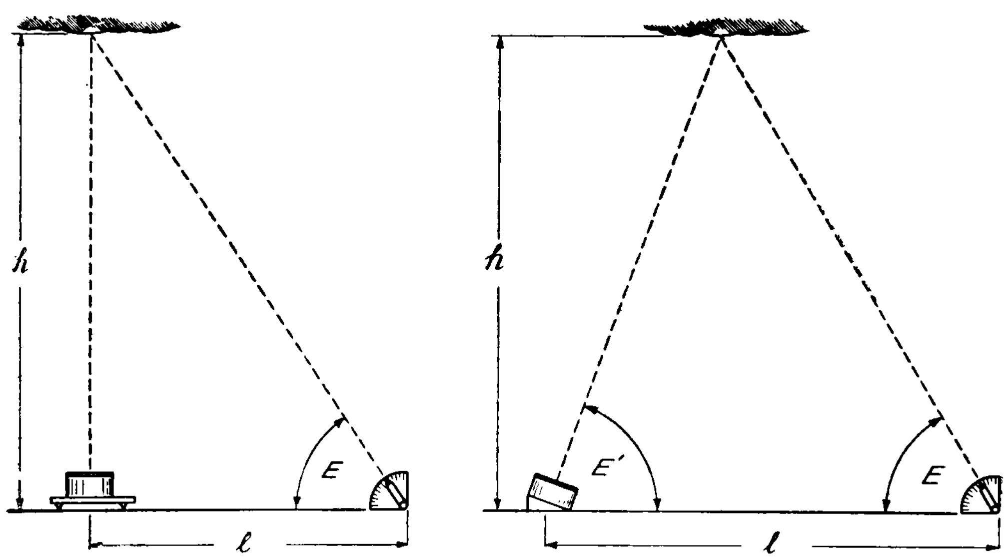

FIG. 120—PRINCIPLE OF CLOUD-HEIGHT MEASUREMENT WITH SEARCHLIGHT

An ordinary searchlight in conjunction with a visual elevation indicator, called a clinometer or alidade, can only be used at night. To extend the method to day-time use, it is necessary to modulate the searchlight beam and use a photo-electric cell at the focus of a lens or mirror as the light detector. The output from the photo-electric cell is fed to an amplifier which is tuned to the same frequency as the modulation of the searchlight beam. In this way the effect of the daylight (which may be up to 10^6 times brighter than the spot produced by the searchlight beam) can be eliminated, and the output of the amplifier reaches a maximum when the photo-electric " telescope " is pointed at the spot. The angle of elevation then enables the height to be calculated. The day-time cloud height can also be measured by an optical adaptation of radar methods. If a very short pulse of light is directed vertically upwards the time it takes to reach the cloud surface and return to the earth will be proportional to the height of the cloud. These two forms of day-time cloud searchlights are still being developed, and so no further details are given in this edition of this Handbook.

Other triangulation methods.—If a measurement of azimuth and elevation of some recognizable feature of a cloud is made simultaneously by two observers at known positions it is possible to calculate the height of that feature. The difficulty of applying this method in practice is to ensure that both observations are made at the same time and that both observers are sighting on the same feature. A telephone link is almost essential. To overcome these difficulties it is possible to use two specially mounted cameras (phototheodolites). In general this is a troublesome and expensive method suitable only for special research.

Optical range-finders are of very limited use because the uncertainty in defining the base or edge of the cloud is normally greater than the base-line of the range-finder.

Balloon methods.—Pilot balloons made of rubber, or other easily extensible material, rise in still air at a rate which is reasonably constant for a given size of balloon and a given free lift. Thus, if a balloon with a known rate of ascent is released from the ground and the time which elapses before it enters the cloud is observed, the height of the cloud can be determined. Provided the wind is not too strong, cloud heights up to about 2,000 ft. can be determined with small balloons without instrumental aid ; greater heights can be measured by the use of larger balloons and/or a theodolite or pair of binoculars.

The accuracy of this method depends mainly on the rate of ascent of the balloon remaining constant at a known value. If this differs from that assumed, as will happen if there are up-currents or down-currents for example, or if the balloon is deformed or develops a leak, the result will be in error possibly up to 20 per cent. or more.

Projectiles.—Another possibility is to use a small rocket, and to measure either the time taken for it to disappear into the cloud or the elevation of the spot at which it disappeared into the cloud as viewed from the other end of a measured base-line. The first method would depend for its reliable use on the development of a rocket with a known and constant rate of ascent ; cloud-height measurements would be limited to the maximum point of the rocket trajectory. The elevation method would be inaccurate in appreciable winds, especially if the wind were in the direction of the line adjoining the firing point and the observer, but it would be unaffected by changes in the rate of ascent of the rocket.

10.2.2. Meteorological Office cloud searchlight

The Meteorological Office standard cloud searchlight (Stores Ref., Met. 587) is illustrated in Plate XLV. A parabolic glass mirror is mounted on a substantial horizontal base plate, fitted with levelling screws and a circular spirit-level, and supported above it, at its focus, is a high-efficiency small-filament lamp. The cylindrical sheet-steel cover which protects the lamp and the mirror is provided with a plane sloping glass window at the top. The window is made watertight by two rubber packing rings beneath the metal rim. A gap is left in these rings at the lowest point so that any rain collecting on the window can drain away. The position of the lamp can be adjusted in three dimensions by means of fine adjusting screws. In Fig. 121 the screws marked A move the lamp in a horizontal plane in the direction of the axis of the bulb, the screws marked B move it in a horizontal plane in a direction at right angles to the axis of the bulb and the screws marked C control the vertical movement. In addition the lamp may be rotated about its axis. A brass box riveted to the side of the casing covers the focussing gear, and is fitted with a detachable cover so that adjustments and cleaning can be carried out without removing the main cover. A silica-gel desiccator is placed inside the instrument to prevent condensation of moisture.

A 24-V. 250- or 500-W. lamp is normally used (Stores Ref., Met. 603 and Met. 589 respectively). The power is supplied from the electric mains either through a transformer in the case of a.-c. supply or by inserting a suitable resistance in the leads in the case of d.-c. supply. It is therefore not always possible to change from one type of lamp to another without a circuit modification, either because the transformer ratio or dropping resistance may have to be altered, or because the transformer may not be designed to provide any extra power required.

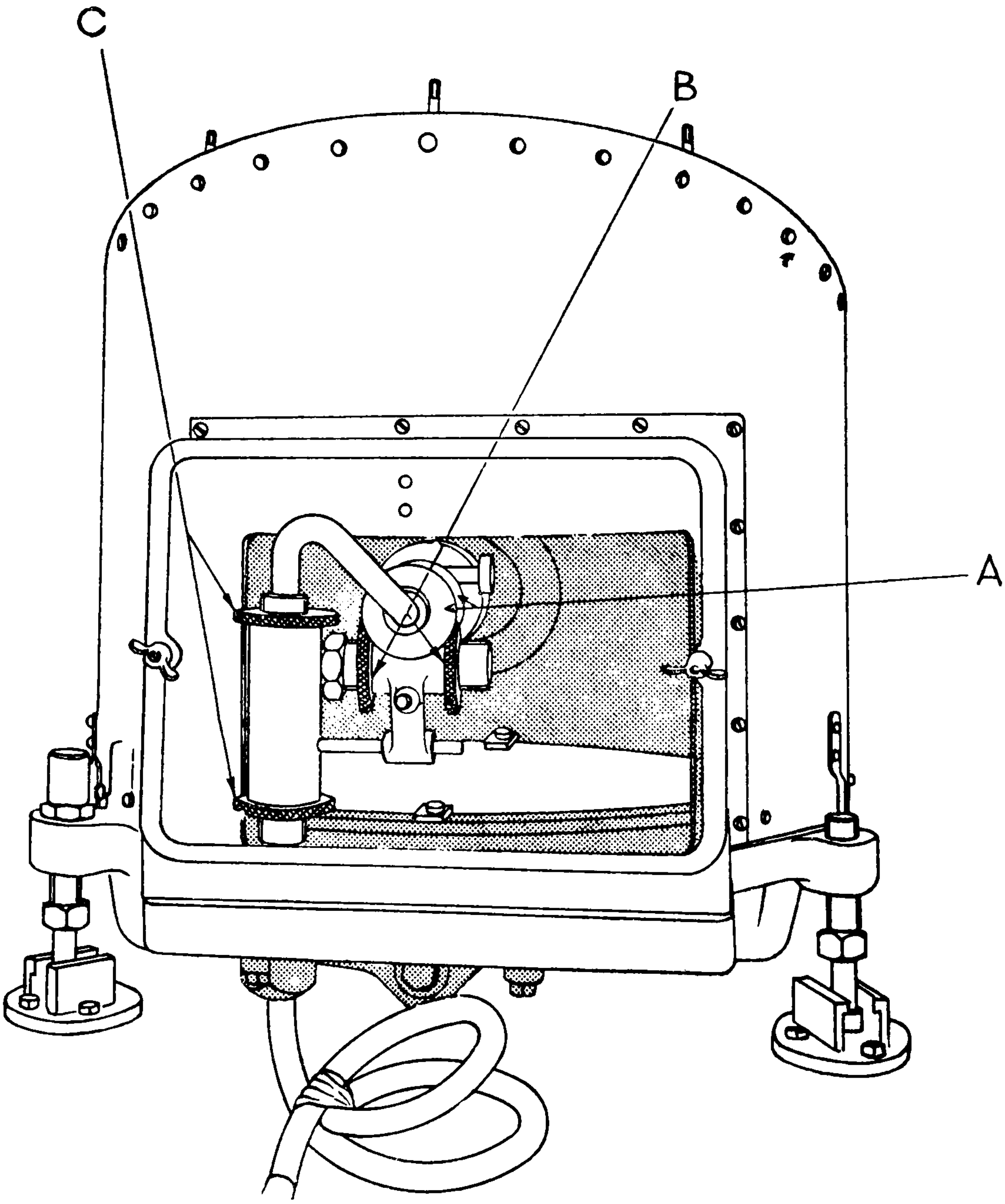

FIG. 121—LAMP ADJUSTMENTS IN CLOUD SEARCHLIGHT

The instrument is usually mounted on the top of a hollow concrete or brickwork plinth with the transformer or dropping resistance mounted inside. The low-tension electric supply is led to the searchlight by a length of rubber-covered cable. In the later a.-c. installations the searchlight is controlled by a switch in the mains supply leads, but in earlier instruments using a.c., and in d.-c. installations, the controlling switch is used to operate a contactor unit, which in turn connects the mains supply to the transformer (or dropping resistance) through a short length of cable only. The controlling switch can be placed at any convenient point ; an extra switch is usually provided in the high-tension circuit at the searchlight itself.

It is also advisable to include a red pilot lamp in the controlling circuit, which lights up when the searchlight is switched on ; it should be placed close to the searchlight switch. This should help materially to prevent the searchlight being accidently left switched on. This is important as the life of the searchlight bulbs is quite short.

Installation.—The site of the searchlight should be chosen so that the base-line between the observation position (at the alidade) and the searchlight itself is about 1,000 ft. long, and so that the whole of the beam (except possibly the lowest 100 ft.) is visible from the alidade. It will, however, usually be necessary to consult with other interested authorities before finally deciding on the position.

At all Air Ministry and Ministry of Civil Aviation stations the installation (including the supply of transformer) is a Works Service, and arrangements should be made with the local Station Engineer or the Superintending Engineer of the Works Area in which the station is situated for the work to be done in accordance with the instructions of the Director-General of Works*.

The controlling switch should be mounted in a convenient position for use, preferably near the alidade, but in certain cases it may be in the meteorological office or in a room near the searchlight which is constantly occupied, so that the light may be turned on after the receipt of a request by telephone. If necessary, two switches and two alidades can be provided so that one searchlight may be used from two different places.

Adjustment of the searchlight.—The searchlight must be adjusted, after it has been installed, so that the beam is truly vertical and focussed to infinity ; i.e. the optical axis of the mirror should be vertical and the filament of the lamp should be on the axis of the mirror at the principal focus.

The following procedure should be carried out :

(i) Level the base by means of the three external foot screws until the bubble of the circular spirit-level is truly central.

(ii) Place a steel ball (about $\frac{3}{4}$ in. in diameter) on the mirror near the white central spot and observe its oscillations in a given direction (which will take place through the lowest point of the mirror). First let the ball oscillate in a direction perpendicular to the line joining two of the mirror levelling screws, and then adjust one of these until the ball passes through the white spot. The third screw should then be adjusted until the white spot is as nearly as possible at the centre of oscillation of the steel ball. This procedure should be repeated until the ball will oscillate symmetrically about the white spot independently of the direction from which it is started.

(iii) Insert a lamp bulb in the holder and move it by means of the two horizontal adjusting screws until the white spot on the mirror is in the same straight line as the filament of the lamp and the image of the filament in the mirror, when viewed from above.

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* See Director-General of Works drawing M & E 8772/43.

(iv) The lamp can be finally focussed on an overcast night (preferably without a moon) by altering the vertical adjusting screw until the diameter of the light spot on the highest cloud present is as small as possible.

After installation the verticality of the beam should be tested with the aid of a theodolite. This should be done with the theodolite in two positions, one near the alidade and one at about the same distance away from the searchlight in a direction at right angles to the line joining the searchlight and alidade. The theodolite should be set up and carefully levelled, but it is not necessary to set the azimuth scale to read true bearings. The azimuth readings of the searchlight itself and of the spot on the cloud should then be measured as accurately as possible, together with the elevation reading of the spot. The deviation of the beam from the vertical in a plane perpendicular to the line joining the theodolite and the searchlight is given by $\Delta A/\tan E$, where ΔA is the difference in azimuth readings and E is the elevation of the spot. This can be seen from Fig. 122. X′ is the position of the searchlight, X′X is vertical, Y is the spot on the cloud, XY is horizontal, and l is the distance between searchlight and theodolite. The deviation, $\Delta\theta$, of the beam from the vertical is given by :

$$\begin{aligned}\Delta\theta &\simeq \mathrm{XY}/\mathrm{X'X} \\ &= \mathrm{X'Y'}/\mathrm{YY'} \\ &\simeq l\Delta A/l \tan E \\ &= \Delta A/\tan E\,.\end{aligned}$$

If the error in the verticality of the beam is more than 1° when viewed from the alidade, or more than 0·5° in the other position, the adjustments (ii) and (iii) above should be carried out again until the necessary accuracy is obtained, or, alternatively, the position of the lamp may be altered by a measured amount to correct the error.

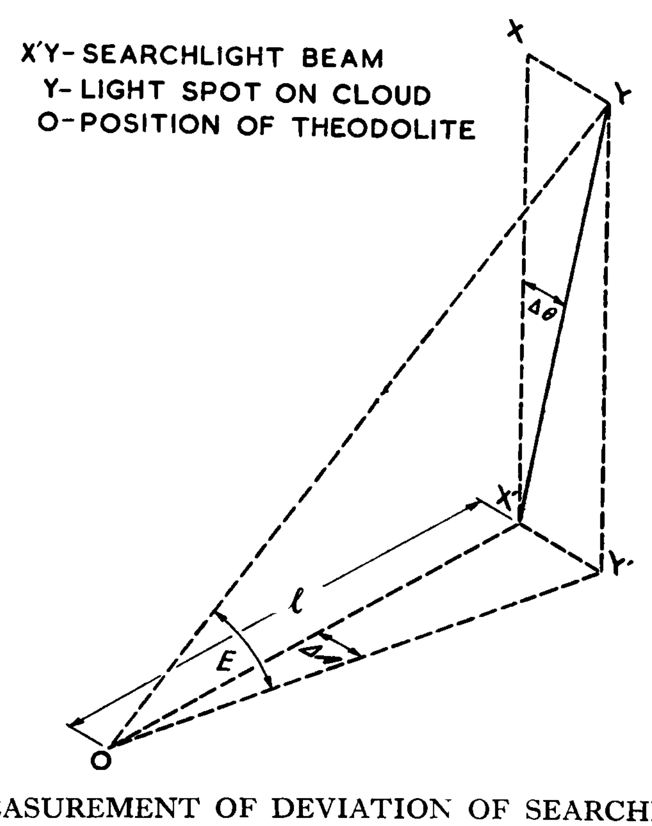


FIG. 122—MEASUREMENT OF DEVIATION OF SEARCHLIGHT BEAM FROM THE VERTICAL

The movement required is about $3\frac{1}{2}$ mm. in the direction of inclination per degree of error. This method of correction would be facilitated by making the theodolite observations from directions parallel to the lamp-adjusting screws.

Method of use.—The alidade is used to measure the angular elevation, *E*, of the spot of light on the cloud. The relation between *E*, the length of the base-line *l* and the cloud height is given in equation (92), p. 375.

A table should be prepared on Form 2328, Measurement of cloud height by means of searchlights, in respect of each alidade in use at the station, giving the correct cloud height for every degree of the alidade reading, making allowance for the height of the alidade above ground level if necessary. The distance between the alidade and the searchlight should be clearly entered in the table, and if more than one alidade is in use at a station the location of the alidade with which the table is to be used should also be marked on the form, so that there should be no danger of the incorrect table being used.

On many occasions some care will be necessary to ensure that the height of the cloud spot at any particular moment fairly represents the height of the lowest layer of cloud. The beam should always be watched carefully for about five minutes if there is any possibility of fragments of cloud below the main cloud base. The elevation of all distinct spots should be measured. The relative amounts of cloud at each height can be estimated very roughly from the relative length of time that each spot occurred, making allowance for the fact that lower clouds will obscure upper clouds.

When the cloud is very low the searchlight may not produce on the cloud base a patch which appears horizontal (either because the cloud is tenuous, or because it is fragmentary and ragged) but instead there is a diffusely illuminated section in the upper part of the searchlight beam. Below this brighter section the beam may be only faintly visible, but if it is raining or if the visibility is poor the lower part of the beam may be somewhat brighter and the contrast between the upper and lower sections of the beam may not be so well marked. In such cases the measurement of the height of the cloud base should be made by setting the alidade on the bottom of the diffusely illuminated beam ; i.e. the place where the searchlight beam undergoes an appreciable change in its apparent brightness.

On a moonless overcast night with reasonable visibility, cloud heights up to 10,000 ft. or above can be measured if the searchlight is focussed properly.

Maintenance and repair.—*Focussing and replacement of the lamps.*—The focussing and verticality of the beam should be checked once a month as the lamp filament is liable to undergo slight changes in shape with time. When replacing a lamp the adjustment for lamp position should be carried out again as the lamps are not identical in dimensions.

Cover glass and mirror.—The cover glass should be cleaned once a week, or more often if necessary. The front surface of the mirror should only be cleaned when necessary, and then only with a clean chamois leather, taking great care to avoid scratching the polished surface.

Desiccator.—The desiccator consists of crystals of silica gel in a perforated aluminium container with a little cobalt chloride as an indicator ; it will continue to function indefinitely provided it is dried from time to time. It should be regenerated by heating in an electric oven, or on an electric stove, provided its temperature is not allowed to exceed about 400° F. The desiccator should be allowed to cool in its container and not be exposed to air until it is about to be put into the searchlight. When dry the crystals appear blue, but when the desiccator requires regeneration the crystals appear pink. It is best to have two desiccators so that one can be kept in the searchlight at all times.

The desiccator should be inspected every week and replaced with a dry one when necessary. If, however, there is an excessive accumulation of water in rainy weather the searchlight cover should be examined to see that it is so orientated that the drainage outlet is at the lowest point of the glass cover and that the rubber packing rings are correctly placed so as not to obstruct the outlet. The rubber rings are likely to loose their elasticity in the course of a year or so, and should then be replaced (Stores Ref., Met. 617 for the horizontal ring and Met. 618 for the vertical packing ring).

Painting.—At all stations the metal parts subject to corrosion should be painted at least once every two years with good-quality rust-preventative paint. At exposed and coastal stations they should be painted once every year, while in the tropics it may be necessary to paint them once every three months.

Accuracy.—The error Δh in the cloud height caused by an error ΔE in the elevation measurement is given by

$$\Delta h = l \sec^2 E \,.\, \Delta E$$

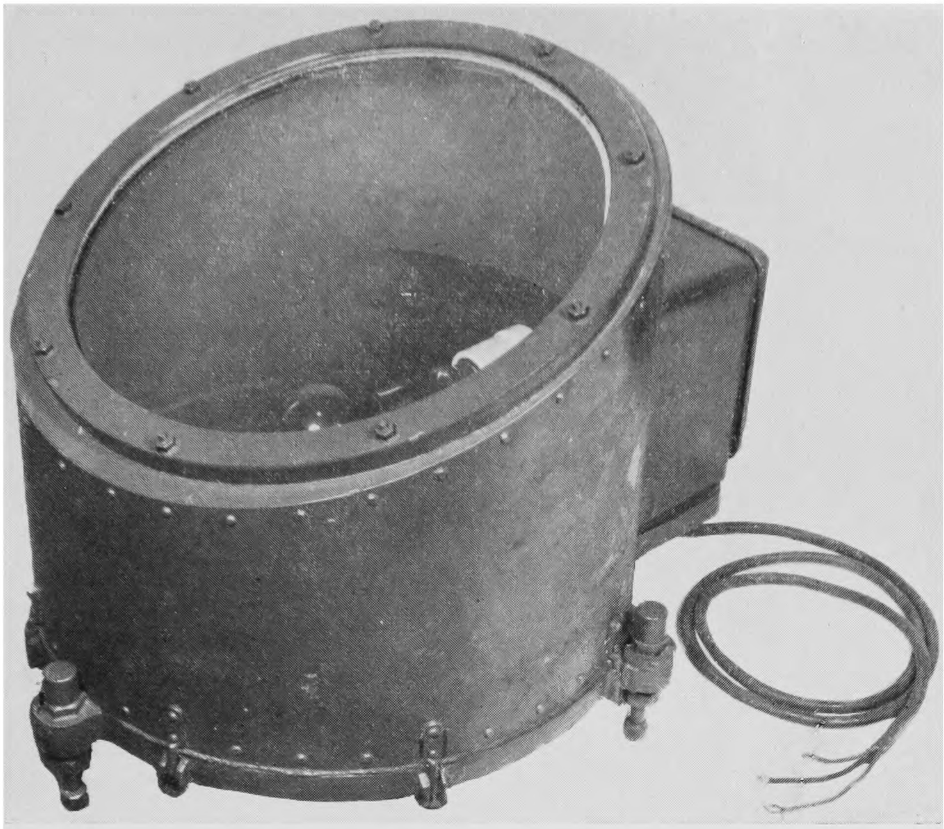
which is a minimum when E is zero. The fractional error on the other hand is given by

$$\frac{\Delta h}{h} = 2 \operatorname{cosec} 2E \,.\, \Delta E$$

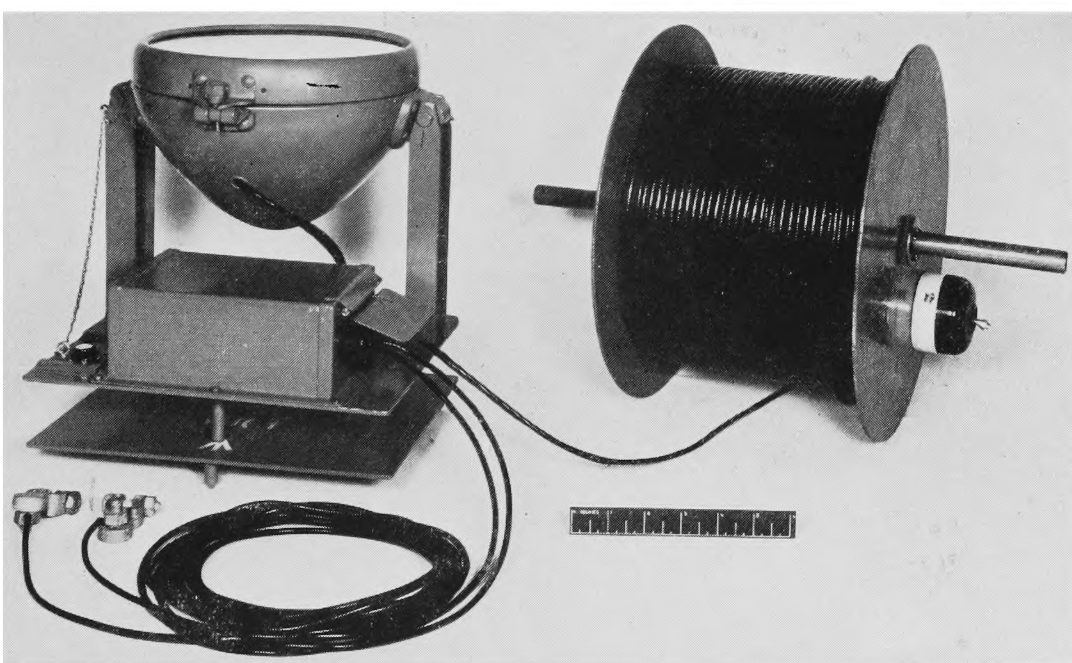
which is a minimum when E is 45° or $h = l$. For l equal to 1,000 ft. the error in h for an error of 1° in E is 17·4 ft. when h is very small, rising to 35 ft. when h is 1,000 ft. and to about 450 ft. when h is 5,000 ft.

10.2.3. Meteorological Office portable cloud searchlight

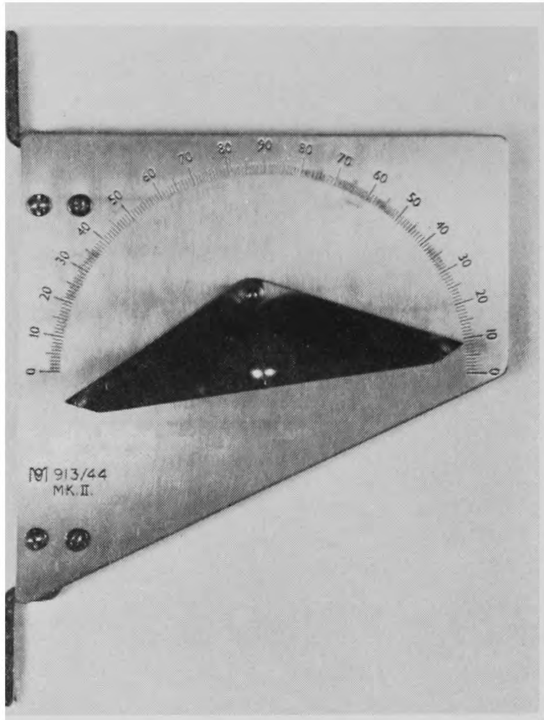
The portable cloud searchlight (Stores Ref., Met. 2733) is designed for use by mobile units or at stations which have no mains electric supply. The searchlight is similar to a car headlamp and is mounted on a simple adjustable stand (Plate XLV). It is provided with a 12-V. 36-W. V-filament double-contact bulb (Stores Ref., Met. 2755), a parabolic reflector and a clear front glass. The stand itself is mounted on a flat base plate fitted with spikes which can be pressed into the ground to provide a firm mounting. The power supply is three 6-V. large-capacity storage batteries, and the whole 18 V. is applied to the bulb, so that it is operated considerably above its normal rating ; this results in a brighter beam at the expense of a shorter life. The lamp is switched on through a d.-c. relay, operated by a tumbler switch at the far end of 1,000 ft. of cable. The relay unit takes 1–2 W. For convenience the cable is wound on a drum with the switch fixed permanently in position to the side of the drum ; the cable can then be unwound by rolling the drum along the ground. The leads from the battery and the near end of the cable are connected to plugs which fit into sockets on the searchlight base (the complete



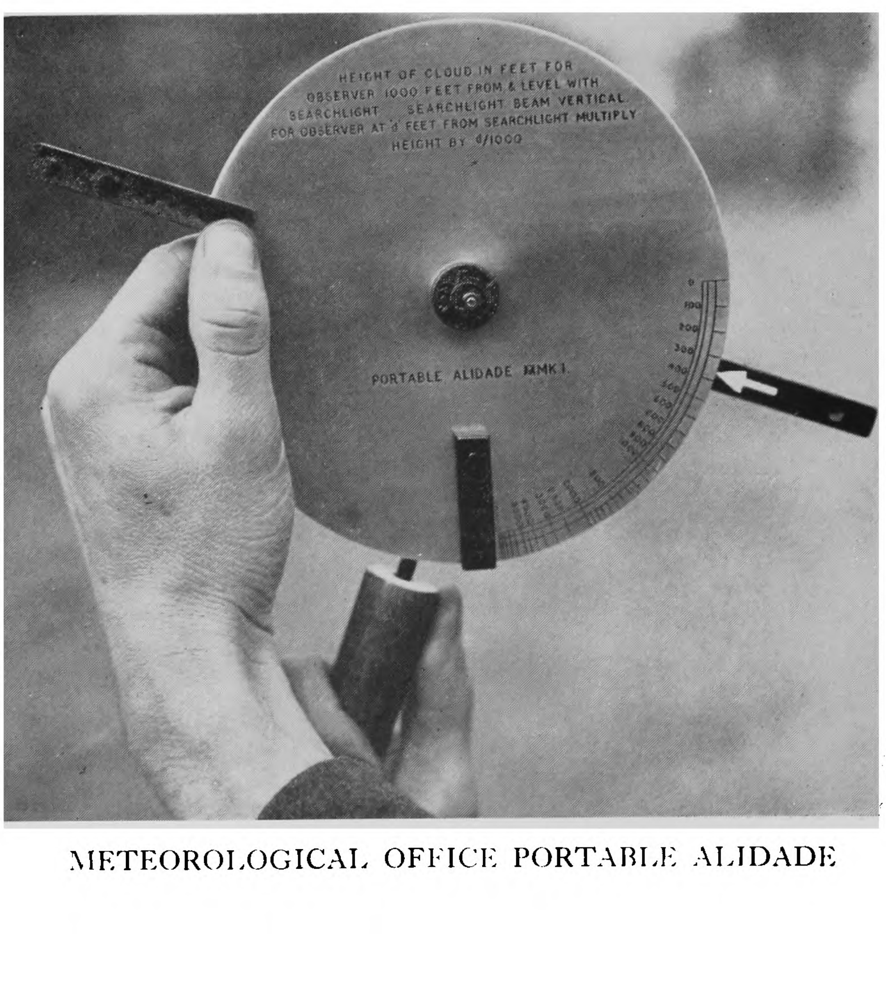
METEOROLOGICAL OFFICE CLOUD SEARCHLIGHT



METEOROLOGICAL OFFICE PORTABLE CLOUD SEARCHLIGHT



METEOROLOGICAL OFFICE UNIVERSAL ALIDADE MK II



METEOROLOGICAL OFFICE PORTABLE ALIDADE

wiring diagram is shown in Fig. 123). A spirit-level is attached for adjusting the searchlight beam to the vertical and a portable alidade (see p. 385) is used to measure the elevation of the searchlight spot. The searchlight and the alidade fit into a stout wooden case when the instrument is not in use. A wooden cover is provided for the batteries.

Installation.—The searchlight base should be placed on a level and firm piece of ground and pushed down so that the spikes go in to their full depth. The spirit-level should be placed on the lamp glass and the central base wing nut slackened off. The levelling screws should be adjusted until the bubble of the spirit-level is in the centre of its circle. The wing nut should then be tightened and the level rechecked to ensure that it has not been disturbed by tightening the wing nut.

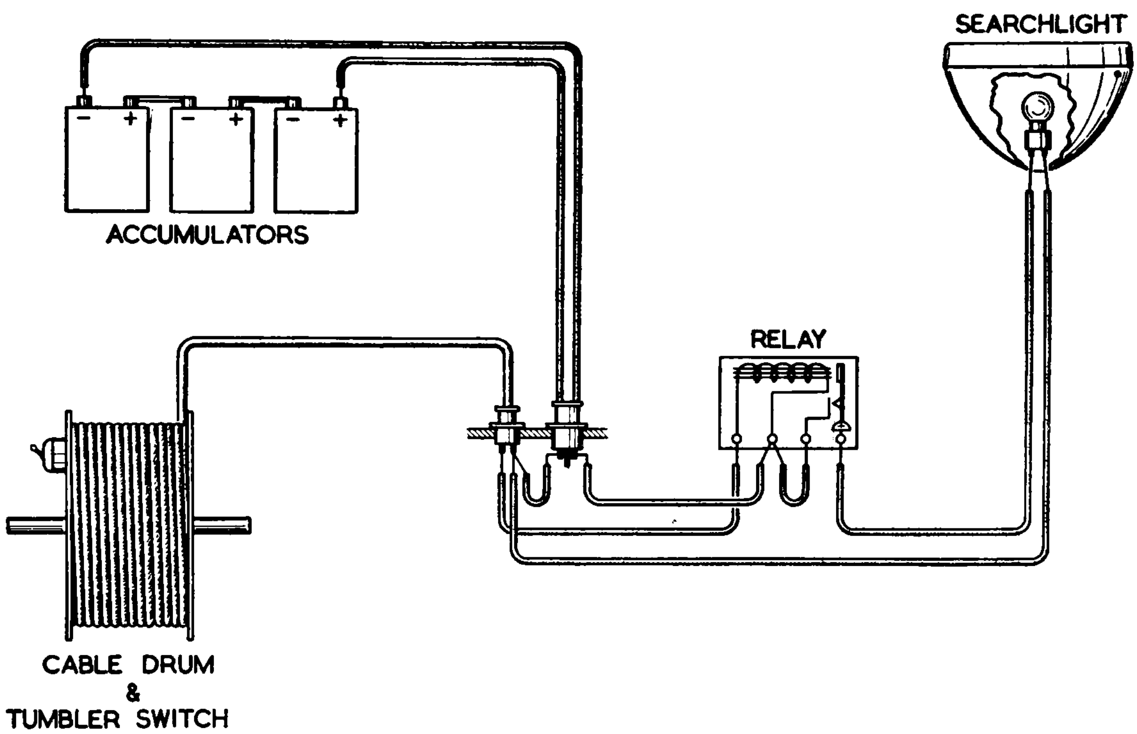


FIG. 123—WIRING DIAGRAM OF PORTABLE CLOUD SEARCHLIGHT

The electrical connexions can then be made ; the plug at the end of the drum cable goes into the small socket of the relay box and the plug at the end of the battery-connecting cable goes in the large socket. The lugs at the other end of the battery cable should be connected to the extreme terminals of the battery. The lamp should light up when the cable drum's switch is operated.

The drum should be moved away from the searchlight in a straight line until it is fully unwound, when it should be approximately 1,000 ft. from the searchlight. The searchlight is now ready to be used in the same manner as the standard instrument.

Method of use.—The alidade with which the instrument is provided is meant to be used only with a base-line of 1,000 ft., and is graduated to read directly in terms of the cloud height. The instructions on p. 381 detailing the procedure to be followed when the cloud is tenuous or when more than one layer is present should be followed carefully.

Maintenance and repair.—*Focussing the lamps.*—No focussing adjustment should be necessary with new instruments but it may be essential after replacing a bulb. The procedure is as follows :

(i) Undo the hexagonal slotted nut on the hinged bolt which holds the rim of the glass to the body of the lamp and remove the lamp front complete with reflector, taking care not to strain the leads to the lamp holder.

(ii) Loosen the knurled screw which clamps the lamp holder in its outer sleeve. The position of the lamp may now be adjusted relative to the reflector.

(iii) Slide the lamp holder backwards or forwards until the narrowest beam of light is obtained, or until the best spot is obtained on a cloud. It is not necessary to put the lamp front back on the body of the lamp until the best focus has been obtained. This adjustment is fairly critical (a movement of a millimetre makes an appreciable difference).

(iv) Tighten the knurled clamping screw and replace the lamp front on the body of the lamp and tighten the hexagonal nut.

Replacement of the lamps.—The average life of the bulb is about 8 hr. when run at 18 V. To replace a bulb the following procedure should be followed :

(i) Follow the instructions (i) and (ii) above, given for adjusting the focus of the lamp.

(ii) Release the two spring clips which secure the circular base of the lamp-holder assembly to the reflector and withdraw the lamp holder from the reflector. If the lamp holder is too firmly fixed to be withdrawn by hand it should be prised off gently with a screwdriver, avoiding strain on the reflector.

(iii) Replace the bulb and then replace the lamp holder inside the reflector and clamp in position with the two spring clips.

(iv) Test the focus and adjust if necessary as described above.

(v) Replace the lamp front on the body of the lamp and tighten the hexagonal nut.

Batteries.—The batteries must be kept well charged and the liquid maintained at the correct level by topping up with distilled water. It is important that the battery terminal posts and connecting lugs be kept clean and free from chemical deposit. If these points are not attended to the relay may fail to operate when the switch on the cable drum is turned on and consequently the lamp fail to light.

Cover glass and reflector.—The cover glass of the searchlight should be kept clean and the reflector may be wiped carefully with a clean chamois leather when absolutely necessary.

Accuracy.—The spot of light produced by this searchlight is less intense than that produced by the standard instrument, but for cloud heights up to at least 3,000 ft. the accuracy is not impaired. Above that height greater difficulty is usually experienced with the portable instrument, but in good conditions measurements of well above 3,000 ft. can be obtained.

10.2.4. Meteorological Office universal alidade Mk II

The universal alidade Mk II (Stores Ref., Met. 665) consists of a brass sight bar mounted on a brass plate so that it can rotate about an axis perpendicular to the plane of the plate ; the ends of the bar are pointed and a pair of sights is fitted (Plate XLVI). When the plate is mounted vertically with the top edge horizontal the inclination of the sight bar to the horizontal is indicated by the reading of one end of the bar against a scale engraved on the plate. The spring at the bearing of the sight bar offers sufficient resistance to keep the sight bar in position when it is set at any elevation, but the resistance is not sufficient to hinder the process of setting the sight bar so that the sights are aligned on a cloud searchlight spot.

The main plate is attached to a swivelling support bracket which can be screwed to a convenient support, such as a window jamb or a vertical post.

Installation.—The alidade must be mounted in a position from which the searchlight beam is visible at all elevations of interest (usually from 5° to 85°). It is usually better to mount the alidade just outside the meteorological office, under shelter if possible without obscuring the spot at high elevations.

The alidade should be screwed firmly to its support in such a position that when the sight bar is placed so that the ends point to 0 on the scale the sight bar is accurately horizontal. This should be checked with a good spirit-level, or, alternatively, the actual elevation of a distant object can be measured with the alidade and the result checked with a balloon theodolite. The support should be facing in such a direction that it is possible for the alidade to be moved until the plane of the brass plate passes through the searchlight.

If it is not convenient for all users of the cloud searchlight to use one alidade, a second alidade may be erected. If the alidade is not mounted near ground level a note should be made of its height above the ground so that allowance can be made. The distance from the alidade to the searchlight should be measured accurately.

Method of use.—The two sights on the sighting bar are brought into line with the cloud spot and the angle of elevation read against the pointed end of the sight bar on the engraved scale. Details as to what part of the searchlight beam to sight on in difficult cases are given on p. 381.

Maintenance and repair.—The alidade should be kept clean and the adjustment checked at intervals with a spirit-level. If the centre bearing of the sight bar becomes slack the centre screw should be tightened ; otherwise the bar may be accidentally moved before the reading is taken. The bearing should be oiled at regular intervals to keep its movements smooth.

Accuracy.—If the instrument is installed accurately the errors in the graduations should not exceed $\frac{1}{2}$°, but it is rarely possible to set the sights on a searchlight spot to a greater accuracy than 1°.

10.2.5. Meteorological Office portable alidade

The portable alidade (Stores Ref., Met. 2026) is used when it is inconvenient or impossible to set up a permanent installation (Plate XLVI). It consists of a sight bar carrying a circular aluminium plate which is free to revolve about an axis perpendicular to the sight bar and passing through the centre of the plate. A weight is fixed to the edge of the plate so that when the handle attached to the sight bar is in a vertical plane any diameter of the plate always takes up a fixed direction relative to the vertical. The angle of elevation of the sight bar can thus be found by engraving a scale on the aluminium plate and having a datum mark on the sight bar itself. As however the alidade is designed for use with the portable cloud searchlight in which the base-line is always 1,000 ft. the elevation scale is graduated directly in the equivalent cloud height. A simple clamp, operated by pressing a strip of metal against the circular plate, enables the position of the latter to be fixed until the reading can be obtained. The sight consists of pointed rods with ball tips, the latter being painted with luminous paint.

Method of use.—The instrument is held in the hand and its position adjusted until the cloud spot and the two ball tips of the sights appear in line, the handle being kept in a vertical plane ; the circular plate is then clamped in position with the thumb and finger of the disengaged hand, and the cloud height read off the engraved scale, opposite the red arrow on the sighting bar. If the cloud searchlight is at a distance l ft., the indicated height should be multiplied by the factor $l/1{,}000$.

It is best to take a mean of several observations, first bringing the sight bar up from below the required elevation and then bringing it down from above. This will minimize the effect of friction and give a more reliable result than would only one observation.

Maintenance and repair.—The alidade should be kept clean and the bearing of the circular plate should be oiled at regular intervals.

Accuracy.—The friction in the centre bearing of the plate is the limiting factor which decides the accuracy of this instrument. An individual setting may be made with the plate up to 2° from the correct position (i.e. an error of 100 ft. at 1,500 ft.) but if a mean of several observations is taken, with the sight bar approaching the spot from elevations above and below the spot, this error should be reduced considerably.

10.2.6. Pilot balloons

Equipment.—The following equipment is usually required to measure cloud height with pilot balloons :

- Hydrogen cylinder
- Key for opening and closing the main valve of the hydrogen cylinder
- Fine-adjustment valve for controlling the rate of flow of the hydrogen
- Pressure gauge for measuring the pressure in the hydrogen cylinder
- Pressure-gauge adapter to allow a fine-adjustment valve and pressure gauge to be used simultaneously
- Balloon filler
- Pair of hoops for use in measuring the size of the smallest balloons used
- Length of rubber tubing to connect the filler to the fine-adjustment valve
- Rubber balloons
- Lanterns and small candles for use at night
- Thread and elastic for use in attaching the lantern to the balloon.

The needs of most stations are met by 100-ft.^{3} cylinders (R.A.F. Ref., 71A/30) or more rarely by the 200-ft.^{3} cylinders (R.A.F. Ref., 71A/31). The 100-ft.^{3} cylinders weigh approximately 110 lb., and are about 5 ft. long; the 200-ft.^{3} cylinders weigh about 200 lb., and are either 6½ or 8½ ft. long. The cylinders are normally filled to a pressure of 120 atmospheres (about 1,800 lb./in.^{2}), but the pressure is reduced to about 100 atmospheres for use in the tropics.

Where it is impracticable to obtain hydrogen compressed in cylinders small hydrogen generators may be used. These are of two main types, high-pressure generators and low-pressure generators. In the former hydrogen is generated in a closed chamber until the pressure exceeds 1,000 lb./in.^{2} The closed chamber may then be used in place of the hydrogen cylinder. In the latter the hydrogen is passed into the balloon as it is generated, and the pressure in the generator never rises very far above atmospheric pressure.

Common chemical reactions used in the preparation of hydrogen are the action of sodium hydroxide solution on ferro silicon or on aluminium, of water on a mixture of iron and magnesium and of water on calcium hydride.

The balloon filler is essentially a hollow brass cylinder with a one-way valve in the centre, one end of which can be fitted into the balloon neck and the other fitted into the piece of rubber tubing. In this way hydrogen can be passed into the balloon without any escaping back when the pressure is removed. The one-way valve can, however, be opened manually by pressing the plunger in the bottom of the filler thus allowing the amount of hydrogen in the balloon to be reduced if necessary. Normally a balloon-filler set Mk IV (Stores Ref., Met. 550) will be used. This comprises a filler as described above together with four weights which can be screwed on to the filler to increase its weight.

There are various sizes of balloons, which can be specified either by their approximate circumferences when fully inflated or by their weights. The sizes used in cloud-height determinations are the 4 gm. (36 in.), 10 gm. (48 in.) and 20 gm. (70 in.). The latter is used only at night, with a light attached to it.

Principle of the method.—The rate at which a balloon ascends in the free air depends upon its size and its " free lift ". The free lift of a balloon is equal to that extra weight which would have to be attached to it to make it float in the air with no tendency to rise or sink. When the balloon is released the upward force on the balloon is equal to the free lift and very soon the drag of the air equals the upward force. The rate of ascent then remains sensibly constant.

It is essential that in all cases where a balloon is used for cloud-height determination the free lift of the balloon should be accurately adjusted to the correct value. If great care is not taken over this, accurate results cannot be obtained. It should be noted that if a candle and lantern are attached to a balloon not only is the free lift immediately reduced but, when more hydrogen is passed into the balloon, its size increases so that the free lift required for the same rate of ascent is greater.

Care of hydrogen cylinders.—Hydrogen being the lightest of gases is particularly prone to leakage. It is highly inflammable, and mixtures with air in a proportion of less than 8 per cent. by volume of hydrogen burn with an almost invisible blue flame. Mixtures containing 8–80 per cent. of hydrogen are highly explosive. Great care must therefore be exercised in the storage and use of hydrogen cylinders.

Storage.—Hydrogen cylinders must not be stored in any building with electric lighting which is not fitted with flameproof electric fittings carrying the Buxton certificate. The building must be adequately ventilated particularly in the peak of the roof. If a suitable building is not available the cylinders should be stored in the open on wooden supports and covered over. It is also advisable in such a case to earth all the cylinders (see (ii) below).

No naked light, burning cigarette or lighted pipe should be introduced at any time into the hut or room where the cylinders are stored, particularly not when a balloon is being filled, and never brought near an inflated balloon. Electric fires, running motors and other electrical apparatus should also be kept well away from the vicinity of all cylinders. A notice should be painted in bold red lettering on the door of the hydrogen room :

NO NAKED LIGHTS

NO SMOKING

Precaution in the use of valve caps.—It is important to note that the presence of oil and grease on cylinders containing certain types of gases can lead to serious explosions. As the valve caps on hydrogen cylinders are interchangeable with a wide range of compressed gas cylinders, it is strictly forbidden to use lubricants to ease the removal of caps from cylinders.

All hydrogen cylinders should be examined on receipt, and any traces of oil or grease found around the thread of the neck of the cylinder should be removed without delay by the application of carbon tetrachloride. This solvent may be obtained from any well known chemist or at Meteorological Office stations through the R.A.F. (Ref. Section 33C/1030). Care should be taken in applying the carbon tetrachloride as its careless or over-generous use will remove the paint from the cylinder. The fumes should not be inhaled.

The valve protection caps should be fitted at all times except when the cylinders are actually in use.

Precautions to be taken in discharging gas.—The following precautions should be taken when discharging a cylinder :

(i) The cylinders are not to be discharged below a pressure of 100 lb./in.^{2} At this pressure they are officially described as " used " cylinders. If the cylinder is completely emptied air is allowed in and the water vapour damages the inner lining. A combined fine-adjustment valve and pressure-gauge adapter should normally be fitted to the cylinder actually in use so that the hydrogen pressure can always be read, but if this is not available the cylinder valve should be closed immediately the pressure in a cylinder falls below that at which it is capable of filling a balloon at a reasonable rate, and the cylinder regarded as used.

(ii) The cylinder should be effectively earthed by copper wire or braiding connected to a rod inserted in the soil, the soil being kept moist by watering if necessary.

(iii) The gas must be discharged slowly. The main valve should not be opened more than a quarter of a turn during the initial stages of discharging a new cylinder.

(iv) The cylinder valve should be closed tightly after use.

(v) Any dust or corrosion should be removed from the valve and orifice of the cylinder. Wire brushes having any ferrous material should not be used for this purpose.

(vi) Valves must be opened by hand. If this cannot be done a raw-hide or wooden mallet may be used to strike the valve key but no hammer or object containing ferrous metal may be used.

(vii) The fire precautions outlined above must be strictly observed. When making balloon ascents at night the lighted candle should not be brought nearer to the balloon than is absolutely necessary.

Testing on receipt.—The pressure of hydrogen in a cylinder should be tested immediately the cylinder is received so that cylinders that have only been partly filled can be detected. The procedure should be as follows :

(i) Unscrew the cylinder cap.

(ii) Fit the pressure gauge to the main tap (the thread on the gauge is left-handed) tightening it by hand or by using a wooden or raw-hide mallet, not by using a hammer or other object containing ferrous material.

(iii) Fit the lever key on the cylinder tap and turn counter-clockwise to release the hydrogen.

(iv) Note the pressure on the dial and then turn off the hydrogen and unscrew the pressure gauge.

The pressure of hydrogen should be about 120 atmospheres (1,800 lb./in.^{2}) when the cylinder is full, but in the tropics this is reduced to 100 atmospheres. If the measured pressure is less than 100 atmospheres (1,500 lb./in.^{2}), or in the tropics, 80 atmospheres (1,200 lb./in.^{2}), a report should be made to the authority responsible for the issue of the cylinders.

Balloons.—*Care and handling.*—Balloons should be stored in a cool place and in the dark. This is especially important in tropical climates. Storage in an ice chest or refrigerator is recommended, but if this is not possible it should be the aim to store the balloons under conditions where the temperature does not exceed 60° F. In all cases arrangements should be made so that the stock is replenished at frequent intervals to reduce the period of storage before use as much as possible.

Before inflating the balloon, any loose French chalk should be shaken out and then the balloon should be warmed and rubbed well between the hands. This reduces the risk of a burst during inflation and helps to make the balloon assume a regular shape.

Sizes and colours.—4-gm. balloons should only be used during daylight when the cloud is at 1,000 ft. or below and the wind is light ; 10-gm. balloons should be used at other times in daylight ; 20-gm. balloons should only be used for cloud-height determination at night, when a lantern and candle have to be carried. 4-gm. and 10-gm. balloons are made in two colours, red and blue (or occasionally black). The blue (or black) balloons should be used when the sky is overcast and the red balloons on days with broken cloud.

Free lifts and rates of ascent.—4-gm. balloons should be inflated until they cannot pass through a hoop of 9½-in. diameter but can pass through a hoop of 10½-in. diameter. Their rate of ascent is then 300 ft./min.

10-gm. balloons should be filled until their free lift is 20 gm. ; if the Mk IV balloon-filling set is used the amount of hydrogen in the balloon should be adjusted until the balloon can just support, without rising in still air, the filler only. When the filler is removed the rate of ascent of the balloon is 400 ft./min.

20-gm. balloons carrying a candle and lantern have to be filled until the free lift is equal to 71·5 gm. plus the weight of candle and lantern. With the Mk IV balloon-filling set this can be accomplished by adjusting the amount of hydrogen in the balloon until the balloon can just support, without rising in still air, the filler plus weight B plus the lantern and candle, or, alternatively, until the balloon can just support the filler plus weights B and D. The rate of ascent of the balloon (with filler and weights removed but carrying the lantern and candle) is then 500 ft./min.

Method of filling the balloon.—(i) Fit the pressure-gauge adapter to the hydrogen cylinder (the thread is left-handed). The wing nut should be tightened by hand or by using a wooden or raw-hide mallet ; metal hammers or objects containing ferrous metal should not be used.

(ii) In one end of the hexagon body of the adapter screw the fine-adjustment valve and in the other the pressure gauge using the same precautions as in (i) above.

(iii) Attach the control-valve end of the balloon filler to the outlet of the fine-adjustment valve by means of rubber tubing.

(iv) Select an appropriate balloon and prepare it for inflation, see above, and then slip the neck over the other end of the balloon filler. If the neck is loose the fitting may be improved by rolling the neck of the balloon back on itself for a turn or so.

(v) Close the controlling tap (a right-hand screw) until it is just finger tight and then slightly open the main valve by means of the main key. Hydrogen can now be admitted to the balloon by slowly opening the tap. The balloon should be filled slowly and steadily, taking care that there is no rush of gas.

(vi) When sufficient gas has been admitted to the balloon turn the main key off hard and close the fine-adjustment tap. Do not screw this tap up tight—the main key must be relied on to prevent the escape of gas from the cylinder. If the balloon assumes an irregular shape when fully inflated, or any leaks are detected, it should be rejected and another one tried.

(vii) The filler can now be withdrawn from the rubber tubing and the amount of hydrogen in the balloon correctly adjusted. For 10-gm. and 20-gm. balloons hydrogen must be released until the balloon and filler, plus appropriate weights, just float in still air ; a 4-gm. balloon must be adjusted to the correct size. Great care must be exercised at this stage to prevent the balloon and filler escaping from the observer's grasp and floating away. The observer should stand well away from any open doors to minimize draughts and take great pains over this adjustment.

(viii) Grasp the neck of the balloon firmly to avoid leakage of hydrogen, remove the filler, stretch the neck of the balloon and tie it tightly in a knot. The balloon is now ready for use.

Following the balloon in day-time.—The balloon should be released from a spot which is free from obstructions in the down-wind direction. If the cloud is low (below 1,000 ft.) or the wind is light the balloon may be followed with the naked eye, but better results are obtained if a telescope, binoculars or theodolite can be used. A stop-watch should be used to measure the time. The base of the cloud should be taken as the point at which the balloon just appears to enter a misty layer before finally disappearing.

Careful watch is required when there are fragments of cloud beneath the main base to make sure that the balloon is not obscured by a lower fragment passing between the balloon and the observer. If this does happen another balloon must usually be sent up, but on some occasions it may be possible to pick the balloon up again after the fragment of cloud has passed away.

Measuring the cloud height at night.—Lanterns (Stores Ref., Met. 140) are normally supplied ready made, but if necessary they can be made on the station by the following method : Cut from thin card two circular discs 3½ in. in diameter to form the ends, and then obtain an oblong sheet of tissue paper 6 in. wide by 12 in. long to form the cylindrical side. Cut a hole 2 in. in diameter in the centre of the disc that is to form the top end and fit a handle of wire to it. Form a cylinder with the tissue paper using the two discs as ends, and then lap the tissue paper about ½ in. over each end and paste it down. The candle should be about 3½ in. long and ⅜ in. in diameter (Stores Ref., Met. 566). The weight of the lantern plus candle should be about 10 gm.

When adjusting the free lift of the 70-in. balloon the lantern and candle should be attached to the balloon and the filler plus weight B used. When the balloon is correctly inflated the lantern should be firmly attached by means of about 5 ft. of thread. If there is an appreciable amount of wind it is useful to include 2–3 ft. of thin (about ¾ mm. square) bare elastic in the suspension of the lantern. This will make a successful launch easier.

The candle of the lantern should always be lit when it is at some distance from the balloon. The lantern is collapsed to allow the candle to be lit and stuck on the bottom piece of cardboard, after which the lantern is pulled out again slowly and smoothly. When launching the balloon a sheltered spot should be chosen, and the balloon allowed to rise slowly until the thread is fully stretched, and then the lantern should be released. If the release is taking place from the roof of a building it may be possible to let the lantern over the side whilst holding the balloon and then release the combination together. Whichever method is adopted the release should be made smoothly to avoid jerking which might extinguish the candle.

The light of the lantern can be followed with the naked eye or with a theodolite. If the cloud is broken care must be taken not to confuse it with a star.

The accuracy of this method depends primarily on how closely the actual rate of ascent of the balloon approximates to the assumed rate. In practice, because of ascending and descending currents and variations in the size and weight of the balloons the errors may be 12 per cent. or more on 10 per cent. of the occasions. The 36-in. balloons, which are often not truly spherical, may be even more inconsistent.

10.3. MEASUREMENT OF CLOUD MOVEMENT

The measurement of the direction and speed of cloud movement is important because thereby information is obtained about the wind at the level of the cloud.

When, however, observations can only be made from one point, it is not possible to determine the true speed of the cloud without at the same time knowing its height. It is, however, possible to measure the angular velocity, ω, of the cloud about a point on the earth's surface vertically beneath the cloud (even though the observer is not himself vertically beneath the cloud). If the height of the cloud, h, is then known its speed, v, can easily be obtained from the equation

$$v = \omega h .$$

The angular velocity of the cloud is called the velocity-height ratio of the cloud and the unit normally used is radians per hour.

The direction of the cloud movement may be obtained easily by sighting a prominent portion of the cloud against a fixed point, and then after a period of 5–10 min. or so sighting the same part of the cloud against the same fixed object. The direction in the horizontal plane in which the eye has had to be moved is the direction from which the cloud is moving. To determine the direction of movement and the velocity-height ratio of the cloud accurately, however, a suitable instrument is required. Such instruments are known as nephoscopes, and may be quite simple in operation. There are two main types : direct-vision nephoscopes and reflecting nephoscopes. In the first, the motion of the cloud is observed and measured directly, while in the second the motion of an image of the cloud in a horizontal plane mirror is observed.

If the absolute speed and direction of cloud is required, observations with theodolites or similar instruments must be made simultaneously from at least two positions. This can be done, but the apparatus required is complex and is not often used. This section is confined to single-station observations.

10.3.1. Besson comb nephoscope

The Besson comb nephoscope (Stores Ref., Met. 161) consists of a vertical brass spindle B bearing at its upper end a cross-piece A 3 ft. long to which seven equidistant vertical spikes are attached, like the prongs of a comb (Fig. 124). The spindle is carried by a number of bearing brackets attached to a pillar of galvanized-iron channel D and is free to rotate about its own axis. Attached to the spindle is a conical direction plate F ; this is to show the direction in which the comb is pointing by reference to the edge of a vertical indicating strip. The compass plate is engraved in degrees from 0° to 360°.

The height of the comb can be adjusted by loosening the milled-head screw which fixes the bearing boss G in position on top of the lowest bearing bracket C. The bracket contains a ball race which bears the main weight of the moving parts. An eye-level boss E is fixed to the spindle above the compass plate and this should be exactly 60 in. below the top of the centre spike (for reasons which will become apparent later).

A cross-piece is fixed to the spindle below the lowest bearing bracket and has attached to it the ends of a 12-yd. loop of cord so that the spindle and comb can be moved from a distance. When not in use the cord is looped around two cord brackets on the main pillar.

Installation.—The nephoscope should be mounted on a firm vertical wooden post at least 5 ft. high and in an open position with a good view of the sky, and

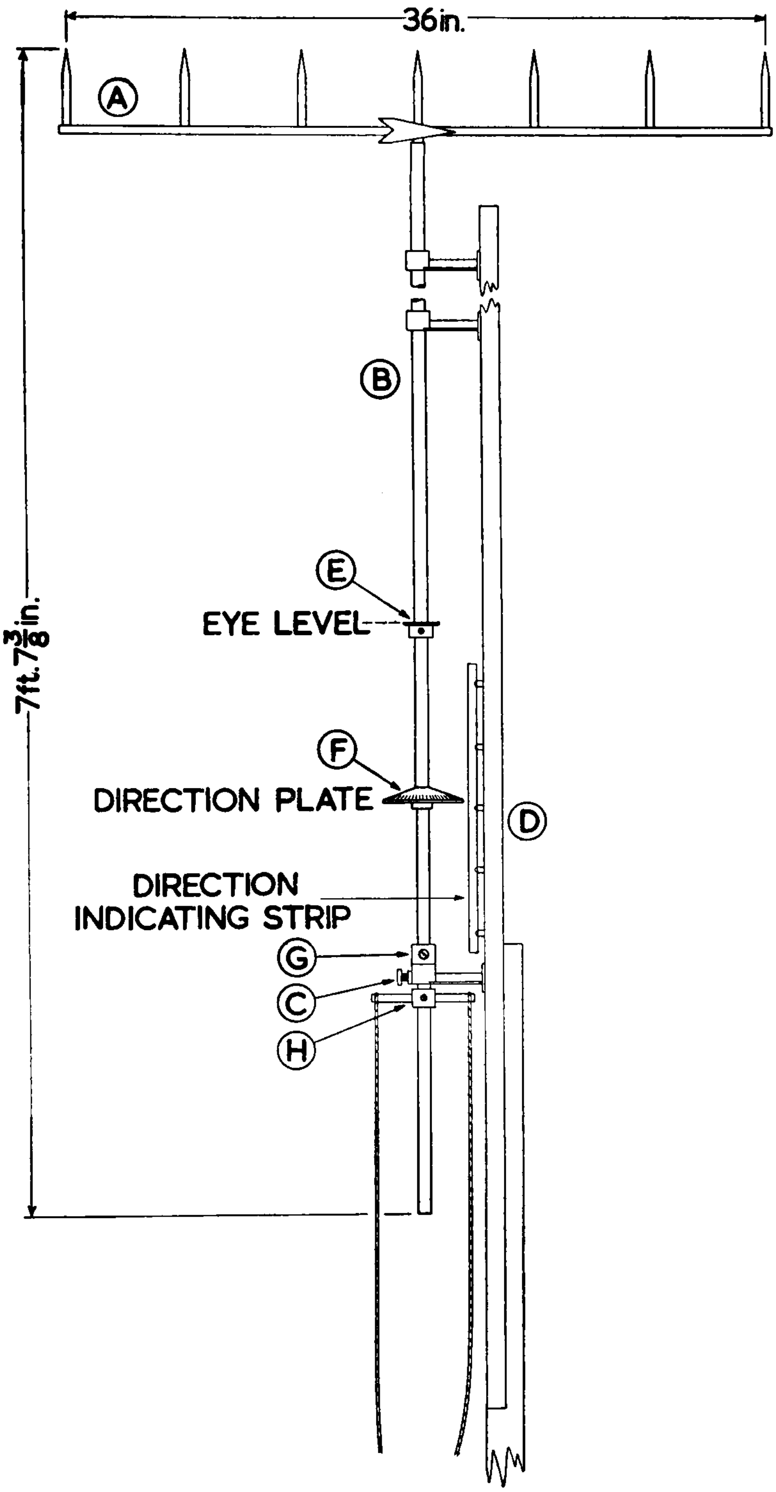


FIG. 124—BESSON COMB NEPHOSCOPE

so that the base of the pillar is between 1 ft. 6 in. and 2 ft. 6 in. above ground level. Screw holes will be found in the iron pillar, and it is an advantage if a narrow rectangular piece of wood of cross-section not exceeding $1\frac{1}{8}$ in. × $\frac{13}{16}$ in. can be fitted to the main post, over which the pillar itself can fit. The spindle and pillar of the nephoscope must be vertical when in position. Before actually erecting the instrument it should be checked that the spikes are in fact 6 in. apart and the eye-level boss is 60 in. below the top of the centre spike. If the spikes are not 6 in. apart, but instead x in., say, the eye-level boss should be at a distance equal to

$10x$ in. below the tip of the centre spike ; if necessary, the position of the eye-level boss should be adjusted, and once adjusted it should not thereafter be altered.

Having erected the nephoscope the compass plate should be adjusted. The rod should be turned until the comb is pointing at some prominent object whose true bearing is known. The screw fixing the compass plate should then be slackened and the compass plate turned until the reading opposite the indicating strip is equal to the bearing of the object at which the comb is pointing $\pm$ 180° ; i.e. when the comb is pointing due north the reading is 180°. The holding screw should then be tightened. There is a small arrow on the base of the comb pointing in a horizontal direction, and this should be used to avoid an ambiguity of 180°. The milled-head screw on the bearing boss should then be loosened and the spindle moved vertically until the eye-level boss is at the average eye level of the observers who will use the nephoscope.

Method of use.—When using the nephoscope, the observer adjusts his own position, and that of the comb, as detailed below, until the cloud appears to move along the tips of the spikes. The time, t, for the cloud to appear to move from one spike to the next is then observed. The compass plate will show the direction of the cloud movement, and the velocity-height ratio can be calculated from the constants of the instrument and the observed time. If a is the distance apart of the spikes and b is the vertical distance from the top of the central spike to the observer's eye level, then the velocity-height ratio (by simple geometry) is given by $a/(bt)$. If t is measured in seconds, the velocity-height ratio $=$ 3,600 $a/(bt)$ radians per hour.

If the instrument has been adjusted as described above and the observer's eye level is at the same height as the eye-level boss then

$$\frac{a}{b} = \frac{1}{10}$$

and the velocity-height ratio $= \dfrac{360}{t}$ radians per hour.

The following detailed procedure should be employed :

(i) If the observer's eye level is not within 3 in. of the eye-level boss, the milled-head screw on the bearing boss should be loosened, and the rod carrying the comb raised or lowered until the eye-level boss is at the same level as the observer's eye. Do not under any circumstances move the eye-level boss up or down the rod.

(ii) Sight a prominent piece of the cloud, whose movement is to be measured, in line with the tip of the central spike and from then on keep the head still. Start a stop-watch at this instant.

(iii) Move the comb by means of the loop of cord or " reins " until the cloud appears to move along the tips of the spikes in the direction of the small arrow, and then stop the stop-watch when the piece of cloud being observed appears in line with the tip of another spike. In this way obtain the time t in seconds for the cloud to appear to move from one spike to the next.

(iv) Read the direction of the cloud movement from the compass plate against the indicating strip and obtain the velocity-height ratio from Table XLIII against the appropriate value of t. This table gives the value of $360/t$.

TABLE XLIII—VELOCITY-HEIGHT RATIO FOR VARIOUS TIMES OF TRAVERSE OF THE CLOUD FROM ONE SPIKE TO THE NEXT OF A BESSON COMB NEPHOSCOPE

t	Seconds									
	0	1	2	3	4	5	6	7	8	9
sec.	*radians per hour*									
00	..	360	180	120	90	72	60	51	45	40
10	36	33	30	28	26	24	23	21	20	19
20	18	17	16	16	15	14	14	13	13	12
30	12	12	11	11	11	10	10	10	9	9
40	9	9	9	8	8	8	8	8	7	7
50	7	7	7	7	7	7	6	6	6	6
60	6	6	6	6	6	6	5	5	5	5

It is most important that the initial sighting should be on the central spike, because if the cloud is sighted first on a spike other than the central one and the comb is then rotated so that the cloud is sighted on another spike, the reading on the compass plate does not give the direction of the motion of the cloud correctly. The reading would only be correct in these circumstances if the nephoscope as well as the observer were to remain stationary between the sighting on one spike and the next. It should be noted that even if the observer does not succeed in turning the nephoscope so that the cloud is sighted on the first or second spike from the centre, the observations will still be accurate if he sights it on the third spike provided he sighted it accurately on the central spike in the first place.

It is also most important that the head should be kept still during the observation. Some form of eye steadier can be used with advantage, and this can often be improvized locally. A device designed by Whipple consisted of a small ring at the end of a pole which could be stood on the ground. The last few feet of the pole was made of flexible metal tubing so that the ring could be adjusted for observers of different heights.

Maintenance.—The nephoscope should be kept clean and the bearing brackets oiled at intervals of three months or so, particularly the lowest bearing bracket which contains the ball bearings which support the weight of the instrument. The orientation of the compass plate should be checked from time to time.

Accuracy and sources of error.—The basic design of this instrument has been unchanged since its introduction by Louis Besson in 1897, but the detailed design has been greatly improved with a view to providing a more reliable and robust instrument which could be handled easily. The main difficulties in its use that still arise, however, are in the arrangements for turning the comb and in the necessity to keep the head stationary. The cross-piece and " reins " method is very simple, but the force required to move the comb varies with the relative position of comb and observer, and in some positions is rather too large for easy manipulation. In addition the cord can foul the main supporting post when the cloud being observed is in certain positions. The difficulty of keeping the head stationary in the absence of a suitable eye steadier has already been mentioned.

10.3.2. Fineman nephoscope Mk II

The Fineman nephoscope Mk II (Stores Ref., Met. 160) is an example of the reflecting nephoscope (Fig. 125). It consists essentially of a mirror A made from

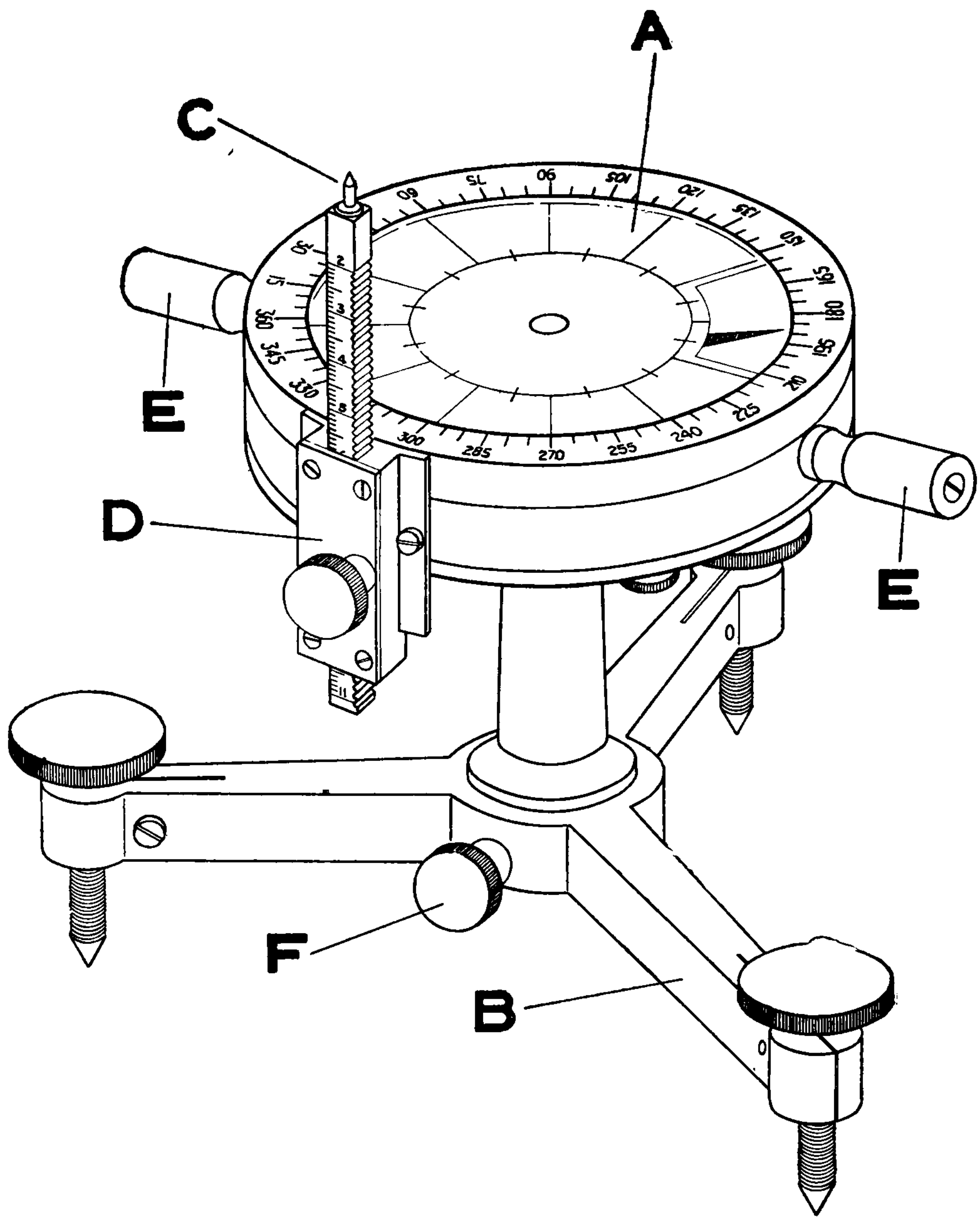


FIG. 125—FINEMAN NEPHOSCOPE MK II

a disc of black glass, mounted on a tripod stand B which is fitted with levelling screws. The glass disc is fitted in a circular brass mount engraved with a scale of degrees from 0° to 360° and the whole can be rotated about a vertical axis through its centre. The main divisions of the scale are continued on the glass disc as radial lines, filled white. Beneath the glass disc is mounted a compass needle, the tip of which can be viewed through a small window of clear glass, near the edge of the black glass mirror. On the surface of the mirror are engraved two concentric circles, filled white and with radii differing by 25 mm.. A vertical pointer C, which can be raised or lowered by a rack and pinion motion D, is attached to the perimeter of a circular collar which can be rotated, independently of the mirror, by the knobs EE about the common vertical axis. A scale of millimetres is engraved on the edge of the pointer to give the height of the pointer tip above the glass surface.

Method of use.—The instrument should be placed in such a position that the image of the cloud whose movement is to be measured can be viewed in the mirror.

A window sill is often convenient or any approximately horizontal flat surface out of doors may be used. The instrument should be levelled by using the levelling screws on the stand, and a circular spirit-level placed on the mirror as a reference, and then orientated so that the graduations on the mirror and its brass mount indicate the corresponding true directions. To do this latter the compass needle is unclamped, by loosening a screw beneath the top of the instrument, and the mirror mount rotated until the south pole of the compass needle (painted black) is seen through the clear-glass window in the mirror and points to the true direction of magnetic south, the screw or clamping lever F at the base of the tripod having been loosened first. In this country the direction of magnetic south is 180° minus the westerly declination for the particular time and place. Further information about magnetic declination is given on p. 419.

The observer should station himself so that the image of a prominent part of the cloud to be observed appears in the centre of the mirror. The pointer should then be rotated and its height adjusted until the image of its tip in the mirror also appears in the centre of the mirror. It is helpful if, by slight adjustment of the observer's position, the height of the tip of the pointer can be made an even number of millimetres above the mirror. This done, the observer should keep the images of the

TABLE XLIV—VELOCITY-HEIGHT RATIO OF CLOUDS IN TERMS OF FINEMAN-NEPHOSCOPE OBSERVATIONS MADE WITH INSTRUMENTS IN WHICH THE DIFFERENCE BETWEEN THE RADII OF TWO CONSECUTIVE CIRCLES IS 25 MM.

Height of pointer tip	Time for the image seconds to travel from one circle to the next															
	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
mm.	*radians per hour*															
30	60	50	43	37	33	30	27	25	23	21	20	19	18	17	16	15
32	56	47	40	35	31	28	26	23	22	20	19	18	17	16	15	14
34	53	44	38	33	29	26	24	22	20	19	18	17	16	15	14	13
36	50	42	36	31	28	25	23	21	19	18	17	16	15	14	13	12
38	47	39	34	30	26	24	22	20	18	17	16	15	14	13	12	12
40	45	37	32	28	25	23	21	19	17	16	15	14	13	13	12	11
42	43	36	31	27	24	21	19	18	16	15	14	13	13	12	11	11
44	41	34	29	26	23	20	19	17	16	15	14	13	12	11	11	10
46	39	33	28	24	22	20	18	16	15	14	13	12	12	11	10	10
48	38	31	27	23	21	19	17	16	14	13	13	12	11	10	9·9	9·4
50	36	30	26	22	20	18	16	15	14	13	12	11	11	10	9·5	9·0
52	35	29	25	22	19	17	16	14	13	13	12	11	10	9·6	9·1	8·7
54	33	28	24	21	19	17	15	14	13	12	11	10	9·8	9·3	8·8	8·3
56	32	27	23	20	18	16	15	13	12	12	11	10	9·5	9·0	8·5	8·0
58	31	26	22	19	17	15	14	13	12	11	10	9·7	9·1	8·6	8·1	7·8
60	30	25	21	19	17	15	14	13	12	11	10	9·4	8·8	8·3	7·9	7·5
62	29	24	21	18	16	15	13	12	11	10	9·7	9·1	8·5	8·1	7·6	7·3
64	28	23	20	18	16	14	13	12	11	10	9·4	8·8	8·3	7·8	7·4	7·0
66	27	23	19	17	15	14	12	11	10	9·8	9·1	8·5	8·0	7·6	7·2	6·8
68	26	22	19	17	15	13	12	11	10	9·5	8·8	8·3	7·8	7·4	7·0	6·6
70	26	21	18	16	14	13	12	11	9·9	9·2	8·6	8·0	7·5	7·1	6·8	6·4
72	25	21	18	16	14	13	11	10	9·6	8·9	8·3	7·8	7·3	6·9	6·6	6·2
74	24	20	17	15	14	12	11	10	9·4	8·7	8·1	7·6	7·1	6·8	6·4	6·1
76	24	20	17	15	13	12	11	9·9	9·1	8·5	7·9	7·4	7·0	6·6	6·2	5·9
78	23	19	16	14	13	12	10	9·6	8·9	8·3	7·7	7·2	6·8	6·4	6·1	5·8
80	23	19	16	14	13	11	10	9·4	8·8	8·0	7·5	7·0	6·6	6·3	5·9	5·6

cloud and pointer tip in coincidence by moving his head. The point on the circumference at which the cloud appears to leave the mirror gives the direction from which the cloud is coming. The velocity-height ratio is determined by noting the time required for the image to appear to travel from the inner mirror circle to the outer and at the same time noting the height of the pointer tip above the mirror.

If a be the difference between the radii of the circles, b be the height of the tip of the pointer above the reflecting surface and t be the time required for the cloud image to travel the distance a, then the velocity-height ratio is equal to $a/(bt)$. If t is measured in seconds the velocity-height ratio is $3{,}600a/(bt)$ radians per hour. In this instrument a is 25 mm. Table XLIV gives the value of the velocity-height ratio corresponding to $a = 25$ mm., values of b from 30 to 80 mm. and values of t from 50 to 200 sec. For values of b and t outside this range, multiply the actual values of b or t by a simple factor so as to bring it within the compass of the table and multiply the corresponding tabulated value of the velocity-height ratio by the same factor to obtain the correct result.

It will be seen that the time required to make an observation is smaller when the tip of the pointer is high, than when the tip of the pointer is low.

Maintenance.—Little maintenance is required beyond keeping the instrument clean and applying a little clock oil to the moving parts at intervals of three months or so. It should always be replaced in its box after use.

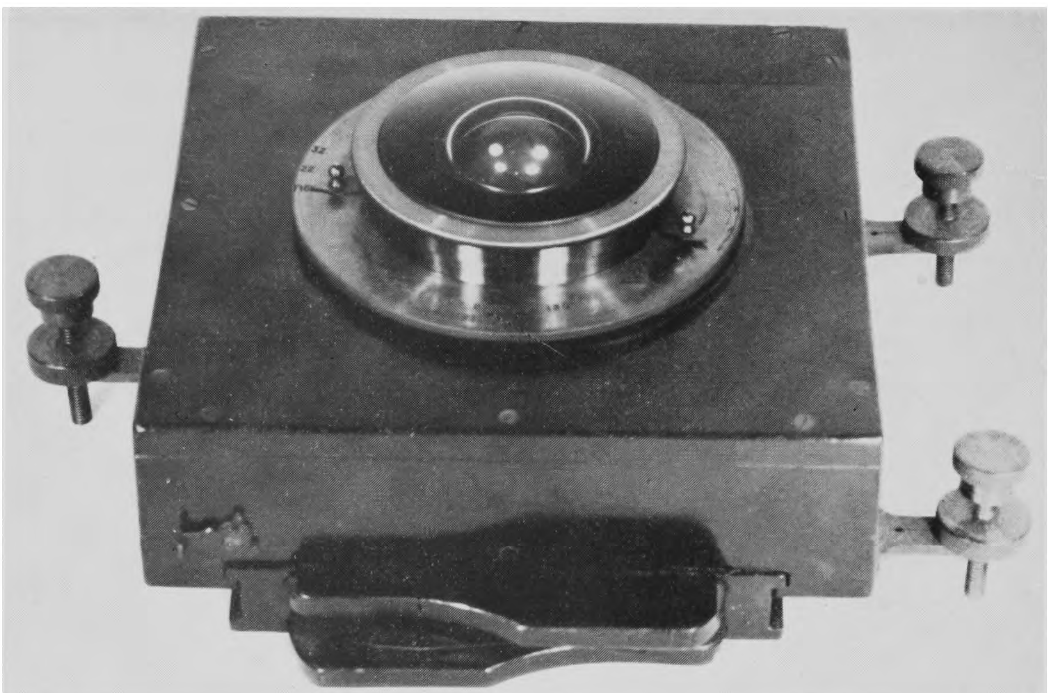
Accuracy and sources of error.—This nephoscope is somewhat easier to operate than the Besson comb nephoscope because it is not essential to keep the head in exactly the correct position throughout the observation. The only times when this is essential is at the beginning and the end of the observation. It is therefore easier to get accurate results from clouds with a small velocity-height ratio.

10.4. CLOUD PHOTOGRAPHY

The following section is intended mainly as a guide to indicate some of the changes from normal photographic practice which the taking of cloud photographs requires. It does not set out to give complete instructions for the taking of the photographs, and should be used in conjunction with the normal sources of information about photography.

All black and white photographs (i.e. prints) are basically pictures built up of various shades of white, through grey to the complete absence of white (i.e. black). Actual cloud scenes, however, in addition to a brightness contrast (corresponding to the print) usually have the extra factor of the colour contrast between the (more or less) blue sky and the white or grey clouds. The colour contrast may be present even if there is no appreciable brightness contrast, and this has to be rendered in the final print.

The colour contrast between the sky and the cloud can be reproduced on the print as a brightness contrast by using a coloured filter in front of the camera lens and either panchromatic or orthochromatic film or plates. The variation in



HILL'S CLOUD CAMERA

sensitivity of modern panchromatic films and plates with wave-length is, however, practically the same as that of the average human eye, and they are not predominantly sensitive to the shorter wave-lengths at the blue end of the visible spectrum as are ordinary films or (to a less extent) orthochromatic films. A filter is therefore only required, normally, to emphasize the contrast between the cloud and the sky. For most types of sky with broken cloud, where there is already an appreciable brightness contrast present, a pale yellow filter can be used with good effect, but for very thin cirrus clouds against a blue sky it is often necessary to use a deep red filter (and panchromatic film). In this latter case the blue sky can be rendered nearly black on the final print with the clouds showing up plainly. For intermediate subjects a deep yellow or orange filter may be used. If a filter were not used in the case of the very thin cirrus clouds they would be almost impossible to photograph successfully because of the small brightness contrast between them and the sky. If considerable haze is present so that the sky is blue-white instead of blue the filter will not have so much effect, i.e. a deep red filter may be required in place of a yellow filter.

Particular attention must be paid to the exposure given to the film. The range of brightness in an ordinary landscape including clouds and sky is very great, and thus an accurate exposure is required, but if attention is concentrated on the clouds and sky alone there is more latitude. As a rough guide it may be assumed that the exposure necessary is about one tenth of that which would be given to a distant landscape under the same conditions of illumination. Allowance must however be made for the effect of any filter used. The manufacturers of the filter will supply the necessary factor by which the exposure should be multiplied, but it should be realized that this factor varies with the type of film material used, and should also be adjusted if the predominant illumination has a different spectral distribution to the normal ; e.g. at sunset the factor of a red or yellow filter would often be reduced.

The best type of film material to use is one of the slower-speed fine-grain panchromatic types, but good results can be obtained with other material in cases where there are large brightness contrasts. When the sky is completely overcast a filter does not help, and reliance must be placed on correct exposure and development. When using colour film a filter should not of course be used. Very careful attention to exposure is required with these films to obtain a good rendering.

Cloud negatives must be developed and printed correctly but no special technique is required.

10.4.1. Hill's cloud camera

An ingenious lens for taking photographs of the whole sky was described by Hill[77] in 1923, Plate XLVII, the whole hemisphere being projected on to a flat plate. There is, inevitably, distortion in such a photograph when compared with a normal cloud photograph, but it enables a clear picture of the whole sky to be obtained.

CHAPTER 11

MARINE OBSERVATIONS

This chapter describes the differences between the instruments employed for making meteorological observations on board ships and their method of use, and those used for normal land-based observations. Reference should be made to the previous chapters for detailed description of instruments which are common to both land and sea use.

It is more difficult to obtain accurate observations at sea than on land, because the presence and movement of the ship change the condition and flow of the surrounding air and also directly affect some instruments themselves. Great care is required to obtain observations which are representative of the conditions in the surrounding free air and water. Instruments for ordinary marine use have to be especially robust in construction and simple to operate, because observations at sea (apart from those made on ocean weather ships and certain naval vessels) are not usually made by trained meteorologists and the weather conditions under which they have to be used tend to be more severe and are certainly more varied than at most land stations. Much useful information is given in the " Admiralty weather manual "[78] and in the " Marine observer's handbook "[79].

11.1. MEASUREMENT OF PRESSURE

The methods of measuring pressure are generally similar to those used on land and most of the detailed description will be found in Chapter 2. Except in small trawlers where there is only room for an aneroid, all British " selected " ships are supplied with mercury barometers.

11.1.1. Mercury barometers

The Meteorological Office Kew-pattern marine barometer has been fully described and details of its installation, method of use, maintenance, sources of error and reduction of the readings given in Chapter 2. In most cases it will be found convenient and sufficiently accurate to use the Gold slide (p. 32) to obtain the necessary correction to the observed reading.

11.1.2. Aneroid barometers

A precision aneroid barometer (p. 18) is a very suitable instrument for measuring pressure at sea, because it can be made less sensitive to mechanical acceleration, produced by the rolling and pitching of the ship, than a mercury barometer, and thus there is less pumping. The main objection to its use is its liability to zero drift (especially when new). Consequently it should be compared frequently with a mercury barometer (at least once a month and more often of possible). Details of the construction of aneroid barometers and the methods used for compensating for temperature changes are described on p. 59. Aneroid barometers of the required stability and precision are under development.

11.1.3. Barographs

All " selected " ships are supplied by the Meteorological Office with an aneroid barograph to keep a record of the pressure and to indicate the barometric tendency for synoptic purposes. The problems encountered are described on p. 73 and a description is given of the oil-damped barograph, which is the most satisfactory instrument at present available for this purpose. This instrument enables records to be obtained which are of comparable quality to those obtained at land stations.

11.2. MEASUREMENT OF AIR TEMPERATURE AND HUMIDITY

The methods used on ships to measure the air temperature and humidity are generally similar to those used on land, but special attention has to be paid to the exposure of the thermometer. A single fixed screen, for instance, cannot always have the best exposure available, and is therefore seldom used at sea.

Wet- and dry-bulb mercury-in-glass thermometers are generally used to measure the humidity, and these may be either exposed in a louvered screen using the natural ventilation due to the wind and ship's motion, or used in an aspirated psychrometer of some kind.

For routine observations for synoptic purposes the British Meteorological Office recommend the use of a well exposed louvered screen ; but at sea, as on land, when measurements of high precision are required, an aspirated psychrometer should be used.

In either case, whether an aspirated psychrometer or a louvered screen is used, the exposure should be such that the air comes direct from the sea and has not passed over the ship at all. If this is impracticable the distance travelled over the ship should be a minimum. The instruments should be as high as possible above deck level. If the relative wind is light it may be almost impossible to obtain a measurement in air which is not seriously contaminated by the ship ; in these circumstances a temporary change of course would enable a satisfactory observation to be made.

11.2.1. Marine thermometer screen Mk III

The marine thermometer screen Mk III (Stores Ref., Met. 418) is a small white painted wooden screen with louvered sides, designed to house a pair of mercury-in-glass thermometers (Plate XLVIII). It has a stout metal ring fixed to the top of the roof so that it can be slung in a suitable position when an observation is required. The four sides have single louvers, and the outer roof of the screen is gable-shaped with a small air space between that and the top of the screen proper. Five holes drilled in the top of the screen allow the air to circulate freely. The base of the screen differs from the other types of thermometer screen in use in that it is louvered and does not consist of flat overlapping boards separated by an air space. There is only one door to the screen. The clear inside space is approximately 15 in. × 7 in. × 4 in.

The thermometers used are the porcelain or plastic mounted thermometers (Mk 1A, 1B or 1C according to the climatic conditions expected, see p. 110) mounted in air-thermometer protectors (see p. 122). The thermometer protectors are hung from two screws near the top of a mahogany thermometer support and are held in position in two recesses in the lower bar of the support by brass turn-buttons. A metal fitting fixed to the base of the screen is used to hold the water bottle for the wet-bulb thermometer.

Method of use.—Screens are normally mounted at bridge level, and preferably two screens should be fitted as far outboard as possible, one on each side of the bridge. If only one screen is available it should not be permanently mounted in one place, because the best site depends on the relative wind. Between 15 and 30 min. before the observation is required the screen should be slung in the best available site, chosen in accordance with the principles outlined above. The screen should be at least 5 ft. above deck level.

The care of the wet bulb, method of taking the readings and the calculation of the dew point, relative humidity and vapour pressure are fully described in Chapter 4. Because of the extra risk of contamination with sea spray, it is necessary to change the muslin caps on the wet-bulb thermometer more frequently than at a land station. It should be done at least once a week, and at any other time that it is expected that the wick has become contaminated with sea water.

Special care should be taken about the following points :

(i) The screen should be slung so that the sun cannot shine on the thermometers when the door of the screen is opened.

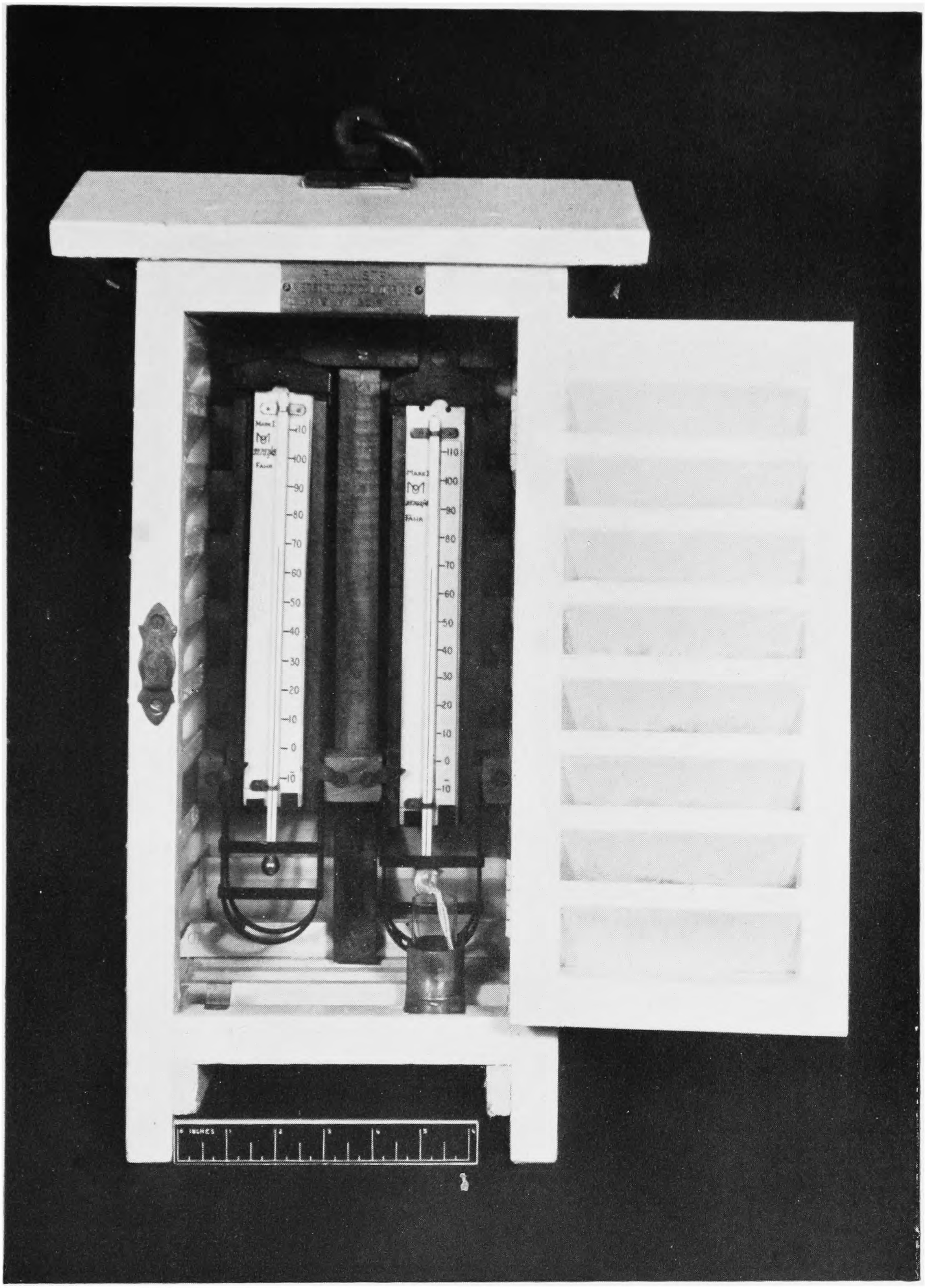
(ii) As the average wind speed in the screen is usually higher than in a similar screen at a land station the length of wick between the wet-bulb thermometer and the water bottle should be kept quite short (2–4 in. is suitable), and a cap fitted to the water bottle itself.

(iii) Wherever possible the orientation of the screen should be adjusted so that the dry-bulb thermometer is to the windward of the wet-bulb thermometer, to prevent the dry bulb being cooled by air which has passed over the wet bulb.

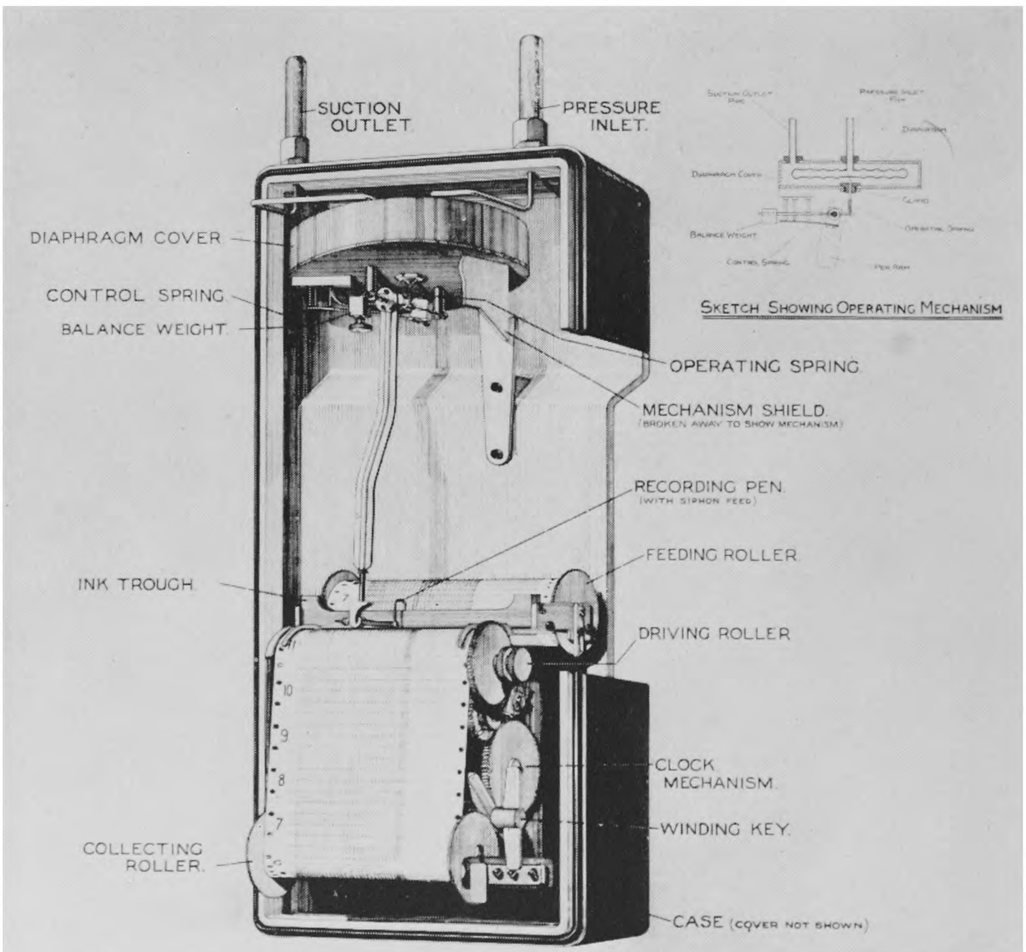
(iv) The bulb of the dry-bulb thermometer may in time become encrusted with salt which should be carefully scraped off as it will otherwise affect the reading.

Maintenance.—The screen should be kept clean and the paint renewed as necessary.

Accuracy.—Because of the motion of the ship and the stronger surface winds at sea the air flow through the screen will, in general, be greater than that through a screen on land under the same weather conditions. The errors due to radiation heating of the screen will therefore also, in general, be less than that of a similar screen on land except on days when the relative wind is light or zero. A more serious danger is, however, that the temperature of the air itself may be altered by contact with the ship before it reaches the screen, and on days when the relative wind is light or zero the error may be considerable. This can only be avoided by careful siting to give the best exposure.



MARINE THERMOMETER SCREEN MK III



DIAPHRAGM WIND-SPEED RECORDER

11.2.2. Marine thermometer screen Mk II

The portable marine screen Mk II (Stores Ref., Met. 419) is an obsolete model. The main points of difference between it and the marine screen Mk III are :

(i) The portable screen is larger and consequently heavier. The clear inside dimensions (without the thermometer support) are 14¼ in. tall by 13 in. wide by 11 in. deep.

(ii) The portable screen has not a double roof ; its flat roof consists of a single thickness of wood.

(iii) The floor of the portable screen is similar to that of the Stevenson screen and is not louvered.

The portable screen is used in the same way as the Mk III marine screen. It was superseded by the Mk III screen because of the factors outlined in (i) and (ii) above.

11.2.3 Aspirated psychrometers

Any of the latest patterns of Meteorological Office aspirated psychrometers may be used on ships ; the hand-aspirated psychrometer is especially convenient for routine use.

The place of observation with the aspirated psychrometer should be carefully chosen ; it will often be found practicable to rest the hand psychrometer on the rail at the windward side of the deck and point the perspex duct out over the sea. The duct should not, however, be pointed in the direction of the sun so that direct solar radiation can fall on the thermometer bulbs.

Full description and details as to the method of use of these psychrometers are given in Chapter 4. As with screen psychrometers special care must be taken at sea to avoid contamination of the wet bulb with sea-water spray, and if any doubt is felt the wet-bulb wick should be changed.

If an electrically aspirated psychrometer is being used it will normally be necessary to provide four brackets from which the instrument can be suspended, with a power point near each. These positions should be such that a good exposure can be obtained in all (relative) wind directions. The recommended positions are :

(i) One right forward so that the psychrometer hangs a few inches forward of the stem of the ship.

(ii) One right aft so that the instrument can hang a few inches over the stern.

(iii) One on each side of the fore bridge. These two should be as far over the sides of the bridge as is consistent with the thermometer being easily read.

In each case the bulbs of the thermometer should be at least 5 ft. above deck level. It is advisable to splice a lanyard to the psychrometer frame and attach the other end to the observer while the instrument is being used, as a precaution against possible loss overboard, but the lanyard should be at least 10 ft. long, so that the observer can get well away from the psychrometer while the thermometers are approaching the true air temperature.

11.2.4. Recording air temperature

A continuous remote record of the dry- and wet-bulb temperature can conveniently be made by means of the mercury-in-steel thermograph (dry and wet bulb). This instrument is fully described in Chapters 3 and 4.

The recorder should be mounted with the pen arms athwartships in a position as free as possible from vibration, moisture and dust. To help to diminish the effects of vibration the recorder should be placed on pieces of sponge rubber or pieces of rubber tubing. The movement of the recorder on the cushion will lead to a slight flexing of the capillary tubing, and an adequate length of tubing must therefore be left clear of the bulkhead. The screen housing the thermometer bulbs should be fixed in such a position in the ship that the best exposure possible is obtained for the greatest length of time. Normally a position on the foremast or high on the fore superstructure should be chosen. Having decided on the position of the recorder and of the screen the course to be taken by the capillary tubing should be decided. Any intervening decks or bulkheads should be drilled to permit the passage of the bulbs and compensators, which are nearly one inch in diameter. It should be remembered that on no account should the capillary tubing be cut.

The wick on the wet bulb should be changed at least once a week and more often when it is suspected that the wick has become contaminated with sea spray. The screen should be washed regularly.

11.3. MEASUREMENT OF SEA-SURFACE TEMPERATURE

11.3.1. General

Two methods of measuring sea-surface temperature are used ; in the first the temperature of the sea water is obtained by lowering a bucket overboard and measuring the temperature of the sample obtained ; in the second method the temperature of the sea water in the engine-room intake is measured. The temperature measured by the first method is approximately the average temperature of about the first 6 in. or so, while the second temperature is that at a depth which may be anything between 10 and 30 ft., depending on the size of the vessel and, in the case of a large ship, may be as much as 30 ft. when loaded and as little as 20 ft. when light. The difference in temperature between the surface and the depth of the intake may be appreciable when the sea is calm and the sun is shining brightly. Intake readings are also liable to certain siting errors. For these reasons the intake method is not normally recommended. In large ships travelling at speeds above 15 kt., the bucket method is not always practicable and in such cases the intake method has to be used.

Sources of error in making sea-temperature measurements with buckets.—Errors arise in bucket measurements chiefly from the following sources :

(i) The initial temperature of the bucket is generally different from that of the sea (E_B)

(ii) The water in the bucket may change its temperature before the reading is taken owing to the processes of heat exchange and evaporation (E_C)

(iii) The initial temperature of the thermometer is generally different from that of the sample (E_T)

(iv) Because of its thermal lag the thermometer may take an appreciable time to indicate the true temperature of the sample (E_L)

(v) If the thermometer has to be removed from the bucket when taking a reading it may no longer indicate the true water temperature (E_N)

(vi) The thermometer may have scale errors (E_S).

These errors can be minimized by good design of the bucket and thermometer, careful observation and the application of thermometer corrections as determined by the National Physical Laboratory. A rough indication of the probable magnitude of the important errors is given later.

11.3.2. Meteorological bucket Mk IIA

The meteorological bucket Mk IIA (Stores Ref., Met. 1200) is the form of bucket in general use.

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

Method of use.—The bucket should be let into the water forward of all outlet pipes after making fast to the deck rail or other firm support the rope connected to the bucket handle. After letting the bucket trail in the water for at least 30 sec., keeping the bucket just below the sea surface as far as possible, it should be withdrawn quickly, placed in the shade and out of the wind, the thermometer inserted in the bucket and the water vigorously stirred. The temperature recorded by the thermometer should then be read to the nearest $0{\cdot}1°$ F. when it attains a steady value (after about 30 sec.). The bulb of the thermometer should be kept well beneath the surface of the water throughout with continuous stirring, and the reading should be taken without undue delay as soon as the temperature of the thermometer becomes steady or the rate of change of temperature becomes less than $0{\cdot}1°$ F./min. ; the thermometer should not be withdrawn from the water until the reading has been taken. It is not advisable to keep the bucket trailing for longer than 1 min. as this period is more than sufficient to allow the bucket to take up the water temperature and any longer immersion shortens the life of the bucket.

Maintenance.—The bucket should be emptied completely after use and stored in the shade in as cool a place as possible.

Accuracy.—When using this bucket errors E_B and E_C may be large. E_B can, however, be reduced appreciably by taking a first sample, leaving it in the bucket for 2 min. together with the thermometer to be used, then removing the thermometer and emptying out the water and taking another sample quickly. If this procedure is followed carefully and the temperature read quickly as soon as the thermometer reaches a steady value the sea temperature should normally be obtained with an accuracy of about $\pm\ 0{\cdot}2°$ F.

11.3.3. Sea thermometer protector

The temperature of the water in the sea bucket may be measured with a porcelain mounted thermometer (p. 112) used in a sea thermometer protector (Stores Ref., Met. 405). This protector is similar to the air thermometer protector (p. 122), but with the open cage surrounding the thermometer bulb replaced by a metal cup of the same shape. This cup forms a reservoir for retaining a small quantity of the sea water around the bulb while the temperature is being read. This is very necessary since an ordinary porcelain mounted thermometer may on some occasions have to be withdrawn slightly from the bucket to enable it to be read, as, for example, when only a small sample is in the bucket. It is, however, preferable to read the temperature without withdrawing the thermometer from the bucket, whenever possible, and this can usually be done. The presence of the small reservoir makes it all the more necessary when using this thermometer to stir the water in the bucket vigorously with the thermometer before taking the reading.

In order to achieve the most accurate result it is desirable to take two samples of water when using this thermometer, and to immerse the thermometer in the first sample for about 2 min. before inserting it in the second sample, as the thermal capacity of the thermometer is comparatively high (equivalent to 35 gm. of water) and error E_T will be large if the thermometer temperature differs appreciably from the sea temperature. For example if the sample of water is 2,500 gm. (an average value) and the thermometer temperature differs from the sea temperature by 20° F. E_T would be 0·3° F. In the second sample the thermometer should be read after it has been immersed for about 30 sec.

11.3.4. Engine-room intake thermometer

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

Alternatively a thermometer can be held under a tap from the intake taking care that the bulb is completely immersed and holding it long enough to ensure that a correct reading is obtained. In many engine-rooms the intake pipe is inconveniently situated, and great care has to be taken to avoid parallax errors. The thermometer or the tap for taking water samples may also be situated a long way from the ship's side and in a very heated part of the engine-room, so that the temperature of the water is not the true sea temperature. This is one of the reasons why the intake temperature method of measuring sea temperature is not recommended when the bucket method is practical.

11.3.5. Mercury-in-steel thermograph (sea temperature)

The mercury-in-steel thermograph (sea temperature) (Stores Ref., Met. 909) has one thermometer bulb only, and, correspondingly, one Bourdon tube and pen arm. It is intended to record the sea temperature by the bulb being placed in the ship's condenser intake or in a special recess in the ship's side constructed to permit a flow of sea water past the bulb. In either case great care must be taken in choosing the site of the bulb to ensure that the temperature actually recorded is as representative as possible of the sea temperature and is as little affected as possible by the ship's temperature.

The care of the recorder and its method of use are similar to the mercury-in-steel thermograph (dry and wet bulb) and are dealt with fully on p. 144.

The range of these instruments varies ; some cover temperatures from 30° to 90° F., but some have the more extended range of 25° to 105° F.

11.4. MEASUREMENT OF SURFACE WIND

The measurement of the surface wind speed at sea is complicated by the effect of the motion of the ship. An anemometer or wind vane exposed on a mast, for instance, will respond to the " relative wind " which is the vectorial difference between the wind velocity and the ship's velocity. Thus, if, in Fig. 126, OA is the direction of the ship's track and OC represents its speed, and similarly OB represents the wind velocity, then the wind velocity experienced on the ship is given by CB and this is called the relative wind. To obtain the true wind from the relative wind it is necessary to combine the relative wind with the course and speed of the ship. This can be done graphically or by means of specially constructed tables, or automatically by means of a true-wind resolver (see p. 408).

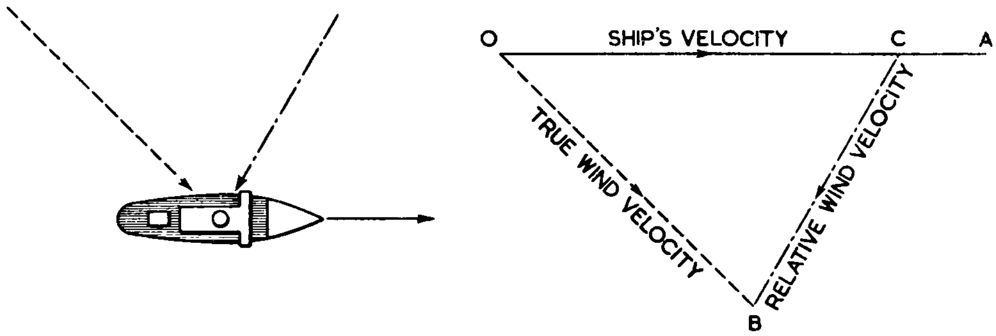


FIG. 126—DIAGRAM SHOWING RELATION BETWEEN TRUE WIND AND RELATIVE WIND

Most types of wind-velocity instruments as used on land could be adapted for use on ships. The exceptions are those instruments which are sensitive to the rolling and pitching motion of the ship (e.g. the cup contact anemometers Mk II and III with mercury switches). It is probable that the hand anemometer (p. 215) would be very useful where a permanent anemometer is not fitted. It is an advantage if a wind vane is fitted with some form of damping mechanism, either in the vane itself or in the indicator, to reduce the effect of fluctuations caused by the rolling and pitching of the ship. The wind vane will only indicate the direction of the wind relative to the ship's heading.

The exposure of anemometers and wind vanes should be chosen so that the effect of disturbances due to the ship and its superstructure are reduced to a minimum. This will usually entail mounting the anemometer or vane as high as possible. It should also be mounted as far forward as possible at this height since the relative wind will, on the average, have a component from ahead.

11.4.1. Diaphragm wind-speed recorder

The Diaphragm wind-speed recorder consists of a pressure-tube anemograph Mk II head (see p. 217) connected by pressure and suction tubes to a recording apparatus in which a sensitive aneroid pressure gauge operates a recording pen by means of a spindle and lever (Plate XLIX). The pressure gauge consists of a hollow diaphragm, which is connected to the pressure tube, and this is situated in a static box which in turn is connected to the suction tube. The difference in pressure between the inside and outside of the diaphragm causes it to be deformed and move the spindle. A spring on the pen arm which comes into contact with successive screws of different lengths makes the speed scale approximately uniform.

Details of the installation and operation of these instruments are given in the " Admiralty weather manual "[78]. The records are of relative wind, not true wind.

11.4.2. True-wind resolvers

Several different instruments have been developed for recording automatically the true wind. The information fed into this type of instrument is the relative wind speed and direction and the speed and direction of the ship's movement. The relative wind is resolved, either mechanically or electrically, into components along and at right angles to the ship's fore and aft line ; the appropriate correction is then made to the first component for the ship's speed and the two components are next re-combined to give the true wind speed and true direction relative to the ship's heading. A correction to the direction is then made for the direction of the ship's heading.

None of these true-wind resolvers has yet reached the stage of reliability at which it can be recommended for general use.

11.5. MEASUREMENT OF PRECIPITATION

The difficulties about measuring precipitation on a ship are that as the ship is not a steady platform the mouth of a gauge does not remain horizontal, and that no site on the ship is free from sea spray and reasonably sheltered from the wind yet unaffected by large obstacles. As the ship is normally in motion, any precipitation recorded will not be representative of one spot. In general it will also not be equal to the average fall over the track taken during the period under consideration. Nevertheless, if accurate measurement could be made by ships at sea they would be of great value for climatological work.

Experiments are proceeding with various types of rain-gauges at various sites aboard ships, and with various methods of estimating the percentage of sea water in the gauge.

11.6. MEASUREMENT OF VISIBILITY

The measurement of visibility at sea, like the measurement of precipitation, presents many more difficulties than the corresponding land observations. In general there are no fixed objects spaced at suitable distances from the ship which can be used to estimate the visibility in daylight and no lights which could be used at night. If other ships are within sight their distance is not usually known and has to be estimated.

The visibility-measuring instruments in which a base-line is used with a light at one end, e.g. the Gold visibility meter and the photo-electric visibility meter, need a longer base-line than the majority of ships can provide ; the air along the base-line is in any case very likely to be unrepresentative of the surrounding free air because of contamination by smoke, or heating by contact with the ship. The best instrument available at present is the Loofah hazemeter. This should be mounted in as free an exposure as possible so that the air reaches it with the minimum of contact with the ship. A description of this instrument and its method of use are given on p. 368. The Waldrum range meter (p. 360) can be used if a suitable object, such as a ship at a known distance, is available.

Failing a suitable instrument, and any suitable objects, the visibility has to be estimated by the appearance of the horizon and the general light conditions.

11.7. CLOUD OBSERVATIONS

Cloud observations at sea are similar to those on land, but the irregular movement and restricted space of a ship greatly limit the instrumental observation of cloud height and cloud movement. Balloons can be employed for cloud-height measurement using the time-of-ascent method, but their use is restricted to ocean weather ships and other ships with trained meteorologists, because of the objection to the stowage of hydrogen in merchant ships raised by the risk of fire, and because observations with balloons take more time than voluntary observers can spare from their normal duties.

The base-line available on most ships is too short for cloud-searchlight observations or for double theodolite ascents with a balloon, but the height of the cloud base can be obtained accurately from an ocean weather ship when a radio-sonde ascent is made.

Cloud-movement observations with normal-type nephoscopes are impossible, except perhaps in very calm conditions, but even then a height for the cloud would have to be assumed and a correction applied to the observed cloud velocity to make allowance for the ship's velocity.

CHAPTER 12

MISCELLANEOUS INSTRUMENTS AND ACCESSORIES

12.1. INSPECTOR'S KITS

12.1.1. Inspector's climatological kit Mk V

The inspector's climatological kit Mk V (Stores Ref., Met. 374) contains all the instruments, tools and equipment (apart from a mercury barometer) which are likely to be required when a meteorological station is inspected (Plate L). The following items are included in the kit :

Inspector's rain measure Mk II graduated in inches and millimetres for a 5-in. rain-gauge

Set of test gauges for a 5-in. diameter rain-gauge

Set of test gauges for an 8-in. diameter rain-gauge

Hook spanner for adjusting a sunshine recorder

Sphere centring gauge for a sunshine recorder

Inspector's thermometer (temperate range) with National Physical Laboratory certificate

Prismatic compass and clinometer with instructions for use

Spirit-level

Writing diamond

Various tools including a gimlet, plumber's penknife, pair of side-cutting pliers, pair of scissors, two screwdrivers, an adjustable wrench and a 2-ft. folding boxwood rule

Bottle of clock oil

Lampblack for renovating graduations on thermometers

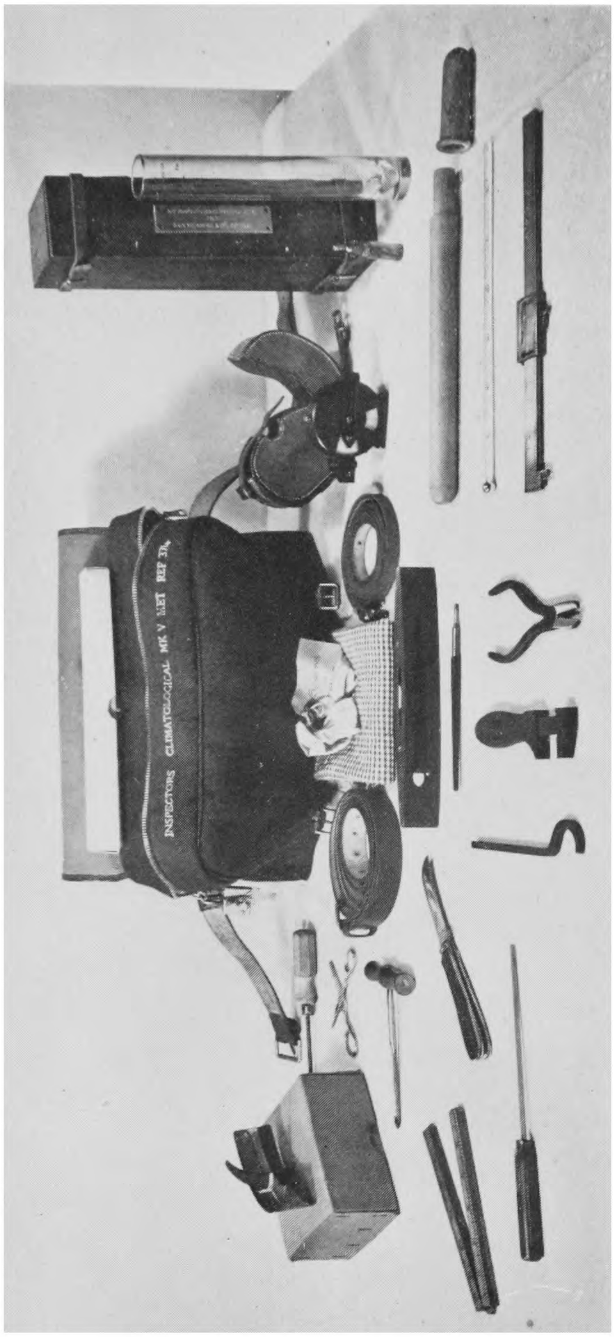
Packet of muslin and wick for wet-bulb thermometers

Household duster

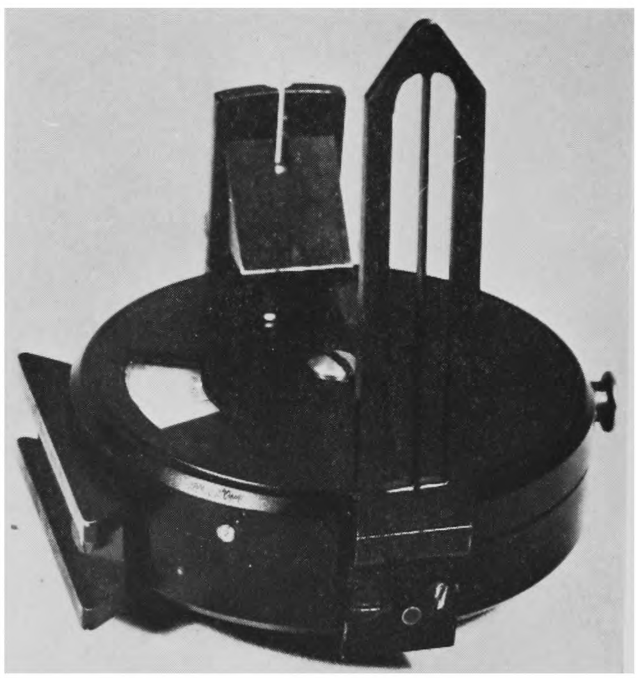
Various nails and screws

Copies of various Meteorological Office publications and forms, including the " Observer's handbook "[74].

These items are carried in a canvas bag with a zip fastener top and a covering flap fastened with leather straps. The bag is fitted with a leather carrying strap long enough to enable the bag to be carried over the shoulder. There are no inside compartments, and the miscellaneous tools are wrapped in the duster. If, in addition, a barometer is required this should be regarded as a separate item. A Kew-pattern station barometer graduated in inches and millibars (Stores Ref., Met. 501) is suitable.



INSPECTOR'S CLIMATOLOGICAL KIT MK V



CLINOMETER COMPASS

The test gauges are used to test the diameter of the apertures of rain-gauges. Each test gauge consists of a shaped steel strip, either one or two edges of which are accurately made to known lengths. A projection at each end of the strip enables the gauge to rest on top of the funnel of the rain-gauge while the measured edge projecting inside the funnel rim indicates a lower limit to the inside diameter. The first set of test gauges, Mk 1A, have strips with the following lengths :

No. 1. 5·025 in. and 4·975 in.
No. 2. 5·010 in. and 4·990 in.
No. 3. 5·000 in.

The second set, Mk 1B, have strips with the following lengths :

No. 4. 8·025 in. and 7·975 in.
No. 5. 8·010 in. and 7·990 in.
No. 6. 8·000 in.

The spanner hook consists of a square bar of tool steel with a semicircular hook at one end and a protruding pin near the end of the hooked portion.

The method of use of the clinometer compass is described on p. 418 ; the other instruments are straightforward or have already been described in earlier chapters, but the most important details in their use in testing instruments at a meteorological station however is outlined below.

12.1.2. Inspector's climatological kit Mk IV

This kit was in general use before the Mk V kit was introduced. The main differences between the Mk IV and the Mk V kit are

(i) The Mk IV kit is packed in a wooden case with separate compartments for many items.

(ii) The test gauges for ascertaining the diameter of rain-gauge funnels are not supplied in the Mk IV kit, but in their place is a 12-in. steel rule.

(iii) The rain measure in the Mk IV kit is only graduated in inches, but a special pipette is provided which can be used to test both inch and millimetre rain measures. The method of using the pipette is explained below (p. 416).

The main advantages of the Mk V kit over the Mk IV is that the Mk V kit is lighter (by about 3 lb.) and costs less.

12.1.3. Inspector's rainfall kit Mk VI

The inspector's rainfall kit Mk VI (Stores Ref., Met. 250) is for use when inspecting rainfall stations only. It contains the following items :

Inspector's rain measure Mk II graduated in millimetres and inches for a 5-in. rain-gauge
Set of test gauges for a 5-in. rain-gauge
Set of test gauges for an 8-in. rain-gauge
Spirit-level
Prismatic compass and clinometer
Writing diamond
1-ft. steel rule
Household duster.

It is not necessary to take this kit as well as an inspector's climatological kit Mk V, as the latter includes the equipment required for inspecting rainfall stations.

12.1.4. Inspector's earth thermometer kit Mk VII

The inspector's earth thermometer kit Mk VII (Stores Ref., Met. 1218) comprises an inspector's earth thermometer (Stores Ref., Met. 528), an armoured vulcanite tube to encase the thermometer (Stores Ref., Met. 529) and a steel pin to make holes in the ground for the vulcanite tube (Stores Ref., Met. 530). The use of this kit for inspecting earth thermometers has been fully described in the relevant section (p. 124).

12.1.5. Inspector's pressure-tube anemometer kit Mk VIII

The inspector's pressure-tube anemometer kit Mk VIII (Stores Ref., Met. 1228) contains the following items :

Portable manometer
Pressure inlet fitting
Spirit-level, 6 in.
Prismatic compass
Circular ivory protractor, 5 in. or 6 in.
Rubber bungs and rubber strip
Safety belt
Screwdriver, 6 in. × $\frac{5}{32}$ in.
Adjustable spanner, 12 in. or 9 in.
Spanner, 6 B.A.–8 B.A., D.E.
Spanner, 2 B.A.–4 B.A., D.E.
Pliers, 6 in. SC
Ball of sisal string
Household duster
$\frac{1}{2}$ lb. cotton waste.

The use of items of this kit in testing and calibrating pressure-tube anemometers has been described in the various sections on these instruments in Chapter 5.

12.2. TESTING INSTRUMENTS AT OBSERVING STATIONS

The detailed procedure for the inspection of an independent observing station by an official of the Meteorological Office is given in Form 3013, Notes for the guidance of inspectors. The following notes summarize the instructions for carrying out the instrument tests which are normally included in such inspections.

At official meteorological stations the instruments should be examined by the officer-in-charge at weekly intervals to ensure that they are being maintained in accordance with the instructions given in this Handbook, and Senior Meteorological Officers should include a general examination of the instrumental equipment in their normal six-monthly inspection of stations under their control.

12.2.1. Barometers

The inspector's barometer should be suspended close to, and as nearly as possible at the same level as, the station barometer ; if the cisterns are not at the same level the actual difference in height should be measured. The site of the station barometer should comply with the conditions outlined on p. 24; if this is not so, the inspector's barometer should be placed in the best position available. The barometer should then be left for as long as possible (at least an hour) to allow it to reach thermal equilibrium with its surroundings. If the station barometer is not mounted on gimbals its verticality should be tested and corrected if necessary.

The readings of the two instruments should be compared after making corrections to each reading for the temperature of the respective attached thermometers (using the table appropriate to the type of barometer and units used), and correcting the reading of the inspector's barometer for the appropriate index error as shown by the National Physical Laboratory certificate, interpolating as necessary, and for the difference in height between the two cisterns (if any). Table LVI or Table LVII should be used for the last correction; this should be added to the reading of the inspector's barometer if this instrument is above the station barometer, but subtracted if the reverse is the case. This correction can be obtained to the second decimal place in millibars by observing the correction for ten times the actual difference in height and dividing the result by ten. The attached thermometers should be read to the nearest 0·1° A. and any thermometer corrections allowed for.

If time permits, further readings should be taken at half-hourly intervals, and, if possible, in conditions of rising, steady and falling pressure. Readings should not, however, be taken if the outside wind is strong (force 5 or more) or if the pressure is changing rapidly (1 mb. an hour or more), as satisfactory comparisons cannot be made in these conditions. The precautions to be followed when making a reading are described in Chapter 2. The correction to the station barometer is given by the reading of the inspector's barometer minus the reading of the station barometer.

If the correction is large and positive there may be air in the tube. This can be tested by slowly inclining the barometer and listening for the " click " as the mercury meets the top of the tube. If this is distinct the vacuum is satisfactory, but if it is muffled, air is probably present above the mercury. Air bubbles can sometimes be seen at the top of the tube if the cap is removed (see p. 51). It is important that the illumination of the barometer tube should be adequate (see p. 24).

An example of the calculations involved is given below for a Meteorological Office Kew-pattern barometer graduated in millibars. A similar procedure should be used for barometers of other types. It will be seen that the corrections are worked out to the second decimal place in millibars before rounding the total to the nearest tenth of a millibar. If an inch barometer is being tested the computations should be made to the nearest 0·001 in.

The variation of gravity with latitude and height is neglected. The correction for this last factor need not be applied since it affects both barometers equally.

The inspector's barometer has the following index corrections (from National Physical Laboratory certificate) :

900 mb.	− 0·1 mb.
950 mb.	− 0·1 mb.
1000 mb.	− 0·1 mb.
1050 mb.	− 0·2 mb.

The cistern of the inspector's barometer is 6 ft. below the station barometer being tested.

Inspector's barometer (Meteorological Office Kew-pattern) reading	= 1025·4 mb.
Attached thermometer reading	= 291·2° A.
Correction to attached thermometer	= + 0·1° A.
Therefore corrected attached thermometer reading ..	= 291·3° A.
Index error of barometer	= − 0·15 mb.
Correction for difference in height between station and inspector's barometer (air temperature = 291·3° A. = 65° F. approx.)	= − 0·21 mb.
Temperature correction of barometer	= − 1·10 mb.
Therefore true pressure at the level of the station barometer = 1025·4 mb. + (− 0·15 − 1·10 − 0·21) mb. ..	= 1023·9 mb.
Station barometer reading (Meteorological Office Kew-pattern)	= 1024·8 mb.
Attached thermometer reading	= 291·6° A.
Correction to attached thermometer reading	= 0·0° A.
Temperature correction of barometer	= − 1·15 mb.
Therefore reading of station barometer after applying temperature correction = 1024·8 − 1·1	= 1023·7 mb.
Therefore correction to station barometer = 1023·9 — 1023·7	= + 0·2 mb.

12.2.2. Thermometers

An inspector's thermometer should be used to test other thermometers in a large water bath whose temperature is constant. A large bucket nearly full is suitable. Constancy of temperature can be achieved by making the temperature of the bath equal to, or slightly below, the air temperature and shielding it from radiation from the sun and sky (preferably by taking it indoors if the illumination is sufficient) and keeping it well stirred. In any case the thermometers must be shielded from radiation during the test.

The inspector's thermometer and the thermometer under test should be held with their bulbs as near to each other as possible, and immersed in the bath up to the top of the liquid column ; they should be left there for at least two minutes before a reading is taken, keeping the bath well stirred all the time. When taking a reading it is important that the stems should be kept immersed so that as much of the liquid columns as possible is under water, but the tops of the columns should be clear of the water surface. The stems should be perpendicular to the line joining the eye and the top of the liquid column, to avoid parallax errors. A series of readings should be taken and the final steady difference between the two readings noted. After applying any necessary correction to the reading of the inspector's thermometer (obtained from the National Physical Laboratory certificate) the necessary correction to the thermometer under test can be obtained.

When large errors are found the cause should, if possible, be ascertained. The errors to which spirit thermometers are liable are discussed on p. 88, and the ways of dealing with some of them are outlined. With ordinary mercury thermometers the mercury column should be examined for breaks, and, if found, the column should be rejoined if possible by shaking the mercury down gently. If any causes of error are remedied the thermometer should be re-tested afterwards.

Special care is needed with a maximum thermometer. Before testing it in the water bath the temperature indicated by it must be below that of the bath itself. This can be accomplished by inserting the thermometer in the bath as a preliminary measure, withdrawing it and waving it around vigorously in the air, and finally re-setting it. It should then indicate approximately the wet-bulb temperature of the air, which should normally be sufficiently below the temperature of the bath for the purpose.

Earth thermometers of the Symons pattern should be left in the bath at least 30 min., and preferably 60 min., before taking a reading. Right-angled mercury-in-glass earth thermometers must be tested *in situ* (to avoid disturbing the site) with a special inspector's earth thermometer. A hollow vulcanite tube with a metal base is inserted in the ground to the correct depth about an inch from the earth thermometer, and the special inspector's thermometer lowered inside it so that its bulb is level with the bulb of the earth thermometer. A steel pin is provided for making the necessary hole in the ground. Marks are placed on the outside of the hollow tube at 4 in. and 8 in. above the base. Water at a temperature equal to that of the earth thermometer or midway between that indicated by the two earth thermometers (the 4-in. and the 8-in. ones), if both are close together, should be poured gently so that it runs down the earth thermometer stems. This helps to stabilize the readings and provides good thermal contact between the inspector's thermometer and those under test. The comparison between the readings can then be carried out.

If the corrections to the earth thermometers found in this way are greater than 0·5° F. the thermometers should be removed and tested in a water bath. Causes of error in these thermometers have been discussed on p. 124 together with the methods of remedying some of them.

12.2.3. Sunshine recorders

The method of installing these instruments has been described on p. 308. When an instrument is badly out of adjustment it will be necessary to re-set the instrument properly, but in view of the difficulty in adjusting a sunshine recorder with accuracy at a single attempt it is, in general, better not to interfere with an instrument which is only slightly out of adjustment, unless the inspector feels able to effect a real improvement.

12.2.4. Rain measures

It will occasionally be necessary to test measures which have not already been certified either by the Meteorological Office or the British Rainfall Organization or another inspector. A taper measure graduated in inches and millimetres for a 5-in. rain-gauge is included in the Mk V kit ; the Mk IV kit, however, has a rain measure graduated in inches only, but a special pipette is included as well. Either the rain measure or the pipette may be used as standards.

The special pipette (Fig. 127) has on one side of the stem a number of graduations headed " in." and on the other side a number of graduations headed " mm.". In each case the upper unmarked graduation is the zero line, and the figuring of the graduations indicates the standard quantities (measured from the zero line) corresponding to the lower graduations in the rain measures for use with 5-in. and 8-in. rain-gauges. The number in the brackets (either 5 or 8) gives the type of rain-gauge with which the measuring glass is used, and the first figure gives the equivalent amount of rainfall (in inches on the side marked " in." and in millimetres on the side marked " mm."). Thus the graduation marked 0·20 (5) on the mm. side indicates that the volume of water in the pipette between the mark and the zero line is equal to the volume of water which would be collected in a 5-in. rain-gauge if 0·20 mm. of rain fell.

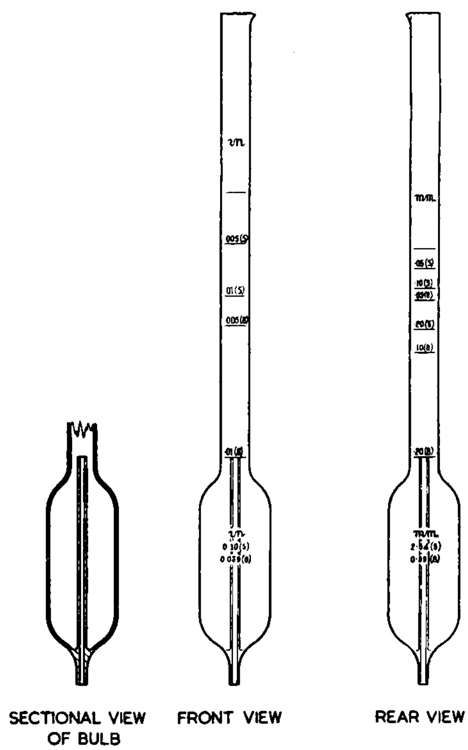


FIG. 127—SPECIAL PIPETTE FOR TESTING RAIN MEASURES

The quantities so indicated are obtained by sucking water into the pipette, adjusting the level to the zero line, and then allowing the water to run from the pipette into the measure under test until the level in the stem of the pipette stands at the graduation required. The pipette should be kept vertical throughout.

The lower part of the pipette consists of a bulb containing an inner tube. If water is drawn in until it stands above the top of this inner tube and is then allowed to subside the level will only fall to the top of the inner tube. A definite quantity of water is thus automatically retained in the pipette and can be obtained by pouring it out from the stem. This quantity of water corresponds to

0·10 in. or 2·54 mm. in a 5-in. rain-gauge

0·039 in. or 0·99 mm. in an 8-in. rain-gauge.

The taper measures may be used by direct comparison. If the measure under test is for use with an 8-in. rain-gauge (or is graduated in millimetres for use with a

5-in. rain-gauge and a Mk IV kit is being used) Table XLV should be used to work out the correct reading corresponding to a given reading in the inch measure for a 5-in. gauge.

TABLE XLV—CORRESPONDING READINGS WITH DIFFERENT RAIN MEASURES

Taper measure for 5-in. rain-gauge	Corresponding amounts indicated by		
	5-in. rain measure	8-in. rain measure	8-in. rain measure
in.	mm.	in.	mm.
0·1	2·54	0·039	0·99
0·2	5·08	0·078	1·98
0·3	7·62	0·117	2·98
0·4	10·16	0·156	3·97
0·5	12·70	0·195	4·96

Inch measures should first be tested at 0·01 in. and 0·005 in. (if marked). This water should be poured out and the measure shaken free from adhering drops (as far as possible) and then tested at or near the following points : 0·10, 0·20, 0·30, 0·40 and 0·50 in.

Millimetre measures are first tested at 0·10 and 0·05 mm. and then at intervals of about 2 mm. over the main part of the scale. The reliability of these tests depends essentially on the accuracy in reading both the measures under test and the standard measure. The utmost care should be taken to keep the measures vertical and to avoid errors of parallax.

A measure may be certified by an inspector as class A provided that

(i) Lower part of the measure is of a taper or conical form with the taper extending up to the graduation 0·05 in. or 1·0 mm.

(ii) Errors at any graduation point do not exceed the limits given in the Meteorological Office specification for this class of measure (see p. 267); that is for millimetre measures the errors must not exceed ± 0·02 mm. below 2·0 mm. and ± 0·05 mm. at or above 2·0 mm. ; and for inch measures the errors must not exceed ± 0·001 in. below 0·10 in. and ± 0·003 in. at or above 0·10 in.

(iii) Graduations are clearly engraved, correctly numbered and spaced uniformly and not less than 1·5 mm. apart over the cylindrical portion of the measure. Graduations must be shown for each 0·01 in. or 0·1 mm.

(iv) Glass is in good condition.

(v) Measure is clearly marked with the diameter of the gauge with which it is to be used.

Certification is effected by writing on the measure the initials B.R.O.(F). followed by the date and the inspector's initials (e.g. B.R.O.(F). 6/50/R.H.C.), using the writing diamond.

A measure may be certified class B provided that

(i) It is flat bottomed.

(ii) Errors do not exceed, for millimetre measures ± 0·02 below 1·0 mm. and ± 0·05 mm. at or above 1·0 mm., and for inch measures ± 0·001 in. below 0·05 in. and ± 0·005 in. at or above 0·05 in.

(iii) Graduations are clearly engraved, correctly numbered and spaced uniformly and not less than 1·5 mm. apart over the cylindrical portion of the measure. Graduations must be shown for each 0·01 in. or 0·1 mm.

(iv) Glass is in good condition.

(v) Measure is clearly marked with the diameter of the gauge with which it is to be used.

Certification is effected by writing on the measure the mark B followed by the date and the inspector's initials. These measures will not be given the B.R.O. mark.

A measure will be rejected if the errors are found to be :

For millimetre measures	± 0·03 mm. or more below 1·0 mm. ± 0·15 mm. or more at or above 1·0 mm.
For inch measures	± 0·003 in. or more below 0·10 in. ± 0·015 in. or more at or above 0·10 in.

A rejected measure will be marked with the sign # followed by the inspector's initials and the date.

Any measures which fall between the specification for class B and that for rejection will not be marked.

12.2.5. Rain-gauges

The diameter of the rim of the funnel should be measured at two places and noted to the nearest 0·01 in. Normally the two diameters measured should be at right angles and, as nearly as possible, the greatest and least diameters. The test gauges in the Mk V kit may be used or the calipers as carried in some of the older Mk II rainfall kits. Failing these the steel rule should be used, but great care is needed when using this to see that the diameter is not under-estimated. Distorted rims can sometimes be adjusted by gentle pressure from the inside.

The gauge should then be tested for leaks by filling up each part with water (the funnel outlet will, or course, have to be stopped up beforehand). The funnel should also be inverted and the space between the outer cylindrical part and the funnel itself filled with water. This will disclose any leaks in the joints of the outer cylindrical part. Any leaks should be repaired. The levelling of the rim should also be checked with the spirit-level.

When inspecting rain-gauges attention must be paid to the exposure. The considerations to be borne in mind are given on p. 264, and if an alternative site near by is considered to be better than that actually in use a recommendation to that effect should be given.

12.3. CLINOMETER COMPASS

This instrument (Stores Ref., Met. 330) is a combined clinometer (an instrument for measuring angular elevations) and a prismatic compass (an instrument for measuring azimuths with reference to magnetic north) (Plate LI). The green card carries the compass and becomes free when the front sight (the one with a long frame and a central thin strip of metal) is raised, and the instrument held so that the axis of the cylindrical case is vertical. The rear sight consists of a slit mounted above the prism which is used to view the scale printed on the card ; it also has to be raised into position before use. When the eye is placed close to the back sight and the central strip in the front sight is aligned in the centre of the slit it is also possible to see the scale divisions of the compass card.

The upper white card is controlled by gravity, and can only be used when the stud on the side of the instrument case above the maker's name is pulled out and the axis of the case is placed horizontal. The eye-piece in the back sight then allows the elevation scale to be viewed. To bring this scale into focus the position of the back sight should be adjusted, by moving it away from the instrument case. A separate window is also provided for viewing the elevation scale directly, instead of through the prism.

12.3.1. Observations of azimuth

To obtain the bearing of an object in azimuth from the position of observation proceed as follows :

(i) Erect the prism and front sight.

(ii) See that the white disc is clamped in such a position that it does not obstruct the prism window.

(iii) Place the instrument on a level surface (or hold it so that the axis of the cylindrical case is vertical) and adjust the height of the prism until the graduations on the green card and distant objects can both be seen clearly at the same time when the eye is close to the prism.

(iv) Rotate the instrument until the point under observation is seen in line with the central strip on the front sight, and this in turn appears in the centre of the slit in the back sight. The compass card will then show the azimuth measured from magnetic north. The movements of the card may be damped by pressing the plunger beneath the front sight, but it is important that the card should be swinging freely when the observation is taken. This requires great care when the instrument is held in the hand.

(v) Correct the azimuth reading to a bearing from true north by subtracting the value of the westerly declination (in the British Isles) or by adding the value of the easterly declination, as appropriate. See Fig. 128 for the value of the declination in the British Isles. It should be noted that the declination changes from year to year and its rate of decrease or increase is not constant. The latest information available should be used.

It is most important to ensure that there is no magnetic material in the immediate neighbourhood of the point from which the observations are taken (including objects on the observer himself). If this precaution is not observed the readings may be seriously in error.

12.3.2. Observations of elevation

To take an observation of the elevation of any object as subtended at the observation point :

(i) Erect the prism and front sight and unclamp the white card by pulling out the stud on the side of the instrument close to the maker's name.

FIG. 128—ISOGONALS OR LINES OF EQUAL WESTERLY DECLINATION, 1948·5 (JUNE 1948)

The lines are based on data supplied by the Ordnance Survey for the epoch 1948·5 and on observations at fixed observatories. The values of westerly declination at observatories in the United Kingdom were : Lerwick (60·1°N. 1·2°W.) 11° 1′, Eskdalemuir (55·3°N. 3·2°W.) 11° 49′, Abinger (51·2°N. 0·4°W.) 9° 35′. At present westerly declination is decreasing in the area shown at about 8′ per annum.

(ii) Adjust the position of the prism mounting in its grooves so that the scale on the white card is in focus.

(iii) With the axis of the cylindrical case held accurately horizontal align the object with the centre strip of the front sight and the centre of the slit in the back sight. The elevation can then be read off the outermost scale visible in the eye-piece. The movement of the disc can be damped by means of the plunger to the right of the prism but when the actual reading is taken the card should be free.

12.3.3. Observations of the slope of a plane surface

The instrument should be placed upright on the surface whose slope is required, so that it is resting on its base with axis of the case horizontal, and the clamping stud withdrawn. The slope can then be read on the scale on the white card through the lower window, opposite the fiducial line. If the clinometer is tested on a spirit-level in this way it is possible to determine accurately any zero error in the scale.

12.3.4. Measurement of differences in height

It is sometimes necessary to determine the height of a barometer cistern or rain-gauge above mean sea level. The following procedure can be used when the height required cannot be determined directly from a large-scale Ordnance Survey map or other plan (of a scale of 6 in. to the mile, or more). In most cases, however, before the procedure outlined below is followed it will be found helpful to consult the surveyor to the local authority in whose area the station is, or other similar person, as they will probably be able to give useful advice, and in many cases may be able to supply directly the information required.

From an Ordnance Survey map of the largest scale obtainable note carefully the position of the nearest point to the station whose height, h_1, is accurately known. A bench-mark should be selected for this purpose if one is available. Heights which may serve are also sometimes marked against roads. Measure on the map, or directly by means of a tape measure, the distance, d, in feet between the point selected and the point at the station whose height is required. The elevation, E, of the point whose height is required from the point whose height is known should then be obtained with the clinometer. If h_2 is this required height and h_3 is the height of the observer's eye above the point whose height is known then

$$h_2 = h_1 + h_3 \pm d \tan E.$$

The plus sign is taken if h_2 is greater than $(h_1 + h_3)$ and the minus sign if h_2 is less than $(h_1 + h_3)$, taking E as always positive. It will be necessary to determine d and E with the utmost possible accuracy. At least five independent measurements of E should be made, and the mean value taken (to the nearest $0 \cdot 1°$). It will be necessary to determine the zero error of the scale and if necessary allow for it.

If the final point is not visible from the starting point the operation will have to be carried out in two or more stages. The accuracy obtainable in this way will not be very great, and as the height is usually required to the nearest foot a more accurate instrument will be required if d exceeds about 80 to 100 yd. A pilot-balloon theodolite may be used for distances up to ten times these amounts if extreme care is taken in levelling the instrument, and readings to the nearest $0 \cdot 01°$ are taken.

12.4. SCALES

12.4.1. Geostrophic wind scales

Geostrophic wind scales are printed on clear perspex or other transparent material, and are used to obtain the value of the geostrophic wind speed from the pressure gradient, as indicated on synoptic charts by the distance apart of the isobars or contour lines of a constant-pressure surface. The geostrophic wind speed, G, is given by

$$G = \text{pressure gradient}/2\omega\rho \sin \phi,$$

where ω is the angular velocity of the earth about its axis, ρ is the density of the air, and ϕ is the latitude.

The simplest form of geostrophic scale (Fig. 129) is drawn on the assumption of a standard density, latitude, chart scale and pressure interval between the isobars. The geostrophic wind speed is then inversely proportional to the distance

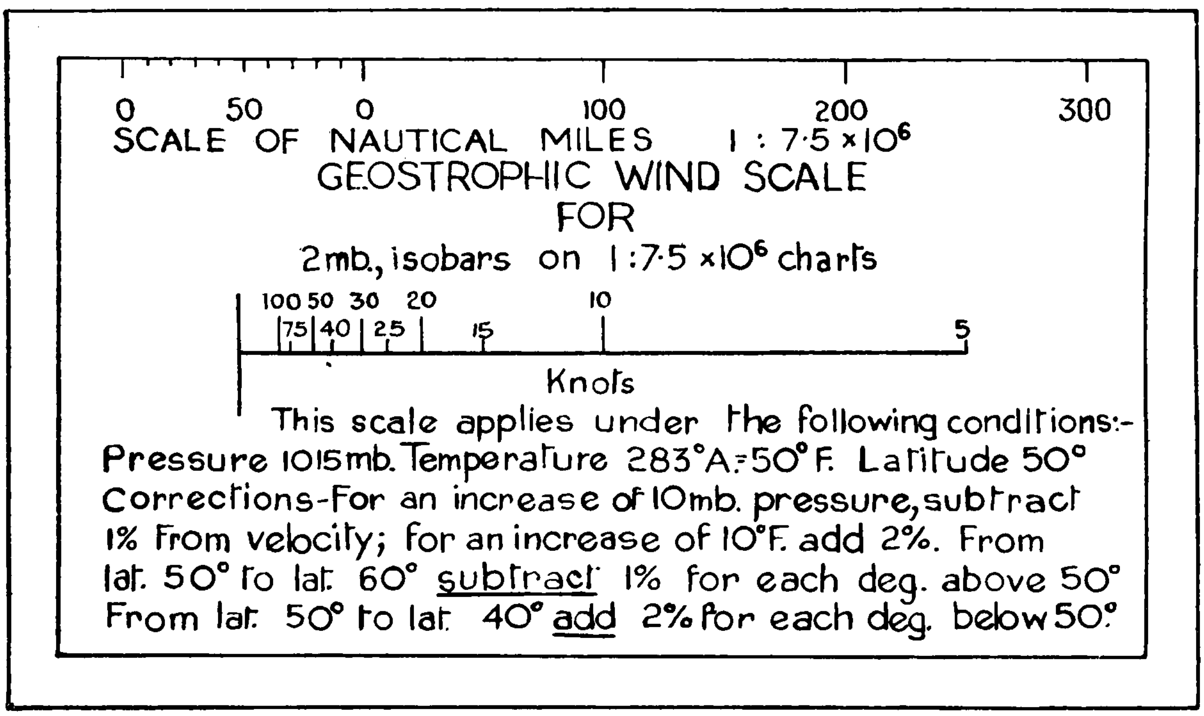


FIG. 129—GEOSTROPHIC WIND SCALE FOR ONE LATITUDE

between the isobars, measured in a direction normal to the isobars. If the pressure interval between the isobars is doubled the indicated wind speed should also be doubled ; if the chart scale is halved (e.g. a chart scale of $1 : 2 \times 10^7$ is used instead of a chart scale of $1 : 10^7$) then the indicated wind speed should be halved. Most working charts used in the Meteorological Office are of the conformal conic projection type with two standard parallels ; these charts do not have a uniform chart scale over the whole range of latitudes covered, and consequently allowance has to be made for the change in chart scale as well as the change in latitude when using the wind scale in other latitudes than the standard.

Such scales as these have the standard conditions assumed marked upon them. The appropriate corrections to the measured speed for small deviations from these conditions are also given as a certain percentage of the indicated wind speed per unit deviation. This procedure will obviously be incorrect for large variations in latitude, and such scales should only be used within about 10° of the standard latitude. The corrections for variations in air temperature and air pressure are usually small and can often be neglected.

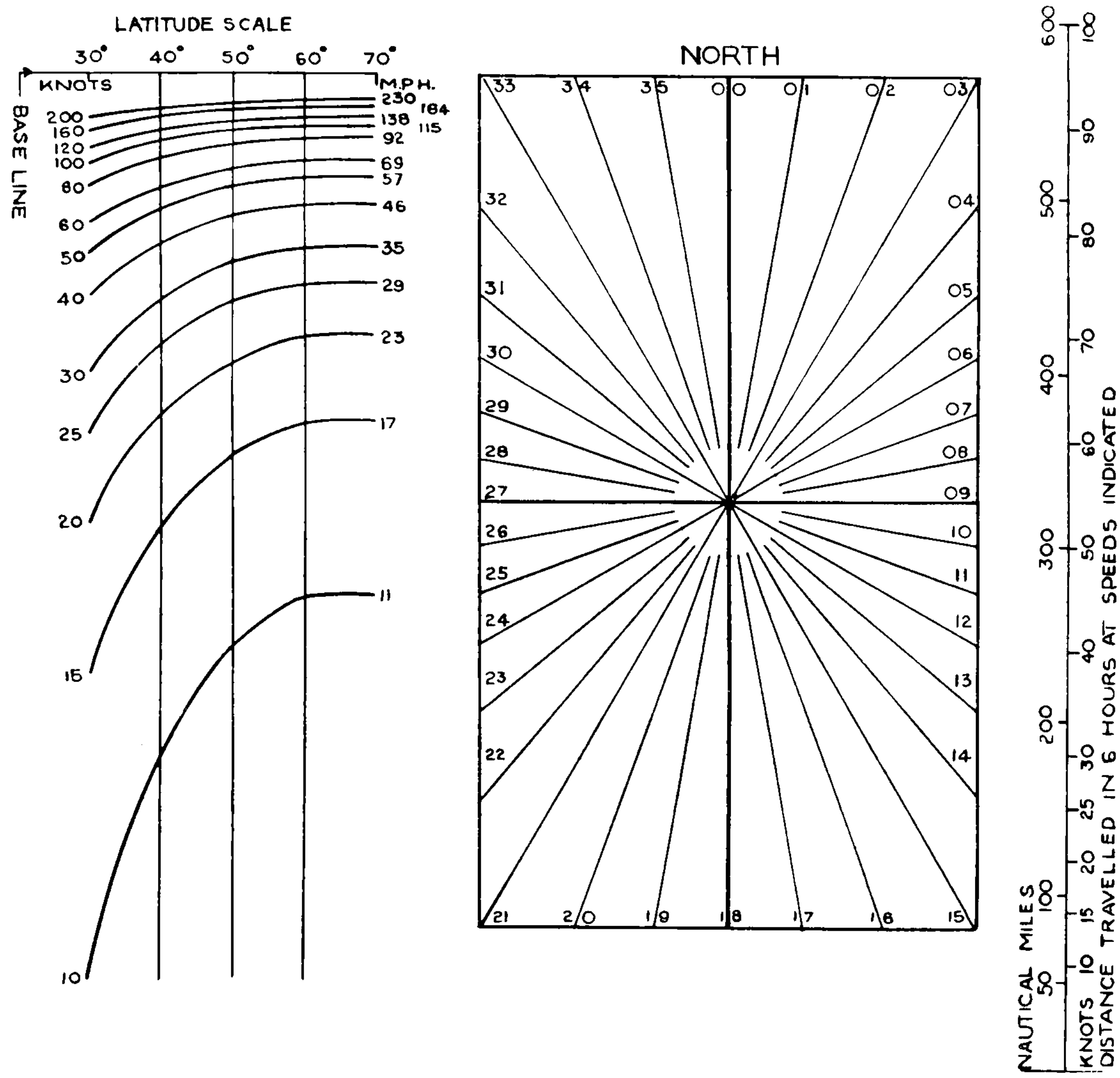


FIG. 130—GEOSTROPHIC WIND SCALE FOR A RANGE OF LATITUDES

For use on pressure contour charts

When a large range of latitudes has to be covered a special type of scale which allows for this should be used (Fig. 130). Corrections for the variation in chart scale with latitude can be incorporated with the changes needed to allow for the variation in the term sin ϕ.

Scales for use with the contour lines of a constant-pressure surface are independent of the density of the air and can be used for any pressure.

A list of the various geostrophic scales in use at present is given in Table XLVI.

It should be noted that a geostrophic wind scale can be used with other charts than those for which it is primarily intended provided the indicated wind speed is suitably adjusted.

TABLE XLVI—TYPES OF GEOSTROPHIC WIND SCALES

Stores Ref.	Scale of chart used	Range of latitude	Wind speed in	Isobar or contour-line intervals
Met. 536	1 : 10^7	45–65°	miles per hour	Isobars for every 2 mb.
Met. 625	1 : 2 × 10^6	40–60°	miles per hour	
Met. 626	1 : 7·5 × 10^6	40–60°	miles per hour	
Met. 640	1 : 5 × 10^6 or 1 : 7·5 × 10^6	40–65°	miles per hour	Contour lines for every 200 ft.
Met. 755	1 : 5 × 10^6	40–65°	knots	Isobars for every 2 mb.
Met. 1020	1 : 7·5 × 10^6	40–60°	knots	
Met. 1021	1 : 12·5 × 10^6	40–60°	knots	
Met. 1027	1 : 12·5 × 10^6	30–70°	knots and miles per hour	Contour lines for every 200 ft.
Met. 1057	1 : 2 × 10^7	20–50°	knots	
Met. 2809	1 : 7·5 × 10^6	30–70°	knots and miles per hour	

12.4.2. Measuring scales

Numerous measuring scales have been made for measuring the charts of various recording instruments. These are mostly straightforward in operation and need no comment. A list of the commoner scales in use is given in Table XLVII.

TABLE XLVII—MEASURING SCALES IN COMMON USE

Stores Ref.	Scale
Met. 211	Direction scale for pressure-tube anemograph
Met. 212	Diurnal-range scale for pressure-tube anemograph
Met. 213	Scale for measuring speed in metres per second on pressure-tube anemograph
Met. 213A	Scale for measuring speed in miles per hour on pressure-tube anemograph
Met. 986	Scale for measuring speed in knots on pressure-tube anemograph
Met. 533	Speed-distribution scale (miles per hour) for use on pressure-tube anemograph
Met. 989	Speed-distribution scale (knots) for use on pressure-tube anemograph
Met. 2748	Scale for Baxendell wind-direction recorder
Met. 220	Duration of sunshine scale
Met. 559	Duration of rainfall (millimetres) on the Meteorological Office tilting-siphon rain recorder
Met. 2830	Duration of rainfall (inches) on the Meteorological Office tilting-siphon rain recorder

12.5. DRAWING INSTRUMENTS

Good drawing instruments are precision instruments, and should therefore always be treated carefully, kept scrupulously clean and in a safe place when not in use, preferably in a special box. Pens should be cleaned after use, using methylated spirit or other non-corrosive solvent, and, if of the normal drawing type consisting of two adjustable steel nibs, the nibs should be slackened off until they are just not touching at the points.

Pencil leads and pencils should be kept sharpened. It is useful to have three different shaped points available ; chisel-shaped, needle-shaped and triangular-shaped (see Fig. 131). The needle-shaped point is only used for very fine work as it wears down very quickly. The chisel-shaped point is useful for general purpose work, while the triangular point can be used to a certain extent as either a needle- or a chisel-shaped point. A selection of pencils of various hardnesses should be kept, ranging from about 2B to 4H, the one actually used being dependent on the work to be done. Pencils can be sharpened easily by using a dead smooth file on the lead after the wood has been cut. The wood should be kept well pared back in order that the point shall not be obscured in use.

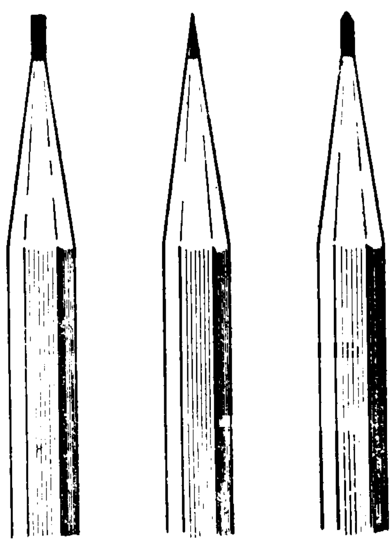


FIG. 131—PENCIL POINTS

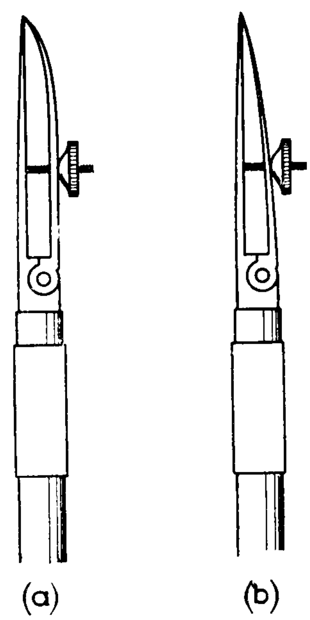


FIG. 132—DRAWING PENS

The usual shape of pen point is shown in Fig. 132 (*a*). A much more satisfactory shape for fine work is that at Fig. 132 (*b*). When one or both the nibs are too curved it is difficult for the ink to be held in place and for it to flow evenly and steadily, and if too much ink is placed between the nibs it is liable to spill as the pen is tilted. It is possible to remedy this defect sometimes by opening the nibs and carefully straightening them. This must be carried out with great care for the highly tempered steel can easily be fractured. Pens should be charged with ink by placing a small drop between the nibs with a dropper, not by dipping them into the ink.

The use of compasses is straightforward provided a suitable pencil lead or pen is used. The points should be kept needle sharp, and adjusted so that the total length of the arm holding the pencil lead or pen is about $\frac{1}{32}$ in. shorter than the other arm. This allows for the depth of penetration of the needle into the drawing surface.

T-squares and drawing boards need careful handling and storage to prevent damage and deterioration. When using a set square in conjunction with a T-square it is advisable to use the largest size available ; there is then less likelihood of error in its setting and less need to join lines.

12.6. MECHANICAL AIDS TO COMPUTING

Much useful information on this subject will be found in " Machines and appliances in government offices "[80], see especially p. 23 and p. 40.

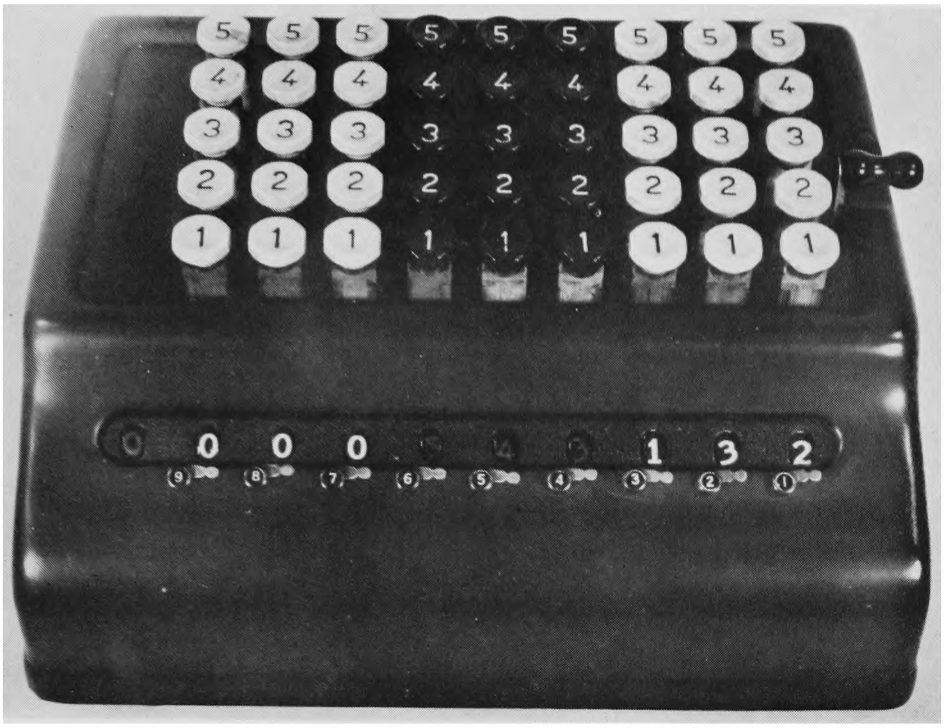
12.6.1. Adding machines

Simple adding machines of the type shown in Plate LII are used for many branches of meteorological computation. Eight columns of keys are provided with five keys (numbered 1 to 5) in each column. If a key is depressed the corresponding number appears in the window below the key board and in the same column. Each additional key depressed causes the corresponding number to be added to the sum already showing on the counters behind the window. A series of numbers can thus be rapidly added. For figures above 5 it will be necessary to depress two keys in the same column which together add up to the required figure ; e.g. eight would be added by depressing the key marked 4 twice, or by depressing 5 followed by 3. Care must be taken to keep the same columns for the units figure, tens figure, hundreds figure, etc. for each number in the sum. A lever on the right-hand side enables the counters to be re-set to zero when necessary.

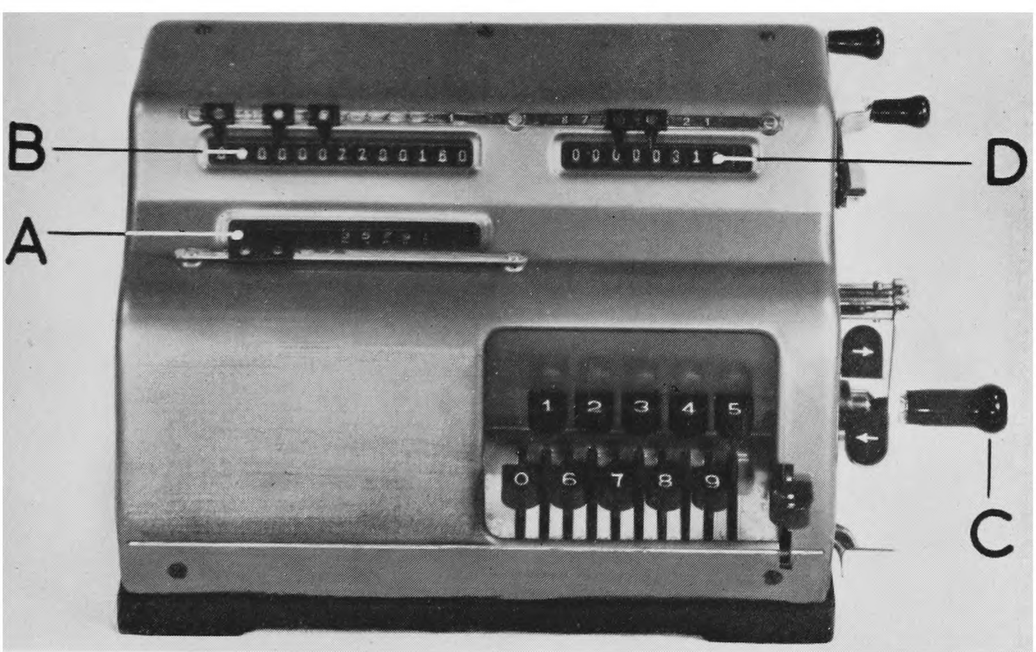
12.6.2. Calculating machines

Calculating machines are machines designed to perform arithmetical computations (e.g. multiplication, division, addition and subtraction). They are of varying degrees of complexity, but it is only proposed here to mention briefly two small machines which are useful in the statistical computations often met with when working with climatological data. The card operated, tabulating and sorting machines and the very large electronic calculating machines are outside the scope of this Handbook, although they can be used in meteorological investigations. The two machines mentioned are typical of what may be called " hand-operated " and " automatic " desk calculating machines ; they were selected merely to demonstrate the general principles.

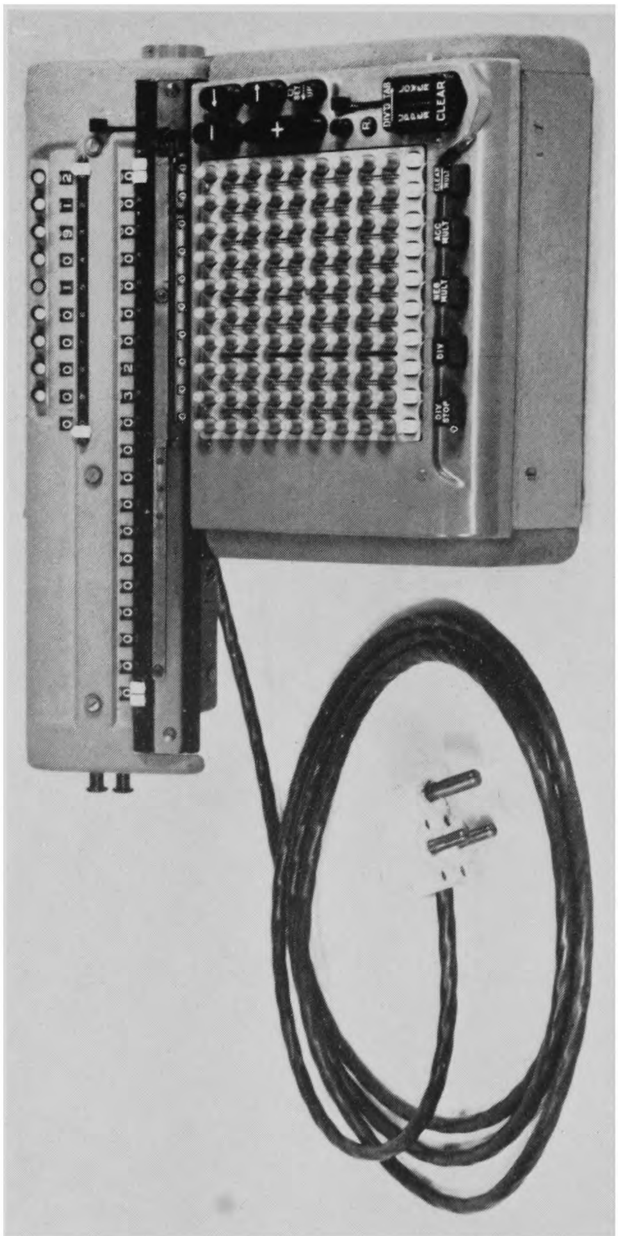
In the machine illustrated in Plate LII any number set up in the lower left-hand window A, obtained by depressing the keys marked 0–9, can be added to or subtracted from the total shown in the upper window B as many times as is necessary by turning the handle C the same number of times either forwards (for addition) or backwards (for subtraction). By shifting the number in A to the left or right, by depressing one or other of the knobs on the right, it is possible, in effect, to multiply or divide it by 10, 100, 1,000, etc. The number of times the handle is rotated is recorded in the window D due account being taken of any variation in the position of the number in A. Thus if the handle is rotated once when the number in A is in its initial position and twice when it is moved one space to the left the number in the window D is 21 ($2 \times 10 + 1$) not 3, and the figure shown in window B has been increased or decreased by twenty-one times the figure in window A. Window B can of course indicate zero to begin with if necessary. If the handle is rotated both backwards and forwards the number in the window D is the net number of times rotated in the initial direction used. Multiplication can thus be carried out as a process of continued addition, and division in a similar way by a process of continued subtraction.



ADDING MACHINE



HAND-OPERATED DESK CALCULATING MACHINE



AUTOMATIC DESK CALCULATING MACHINE

A much more advanced type of machine is the high-speed computing machine shown in Plate LIII. Instead of having to turn a handle by hand the two numbers which have to be divided or multiplied are set up one after the other and appropriate buttons pressed. An electric motor then performs the mechanical operations required automatically and more quickly than would be possible by hand.

Provision is also made for squaring a number, storing the results of operations already performed, and performing other operations especially useful for involved statistical computations. Special instructions are normally supplied with this type of machine.

12.7. TABLES FOR CORRECTING BAROMETER READINGS

TABLE XLVIII—TEMPERATURE CORRECTION OF THE METEOROLOGICAL OFFICE KEW-PATTERN BAROMETER MK I

Millibar graduations

To be used with barometers with National Physical Laboratory certificate dated on or before December 31, 1954.

Corrections to be applied to the readings of Meteorological Office Kew-pattern mercury barometers Mk I to reduce them to 285° A.

If the temperature of the attached thermometer is {above / below} 285° A. {subtract / add} the correction

Attached thermometer (**add** correction)	Barometer reading (mb.)										Attached thermometer (**subtract** correction)
	860	880	900	920	940	960	980	1000	1020	1040	
°A.	*millibars*										°A.
284	0·15	0·15	0·15	0·16	0·16	0·16	0·17	0·17	0·17	0·18	286
283	0·30	0·30	0·31	0·32	0·32	0·33	0·34	0·34	0·35	0·36	287
282	0·44	0·45	0·46	0·47	0·48	0·49	0·50	0·51	0·52	0·53	288
281	0·59	0·61	0·62	0·63	0·64	0·66	0·67	0·68	0·70	0·71	289
280	0·74	0·76	0·77	0·79	0·81	0·82	0·84	0·85	0·87	0·89	290
279	0·89	0·91	0·93	0·95	0·97	0·99	1·01	1·03	1·05	1·07	291
278	1·04	1·06	1·08	1·11	1·13	1·15	1·17	1·20	1·22	1·24	292
277	1·18	1·21	1·24	1·26	1·29	1·31	1·34	1·37	1·39	1·42	293
276	1·33	1·36	1·39	1·42	1·45	1·48	1·51	1·54	1·57	1·60	294
275	1·48	1·51	1·55	1·58	1·61	1·64	1·67	1·71	1·74	1·77	295
274	1·63	1·66	1·70	1·73	1·77	1·81	1·84	1·88	1·91	1·95	296
273	1·77	1·81	1·85	1·89	1·93	1·97	2·01	2·05	2·09	2·13	297
272	1·92	1·97	2·01	2·05	2·09	2·13	2·18	2·22	2·26	2·30	298
271	2·07	2·12	2·16	2·21	2·25	2·30	2·34	2·39	2·43	2·48	299
270	2·22	2·27	2·32	2·36	2·41	2·46	2·51	2·56	2·61	2·66	300
269	2·37	2·42	2·47	2·52	2·57	2·63	2·68	2·73	2·78	2·83	301
268	2·51	2·57	2·62	2·68	2·73	2·79	2·85	2·90	2·95	3·01	302
267	2·66	2·72	2·78	2·84	2·89	2·95	3·01	3·07	3·13	3·19	303
266	2·81	2·87	2·93	2·99	3·05	3·12	3·18	3·24	3·30	3·36	304
265	2·95	3·02	3·08	3·15	3·21	3·28	3·35	3·41	3·48	3·54	305
264	3·10	3·17	3·24	3·31	3·37	3·44	3·51	3·58	3·65	3·72	306
263	3·25	3·32	3·39	3·46	3·53	3·61	3·68	3·75	3·82	3·89	307
262	3·40	3·47	3·55	3·62	3·69	3·77	3·85	3·92	3·99	4·07	308
261	3·54	3·62	3·70	3·78	3·85	3·93	4·01	4·09	4·17	4·25	309
260	3·69	3·77	3·85	3·93	4·01	4·10	4·18	4·26	4·34	4·42	310
259	3·84	3·92	4·01	4·09	4·17	4·26	4·34	4·43	4·51	4·60	311
258	3·98	4·07	4·16	4·25	4·33	4·42	4·51	4·60	4·69	4·77	312
257	4·13	4·22	4·31	4·40	4·49	4·59	4·68	4·77	4·86	4·94	313
256	4·28	4·37	4·47	4·56	4·65	4·75	4·84	4·94	5·03	5·12	314
255	4·42	4·52	4·62	4·72	4·81	4·91	5·01	5·11	5·20	5·30	315

TABLE XLVIIIA—TEMPERATURE CORRECTION OF THE METEOROLOGICAL OFFICE KEW-PATTERN BAROMETER MK II

Millibar graduations

To be used with barometers with National Physical Laboratory certificate dated on or after January 1, 1955.

Corrections to be applied to the readings of Meteorological Office Kew-pattern mercury barometers Mk II to reduce them to 0°C.

If the temperature of the attached thermometer is {above / below} 0°C. (273°A.) the correction is {negative / positive}.

Attached thermometer °A.	Attached thermometer °C.	920	940	960	980	1000	1020	1040	Attached thermometer °C.	Attached thermometer °A.
		millibars								
		+	+	+	+	+	+	+		
271	−2	0·32	0·32	0·33	0·34	0·34	0·35	0·36	−2	271
272	−1	0·16	0·16	0·16	0·17	0·17	0·17	0·18	−1	272
		−	−	−	−	−	−	−		
273	0	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0	273
274	1	0·16	0·16	0·16	0·17	0·17	0·17	0·18	1	274
275	2	0·32	0·32	0·33	0·34	0·34	0·35	0·36	2	275
276	3	0·48	0·48	0·49	0·50	0·51	0·52	0·53	3	276
277	4	0·63	0·64	0·65	0·67	0·68	0·70	0·71	4	277
278	5	0·79	0·80	0·82	0·84	0·85	0·87	0·89	5	278
279	6	0·95	0·97	0·99	1·01	1·03	1·05	1·07	6	279
280	7	1·11	1·13	1·15	1·18	1·20	1·22	1·25	7	280
281	8	1·26	1·29	1·32	1·35	1·38	1·40	1·43	8	281
282	9	1·42	1·45	1·48	1·52	1·55	1·57	1·60	9	282
283	10	1·58	1·61	1·64	1·68	1·71	1·74	1·77	10	283
284	11	1·74	1·77	1·81	1·84	1·88	1·91	1·95	11	284
285	12	1·89	1·93	1·97	2·01	2·05	2·09	2·13	12	285
286	13	2·05	2·09	2·13	2·18	2·22	2·26	2·30	13	286
287	14	2·21	2·25	2·30	2·34	2·39	2·44	2·48	14	287
288	15	2·36	2·41	2·46	2·51	2·56	2·61	2·66	15	288
289	16	2·52	2·57	2·63	2·68	2·73	2·78	2·83	16	289
290	17	2·68	2·73	2·79	2·84	2·90	2·96	3·01	17	290
291	18	2·84	2·89	2·95	3·01	3·07	3·13	3·19	18	291
292	19	2·99	3·05	3·12	3·18	3·24	3·30	3·36	19	292
293	20	3·15	3·22	3·28	3·35	3·41	3·48	3·54	20	293
294	21	3·31	3·38	3·44	3·51	3·58	3·65	3·72	21	294
295	22	3·46	3·54	3·61	3·68	3·75	3·82	3·89	22	295
296	23	3·62	3·70	3·77	3·84	3·92	3·99	4·07	23	296
297	24	3·78	3·86	3·93	4·01	4·09	4·17	4·25	24	297
298	25	3·93	4·02	4·10	4·18	4·26	4·34	4·42	25	298
299	26	4·09	4·18	4·26	4·34	4·43	4·51	4·60	26	299
300	27	4·25	4·34	4·42	4·51	4·60	4·69	4·77	27	300
301	28	4·40	4·49	4·59	4·68	4·77	4·86	4·95	28	301
302	29	4·56	4·65	4·75	4·84	4·94	5·03	5·13	29	302
303	30	4·72	4·81	4·91	5·01	5·11	5·20	5·30	30	303
304	31	4·88	4·97	5·07	5·18	5·28	5·37	5·47	31	304
305	32	5·03	5·13	5·24	5·34	5·44	5·55	5·65	32	305
306	33	5·19	5·29	5·40	5·51	5·61	5·72	5·82	33	306
307	34	5·34	5·45	5·56	5·67	5·78	5·89	6·00	34	307
308	35	5·50	5·61	5·72	5·84	5·95	6·06	6·17	35	308
309	36	5·65	5·76	5·88	6·00	6·11	6·23	6·35	36	309
310	37	5·81	5·92	6·04	6·17	6·28	6·40	6·53	37	310
311	38	5·97	6·09	6·21	6·34	6·46	6·58	6·71	38	311
312	39	6·13	6·25	6·37	6·51	6·63	6·75	6·88	39	312
313	40	6·28	6·41	6·54	6·67	6·80	6·93	7·06	40	313

TABLE XLIX—TEMPERATURE CORRECTION OF THE METEOROLOGICAL OFFICE KEW-PATTERN BAROMETER MK I

Inch graduations

To be used with barometers with National Physical Laboratory certificate dated on or before December 31, 1954.

Corrections to be applied to the readings to the Meteorological Office Kew-pattern mercury barometers Mk I to reduce them to standard temperature conditions.

Attached thermometer	Barometer reading (in.)										
	26·0	26·5	27·0	27·5	28·0	28·5	29·0	29·5	30·0	30·5	31·0
°F.						*inches*					
	+	+	+	+	+	+	+	+	+	+	+
0	0·076	0·077	0·078	0·080	0·081	0·082	0·084	0·085	0·086	0·088	0·089
1	0·073	0·075	0·076	0·077	0·078	0·080	0·081	0·082	0·083	0·085	0·086
2	0·071	0·072	0·073	0·074	0·076	0·077	0·078	0·079	0·081	0·082	0·083
3	0·068	0·070	0·071	0·072	0·073	0·074	0·075	0·077	0·078	0·079	0·080
4	0·066	0·067	0·068	0·069	0·070	0·071	0·073	0·074	0·075	0·076	0·077
5	0·063	0·064	0·066	0·067	0·068	0·069	0·070	0·071	0·072	0·073	0·074
6	0·061	0·062	0·063	0·064	0·065	0·066	0·067	0·068	0·069	0·070	0·071
7	0·058	0·059	0·060	0·061	0·062	0·063	0·064	0·065	0·066	0·067	0·068
8	0·056	0·057	0·058	0·059	0·060	0·061	0·061	0·062	0·063	0·064	0·065
9	0·053	0·054	0·055	0·056	0·057	0·058	0·059	0·060	0·060	0·061	0·062
10	0·051	0·052	0·053	0·053	0·054	0·055	0·056	0·057	0·058	0·058	0·059
11	0·048	0·049	0·050	0·051	0·052	0·052	0·053	0·054	0·055	0·056	0·056
12	0·046	0·047	0·047	0·048	0·049	0·050	0·050	0·051	0·052	0·053	0·053
13	0·043	0·044	0·045	0·045	0·046	0·047	0·048	0·048	0·049	0·050	0·050
14	0·041	0·042	0·042	0·043	0·044	0·044	0·045	0·045	0·046	0·047	0·047
15	0·038	0·039	0·040	0·040	0·041	0·041	0·042	0·043	0·043	0·044	0·045
16	0·036	0·036	0·037	0·038	0·038	0·039	0·039	0·040	0·040	0·041	0·042
17	0·033	0·034	0·034	0·035	0·035	0·036	0·037	0·037	0·038	0·038	0·039
18	0·031	0·031	0·032	0·032	0·033	0·033	0·034	0·034	0·035	0·035	0·036
19	0·028	0·029	0·029	0·030	0·030	0·031	0·031	0·031	0·032	0·032	0·033
20	0·026	0·026	0·027	0·027	0·027	0·028	0·028	0·029	0·029	0·029	0·030
21	0·023	0·024	0·024	0·024	0·025	0·025	0·025	0·026	0·026	0·026	0·027
22	0·021	0·021	0·021	0·022	0·022	0·022	0·023	0·023	0·023	0·024	0·024
23	0·018	0·019	0·019	0·019	0·019	0·020	0·020	0·020	0·020	0·021	0·021
24	0·016	0·016	0·016	0·017	0·017	0·017	0·017	0·017	0·018	0·018	0·018
25	0·013	0·014	0·014	0·014	0·014	0·014	0·014	0·015	0·015	0·015	0·015
26	0·011	0·011	0·011	0·011	0·011	0·011	0·012	0·012	0·012	0·012	0·012
27	0·008	0·008	0·009	0·009	0·009	0·009	0·009	0·009	0·009	0·009	0·009
28	0·006	0·006	0·006	0·006	0·006	0·006	0·006	0·006	0·006	0·006	0·006
29	0·003	0·003	0·003	0·003	0·003	0·003	0·003	0·003	0·003	0·003	0·003
30	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·000	0·000	0·000	0·000
	—	—	—	—	—	—	—	—	—	—	—
31	0·002	0·002	0·002	0·002	0·002	0·002	0·002	0·002	0·002	0·003	0·003
32	0·004	0·004	0·004	0·005	0·005	0·005	0·005	0·005	0·005	0·005	0·006
33	0·007	0·007	0·007	0·007	0·007	0·008	0·008	0·008	0·008	0·008	0·009
34	0·009	0·009	0·010	0·010	0·010	0·010	0·010	0·011	0·011	0·011	0·011
35	0·012	0·012	0·012	0·012	0·013	0·013	0·013	0·014	0·014	0·014	0·014
36	0·014	0·014	0·015	0·015	0·015	0·016	0·016	0·016	0·017	0·017	0·017
37	0·017	0·017	0·017	0·018	0·018	0·018	0·019	0·019	0·020	0·020	0·020
38	0·019	0·019	0·020	0·020	0·021	0·021	0·022	0·022	0·022	0·023	0·023
39	0·021	0·022	0·022	0·023	0·023	0·024	0·024	0·025	0·025	0·026	0·026
40	0·024	0·024	0·025	0·026	0·026	0·027	0·027	0·028	0·028	0·029	0·029
41	0·026	0·027	0·028	0·028	0·029	0·029	0·030	0·030	0·031	0·031	0·032
42	0·029	0·030	0·030	0·031	0·031	0·032	0·033	0·033	0·034	0·034	0·035
43	0·031	0·032	0·033	0·033	0·034	0·035	0·035	0·036	0·037	0·037	0·038
44	0·034	0·035	0·035	0·036	0·037	0·037	0·038	0·039	0·039	0·040	0·041
45	0·036	0·037	0·038	0·039	0·039	0·040	0·041	0·042	0·042	0·043	0·044
46	0·039	0·040	0·040	0·041	0·042	0·043	0·044	0·044	0·045	0·046	0·047
47	0·041	0·042	0·043	0·044	0·045	0·046	0·046	0·047	0·048	0·049	0·050
48	0·044	0·045	0·046	0·046	0·047	0·048	0·049	0·050	0·051	0·052	0·053
49	0·046	0·047	0·048	0·049	0·050	0·051	0·052	0·053	0·054	0·055	0·056

TABLE XLIX—TEMPERATURE CORRECTION OF THE METEOROLOGICAL OFFICE KEW-PATTERN BAROMETER MK I—*continued*

Inch graduations

To be used with barometers with National Physical Laboratory certificate dated on or before December 31, 1954.

Corrections to be applied to the readings of the Meteorological Office Kew-pattern mercury barometers Mk I to reduce then to standard temperature conditions.

Attached thermometer	Barometer reading (in.)										
	26·0	26·5	27·0	27·5	28·0	28·5	29·0	29·5	30·0	30·5	31·0
°F.						*inches*					
	—	—	—	—	—	—	—	—	—	—	—
50	0·049	0·050	0·051	0·052	0·053	0·054	0·055	0·056	0·057	0·058	0·058
51	0·051	0·052	0·053	0·054	0·055	0·056	0·057	0·058	0·059	0·060	0·061
52	0·054	0·055	0·056	0·057	0·058	0·059	0·060	0·061	0·062	0·063	0·064
53	0·056	0·057	0·058	0·060	0·061	0·062	0·063	0·064	0·065	0·066	0·067
54	0·059	0·060	0·061	0·062	0·063	0·064	0·066	0·067	0·068	0·069	0·070
55	0·061	0·062	0·064	0·065	0·066	0·067	0·068	0·070	0·071	0·072	0·073
56	0·064	0·065	0·066	0·067	0·069	0·070	0·071	0·072	0·074	0·075	0·076
57	0·066	0·067	0·069	0·070	0·071	0·073	0·074	0·075	0·076	0·078	0·079
58	0·069	0·070	0·071	0·073	0·074	0·075	0·077	0·078	0·079	0·081	0·082
59	0·071	0·072	0·074	0·075	0·077	0·078	0·079	0·081	0·082	0·083	0·085
60	0·074	0·075	0·076	0·078	0·079	0·081	0·082	0·084	0·085	0·086	0·088
61	0·076	0·078	0·079	0·080	0·082	0·083	0·085	0·086	0·088	0·089	0·091
62	0·079	0·080	0·082	0·083	0·085	0·086	0·088	0·089	0·091	0·092	0·094
63	0·081	0·083	0·084	0·086	0·087	0·089	0·090	0·092	0·093	0·095	0·097
64	0·083	0·085	0·087	0·088	0·090	0·091	0·093	0·095	0·096	0·098	0·099
65	0·086	0·088	0·089	0·091	0·093	0·094	0·096	0·097	0·099	0·101	0·102
66	0·088	0·090	0·092	0·094	0·095	0·097	0·099	0·100	0·102	0·104	0·105
67	0·091	0·093	0·094	0·096	0·098	0·100	0·101	0·103	0·105	0·107	0·108
68	0·093	0·095	0·097	0·099	0·101	0·102	0·104	0·106	0·108	0·109	0·111
69	0·096	0·098	0·100	0·101	0·103	0·105	0·107	0·109	0·110	0·112	0·114
70	0·098	0·100	0·102	0·104	0·106	0·108	0·110	0·111	0·113	0·115	0·117
71	0·101	0·103	0·105	0·107	0·108	0·110	0·112	0·114	0·116	0·118	0·120
72	0·103	0·105	0·107	0·109	0·111	0·113	0·115	0·117	0·119	0·121	0·123
73	0·106	0·108	0·110	0·112	0·114	0·116	0·118	0·120	0·122	0·124	0·126
74	0·108	0·110	0·112	0·114	0·116	0·118	0·121	0·123	0·125	0·127	0·129
75	0·111	0·113	0·115	0·117	0·119	0·121	0·123	0·125	0·127	0·130	0·132
76	0·113	0·115	0·117	0·120	0·122	0·124	0·126	0·128	0·130	0·132	0·135
77	0·116	0·118	0·120	0·122	0·124	0·127	0·129	0·131	0·133	0·135	0·137
78	0·118	0·120	0·123	0·125	0·127	0·129	0·131	0·134	0·136	0·138	0·140
79	0·121	0·123	0·125	0·127	0·130	0·132	0·134	0·136	0·139	0·141	0·143
80	0·123	0·125	0·128	0·130	0·132	0·135	0·137	0·139	0·142	0·144	0·146
81	0·125	0·128	0·130	0·133	0·135	0·137	0·140	0·142	0·144	0·147	0·149
82	0·128	0·130	0·133	0·135	0·138	0·140	0·142	0·145	0·147	0·150	0·152
83	0·130	0·133	0·135	0·138	0·140	0·143	0·145	0·148	0·150	0·153	0·155
84	0·133	0·135	0·138	0·140	0·143	0·145	0·148	0·150	0·153	0·155	0·158
85	0·135	0·138	0·140	0·143	0·146	0·148	0·151	0·153	0·156	0·158	0·161
86	0·138	0·140	0·143	0·146	0·148	0·151	0·153	0·156	0·159	0·161	0·164
87	0·140	0·143	0·146	0·148	0·151	0·153	0·156	0·159	0·161	0·164	0·167
88	0·143	0·145	0·148	0·151	0·153	0·156	0·159	0·162	0·164	0·167	0·170
89	0·145	0·148	0·151	0·153	0·156	0·159	0·162	0·164	0·167	0·170	0·172
90	0·148	0·150	0·153	0·156	0·159	0·162	0·164	0·167	0·170	0·173	0·175
91	0·150	0·153	0·156	0·159	0·161	0·164	0·167	0·170	0·173	0·175	0·178
92	0·153	0·155	0·158	0·161	0·164	0·167	0·170	0·173	0·175	0·178	0·181
93	0·155	0·158	0·161	0·164	0·167	0·170	0·172	0·175	0·178	0·181	0·184
94	0·158	0·160	0·163	0·166	0·169	0·172	0·175	0·178	0·181	0·184	0·187
95	0·160	0·163	0·166	0·169	0·172	0·175	0·178	0·181	0·184	0·187	0·190
96	0·162	0·165	0·169	0·172	0·175	0·178	0·181	0·184	0·187	0·190	0·193
97	0·165	0·168	0·171	0·174	0·177	0·180	0·183	0·186	0·190	0·193	0·196
98	0·167	0·170	0·174	0·177	0·180	0·183	0·186	0·189	0·192	0·196	0·199
99	0·170	0·173	0·176	0·179	0·183	0·186	0·189	0·192	0·195	0·198	0·202
100	0·172	0·175	0·179	0·182	0·185	0·188	0·192	0·195	0·198	0·201	0·204

TABLE XLIXA—TEMPERATURE CORRECTION OF THE METEOROLOGICAL OFFICE KEW-PATTERN BAROMETER MK II

Inch graduations

To be used with barometers with National Physical Laboratory certificate dated on or after January 1, 1955.

Corrections to be applied to the readings of the Meteorological Office Kew-pattern mercury barometers Mk II to reduce them to 32° F. All corrections are negative.

Attached thermometer	Barometer reading (in.)										
	26·0	26·5	27·0	27·5	28·0	28·5	29·0	29·5	30·0	30·5	31·0
°F.						*inches*					
	—	—	—	—	—	—	—	—	—	—	—
50	0·045	0·045	0·046	0·047	0·048	0·049	0·050	0·050	0·051	0·052	0·053
51	0·047	0·048	0·049	0·050	0·051	0·051	0·052	0·053	0·054	0·055	0·056
52	0·050	0·051	0·051	0·052	0·053	0·054	0·055	0·056	0·057	0·058	0·059
53	0·052	0·053	0·054	0·055	0·056	0·057	0·058	0·059	0·060	0·061	0·062
54	0·055	0·056	0·057	0·058	0·059	0·060	0·061	0·062	0·063	0·064	0·065
55	0·057	0·058	0·059	0·060	0·061	0·062	0·063	0·064	0·065	0·066	0·067
56	0·060	0·061	0·062	0·063	0·064	0·065	0·066	0·067	0·068	0·069	0·070
57	0·062	0·063	0·064	0·065	0·067	0·068	0·069	0·070	0·071	0·072	0·073
58	0·064	0·066	0·067	0·068	0·069	0·070	0·072	0·073	0·074	0·075	0·076
59	0·067	0·068	0·069	0·071	0·072	0·073	0·074	0·076	0·077	0·078	0·079
60	0·069	0·071	0·072	0·073	0·075	0·076	0·077	0·078	0·080	0·081	0·082
61	0·072	0·073	0·075	0·076	0·077	0·078	0·080	0·081	0·082	0·084	0·085
62	0·074	0·076	0·077	0·078	0·080	0·081	0·083	0·084	0·085	0·087	0·088
63	0·077	0·078	0·080	0·081	0·082	0·084	0·085	0·087	0·088	0·089	0·091
64	0·079	0·081	0·082	0·084	0·085	0·087	0·088	0·090	0·091	0·092	0·094
65	0·082	0·083	0·085	0·086	0·088	0·089	0·091	0·092	0·094	0·095	0·097
66	0·084	0·086	0·087	0·089	0·090	0·092	0·094	0·095	0·097	0·098	0·100
67	0·087	0·088	0·090	0·091	0·093	0·095	0·096	0·098	0·099	0·101	0·103
68	0·089	0·091	0·092	0·094	0·096	0·097	0·099	0·101	0·102	0·104	0·106
69	0·092	0·093	0·095	0·097	0·098	0·100	0·102	0·103	0·105	0·107	0·108
70	0·094	0·096	0·098	0·099	0·101	0·103	0·104	0·106	0·108	0·110	0·111
71	0·097	0·098	0·100	0·102	0·104	0·105	0·107	0·109	0·111	0·112	0·114
72	0·099	0·101	0·103	0·105	0·106	0·108	0·110	0·112	0·114	0·115	0·117
73	0·102	0·103	0·105	0·107	0·109	0·111	0·113	0·115	0·116	0·118	0·120
74	0·104	0·106	0·108	0·110	0·112	0·114	0·115	0·117	0·119	0·121	0·123
75	0·106	0·108	0·110	0·112	0·114	0·116	0·118	0·120	0·122	0·124	0·126
76	0·109	0·111	0·113	0·115	0·117	0·119	0·121	0·123	0·125	0·127	0·129
77	0·111	0·113	0·115	0·118	0·120	0·122	0·124	0·126	0·128	0·130	0·132
78	0·114	0·116	0·118	0·120	0·122	0·124	0·126	0·128	0·131	0·133	0·135
79	0·116	0·118	0·121	0·123	0·125	0·127	0·129	0·131	0·133	0·135	0·138
80	0·119	0·121	0·123	0·125	0·127	0·130	0·132	0·134	0·136	0·138	0·141
81	0·121	0·123	0·126	0·128	0·130	0·132	0·135	0·137	0·139	0·141	0·143
82	0·124	0·126	0·128	0·131	0·133	0·135	0·137	0·140	0·142	0·144	0·146
83	0·126	0·129	0·131	0·133	0·135	0·138	0·140	0·142	0·145	0·147	0·149
84	0·129	0·131	0·133	0·136	0·138	0·140	0·143	0·145	0·147	0·150	0·152
85	0·131	0·134	0·136	0·138	0·141	0·143	0·145	0·148	0·150	0·153	0·155
86	0·134	0·136	0·138	0·141	0·143	0·146	0·148	0·151	0·153	0·156	0·158
87	0·136	0·139	0·141	0·144	0·146	0·148	0·151	0·153	0·156	0·158	0·161
88	0·139	0·141	0·144	0·146	0·149	0·151	0·154	0·156	0·159	0·161	0·164
89	0·141	0·144	0·146	0·149	0·151	0·154	0·156	0·159	0·162	0·164	0·167
90	0·143	0·146	0·149	0·151	0·154	0·157	0·159	0·162	0·164	0·167	0·170

TABLE L—TEMPERATURE CORRECTION OF THE FORTIN BAROMETER STANDARD TEMPERATURE OF SCALE 62° F.

Inch graduations

To be used with barometers with National Physical Laboratory certificate dated on or before December 31, 1954.

Corrections to be applied to the readings of Fortin mercury barometers to reduce them to standard temperature conditions. All corrections are negative.

Attached thermometer	Barometer reading (in.)										
	26·0	26·5	27 0	27·5	28·0	28·5	29·0	29·5	30·0	30·5	31·0
°F.						*inches*					
	+	+	+	+	+	+	+	+	+	+	+
0	0·068	0·069	0·070	0·072	0·073	0·074	0·076	0·077	0·078	0·080	0·081
1	0·065	0·067	0·068	0·069	0·070	0·072	0·073	0·074	0·076	0·077	0·078
2	0·063	0·064	0·065	0·067	0·068	0·069	0·070	0·072	0·073	0·074	0·075
3	0·061	0·062	0·063	0·064	0·065	0·066	0·068	0·069	0·070	0·071	0·072
4	0·058	0·060	0·061	0·062	0·063	0·064	0·065	0·066	0·067	0·069	0·070
5	0·056	0·057	0·058	0·059	0·060	0·061	0·062	0·064	0·065	0·066	0·067
6	0·054	0·055	0·056	0·057	0·058	0·059	0·060	0·061	0·062	0·063	0·064
7	0·051	0·052	0·053	0·054	0·055	0·056	0·057	0·058	0·059	0·060	0·061
8	0·049	0·050	0·051	0·052	0·053	0·053	0·054	0·055	0·056	0·057	0·058
9	0·046	0·047	0·048	0·049	0·050	0·051	0·052	0·053	0·054	0·054	0·055
10	0·044	0·045	0·046	0·046	0·047	0·048	0·049	0·050	0·051	0·052	0·053
11	0·042	0·043	0·043	0·044	0·045	0·046	0·047	0·047	0·048	0·049	0·050
12	0·039	0·040	0·041	0·042	0·042	0·043	0·044	0·044	0·045	0·046	0·047
13	0·037	0·038	0·038	0·039	0·040	0·040	0·041	0·042	0·043	0·043	0·044
14	0·035	0·035	0·036	0·036	0·037	0·038	0·039	0·039	0·040	0·041	0·041
15	0·032	0·033	0·033	0·034	0·035	0·035	0·036	0·036	0·037	0·038	0·038
16	0·030	0·030	0·031	0·031	0·032	0·033	0·033	0·034	0·034	0·035	0·036
17	0·027	0·028	0·029	0·029	0·030	0·030	0·031	0·031	0·032	0·032	0·033
18	0·025	0·026	0·026	0·027	0·027	0·028	0·028	0·029	0·029	0·030	0·030
19	0·023	0·023	0·024	0·024	0·025	0·025	0·025	0·026	0·026	0·027	0·027
20	0·020	0·021	0·021	0·022	0·022	0·022	0·023	0·023	0·024	0·024	0·024
21	0·018	0·018	0·019	0·019	0·019	0·020	0·020	0·021	0·021	0·021	0·022
22	0·016	0·016	0·016	0·017	0·017	0·017	0·017	0·018	0·018	0·018	0·019
23	0·013	0·014	0·014	0·014	0·014	0·015	0·015	0·015	0·015	0·016	0·016
24	0·011	0·011	0·011	0·012	0·012	0·012	0·012	0·012	0·013	0·013	0·013
25	0·009	0·009	0·009	0·009	0·009	0·009	0·010	0·010	0·010	0·010	0·010
26	0·006	0·006	0·006	0·007	0·007	0·007	0·007	0·007	0·007	0·007	0·007
27	0·004	0·004	0·004	0·004	0·004	0·004	0·004	0·004	0·004	0·005	0·005
28	0·001	0·002	0·002	0·002	0·002	0·002	0·002	0·002	0·002	0·002	0·002
	−	−	−	−	−	−	−	−	−	−	−
29	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001
30	0·003	0·003	0·003	0·003	0·003	0·004	0·004	0·004	0·004	0·004	0·004
31	0·006	0·006	0·006	0·006	0·006	0·006	0·006	0·006	0·006	0·007	0·007
32	0·008	0·008	0·008	0·008	0·009	0·009	0·009	0·009	0·009	0·009	0·009
33	0·010	0·011	0·011	0·011	0·011	0·011	0·012	0·012	0·012	0·012	0·012
34	0·013	0·013	0·013	0·013	0·014	0·014	0·014	0·014	0·015	0·015	0·015
35	0·015	0·015	0·016	0·016	0·016	0·017	0·017	0·017	0·017	0·018	0·018
36	0·017	0·018	0·018	0·018	0·019	0·019	0·019	0·020	0·020	0·020	0·021
37	0·020	0·020	0·021	0·021	0·021	0·022	0·022	0·022	0·023	0·023	0·024
38	0·022	0·023	0·023	0·023	0·024	0·024	0·025	0·025	0·026	0·026	0·026
39	0·024	0·025	0·025	0·026	0·026	0·027	0·027	0·028	0·028	0·029	0·029
40	0·027	0·027	0·028	0·028	0·029	0·029	0·030	0·031	0·031	0·032	0·032
41	0·029	0·030	0·030	0·031	0·031	0·032	0·033	0·033	0·034	0·034	0·035
42	0·032	0·032	0·033	0·033	0·034	0·035	0·035	0·036	0·036	0·037	0·038
43	0·034	0·035	0·035	0·036	0·036	0·037	0·038	0·038	0·039	0·040	0·040
44	0·036	0·037	0·038	0·038	0·039	0·040	0·040	0·041	0·042	0·043	0·043
45	0·039	0·039	0·040	0·041	0·042	0·042	0·043	0·044	0·045	0·045	0·046
46	0·041	0·042	0·043	0·043	0·044	0·045	0·046	0·047	0·047	0·048	0·049
47	0·043	0·044	0·045	0·046	0·048	0·048	0·048	0·049	0·050	0·051	0·052
48	0·046	0·047	0·047	0·048	0·049	0·050	0·051	0·052	0·053	0·054	0·054
49	0·048	0·049	0·050	0·051	0·052	0·053	0·054	0·055	0·055	0·056	0·057
50	0·050	0·051	0·052	0·053	0·054	0·055	0·056	0·057	0·058	0·059	0·060

TABLE L—TEMPERATURE CORRECTION OF THE FORTIN BAROMETER STANDARD TEMPERATURE OF SCALE 62° F.—*continued*

Inch graduations

To be used with barometers with National Physical Laboratory certificate dated on or before December 31, 1954.

Corrections to be applied to the readings of Fortin mercury barometers to reduce them to standard temperature conditions. All corrections are negative.

Attached thermometer	Barometer reading (in.)										
	26·0	26·5	27·0	27·5	28·0	28·5	29·0	29·5	30·0	30·5	31·0
°F.	*inches*										
51	0·053	0·054	0·055	0·056	0·057	0·058	0·059	0·060	0·061	0·062	0·063
52	0·055	0·056	0·057	0·058	0·059	0·060	0·061	0·062	0·064	0·065	0·066
53	0·057	0·059	0·060	0·061	0·062	0·063	0·064	0·065	0·066	0·067	0·068
54	0·060	0·061	0·062	0·063	0·064	0·065	0·067	0·068	0·069	0·070	0·071
55	0·062	0·063	0·064	0·065	0·067	0·068	0·069	0·071	0·072	0·073	0·074
56	0·064	0·066	0·067	0·068	0·069	0·070	0·072	0·073	0·074	0·076	0·077
57	0·067	0·068	0·069	0·071	0·072	0·073	0·075	0·076	0·077	0·078	0·080
58	0·069	0·071	0·072	0·073	0·074	0·076	0·077	0·078	0·080	0·081	0·082
59	0·072	0·073	0·074	0·076	0·077	0·078	0·080	0·081	0·083	0·084	0·085
60	0·074	0·075	0·077	0·078	0·080	0·081	0·082	0·084	0·085	0·087	0·088
61	0·076	0·078	0·079	0·080	0·082	0·084	0·085	0·087	0·088	0·090	0·091
62	0·079	0·080	0·082	0·083	0·085	0·086	0·088	0·089	0·091	0·092	0·094
63	0·081	0·083	0·084	0·086	0·087	0·089	0·090	0·092	0·093	0·095	0·096
64	0·083	0·085	0·086	0·088	0·090	0·092	0·093	0·095	0·096	0·097	0·099
65	0·086	0·088	0·089	0·091	0·092	0·094	0·095	0·097	0·099	0·101	0·102
66	0·088	0·090	0·091	0·093	0·095	0·097	0·098	0·100	0·101	0·103	0·105
67	0·090	0·092	0·094	0·096	0·097	0·099	0·101	0·102	0·104	0·106	0·108
68	0·093	0·095	0·096	0·098	0·100	0·102	0·103	0·105	0·107	0·109	0·110
69	0·095	0·097	0·099	0·101	0·012	0·104	0·106	0·108	0·110	0·112	0·113
70	0·097	0·099	0·101	0·103	0·105	0·107	0·109	0·111	0·112	0·114	0·116
71	0·100	0·102	0·103	0·105	0·107	0·109	0·111	0·113	0·115	0·117	0·119
72	0·102	0·104	0·106	0·108	0·110	0·112	0·114	0·116	0·118	0·120	0·122
73	0·104	0·106	0·108	0·110	0·112	0·114	0·116	0·118	0·120	0·122	0·124
74	0·107	0·109	0·111	0·113	0·115	0·117	0·119	0·121	0·123	0·125	0·127
75	0·109	0·111	0·113	0·115	0·117	0·120	0·122	0·124	0·126	0·128	0·130
76	0·111	0·113	0·116	0·118	0·120	0·122	0·124	0·126	0·128	0·131	0·133
77	0·114	0·116	0·118	0·120	0·122	0·125	0·127	0·129	0·131	0·134	0·136
78	0·116	0·118	0·120	0·123	0·125	0·127	0·129	0·132	0·134	0·136	0·138
79	0·118	0·121	0·123	0·125	0·127	0·130	0·132	0·135	0·137	0·139	0·141
80	0·121	0·123	0·125	0·128	0·130	0·133	0·135	0·137	0·139	0·142	0·144
81	0·123	0·126	0·128	0·130	0·132	0·135	0·137	0·140	0·142	0·145	0·147
82	0·125	0·128	0·130	0·133	0·135	0·138	0·140	0·143	0·145	0·148	0·149
83	0·128	0·131	0·133	0·136	0·138	0·140	0·142	0·145	0·147	0·150	0·152
84	0·130	0·133	0·135	0·138	0·140	0·143	0·145	0·148	0·150	0·153	0·155
85	0·132	0·135	0·137	0·140	0·143	0·146	0·148	0·151	0·153	0·156	0·158
86	0·135	0·138	0·140	0·143	0·145	0·148	0·150	0·153	0·155	0·158	0·161
87	0·137	0·140	0·142	0·145	0·148	0·151	0·153	0·156	0·158	0·161	0·163
88	0·139	0·143	0·145	0·148	0·150	0·153	0·155	0·158	0·161	0·164	0·166
89	0·142	0·145	0·147	0·150	0·153	0·156	0·158	0·161	0·164	0·167	0·169
90	0·144	0·147	0·150	0·153	0·155	0·158	0·161	0·164	0·166	0·169	0·172
91	0·146	0·149	0·152	0·155	0·158	0·161	0·163	0·166	0·169	0·172	0·175
92	0·149	0·152	0·154	0·157	0·160	0·163	0·166	0·169	0·172	0·175	0·177
93	0·151	0·154	0·157	0·160	0·163	0·166	0·168	0·171	0·174	0·177	0·180
94	0·153	0·156	0·159	0·162	0·165	0·168	0·171	0·741	0·177	0·180	0·183
95	0·156	0·159	0·162	0·165	0·168	0·171	0·174	0·177	0·180	0·183	0·186
96	0·158	0·161	0·164	0·167	0·170	0·173	0·176	0·179	0·182	0·185	0·188
97	0·160	0·164	0·167	0·170	0·173	0·176	0·179	0·182	0·185	0·188	0·191
98	0·163	0·166	0·169	0·172	0·175	0·178	0·181	0·185	0·188	0·191	0·194
99	0·165	0·168	0·171	0·175	0·178	0·181	0·184	0·187	0·190	0·194	0·197
100	0·167	0·171	0·174	0·177	0·180	0·184	0·187	0·190	0·193	0·197	0·200

TABLE LA—TEMPERATURE CORRECTION OF THE FORTIN BAROMETER STANDARD TEMPERATURE OF SCALE 32° F.

Inch graduations

To be used with barometers with National Physical Laboratory certificate dated on or after January 1, 1955.

Corrections to be applied to the readings of Fortin mercury barometers to reduce them to standard temperature conditions. All corrections are negative.

Attached thermometer	Barometer reading (in.)										
	26·0	26·5	27·0	27·5	28·0	28·5	29·0	29·5	30·0	30·5	31·0
°F.	*inches*										
	—	—	—	—	—	—	—	—	—	—	—
50	0·042	0·043	0·044	0·045	0·046	0·047	0·047	0·048	0·049	0·050	0·051
51	0·045	0·046	0·046	0·047	0·048	0·049	0·050	0·051	0·052	0·053	0·053
52	0·047	0·048	0·049	0·050	0·051	0·052	0·053	0·053	0·054	0·055	0·056
53	0·049	0·050	0·051	0·052	0·053	0·054	0·055	0·056	0·057	0·058	0·059
54	0·052	0·053	0·054	0·055	0·056	0·057	0·058	0·059	0·060	0·061	0·062
55	0·054	0·055	0·056	0·057	0·058	0·059	0·060	0·061	0·062	0·064	0·065
56	0·057	0·058	0·059	0·060	0·061	0·062	0·063	0·064	0·065	0·066	0·067
57	0·059	0·060	0·061	0·062	0·063	0·065	0·066	0·067	0·068	0·069	0·070
58	0·061	0·062	0·064	0·065	0·066	0·067	0·068	0·069	0·071	0·072	0·073
59	0·064	0·065	0·066	0·067	0·068	0·070	0·071	0·072	0·073	0·075	0·076
60	0·066	0·067	0·068	0·070	0·071	0·072	0·074	0·075	0·076	0·077	0·079
61	0·068	0·070	0·071	0·072	0·073	0·075	0·076	0·077	0·079	0·080	0·081
62	0·071	0·072	0·073	0·075	0·076	0·077	0·079	0·080	0·081	0·083	0·084
63	0·073	0·074	0·076	0·077	0·079	0·080	0·081	0·083	0·084	0·086	0·087
64	0·075	0·077	0·078	0·080	0·081	0·083	0·084	0·085	0·087	0·088	0·090
65	0·078	0·079	0·081	0·082	0·084	0·085	0·087	0·088	0·090	0·091	0·093
66	0·080	0·082	0·083	0·085	0·086	0·088	0·089	0·091	0·092	0·094	0·095
67	0·082	0·084	0·085	0·087	0·089	0·090	0·092	0·093	0·095	0·097	0·098
68	0·085	0·086	0·088	0·090	0·091	0·093	0·094	0·096	0·098	0·099	0·101
69	0·087	0·089	0·090	0·092	0·094	0·095	0·097	0·099	0·100	0·102	0·104
70	0·089	0·091	0·093	0·095	0·096	0·098	0·100	0·101	0·103	0·105	0·107
71	0·092	0·093	0·095	0·097	0·099	0·100	0·102	0·104	0·106	0·108	0·109
72	0·094	0·096	0·098	0·099	0·101	0·103	0·105	0·107	0·109	0·110	0·112
73	0·096	0·098	0·100	0·102	0·104	0·106	0·107	0·109	0·111	0·113	0·115
74	0·099	0·101	0·103	0·104	0·106	0·108	0·110	0·112	0·114	0·116	0·118
75	0·101	0·103	0·105	0·107	0·109	0·111	0·113	0·115	0·117	0·119	0·120
76	0·103	0·105	0·107	0·109	0·111	0·113	0·115	0·117	0·119	0·121	0·123
77	0·106	0·108	0·110	0·112	0·114	0·116	0·118	0·120	0·122	0·124	0·126
78	0·108	0·110	0·112	0·114	0·116	0·118	0·121	0·123	0·125	0·127	0·129
79	0·110	0·113	0·115	0·117	0·119	0·121	0·123	0·125	0·127	0·129	0·132
80	0·113	0·115	0·117	0·119	0·121	0·124	0·126	0·128	0·130	0·132	0·134
81	0·115	0·117	0·120	0·122	0·124	0·126	0·128	0·131	0·133	0·135	0·137
82	0·117	0·120	0·122	0·124	0·126	0·129	0·131	0·133	0·136	0·138	0·140
83	0·120	0·122	0·124	0·127	0·129	0·131	0·134	0·136	0·138	0·140	0·143
84	0·122	0·124	0·127	0·129	0·131	0·134	0·136	0·139	0·141	0·143	0·146
85	0·124	0·127	0·129	0·132	0·134	0·136	0·139	0·141	0·144	0·146	0·148
86	0·127	0·129	0·132	0·134	0·137	0·139	0·141	0·144	0·146	0·149	0·151
87	0·129	0·132	0·134	0·137	0·139	0·142	0·144	0·146	0·149	0·151	0·154
88	0·131	0·134	0·136	0·139	0·142	0·144	0·147	0·149	0·152	0·154	0·157
89	0·134	0·136	0·139	0·141	0·144	0·147	0·149	0·152	0·154	0·157	0·159
90	0·136	0·139	0·141	0·144	0·147	0·149	0·152	0·154	0·157	0·160	0·162

TABLE LI—TEMPERATURE CORRECTION OF THE FORTIN BAROMETER

Millibar graduations

To be used with barometers with National Physical Laboratory certificate dated on or before December 31, 1954.

Corrections to be applied to the readings of Fortin mercury barometers to reduce them to 285°A.

If the temperature of the attached thermometer is {above / below} 285° A. {subtract / add} the correction

Attached thermometer (**add** correction)	Barometer reading (mb.) 860	880	900	920	940	960	980	1000	1020	1040	Attached thermometer (**subtract** correction)
°A.	*millibars*										°A.
284	0·14	0·14	0·15	0·15	0·15	0·16	0·16	0·16	0·17	0·17	286
283	0·28	0·29	0·29	0·30	0·31	0·31	0·32	0·33	0·33	0·34	287
282	0·42	0·43	0·44	0·45	0·46	0·47	0·48	0·49	0·50	0·51	288
281	0·56	0·57	0·59	0·60	0·61	0·63	0·64	0·65	0·67	0·68	289
280	0·70	0·72	0·73	0·75	0·77	0·78	0·80	0·82	0·83	0·85	290
279	0·84	0·86	0·88	0·90	0·92	0·94	0·96	0·98	1·00	1·02	291
278	0·98	1·00	1·03	1·05	1·07	1·09	1·12	1·14	1·16	1·19	292
277	1·12	1·15	1·17	1·20	1·23	1·25	1·28	1·30	1·33	1·36	293
276	1·26	1·29	1·32	1·35	1·38	1·40	1·44	1·47	1·50	1·53	294
275	1·40	1·43	1·47	1·50	1·53	1·56	1·60	1·63	1·66	1·70	295
274	1·54	1·58	1·61	1·65	1·69	1·72	1·76	1·79	1·83	1·87	296
273	1·68	1·72	1·76	1·80	1·84	1·88	1·92	1·96	2·00	2·04	297
272	1·82	1·86	1·91	1·95	1·99	2·03	2·08	2·12	2·16	2·21	298
271	1·96	2·01	2·05	2·10	2·15	2·19	2·24	2·28	2·33	2·38	299
270	2·10	2·15	2·20	2·25	2·30	2·34	2·40	2·45	2·49	2·54	300
269	2·25	2·30	2·35	2·40	2·45	2·50	2·55	2·60	2·66	2·71	301
268	2·39	2·44	2·49	2·55	2·61	2·66	2·71	2·77	2·83	2·88	302
267	2·53	2·58	2·64	2·70	2·76	2·81	2·87	2·93	2·99	3·05	303
266	2·67	2·73	2·79	2·85	2·91	2·97	3·03	3·10	3·16	3·22	304
265	2·81	2·87	2·93	3·00	3·07	3·13	3·19	3·26	3·33	3·39	305
264	2·95	3·01	3·08	3·15	3·22	3·28	3·35	3·42	3·49	3·56	306
263	3·09	3·15	3·23	3·30	3·37	3·44	3·51	3·59	3·66	3·73	307
262	3·23	3·30	3·37	3·45	3·53	3·60	3·67	3·75	3·83	3·90	308
261	3·37	3·44	3·52	3·60	3·68	3·75	3·83	3·91	3·99	4·07	309
260	3·51	3·58	3·67	3·75	3·83	3·91	3·99	4·08	4·16	4·24	310
259	3·65	3·73	3·81	3·90	3·99	4·06	4·15	4·24	4·32	4·41	311
258	3·79	3·87	3·96	4·05	4·14	4·22	4·31	4·40	4·49	4·58	312
257	3·93	4·01	4·11	4·20	4·29	4·38	4·47	4·56	4·66	4·75	313
256	4·07	4·16	4·25	4·35	4·45	4·53	4·63	4·73	4·82	4·92	314
255	4·21	4·30	4·40	4·50	4·60	4·69	4·79	4·89	4·99	5·09	315

TABLE LIA—TEMPERATURE CORRECTION OF THE FORTIN BAROMETER STANDARD TEMPERATURE 0° C.

Millibar graduations

To be used with barometers with National Physical Laboratory certificate dated on or after January 1, 1955.

Corrections to be applied to the readings of Fortin mercury barometers to reduce them to 0° C. All corrections are negative.

Attached thermometer	Barometer reading (mb.)									
	880	900	920	940	960	980	1000	1020	1040	1060
°C.	*millibars*									
	—	—	—	—	—	—	—	—	—	—
10·0	1·44	1·47	1·50	1·53	1·57	1·60	1·63	1·66	1·70	1·73
10·5	1·51	1·54	1·58	1·61	1·64	1·68	1·71	1·75	1·78	1·82
11·0	1·58	1·61	1·65	1·69	1·72	1·76	1·79	1·83	1·87	1·90
11·5	1·65	1·69	1·73	1·76	1·80	1·84	1·88	1·91	1·95	1·99
12·0	1·72	1·76	1·80	1·84	1·88	1·92	1·96	2·00	2·03	2·07
12·5	1·79	1·83	1·87	1·92	1·96	2·00	2·04	2·08	2·12	2·16
13·0	1·86	1·91	1·95	1·99	2·03	2·08	2·12	2·16	2·20	2·25
13·5	1·94	1·98	2·02	2·07	2·11	2·16	2·20	2·24	2·29	2·33
14·0	2·01	2·05	2·10	2·14	2·19	2·24	2·28	2·33	2·37	2·42
14·5	2·08	2·13	2·17	2·22	2·27	2·32	2·36	2·41	2·46	2·50
15·0	2·15	2·20	2·25	2·30	2·35	2·40	2·44	2·49	2·54	2·59
15·5	2·22	2·27	2·32	2·37	2·42	2·48	2·53	2·58	2·63	2·68
16·0	2·29	2·35	2·40	2·45	2·50	2·55	2·61	2·66	2·71	2·76
16·5	2·37	2·42	2·47	2·53	2·58	2·63	2·69	2·74	2·80	2·85
17·0	2·44	2·49	2·55	2·60	2·66	2·71	2·77	2·82	2·88	2·94
17·5	2·51	2·57	2·62	2·68	2·74	2·79	2·85	2·91	2·96	3·02
18·0	2·58	2·64	2·70	2·76	2·81	2·87	2·93	2·99	3·05	3·11
18·5	2·65	2·71	2·77	2·83	2·89	2·95	3·01	3·07	3·13	3·19
19·0	2·72	2·78	2·85	2·91	2·97	3·03	3·09	3·16	3·22	3·28
19·5	2·79	2·86	2·92	2·98	3·05	3·11	3·18	3·24	3·30	3·37
20·0	2·87	2·93	3·00	3·06	3·13	3·19	3·26	3·32	3·39	3·45
20·5	2·94	3·00	3·07	3·14	3·20	3·27	3·34	3·40	3·47	3·54
21·0	3·01	3·08	3·14	3·21	3·28	3·35	3·42	3·49	3·56	3·62
21·5	3·08	3·15	3·22	3·29	3·36	3·43	3·50	3·57	3·64	3·71
22·0	3·15	3·22	3·29	3·37	3·44	3·51	3·58	3·65	3·72	3·80
22·5	3·22	3·30	3·37	3·44	3·52	3·59	3·66	3·73	3·81	3·88
23·0	3·29	3·37	3·44	3·52	3·59	3·67	3·74	3·82	3·89	3·97
23·5	3·36	3·44	3·52	3·59	3·67	3·75	3·82	3·90	3·98	4·05
24·0	3·44	3·51	3·59	3·67	3·75	3·83	3·90	3·98	4·06	4·14
24·5	3·51	3·59	3·67	3·75	3·83	3·91	3·99	4·07	4·14	4·22
25·0	3·58	3·66	3·74	3·82	3·90	3·99	4·07	4·15	4·23	4·31
25·5	3·65	3·73	3·82	3·90	3·98	4·06	4·15	4·23	4·31	4·40
26·0	3·72	3·81	3·89	3·97	4·06	4·14	4·23	4·31	4·40	4·48
26·5	3·79	3·88	3·96	4·05	4·14	4·22	4·31	4·40	4·48	4·57
27·0	3·86	3·95	4·04	4·13	4·21	4·30	4·39	4·48	4·57	4·65
27·5	3·93	4·02	4·11	4·20	4·29	4·38	4·47	4·56	4·65	4·74
28·0	4·01	4·10	4·19	4·28	4·37	4·46	4·55	4·64	4·73	4·83
28·5	4·08	4·17	4·26	4·35	4·45	4·54	4·63	4·73	4·82	4·91
29·0	4·15	4·24	4·34	4·43	4·53	4·62	4·71	4·81	4·90	5·00
29·5	4·22	4·32	4·41	4·51	4·60	4·70	4·79	4·89	4·99	5·08
30·0	4·29	4·39	4·49	4·58	4·68	4·78	4·88	4·97	5·07	5·17

TABLE LII—CORRECTIONS FOR REDUCING BAROMETER READINGS TO STANDARD GRAVITY IN LATITUDE 45°, LATITUDE VARIATION

Meteorological Office Mk I barometers

Millibar graduations

To be used with barometers with National Physical Laboratory certificate dated on or before December 31, 1954.

For latitudes {0° to 44° / 46° to 90°} the correction is to be {subtracted / added}.

Meteorological Office Mk I millibar barometers are graduated to read correctly when the temperature is 285° A. and the value of gravity is 980·62 cm./sec.^{2}. This value of gravity is equal to the value of gravity at mean sea level in latitude 45° to within very close limits.

Latitude N. or S.		Pressure (mb.) 920	940	960	980	1000	1020	1040
°	°				*millibars*			
45	45	0·00	0·00	0·00	0·00	0·00	0·00	0·00
44	46	0·09	0·09	0·09	0·09	0·09	0·09	0·09
43	47	0·17	0·17	0·17	0·18	0·18	0·18	0·19
42	48	0·25	0·26	0·26	0·27	0·28	0·28	0·29
41	49	0·33	0·34	0·35	0·36	0·37	0·37	0·38
40	50	0·42	0·43	0·44	0·45	0·46	0·47	0·47
39	51	0·51	0·52	0·53	0·54	0·55	0·56	0·57
38	52	0·59	0·60	0·61	0·63	0·64	0·65	0·67
37	53	0·67	0·69	0·70	0·71	0·73	0·74	0·75
36	54	0·75	0·77	0·78	0·80	0·81	0·83	0·85
35	55	0·83	0·85	0·87	0·89	0·90	0·92	0·94
34	56	0·91	0·93	0·95	0·97	0·99	1·01	1·03
33	57	0·99	1·01	1·03	1·05	1·07	1·09	1·11
32	58	1·07	1·09	1·11	1·13	1·16	1·18	1·20
31	59	1·14	1·17	1·19	1·21	1·24	1·26	1·29
30	60	1·22	1·24	1·27	1·29	1·32	1·35	1·37
29	61	1·29	1·31	1·34	1·37	1·40	1·43	1·45
28	62	1·36	1·39	1·41	1·44	1·47	1·50	1·53
27	63	1·43	1·46	1·49	1·52	1·55	1·58	1·61
26	64	1·50	1·53	1·56	1·59	1·63	1·66	1·69
25	65	1·56	1·59	1·63	1·66	1·69	1·73	1·76
24	66	1·63	1·66	1·69	1·73	1·77	1·80	1·83
23	67	1·69	1·73	1·76	1·79	1·83	1·87	1·91
22	68	1·75	1·79	1·82	1·86	1·89	1·93	1·97
21	69	1·81	1·85	1·89	1·92	1·96	2·00	2·04
20	70	1·86	1·90	1·94	1·98	2·02	2·05	2·10
19	71	1·91	1·95	1·99	2·03	2·07	2·12	2·16
18	72	1·97	2·01	2·05	2·09	2·13	2·17	2·22
17	73	2·01	2·05	2·09	2·14	2·19	2·23	2·28
16	74	2·06	2·11	2·15	2·19	2·23	2·28	2·32
15	75	2·10	2·15	2·19	2·23	2·28	2·33	2·38
14	76	2·14	2·19	2·25	2·29	2·33	2·37	2·42
13	77	2·18	2·23	2·27	2·32	2·37	2·41	2·46
12	78	2·21	2·26	2·31	2·36	2·41	2·45	2·50
11	79	2·25	2·30	2·35	2·39	2·44	2·49	2·54
10	80	2·28	2·33	2·38	2·42	2·47	2·52	2·57
9	81	2·31	2·36	2·41	2·46	2·51	2·56	2·61
8	82	2·33	2·38	2·43	2·48	2·53	2·58	2·63
7	83	2·35	2·40	2·45	2·50	2·55	2·61	2·66
6	84	2·37	2·42	2·48	2·53	2·58	2·63	2·68
5	85	2·39	2·44	2·49	2·54	2·59	2·65	2·70
0	90	2·43	2·49	2·54	2·59	2·64	2·69	2·75

TABLE LIIA—CORRECTIONS FOR REDUCING BAROMETER READINGS TO STANDARD GRAVITY (980·665cm./sec.^{2}), LATITUDE VARIATION

Meteorological Office Mk II barometers

Millibar graduations

To be used with barometers with National Physical Laboratory certificate dated on or after January 1, 1955.

For latitudes {0° to 45° / 46° to 90°} the correction is {negative / positive}.

Meteorological Office Mk II millibar barometers are graduated to read correctly when the temperature is 0° C. and the value of gravity is 980·665 cm./sec.^{2}

Latitude N. or S.	Pressure (mb.) 920	940	960	980	1000	1020	1040
°	millibars						
	+	+	+	+	+	+	+
90	2·39	2·44	2·49	2·54	2·59	2·65	2·70
85	2·35	2·40	2·45	2·50	2·55	2·60	2·66
84	2·33	2·38	2·43	2·48	2·54	2·59	2·64
83	2·31	2·36	2·41	2·46	2·51	2·56	2·62
82	2·29	2·34	2·39	2·44	2·49	2·54	2·59
81	2·27	2·32	2·37	2·41	2·46	2·51	2·56
80	2·24	2·29	2·34	2·38	2·43	2·48	2·53
79	2·21	2·26	2·30	2·35	2·40	2·45	2·50
78	2·17	2·22	2·27	2·32	2·36	2·41	2·46
77	2·14	2·19	2·23	2·28	2·33	2·37	2·42
76	2·10	2·15	2·19	2·24	2·28	2·33	2·37
75	2·06	2·10	2·15	2·19	2·24	2·28	2·33
74	2·02	2·06	2·10	2·15	2·19	2·23	2·28
73	1·97	2·01	2·05	2·10	2·14	2·18	2·23
72	1·92	1·96	2·00	2·05	2·09	2·13	2·17
71	1·87	1·91	1·95	1·99	2·03	2·07	2·11
70	1·82	1·86	1·89	1·93	1·97	2·01	2·05
69	1·76	1·80	1·84	1·87	1·91	1·95	1·99
68	1·70	1·74	1·78	1·81	1·85	1·89	1·92
67	1·64	1·68	1·71	1·75	1·78	1·82	1·86
66	1·58	1·61	1·65	1·68	1·72	1·75	1·79
65	1·52	1·55	1·58	1·61	1·65	1·68	1·71
64	1·45	1·48	1·51	1·54	1·58	1·61	1·64
63	1·38	1·41	1·44	1·47	1·50	1·53	1·56
62	1·31	1·34	1·37	1·40	1·43	1·45	1·48
61	1·24	1·27	1·30	1·32	1·35	1·38	1·40
60	1·17	1·19	1·22	1·24	1·27	1·30	1·32
59	1·09	1·12	1·14	1·17	1·19	1·21	1·24
58	1·02	1·04	1·06	1·09	1·11	1·13	1·15
57	0·94	0·96	0·98	1·00	1·02	1·04	1·06
56	0·86	0·88	0·90	0·92	0·94	0·96	0·98
55	0·78	0·80	0·82	0·84	0·85	0·87	0·89
54	0·70	0·72	0·73	0·75	0·77	0·78	0·80
53	0·62	0·64	0·65	0·66	0·68	0·69	0·70
52	0·54	0·55	0·56	0·58	0·59	0·60	0·61
51	0·46	0·47	0·48	0·49	0·50	0·51	0·52
50	0·38	0·38	0·39	0·40	0·41	0·42	0·42
49	0·29	0·30	0·30	0·31	0·32	0·32	0·33
48	0·21	0·21	0·22	0·22	0·23	0·23	0·23
47	0·12	0·13	0·13	0·13	0·13	0·14	0·14
46	0·04	0·04	0·04	0·04	0·04	0·04	0·04

TABLE LIIA—CORRECTIONS FOR REDUCING BAROMETER READINGS TO STANDARD GRAVITY (980·665 cm./sec.^{2}), LATITUDE VARIATION—*continued*

Meteorological Office Mk II barometers

Millibar graduations

To be used with barometers with National Physical Laboratory certificate dated on or after January 1, 1955.

For latitudes {0° to 45° / 46° to 90°} the correction is {negative / positive}.

Meteorological Office Mk II millibar barometers are graduated to read correctly when the temperature is 0° C. and the value of gravity is 980·665 cm./sec.^{2}

Latitude N. or S.	Pressure (mb.) 920	940	960	980	1000	1020	1040
°				*millibars*			
	—	—	—	—	—	—	—
45	0·05	0·05	0·05	0·05	0·05	0·05	0·05
44	0·13	0·13	0·14	0·14	0·14	0·14	0·15
43	0·22	0·22	0·22	0·23	0·23	0·24	0·24
42	0·30	0·31	0·31	0·32	0·33	0·33	0·34
41	0·38	0·39	0·40	0·41	0·42	0·43	0·43
40	0·47	0·48	0·49	0·50	0·51	0·52	0·53
39	0·55	0·56	0·57	0·59	0·60	0·61	0·62
38	0·63	0·65	0·66	0·67	0·69	0·70	0·72
37	0·71	0·73	0·75	0·76	0·78	0·79	0·81
36	0·80	0·81	0·83	0·85	0·86	0·88	0·90
35	0·88	0·89	0·91	0·93	0·95	0·97	0·99
34	0·95	0·97	1·00	1·02	1·04	1·06	1·08
33	1·03	1·05	1·08	1·10	1·12	1·14	1·17
32	1·11	1·13	1·16	1·18	1·21	1·23	1·25
31	1·18	1·21	1·24	1·26	1·29	1·31	1·34
30	1·26	1·28	1·31	1·34	1·37	1·39	1·42
29	1·33	1·36	1·39	1·42	1·45	1·47	1·50
28	1·40	1·43	1·46	1·49	1·52	1·55	1·58
27	1·47	1·50	1·53	1·57	1·60	1·63	1·66
26	1·54	1·57	1·60	1·64	1·67	1·70	1·74
25	1·60	1·64	1·67	1·71	1·74	1·78	1·81
24	1·67	1·70	1·74	1·78	1·81	1·85	1·88
23	1·73	1·77	1·80	1·84	1·88	1·92	1·95
22	1·79	1·83	1·87	1·91	1·94	1·98	2·02
21	1·85	1·89	1·93	1·97	2·01	2·05	2·09
20	1·90	1·94	1·98	2·03	2·07	2·11	2·15
19	1·95	2·00	2·04	2·08	2·12	2·17	2·21
18	2·01	2·05	2·09	2·14	2·18	2·22	2·27
17	2·05	2·10	2·14	2·19	2·23	2·28	2·32
16	2·10	2·15	2·19	2·24	2·28	2·33	2·37
15	2·14	2·19	2·24	2·28	2·33	2·38	2·42
14	2·18	2·23	2·28	2·33	2·37	2·42	2·47
13	2·22	2·27	2·32	2·37	2·42	2·46	2·51
12	2·26	2·31	2·36	2·41	2·45	2·50	2·55
11	2·29	2·34	2·39	2·44	2·49	2·54	2·59
10	2·32	2·37	2·42	2·47	2·52	2·57	2·62
9	2·35	2·40	2·45	2·50	2·55	2·60	2·66
8	2·37	2·42	2·48	2·53	2·58	2·63	2·68
7	2·40	2·45	2·50	2·55	2·60	2·66	2·71
6	2·41	2·47	2·52	2·57	2·62	2·68	2·73
5	2·43	2·48	2·54	2·59	2·64	2·69	2·75
0	2·47	2·53	2·58	2·63	2·69	2·74	2·79

TABLE LIII—CORRECTIONS FOR REDUCING BAROMETER READINGS TO STANDARD GRAVITY IN LATITUDE 45°, LATITUDE VARIATION

Meteorological Office Mk I barometers

Inch graduations

To be used with barometers with National Physical Laboratory certificate dated on or before December 31, 1954.

For latitudes {0° to 44° / 46° to 90°} the correction is to be {subtracted / added}.

Meteorological Office Mk I inch barometers are graduated to read correctly when the temperature of the scale is 62° F., the temperature of the mercury is 32° F., and the value of gravity is 980·62 cm./sec.[2] This value of gravity is equal to the value of gravity at mean sea level in latitude 45° to within very close limits.

Latitude N. or S.		Pressure (in.) 28	29	30	31
°	°	*inches*			
45	45	0·000	0·000	0·000	0·000
44	46	0·002	0·002	0·002	0·002
43	47	0·005	0·005	0·005	0·005
42	48	0·008	0·008	0·008	0·008
41	49	0·010	0·010	0·011	0·011
40	50	0·012	0·013	0·013	0·014
39	51	0·015	0·015	0·016	0·016
38	52	0·017	0·018	0·019	0·019
37	53	0·020	0·021	0·021	0·022
36	54	0·022	0·023	0·024	0·025
35	55	0·025	0·026	0·027	0·027
34	56	0·027	0·028	0·029	0·030
33	57	0·030	0·031	0·032	0·033
32	58	0·032	0·033	0·034	0·035
31	59	0·034	0·036	0·037	0·038
30	60	0·037	0·038	0·039	0·040
29	61	0·039	0·040	0·041	0·043
28	62	0·041	0·042	0·044	0·045
27	63	0·043	0·045	0·046	0·048
26	64	0·045	0·047	0·048	0·050
25	65	0·047	0·049	0·050	0·052
24	66	0·049	0·051	0·053	0·054
23	67	0·051	0·053	0·055	0·056
22	68	0·053	0·055	0·057	0·058
21	69	0·055	0·056	0·058	0·060
20	70	0·056	0·058	0·060	0·062
19	71	0·058	0·060	0·062	0·064
18	72	0·059	0·062	0·064	0·066
17	73	0·061	0·063	0·065	0·067
16	74	0·062	0·065	0·067	0·069
15	75	0·064	0·066	0·068	0·070
14	76	0·065	0·067	0·069	0·072
13	77	0·066	0·068	0·071	0·073
12	78	0·067	0·070	0·072	0·074
11	79	0·068	0·071	0·073	0·075
10	80	0·069	0·072	0·074	0·076
9	81	0·070	0·072	0·075	0·077
8	82	0·071	0·073	0·076	0·078
7	83	0·071	0·074	0·076	0·079
6	84	0·072	0·075	0·077	0·080
5	85	0·072	0·075	0·078	0·080
4	86	0·072	0·075	0·078	0·080
3	87	0·072	0·075	0·078	0·080
2	88	0·072	0·075	0·078	0·080
1	89	0·073	0·075	0·078	0·080
0	90	0·074	0·076	0·079	0·081

TABLE LIIIA—CORRECTIONS FOR REDUCING BAROMETER READINGS TO STANDARD GRAVITY (980·665 cm./sec.^{2}), LATITUDE VARIATION

Meteorological Office Mk II barometers

Inch graduations

To be used with barometers with National Physical Laboratory certificate dated on or after January 1, 1955.

For latitudes {0° to 45° / 46° to 90°} the correction is {negative / positive}.

Meteorological Office Mk II inch barometers are graduated to read correctly when the temperature is 32° F. and the value of gravity is 980·665 cm./sec.^{2}

Latitude N. or S.	Pressure (in.)			
	28	29	30	31
°	*inches*			
	+	+	+	+
90	0·073	0·075	0·078	0·080
85	0·071	0·074	0·077	0·079
84	0·071	0·074	0·076	0·079
83	0·070	0·073	0·075	0·078
82	0·070	0·072	0·075	0·077
81	0·069	0·071	0·074	0·076
80	0·068	0·071	0·073	0·075
79	0·067	0·070	0·072	0·074
78	0·066	0·069	0·071	0·073
77	0·065	0·067	0·070	0·072
76	0·064	0·066	0·068	0·071
75	0·063	0·065	0·067	0·069
74	0·061	0·064	0·066	0·068
73	0·060	0·062	0·064	0·066
72	0·058	0·061	0·063	0·065
71	0·057	0·059	0·061	0·063
70	0·055	0·057	0·059	0·061
69	0·054	0·055	0·057	0·059
68	0·052	0·054	0·056	0·057
67	0·050	0·052	0·054	0·055
66	0·048	0·050	0·052	0·053
65	0·046	0·048	0·049	0·051
64	0·044	0·046	0·047	0·049
63	0·042	0·044	0·045	0·047
62	0·040	0·041	0·043	0·044
61	0·038	0·039	0·040	0·042
60	0·036	0·037	0·038	0·039
59	0·033	0·035	0·036	0·037
58	0·031	0·032	0·033	0·034
57	0·029	0·030	0·031	0·032
56	0·026	0·027	0·028	0·029
55	0·024	0·025	0·026	0·026
54	0·021	0·022	0·023	0·024
53	0·019	0·020	0·020	0·021
52	0·016	0·017	0·018	0·018
51	0·014	0·014	0·015	0·015
50	0·011	0·012	0·012	0·013
49	0·009	0·009	0·010	0·010
48	0·006	0·007	0·007	0·007
47	0·004	0·004	0·004	0·004
46	0·001	0·001	0·001	0·001

TABLE LIIIA—CORRECTIONS FOR REDUCING BAROMETER READINGS TO STANDARD GRAVITY (980·665 cm./sec.^{2}), LATITUDE VARIATION—*continued*

Meteorological Office Mk II barometers

Inch graduations

To be used with barometers with National Physical Laboratory certificate dated on or after January 1, 1955.

For latitudes {0° to 45° / 46° to 90°} the correction is {negative / positive}.

Meteorological Office Mk II inch barometers are graduated to read correctly when the temperature is 32° F. and the value of gravity is 980·665 cm./sec.^{2}

Latitude N. or S.	Pressure (in.) 28	29	30	31
°	*inches*			
	—	—	—	—
45	0·001	0·001	0·002	0·002
44	0·004	0·004	0·004	0·004
43	0·007	0·007	0·007	0·007
42	0·009	0·009	0·010	0·010
41	0·012	0·012	0·013	0·013
40	0·014	0·015	0·015	0·016
39	0·017	0·017	0·018	0·019
38	0·019	0·020	0·021	0·021
37	0·022	0·023	0·023	0·024
36	0·024	0·025	0·026	0·027
35	0·027	0·028	0·029	0·029
34	0·029	0·030	0·031	0·032
33	0·031	0·033	0·034	0·035
32	0·034	0·035	0·036	0·037
31	0·036	0·037	0·039	0·040
30	0·038	0·040	0·041	0·042
29	0·040	0·042	0·043	0·045
28	0·043	0·044	0·046	0·047
27	0·045	0·046	0·048	0·050
26	0·047	0·048	0·050	0·052
25	0·049	0·051	0·052	0·054
24	0·051	0·053	0·054	0·056
23	0·053	0·055	0·056	0·058
22	0·054	0·056	0·058	0·060
21	0·056	0·058	0·060	0·062
20	0·058	0·060	0·062	0·064
19	0·059	0·062	0·064	0·066
18	0·061	0·063	0·065	0·068
17	0·063	0·065	0·067	0·069
16	0·064	0·066	0·068	0·071
15	0·065	0·068	0·070	0·072
14	0·066	0·069	0·071	0·074
13	0·068	0·070	0·072	0·075
12	0·069	0·071	0·074	0·076
11	0·070	0·072	0·075	0·077
10	0·071	0·073	0·076	0·078
9	0·071	0·074	0·077	0·079
8	0·072	0·075	0·077	0·080
7	0·073	0·075	0·078	0·081
6	0·073	0·076	0·079	0·081
5	0·074	0·077	0·079	0·082
0	0·075	0·078	0·081	0·083

TABLE LIV—CORRECTION FOR REDUCING BAROMETER READINGS TO STANDARD GRAVITY, HEIGHT VARIATION

All mercury barometers

These corrections, which are all negative, relate to the average pressures encountered at the respective heights. Normal pressure variations at a given height affect the correction very little.

Height	Correction	
ft.	*mb.*	*in.*
2,000	−0·18	−0·005
1,800	−0·16	−0·005
1,600	−0·14	−0·004
1,400	−0·13	−0·004
1,200	−0·11	−0·003
1,000	−0·09	−0·003
800	−0·07	−0·002
600	−0·05	−0·001
400	−0·04	−0·001
200	−0·02	−0·001

TABLE LV—REDUCTION OF PRESSURE TO A GIVEN DATUM LEVEL

Height in metres

Pressure at station level 1000 mb. and ambient air temperature 260° A. (8·6° F.)

Height above datum level	Air temperature 260°A. (8·6°F.)	Height above datum level	Air temperature 260°A. (8·6°F.)	Height above datum level	Air temperature 260°A. (8·6°F.)	Height above datum level	Air temperature 260°A. (8·6°F.)
m.	mb.	m.	mb.	m.	mb.	m.	mb.
1	0·13	51	6·71	101	13·34	151	20·01
2	0·26	52	6·84	102	13·47	152	20·14
3	0·39	53	6·98	103	13·61	153	20·27
4	0·52	54	7·11	104	13·74	154	20·41
5	0·66	55	7·24	105	13·87	155	20·54
6	0·79	56	7·37	106	14·00	156	20·67
7	0·92	57	7·51	107	14·14	157	20·81
8	1·05	58	7·64	108	14·27	158	20·94
9	1·18	59	7·77	109	14·40	159	21·07
10	1·31	60	7·90	110	14·54	160	21·20
11	1·44	61	8·04	111	14·67	161	21·34
12	1·58	62	8·17	112	14·80	162	21·47
13	1·71	63	8·30	113	14·94	163	21·61
14	1·84	64	8·43	114	15·07	164	21·74
15	1·97	65	8·57	115	15·20	165	21·88
16	2·10	66	8·70	116	15·33	166	22·01
17	2·23	67	8·83	117	15·47	167	22·14
18	2·36	68	8·96	118	15·60	168	22·28
19	2·50	69	9·10	119	15·73	169	22·41
20	2·63	70	9·23	120	15·87	170	22·55
21	2·76	71	9·36	121	16·00	171	22·68
22	2·89	72	9·49	122	16·13	172	22·81
23	3·02	73	9·63	123	16·27	173	22·95
24	3·15	74	9·76	124	16·40	174	23·08
25	3·28	75	9·89	125	16·53	175	23·22
26	3·41	76	10·02	126	16·66	176	23·35
27	3·55	77	10·16	127	16·80	177	23·48
28	3·68	78	10·29	128	16·93	178	23·62
29	3·81	79	10·42	129	17·07	179	23·75
30	3·94	80	10·55	130	17·20	180	23·89
31	4·07	81	10·69	131	17·33	181	24·02
32	4·20	82	10·82	132	17·47	182	24·16
33	4·34	83	10·95	133	17·60	183	24·29
34	4·47	84	11·08	134	17·73	184	24·43
35	4·60	85	11·22	135	17·87	185	24·56
36	4·73	86	11·35	136	18·00	186	24·70
37	4·86	87	11·48	137	18·14	187	24·83
38	4·99	88	11·61	138	18·27	188	24·97
39	5·13	89	11·75	139	18·40	189	25·11
40	5·26	90	11·88	140	18·54	190	25·24
41	5·39	91	12·01	141	18·67	191	25·37
42	5·52	92	12·14	142	18·80	192	25·51
43	5·66	93	12·28	143	18·94	193	25·64
44	5·79	94	12·41	144	19·07	194	25·78
45	5·92	95	12·54	145	19·20	195	25·91
46	6·05	96	12·67	146	19·34	196	26·05
47	6·19	97	12·81	147	19·47	197	26·18
48	6·32	98	12·94	148	19·60	198	26·32
49	6·45	99	13·08	149	19·74	199	26·45
50	6·58	100	13·21	150	19·87	200	26·59

TABLE LVI—REDUCTION OF PRESSURE TO A GIVEN DATUM LEVEL

Height in feet

Pressure at station level, 1000 mb.*

Height above datum level	Air temperature (° F.) Dry bulb in screen 0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	Height above datum level
ft.					*millibars*						ft.
10	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·3	0·3	10
20	0·8	0·8	0·8	0·8	0·8	0·7	0·7	0·7	0·7	0·7	20
30	1·2	1·2	1·2	1·1	1·1	1·1	1·1	1·1	1·0	1·0	30
40	1·6	1·6	1·6	1·5	1·5	1·4	1·4	1·4	1·4	1·4	40
50	2·0	2·0	2·0	1·9	1·9	1·8	1·8	1·8	1·7	1·7	50
60	2·4	2·4	2·4	2·3	2·3	2·2	2·2	2·1	2·1	2·0	60
70	2·8	2·8	2·8	2·7	2·7	2·6	2·5	2·5	2·4	2·4	70
80	3·3	3·2	3·1	3·0	3·0	2·9	2·9	2·8	2·8	2·7	80
90	3·7	3·6	3·5	3·4	3·4	3·3	3·2	3·2	3·1	3·1	90
100	4·1	4·0	3·9	3·8	3·8	3·7	3·6	3·5	3·5	3·4	100
110	4·5	4·4	4·3	4·2	4·2	4·1	4·0	3·9	3·8	3·7	110
120	4·9	4·8	4·7	4·6	4·5	4·4	4·3	4·2	4·2	4·1	120
130	5·3	5·2	5·1	5·0	4·9	4·8	4·7	4·6	4·5	4·4	130
140	5·7	5·6	5·5	5·4	5·2	5·1	5·0	4·9	4·9	4·8	140
150	6·1	6·0	5·9	5·8	5·6	5·5	5·4	5·3	5·2	5·1	150
160	6·5	6·4	6·3	6·2	6·0	5·9	5·8	5·7	5·6	5·4	160
170	6·9	6·8	6·7	6·6	6·4	6·3	6·1	6·0	5·9	5·8	170
180	7·4	7·2	7·0	6·9	6·7	6·6	6·5	6·4	6·3	6·1	180
190	7·8	7·6	7·4	7·3	7·1	7·0	6·8	6·7	6·6	6·5	190
200	8·2	8·0	7·8	7·7	7·5	7·4	7·2	7·1	7·0	6·8	200
210	8·6	8·4	8·2	8·1	7·9	7·8	7·6	7·5	7·3	7·2	210
220	9·0	8·8	8·6	8·5	8·3	8·1	7·9	7·8	7·7	7·5	220
230	9·4	9·2	9·0	8·8	8·6	8·5	8·3	8·2	8·0	7·9	230
240	9·8	9·6	9·4	9·2	9·0	8·8	8·6	8·5	8·4	8·2	240
250	10·2	10·0	9·8	9·6	9·4	9·2	9·0	8·9	8·7	8·6	250
260	10·6	10·4	10·2	10·0	9·8	9·6	9·4	9·3	9·1	8·9	260
270	11·0	10·8	10·6	10·4	10·2	10·0	9·8	9·6	9·4	9·3	270
280	11·5	11·2	11·0	10·7	10·5	10·3	10·1	10·0	9·8	9·6	280
290	11·9	11·6	11·4	11·1	10·9	10·7	10·5	10·3	10·1	10·0	290
300	12·3	12·0	11·8	11·5	11·3	11·1	10·9	10·7	10·5	10·3	300
310	12·7	12·4	12·2	11·9	11·7	11·5	11·3	11·1	10·8	10·6	310
320	13·1	12·8	12·6	12·3	12·1	11·8	11·6	11·4	11·2	11·0	320
330	13·6	13·3	13·0	12·7	12·4	12·2	12·0	11·8	11·5	11·3	330
340	14·0	13·7	13·4	13·1	12·8	12·5	12·3	12·1	11·9	11·7	340
350	14·4	14·1	13·8	13·5	13·2	12·9	12·7	12·5	12·2	12·0	350
360	14·8	14·5	14·2	13·9	13·6	13·3	13·1	12·8	12·6	12·3	360
370	15·2	14·9	14·6	14·3	14·0	13·7	13·4	13·2	12·9	12·7	370
380	15·6	15·3	14·9	14·6	14·3	14·0	13·8	13·5	13·3	13·0	380
390	16·0	15·7	15·3	15·0	14·7	14·4	14·1	13·9	13·6	13·4	390
400	16·4	16·1	15·7	15·4	15·1	14·8	14·5	14·2	14·0	13·7	400
410	16·8	16·5	16·1	15·8	15·5	15·2	14·9	14·6	14·3	14·0	410
420	17·2	16·9	16·5	16·2	15·9	15·6	15·2	14·9	14·7	14·4	420
430	17·7	17·3	16·9	16·6	16·2	15·9	15·6	15·3	15·0	14·7	430
440	18·1	17·7	17·3	17·0	16·6	16·3	15·9	15·6	15·4	15·1	440
450	18·5	18·1	17·7	17·4	17·0	16·7	16·3	16·0	15·7	15·4	450
460	18·9	18·5	18·1	17·8	17·4	17·1	16·7	16·4	16·1	15·8	460
470	19·3	18·9	18·5	18·2	17·8	17·4	17·1	16·7	16·4	16·1	470
480	19·8	19·3	18·9	18·5	18·1	17·8	17·4	17·1	16·8	16·5	480
490	20·2	19·7	19·3	18·9	18·5	18·1	17·8	17·4	17·1	16·8	490
500	20·6	20·1	19·7	19·3	18·9	18·5	18·2	17·8	17·5	17·2	500

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

TABLE LVI—REDUCTION OF PRESSURE TO A GIVEN DATUM LEVEL—*continued*

Height in feet

Pressure at station level, 1000 mb.*

Height above datum level	Air temperature (° F.) Dry bulb in screen 0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	Height above datum level
ft.					*millibars*						ft.
500	20·6	20·1	19·7	19·3	18·9	18·5	18·2	17·8	17·5	17·2	500
510	21·0	20·5	20·1	19·7	19·3	18·9	18·6	18·2	17·9	17·5	510
520	21·4	20·9	20·5	20·1	19·7	19·3	18·9	18·5	18·2	17·9	520
530	21·9	21·4	20·9	20·5	20·0	19·6	19·3	18·9	18·6	18·2	530
540	22·3	21·8	21·3	20·9	20·4	20·0	19·6	19·2	18·9	18·6	540
550	22·7	22·2	21·7	21·3	20·8	20·4	20·0	19·6	19·3	18·9	550
560	23·1	22·6	22·1	21·7	21·2	20·8	20·4	20·0	19·6	19·2	560
570	23·5	23·0	22·5	22·1	21·6	21·2	20·8	20·3	20·0	19·6	570
580	23·9	23·4	22·9	22·4	21·9	21·5	21·1	20·7	20·3	19·9	580
590	24·3	23·8	23·3	22·8	22·3	21·9	21·5	21·0	20·7	20·3	590
600	24·7	24·2	23·7	23·2	22·7	22·3	21·9	21·4	21·0	20·6	600
610	25·1	24·6	24·1	23·6	23·1	22·7	22·3	21·8	21·4	21·0	610
620	25·5	25·0	24·5	24·0	23·5	23·1	22·6	22·1	21·7	21·3	620
630	26·0	25·5	24·9	24·4	23·9	23·4	23·0	22·5	22·1	21·7	630
640	26·4	25·9	25·3	24·8	24·3	23·8	23·3	22·8	22·4	22·0	640
650	26·8	26·3	25·7	25·2	24·7	24·2	23·7	23·2	22·8	22·4	650
660	27·2	26·7	26·1	25·6	25·1	24·6	24·1	23·6	23·2	22·7	660
670	27·6	27·1	26·5	26·0	25·5	24·9	24·4	24·0	23·5	23·1	670
680	28·1	27·5	26·9	26·3	25·8	25·3	24·8	24·3	23·9	23·4	680
690	28·5	27·9	27·3	26·7	26·2	25·6	25·1	24·7	24·2	23·8	690
700	28·9	28·3	27·7	27·1	26·6	26·0	25·5	25·1	24·6	24·1	700
710	29·3	28·7	28·1	27·5	27·0	26·4	25·9	25·5	25·0	24·5	710
720	29·7	29·1	28·5	27·9	27·4	26·8	26·3	25·8	25·3	24·8	720
730	30·2	29·6	28·9	28·3	27·7	27·1	26·6	26·2	25·7	25·2	730
740	30·6	30·0	29·3	28·7	28·1	27·5	27·0	26·5	26·0	25·5	740
750	31·0	30·4	29·7	29·1	28·5	27·9	27·4	26·9	26·4	25·9	750
760	31·4	30·8	30·1	29·5	28·9	28·3	27·8	27·3	26·7	26·2	760
770	31·8	31·2	30·5	29·9	29·3	28·7	28·1	27·6	27·1	26·6	770
780	32·3	31·6	30·9	30·3	29·6	29·0	28·5	28·0	27·4	26·9	780
790	32·7	32·0	31·3	30·7	30·0	29·4	28·8	28·3	27·8	27·3	790
800	33·1	32·4	31·7	31·1	30·4	29·8	29·2	28·7	28·1	27·6	800
810	33·5	32·8	32·1	31·5	30·8	30·2	29·6	29·1	28·5	28·0	810
820	33·9	33·2	32·5	31·9	31·2	30·6	30·0	29·4	28·8	28·3	820
830	34·4	33·7	32·9	32·2	31·6	30·9	30·3	29·8	29·2	28·7	830
840	34·8	34·1	33·3	32·6	32·0	31·3	30·7	30·1	29·5	29·0	840
850	35·2	34·5	33·7	33·0	32·4	31·7	31·1	30·5	29·9	29·4	850
860	35·6	34·9	34·1	33·4	32·8	32·1	31·5	30·9	30·3	29·7	860
870	36·1	35·3	34·5	33·8	33·2	32·5	31·9	31·2	30·6	30·1	870
880	36·5	35·7	35·0	34·2	33·5	32·8	32·2	31·6	31·0	30·4	880
890	37·0	36·1	35·4	34·6	33·9	33·2	32·6	31·9	31·3	30·8	890
900	37·4	36·5	35·8	35·0	34·3	33·6	33·0	32·3	31·7	31·1	900
910	37·8	36·9	36·2	35·4	34·7	34·0	33·4	32·7	32·1	31·5	910
920	38·2	37·3	36·6	35·8	35·1	34·4	33·7	33·1	32·4	31·8	920
930	38·7	37·8	37·0	36·2	35·4	34·7	34·1	33·4	32·8	32·2	930
940	39·1	38·2	37·4	36·6	35·8	35·1	34·4	33·8	33·1	32·5	940
950	39·5	38·6	37·8	37·0	36·2	35·5	34·8	34·2	33·5	32·9	950
960	39·9	39·0	38·2	37·4	36·6	35·9	35·2	34·6	33·9	33·2	960
970	40·3	39·4	38·6	37·8	37·0	36·3	35·6	34·9	34·2	33·6	970
980	40·8	39·9	39·0	38·2	37·4	36·6	35·9	35·3	34·6	33·9	980
990	41·2	40·3	39·4	38·6	37·8	37·0	36·3	35·6	34·9	34·3	990
1000	41·6	40·7	39·8	39·0	38·2	37·4	36·7	36·0	35·3	34·6	1000

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

TABLE LVII—REDUCTION OF PRESSURE TO A GIVEN DATUM LEVEL

Pressure at station level, 30 in.

Height above datum level	Air temperature (°F.) Dry bulb in screen 0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	Height above datum level
ft.					inches						ft.
10	0·012	0·012	0·012	0·011	0·011	0·011	0·011	0·010	0·010	0·010	10
20	0·025	0·024	0·023	0·023	0·023	0·022	0·022	0·021	0·021	0·020	20
30	0·037	0·036	0·035	0·035	0·034	0·033	0·032	0·032	0·031	0·031	30
40	0·049	0·048	0·047	0·046	0·045	0·044	0·043	0·042	0·042	0·041	40
50	0·062	0·060	0·059	0·058	0·056	0·055	0·054	0·053	0·052	0·051	50
60	0·074	0·072	0·071	0·069	0·068	0·066	0·065	0·064	0·062	0·061	60
70	0·086	0·084	0·083	0·081	0·079	0·077	0·076	0·074	0·073	0·071	70
80	0·098	0·096	0·094	0·092	0·091	0·089	0·087	0·085	0·083	0·081	80
90	0·111	0·108	0·106	0·104	0·102	0·101	0·098	0·095	0·094	0·092	90
100	0·123	0·120	0·118	0·115	0·113	0·111	0·108	0·106	0·104	0·101	100
110	0·135	0·132	0·129	0·127	0·124	0·122	0·119	0·116	0·114	0·112	110
120	0·147	0·144	0·141	0·138	0·136	0·133	0·130	0·127	0·125	0·122	120
130	0·159	0·156	0·153	0·150	0·147	0·143	0·140	0·137	0·135	0·133	130
140	0·171	0·168	0·164	0·161	0·158	0·154	0·151	0·148	0·146	0·143	140
150	0·183	0·180	0·176	0·173	0·169	0·165	0·162	0·159	0·156	0·153	150
160	0·196	0·192	0·188	0·184	0·180	0·176	0·173	0·170	0·166	0·163	160
170	0·209	0·204	0·200	0·196	0·191	0·187	0·184	0·180	0·177	0·173	170
180	0·221	0·216	0·212	0·207	0·202	0·198	0·195	0·191	0·187	0·184	180
190	0·233	0·228	0·223	0·218	0·214	0·209	0·205	0·202	0·198	0·194	190
200	0·246	0·240	0·235	0·230	0·225	0·221	0·217	0·212	0·209	0·205	200
210	0·258	0·252	0·246	0·241	0·236	0·232	0·227	0·223	0·219	0·215	210
220	0·270	0·264	0·258	0·253	0·248	0·243	0·238	0·234	0·230	0·226	220
230	0·282	0·276	0·270	0·265	0·259	0·254	0·249	0·245	0·241	0·236	230
240	0·294	0·288	0·282	0·277	0·271	0·265	0·260	0·255	0·251	0·247	240
250	0·306	0·300	0·294	0·288	0·282	0·276	0·271	0·266	0·262	0·258	250
260	0·319	0·312	0·306	0·299	0·293	0·287	0·282	0·278	0·272	0·268	260
270	0·331	0·324	0·318	0·311	0·305	0·299	0·293	0·289	0·283	0·278	270
280	0·344	0·336	0·330	0·322	0·316	0·310	0·305	0·299	0·293	0·289	280
290	0·356	0·348	0·342	0·334	0·328	0·322	0·316	0·310	0·304	0·299	290
300	0·369	0·360	0·354	0·345	0·339	0·333	0·327	0·321	0·315	0·309	300
310	0·382	0·373	0·366	0·357	0·350	0·344	0·338	0·332	0·325	0·319	310
320	0·394	0·385	0·378	0·369	0·362	0·355	0·349	9·343	0·335	0·329	320
330	0·407	0·398	0·390	0·381	0·373	0·365	0·359	0·353	0·346	0·340	330
340	0·419	0·410	0·402	0·393	0·385	0·376	0·370	0·364	0·356	0·350	340
350	0·432	0·423	0·414	0·405	0·396	0·387	0·381	0·375	0·366	0·360	350
360	0·444	0·435	0·425	0·416	0·407	0·398	0·392	0·385	0·377	0·370	360
370	0·456	0·447	0·437	0·428	0·419	0·410	0·403	0·395	0·388	0·380	370
380	0·468	0·459	0·448	0·439	0·430	0·421	0·413	0·406	0·398	0·391	380
390	0·480	0·471	0·460	0·451	0·442	0·433	0·424	0·416	0·409	0·401	390
400	0·492	0·483	0·471	0·462	0·453	0·444	0·435	0·426	0·420	0·411	400
410	0·505	0·495	0·483	0·474	0·464	0·455	0·446	0·437	0·430	0·421	410
420	0·517	0·507	0·495	0·486	0·476	0·467	0·457	0·448	0·440	0·431	420
430	0·530	0·519	0·507	0·498	0·487	0·478	0·467	0·458	0·451	0·442	430
440	0·542	0·531	0·519	0·510	0·499	0·490	0·478	0·469	0·461	0·452	440
450	0·555	0·543	0·531	0·522	0·510	0·501	0·489	0·480	0·471	0·462	450
460	0·568	0·555	0·543	0·533	0·521	0·512	0·500	0·491	0·482	0·473	460
470	0·580	0·567	0·555	0·545	0·533	0·523	0·512	0·502	0·493	0·484	470
480	0·593	0·579	0·567	0·556	0·544	0·533	0·523	0·512	0·503	0·494	480
490	0·605	0·591	0·579	0·568	0·556	0·544	0·535	0·523	0·514	0·505	490
500	0·618	0·603	0·591	0·579	0·567	0·555	0·546	0·534	0·525	0·516	500

TABLE LVII—REDUCTION OF PRESSURE TO A GIVEN DATUM LEVEL—*continued*

Pressure at station level, 30 in.

Height above datum level	Air temperature (°F.) Dry bulb in screen 0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	Height above datum level
ft.					*inches*						ft.
500	0·618	0·603	0·591	0·579	0·567	0·555	0·546	0·534	0·525	0·516	500
510	0·631	0·616	0·603	0·591	0·578	0·566	0·557	0·545	0·536	0·526	510
520	0·643	0·628	0·615	0·603	0·590	0·578	0·568	0·556	0·547	0·536	520
530	0·656	0·641	0·627	0·615	0·601	0·589	0·578	0·566	0·557	0·547	530
540	0·668	0·653	0·639	0·627	0·613	0·601	0·589	0·577	0·568	0·557	540
550	0·681	0·666	0·651	0·639	0·624	0·612	0·600	0·588	0·579	0·567	550
560	0·693	0·678	0·663	0·650	0·635	0·623	0·611	0·599	0·589	0·577	560
570	0·705	0·690	0·675	0·662	0·647	0·635	0·623	0·610	0·599	0·587	570
580	0·717	0·702	0·687	0·673	0·658	0·646	0·634	0·620	0·610	0·598	580
590	0·729	0·714	0·699	0·685	0·670	0·658	0·646	0·631	0·620	0·608	590
600	0·741	0·726	0·711	0·696	0·681	0·669	0·657	0·642	0·630	0·618	600
610	0·754	0·739	0·723	0·708	0·693	0·680	0·668	0·653	0·641	0·629	610
620	0·766	0·751	0·735	0·720	0·705	0·692	0·679	0·664	0·652	0·640	620
630	0·779	0·764	0·747	0·732	0·717	0·703	0·689	0·674	0·662	0·650	630
640	0·791	0·776	0·759	0·744	0·729	0·715	0·700	0·685	0·673	0·661	640
650	0·804	0·789	0·771	0·756	0·741	0·726	0·711	0·696	0·684	0·672	650
660	0·817	0·801	0·783	0·767	0·752	0·737	0·722	0·707	0·695	0·682	660
670	0·829	0·813	0·795	0·779	0·764	0·748	0·733	0·719	0·706	0·692	670
680	0·842	0·825	0·807	0·790	0·775	0·758	0·743	0·730	0·716	0·703	680
690	0·854	0·837	0·819	0·802	0·787	0·769	0·754	0·742	0·727	0·713	690
700	0·867	0·849	0·831	0·813	0·798	0·780	0·765	0·753	0·738	0·723	700
710	0·880	0·862	0·843	0·825	0·809	0·791	0·776	0·764	0·749	0·734	710
720	0·892	0·874	0·855	0·837	0·821	0·803	0·788	0·775	0·760	0·745	720
730	0·905	0·887	0·867	0·849	0·832	0·814	0·799	0·785	0·770	0·755	730
740	0·917	0·899	0·879	0·861	0·844	0·826	0·811	0·796	0·781	0·766	740
750	0·930	0·912	0·891	0·873	0·855	0·837	0·822	0·807	0·792	0·777	750
760	0·943	0·924	0·903	0·885	0·866	0·848	0·833	0·818	0·802	0·787	760
770	0·955	0·936	0·915	0·897	0·878	0·860	0·844	0·829	0·812	0·797	770
780	0·968	0·948	0·927	0·909	0·889	0·871	0·854	0·839	0·823	0·808	780
790	0·980	0·960	0·939	0·921	0·901	0·883	0·865	0·850	0·833	0·818	790
800	0·993	0·972	0·951	0·933	0·912	0·894	0·876	0·861	0·843	0·828	800
810	1·006	0·985	0·963	0·944	0·924	0·905	0·887	0·872	0·854	0·839	810
820	1·018	0·997	0·975	0·956	0·936	0·917	0·899	0·883	0·865	0·850	820
830	1·031	1·010	0·987	0·967	0·948	0·928	0·910	0·893	0·875	0·860	830
840	1·043	1·022	0·999	0·979	0·960	0·940	0·922	0·904	0·886	0·871	840
850	1·056	1·035	1·011	0·990	0·972	0·951	0·933	0·915	0·897	0·882	850
860	1·069	1·047	1·024	1·002	0·983	0·962	0·944	0·926	0·908	0·892	860
870	1·082	1·059	1·036	1·014	0·995	0·974	0·956	0·937	0·919	0·902	870
880	1·096	1·071	1·049	1·026	1·006	0·985	0·967	0·947	0·929	0·913	880
890	1·109	1·083	1·061	1·038	1·018	0·997	0·979	0·958	0·940	0·923	890
900	1·122	1·095	1·074	1·050	1·029	1·008	0·990	0·969	0·951	0·933	900
910	1·135	1·108	1·086	1·062	1·040	1·019	1·001	0·980	0·962	0·944	910
920	1·147	1·120	1·098	1·074	1·052	1·031	1·012	0·992	0·973	0·955	920
930	1·160	1·133	1·110	1·086	1·063	1·042	1·022	1·003	0·983	0·965	930
940	1·172	1·145	1·122	1·098	1·075	1·054	1·033	1·015	0·994	0·976	940
950	1·185	1·158	1·134	1·110	1·086	1·065	1·044	1·026	1·005	0·987	950
960	1·198	1·171	1·146	1·122	1·098	1·076	1·055	1·037	1·016	0·997	960
970	1·210	1·183	1·158	1·134	1·110	1·088	1·067	1·048	1·027	1·007	970
980	1·223	1·196	1·170	1·146	1·122	1·099	1·078	1·058	1·037	1·018	980
990	1·235	1·208	1·182	1·158	1·134	1·111	1·090	1·069	1·048	1·028	990
1,000	1·248	1·221	1·194	1·170	1·146	1·122	1·101	1·080	1·059	1·038	1,000

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