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ON THE DESIGN OF THE KEW PATTERN BAROMETER

BY

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ON THE DESIGN OF THE KEW PATTERN BAROMETER

ABSTRACT

1. A graphical method of finding the bore of the barometer tube at the top when the length of a scale division and the diameter of the cistern are known, is described.

2. It is proved that, in a marine barometer having a straight piece of capillary of uniform bore, the "falling time" is logarithmic and varies directly as the cross-section of the tube at the top and the length of the capillary and inversely as the square of the capillary cross-section.

3. In verification of the theory an experimental Kew pattern barometer has been made, the special features of which are :—

(i) A large flat cistern fitted with a device for accurately adjusting the standard temperature of the barometer.
(ii) A barometric scale almost as open as that of the Fortin barometer.
(iii) A straight piece of capillary of definite length and known cross-section.
(iv) The "falling" and "lagging" times are in accordance with Stokes's theory and the instrument is portable.

4. The data set out in the paper give practically unlimited choice in the various dimensions of the component parts of the tube of the Kew Pattern Barometer.

5. APPENDIX.—A specification of the Kew Pattern Barometer has been drawn up, removing the distinction between the cross-sections of the tube at the top in the station and marine type.

INTRODUCTORY

THE measurement of atmospheric pressure by means of the mercury barometer involves three distinct operations: the first is the determination of the length of the column of mercury supported by the atmosphere, the second is the determination of the density of the mercury in the tube, and the third is the determination of the value of gravity at the place of measurement. The density of mercury, and, consequently, the length of the barometric column, and the length of the graduations of the scale with which the barometric column is measured, all depend on their respective temperatures. Hence, corrections must be applied to the observed barometric readings for deviations of temperatures from the standard besides the usual index corrections. Many types of direct reading mercury barometers have been invented, of which the Fortin is usually employed for the precise measurement of atmospheric pressure. The openness of the scale and the adjustable capacity of the cistern are its special features. The temperature corrections which depend only on the density changes of mercury and the expansion of the brass scale are easy to compute and apply. The changes of level of mercury in the cistern, due to the variation of the temperature of mercury and the atmospheric pressure, are eliminated by adjusting the free surface of the mercury in the cistern to a fixed point of the measuring scale and the vernier is set at the top of the barometric column. Thus, each time the barometer is read two distinct adjustments must be made, which require skilful manipulation and time. In particular, the accurate adjustment of the cistern is both difficult and tedious. The Fortin barometer is therefore not so convenient an instrument for the average meteorological observer as the Kew pattern barometer.

The Kew pattern barometer is the outcome of attempts to adapt the Fortin barometer to the taking of observations of atmospheric pressure at sea. On board ship, the adjustment of the mercury in the cistern to a fixed point is impracticable. Moreover, the effects of tremors, pitching and rolling, are to produce considerable oscillations of mercury which seriously interfere with the correct setting of the vernier. On account of these practical difficulties the Kew pattern barometer is provided with

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a cistern which is rigidly fixed to the glass tube and the capacity of the cistern, unlike that of the Fortin, is not adjustable. It will be observed that the Kew pattern barometer is virtually a U-tube, with limbs of unequal cross-sections, and hence the instrument suffers from two disadvantages, viz., that the barometric scale is contracted and the temperature coefficient is rather higher than in the case of the Fortin. In order to prevent " pumping " at sea the tube of the Kew pattern barometer for marine use is constricted in the middle. The introduction of the constriction makes the response of this type of barometer to atmospheric pressure changes rather slow. The barometer, however, is pre-eminently a meteorological instrument, as the setting of the vernier at the top of the mercury meniscus is all that is required in the way of adjustment. This latter advantage recommended its use also on land in spite of the well-known defects of sluggishness, and the contracted scale and higher temperature coefficient as compared with the Fortin.

The Kew pattern barometers now in actual use are of two types, viz., the marine type and the station type. In the latter type the constriction in the middle of the glass tube is dispensed with. The present position of the station type in relation to the marine type will be more fully discussed elsewhere. Hitherto the design of the Kew pattern barometer has been left almost entirely to the makers. The objects of the present paper are :—

(i) To suggest the best compromise possible between theoretical requirements and practical considerations without unduly interfering with present practice in workshops.

(ii) To consider in detail and standardize the dimensions of the several parts of this instrument.

(iii) To specify a closer tolerance in the " falling time " than in the case of existing barometers of the marine type.

(iv) To construct an experimental barometer (marine type), in which the lag is much smaller than in most existing barometers of this type.

PART I

§ 1. The Principle of Graduation

In the Kew pattern barometer the fluctuations of the level of mercury, consequent upon the changes of the atmospheric pressure, are allowed for by contracting the Fortin scale. The amount of contraction is determined by the effective cross-section of the cistern and the bore of the tube at the top. According to Laplace's equation the atmospheric pressure $P = g\rho h$ where g is the acceleration due to gravity, ρ the density of mercury, and h the barometric height. Representing an increment of pressure by δP we have:—

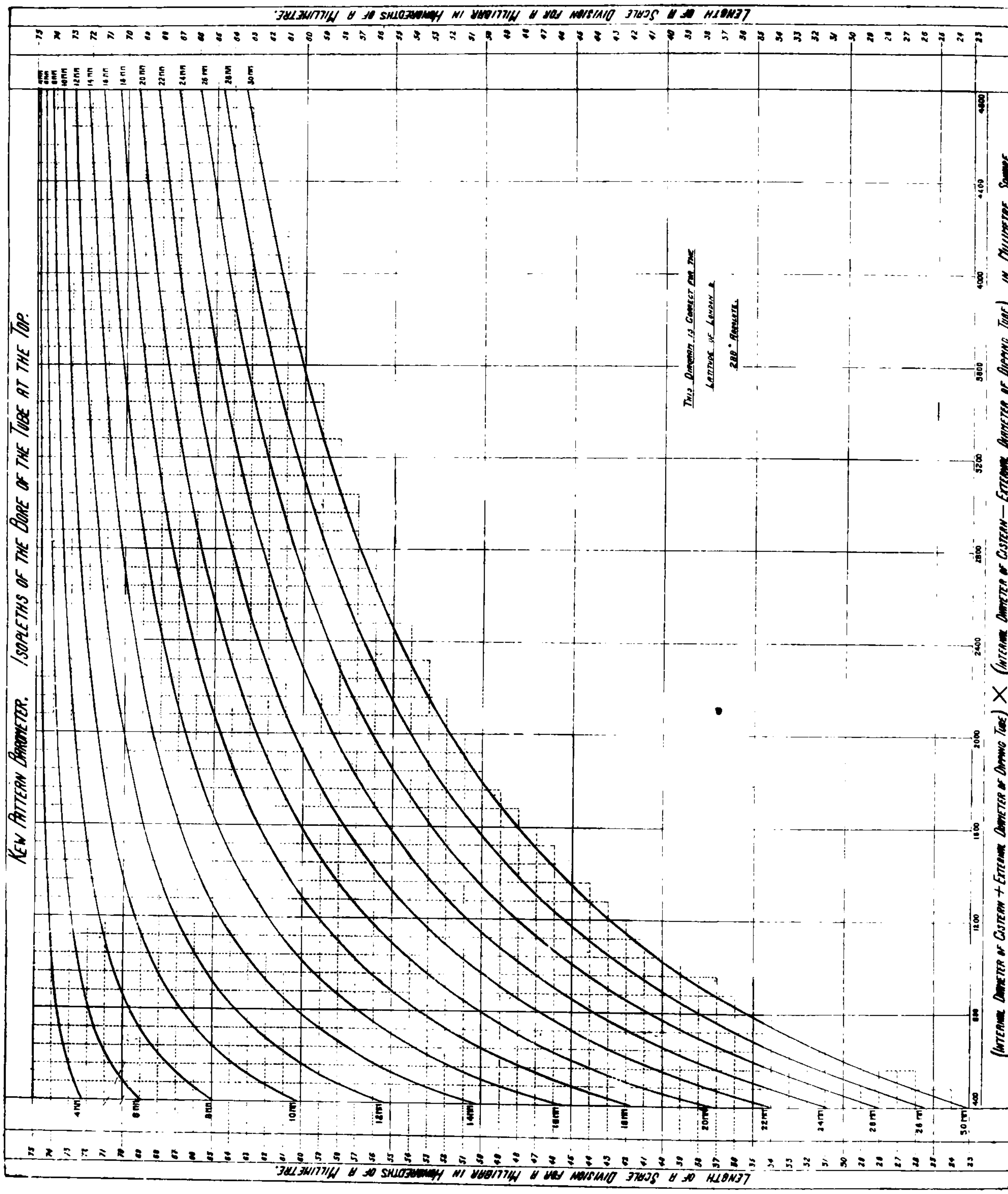
$$\delta P = g\rho\delta X \quad : \quad : \quad : \qquad (1)$$

where δX is a small element of the Fortin scale. In the case of the Kew pattern barometer, however, an increment of atmospheric pressure depresses the level of mercury in the cistern, producing the rise of level at the top of the glass tube. A portion of the dipping tube is thus exposed, and the barometric height must therefore be measured from the new level of mercury in the cistern. Let x be the height of mercury in the tube and y the height of the free surface of mercury in the cistern, both measured from the bottom of the cistern. From considerations of the conservation of volume at *constant temperature*, we may write down the following equations for a small increment of pressure δP. Let a be the internal radius of the tube at the top, b the external radius of the dipping tube, and c the internal radius of the cistern, then :—

$$a^2\delta x = (c^2 - b^2)\ \delta y \quad : \quad : \quad : \qquad (2)$$

To face page 205.

FIG. 1.



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Remembering that the variations of level of mercury in the tube and the cistern are in opposite directions, we have :—

$$\delta P = g\rho\,(\delta x + \delta y) \quad : \; : \; : \qquad (3)$$

or from (1) and (3)

$$\delta X = \delta x + \delta y \quad : \; : \; : \qquad (4)$$

and from (2) and (4)

$$\delta x = \frac{c^2 - b^2}{c^2 - b^2 + a^2}\,\delta X \quad : \; : \; : \qquad (5)$$

In equation (5) we may regard δX as a scale division of the Fortin and δx a scale division of the Kew pattern barometer. Thus, a scale division of the Kew pattern barometer is smaller than that of the Fortin in the ratio $(c^2 - b^2) / (c^2 - b^2 + a^2)$. From equations (1) and (5) :—

$$\frac{a^2}{c^2 - b^2} = \frac{\delta P}{g\rho\delta x} - 1 \quad : \; : \; : \qquad (6)$$

The Kew pattern barometer with a millibar scale is usually so designed that it reads correctly at mean sea level in latitude 45° and at 285a. The temperature 285a is therefore the standard temperature of the instrument. The choice has the advantage that, in this country, the positive and negative values of the temperature corrections which are to be applied to the daily barometric readings are brought within narrower limits than would be the case if the standard temperature were 273a, as in the case of the " baromil "* barometer. As far as the London instrument makers are concerned, the practice regarding standard temperature, viz., 285a in latitude 45° at mean sea level, is equivalent to the barometer reading correct in latitude 52° and at 289a.

Putting $c^2 - b^2 = S^2$ in equation (6) : : :

we have :—

$$\frac{a^2}{S^2} = \frac{\delta P}{g\rho\delta x} - 1 \quad : \; : \; : \qquad (7)$$

In C.G.S. units

$\delta P =$ one dyne/cm², $g = 981 \cdot 19$ cm/s² in London and $\rho = 13 \cdot 5560$ gm/cm³ at 289a.

then

$$\frac{a^2}{S^2} = \frac{7518 \times 10^{-8}}{\delta x} - 1 \quad : \; : \; : \qquad (8)$$

Thus, if S^2 is known, we can compute values of a^2 for different values of δx. Fig. 1 was obtained by plotting a^2 against S^2 for given values of δx. The isopleths of a^2 were then drawn in the usual way, but these were marked to shew $2a$, the bore of the tube at the top. From this graph each of the three factors, viz., the cross-section of the tube at the top, the effective cross-section of the cistern and the length of a scale division could be found if the other two are known. As to the effect of variation of temperature, it may be noted here that as the coefficients of expansion of glass and iron are very nearly the same, the ratio $(c^2 - b^2) / (c^2 - b^2 + a^2)$ remains unaltered. In other words, temperature changes have no appreciable effect on the " magnification " of the barometer $(c^2 - b^2)/a^2$. It should be noted, however, that the length of a millibar scale division (on invar) is increased by about two parts in a thousand if the standard temperature of mercury is raised by 10° C.

The permissible limit for capacity correction of the barometer tube is only four parts in a thousand,† and hence, Fig. 1 is of practical value in the repair of barometers, especially when the tube is to be replaced. The following rules have been framed for workshop practice. To find the appropriate bore of the tube at the top :—

(*a*) Measure‡ the internal diameter of the cistern and the external diameter of the dipping tube in millimetres and multiply together their sum and difference. Find this number on the horizontal axis of the graph.

---

* The " baromil " as defined by Sir Napier Shaw is the height of mercury column which produces a pressure of one millibar in latitude 45° at sea level and the temperature of freezing water.

† *Report of the Kew Committee*, 1868–1869, p. 5.

‡ This could easily be done by means of internal callipers after carefully unscrewing the cistern and pushing the tube to one side.

(*b*) Measure carefully the length of the scale corresponding with 200 mb. in millimetres and calculate the length of *one scale division*. Find this number on the vertical axis of the graph.

(*c*) Find on which isopleth of the bore of the tube at the top, the intersection of the vertical line through the first point and the horizontal line through the second point, lies.

If the point of intersection is not on one of the isopleths of the bore of the tube a slight interpolation is necessary. The following is an example of the use of Fig. 1. In a barometer it was found that :—

$$2c = 30 \text{ mm.}, \; 2b = 7 \text{ mm., and 200mb. on the scale} = 142 \cdot 8 \text{ mm.}$$

Accordingly $(2c + 2b) \times (2c - 2b) = 37 \times 23 = 851 \text{ mm}^2$ and a millibar scale division $= 0 \cdot 714$ mm.

Thus, from Fig. 1, the bore* of the tube at the top, $2a$, should be about 7 mm.

At present, the graduations of a given barometer have to be adapted to the dimensions of its tube and cistern. If a standard scale could be adopted, workshop practice in the matter of graduations could be simplified and that in turn would make possible a distinct improvement in workmanship without increasing expenditure. With the help of a diagram such as that shown in Fig. 1, it is a simple matter to pair off tubes and cisterns for use with a standard scale. For practical use only a portion of Fig. 1 is required and this part should be drawn on a large scale.

In existing barometers the scale is contracted by from 3 to as much as 10 per cent. in comparison with the Fortin, but the scale of the experimental barometer constructed to the specification given below is almost as open as that of the Fortin. The method by which this improvement has been achieved in practice is explained in Section 3.

§ 2. The Choice of the Cistern

(i) *Dimensions*.—The chief defects in the design of the cisterns of barometers on the market are generally :—small internal diameter,† diaphragms inside the cistern, and vent holes on the upper side of the lid of the cistern. The first defect is mainly responsible for the contracted barometric scale, the second complicates the movement of air in the cistern when the barometer is in transit and brings the air too close to the mouth of the dipping tube, whilst the third often admits dust inside the cistern. Barometers in transit are put either in horizontal or in the inverted position to prevent violent oscillations of mercury in the glass tube. In these positions the top part of the tube, usually about 10 centimetres in length, is filled with mercury and consequently there is an additional air space in the cistern. Obviously, the additional volume of air in the cistern is proportional to $a^2 / (c^2 - b^2)$, which varies between 1/18 to 1/25 in British barometers. In the interests of portability the barometer must be light, mercury tight and the depth of the additional air space must be as small as possible.

From the theoretical standpoint c should be large, so that :—

(*a*) δx may be large, thus ensuring openness of scale (*see* equation 6).

(*b*) the additional temperature correction‡ (which is proportional to $M/4c^2$ where M is the total mass of mercury in the barometer), may be small;

(*c*) the depth of the additional volume of air as explained above may be small, thus keeping the air in the cistern at a safe distance from the dipping tube;

---

* In this type $2a = 0 \cdot 25$ in. nominally.

† The range of variation of the internal diameter of the cistern in existing barometers is usually between 30 mm. and 52 mm.

‡ *Observer's Handbook*, 1921 Edition, p. 18. See also *Dictionary of Physics*, Part III, p. 153; " Barometers and Manometers," F. A. Gould.

(*d*) the free surface of mercury in the cistern may be almost flat so that there may be less likelihood of the barometric reading being vitiated by changes in the curvature of the mercury meniscus in the cistern.

(*e*) in the test of "falling time" the actual loss of head may be very nearly the same as the effective loss of head. This point will be more fully discussed in Sections 4 and 6.

From the practical standpoint, however, the disadvantage of having c large is to make M large, which is undesirable, because both the temperature correction and the weight of the barometer are increased. The best course is to keep $M/4c^2$ within reasonable limits. It will be observed that $M/4c^2$ is small when the depth of the cistern d is small. Thus, we arrive at the conclusion that the cistern ought to be a wide but shallow cylinder. In this connexion it is interesting to note that the cisterns of some French and German barometers are large and flat. Fig. 1 is of great help in choosing the upper limit of c. It will be seen that for a given value of a the rate of increase of δx with respect to $(c^2 - b^2)$ is very small beyond $(4c^2 - 4b^2) =$ 4000 sq. mm.

The internal diameter of the cistern of the experimental barometer has therefore been chosen as 6·6 cm. and the depth as 3·5 cm. Considerations which have influenced the choice of the depth of the cistern will be discussed further in the next section.

(ii) *The vent hole.*—The tubes of some barometers are often mounted on a boxwood collar, owing probably to its porous nature, whilst in others the cistern is provided with a vent hole. The boxwood collar appears to be rather thick, and hence there is the possibility of introducing a factor of lag, however small, in the readings of the barometer. On the other hand, the vent holes on the upper surface of the lid often admit dust into the cistern, and there is always danger of mercury leaking through the hole.

As in a sheltered place the dust accumulates more readily on a horizontal than on a vertical surface, the vent hole of the experimental barometer is placed on the side of the lid of the cistern with a thin leather washer inside the cistern protecting the mercury from dirt (*see* Fig. 7). The washer, whilst not interfering with the immediate response of the barometer to atmospheric pressure changes, renders the cistern mercury-tight.

(iii) *The cistern plunger.*—When assembling the barometer, it is very difficult to adjust the right quantity of mercury in the cistern. In the experimental barometer provision has therefore been made for altering the capacity of the cistern. The device (*see* Fig. 7) and its advantages will be discussed in Section 6.

§ 3. The Choice of the Glass Tube

The top part of the tube in modern barometers is between 19 and 21 cm. in length. The pipette in the middle, which is attributed to Gay Lussac (*see* Fig. 6), is simply an air trap. The rest of the tube has rather a narrow bore. In the following paragraphs the dimensions of various parts of the tube are discussed.

(i) *The bore of the glass tube at the top.*—The bore of some marine barometer tubes is as small as 6 mm., whilst the bore of some station barometer tubes is as much as 11 mm. Obviously there should be some kind of uniformity for both types, as in actual meteorological practice it is often found to be economical to convert one type into another by changing the tube only. The following is a summary of the important points which should guide the choice of the bore of the tube at the top. It is desirable that a should be small, so that :—

(*a*) δx may be large (*see* equation 6),

(*b*) M may be small and therefore the additional temperature correction may be small,

(c) the amount of mercury required to fill the top may be small and therefore the additional volume of air in the cistern in the inverted or horizontal positions of the barometer may be small,

The disadvantage of having a small is to increase the uncertain effects of capillarity on the top of the mercury column. Moreover, as the atmospheric pressure falls, the highly curved meniscus at the top tries to compensate for the defect of pressure by diminishing its curvature, thus retarding the indications of the barometer. It should be remembered, however, that observers prefer a menicus to a flat mercury surface, as in the case of barometers having a tube of wide bore at the top. The mercury meniscus is therefore decidedly an advantage as long as the present vernier method of measuring barometric height is retained. In many existing station barometers the bore* of the tube at the top is about 8 mm. From Fig. 2, which

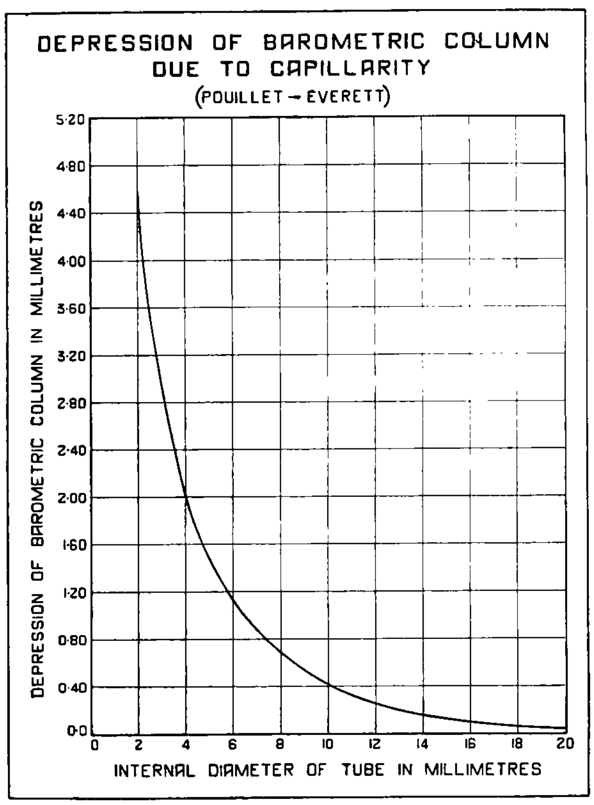


FIG. 2.

is based on Pouillet's data and which shows the relation between the diameter of the glass tube and the depression of the barometric column due to capillarity, it will be seen that the slope of the graph when $2a = 8$ mm., is about 45°. The change in the circumference of the tube owing to temperature variations is very small, and the temperature coefficient of the surface tension of mercury is of the order of about half a dyne per centimetre per degree centigrade, the force decreasing with temperature. Thus, the errors due to the variation of capillarity in a tube of 8 mm. bore have an even chance of being either positive or negative, and will tend to cancel each other in the case of long period averages of barometric readings. The error in the readings arising out of the variability of the angle of contact between glass

* The bore of the tube at top in the Kew pattern barometer, station type, is nominally 0·3 in.

and mercury at the top of the tube are eliminated to a great extent by tapping. It is proposed, therefore, to adhere to the bore of 8 mm. diameter* at the top of the tube for the station barometer and also to adopt this for the marine type.

(ii) *Portability.*—It will be observed from the dimensions of a, b and c, given in Table I, that in the case of the experimental barometer the ratio $a^2 \mid (c^2 - b^2)$ is about 1/65, which is even less than half the ratio in ordinary barometers, or, in other words, the " magnification " of the experimental barometer is more than twice as much as in the case of ordinary barometers. The scheme has the advantage that the depth of additional air space in the cistern when the barometer is in transit is as small as possible, and hence the instrument is portable without the aid of any special device to plug the mouth of the dipping tube. The lower limit of the depth of the cistern, viz. 3·5 cm. was chosen from the consideration that the mouth of the dipping tube should be well covered with mercury in the inverted or horizontal position of the barometer. The plunger which has been added to the cistern of the experimental barometer (*see* Fig. 7) can, if desired, be used for further reducing the air space in the cistern while the barometer is being carried from place to place. The only objection to the plunger is that it makes the barometer rather heavy.

(iii) *The Dipping Tube.*—The dipping portions of the glass tube of existing barometers are rather thick and in some very old patterns they are even pear-shaped. As the effective cross-section of the cistern is reduced by the dipping tube, its external diameter should be as small as is consistent with the strength of the glass tube. It should be remembered that the evenness of the graduations of the barometric scale depends on the correct cylindrical shape of the dipping tube. In the experimental barometer the external diameter of the dipping tube has been chosen to be 3 mm. and the length to be about half the depth of the cistern, viz., $1\frac{1}{2}$ cm.

To sum up, it will be seen from Table I that the experimental barometer has a cistern of 66 mm. internal diameter and 35 mm. in depth, and the internal diameter at the top part of the glass tube is 8 mm. From Fig. 1 we find that the length of a millibar scale division is 0·741 mm., which is almost as big as that of the Fortin (0·752 mm. in latitude 45° at 285a) for all practical purposes. The middle portion of the tube is of much narrower bore than the top. The point will be discussed further in the following sections.

(iv) *Temperature Coefficient.*—The total quantity of mercury in this barometer is of the order of $1\frac{1}{2}$ kilogrammes. As far as the additional temperature coefficient is concerned it is to be noted that the value of $M/4c^2$ is of the order of 35 in C.G.S. units, but in existing barometers, the mean value is of the order of 45 C.G.S. units. Hence, the temperature correction is slightly smaller in the case of the experimental barometer than in existing barometers.

PART II

§ 4. The Principle of the Marine Barometer.

(i) *The Falling Time.*—In the marine type, the specification of the extent of constriction in the middle of the tube which will prevent " inconvenient oscillations at sea " without unduly interfering with the responsiveness of the barometer to pressure changes, is difficult. In order to arrive at a practical solution of the problem Welsh†

* As far as meteorological observations are concerned, the error introduced in barometric readings by the variation of the angle of contact in the vacuum at the top of the tube is not serious when both mercury and glass are clean and the barometer is tapped before a reading is taken. It is also easier to set the vernier on the top of the mercury meniscus in a tube of this bore than in a tube of wider bore. See *Q. J. R. Metcor. Soc.*, Vol. XLII, 1916, p. 10.

† The investigation originated from the inquiry of Lieut. Maury of the U.S.A. Navy. See *Report of the Kew Committee* for 1853–1854, pp. 4–6.

undertook two voyages in 1854, one from London to Leith and back and the other to the Island of Jersey. The general conclusions arrived at in these trials were rather vaguely summed up by Gassiot* as follows :—

> " In order to reduce the pumping of mercury to convenient limits, it is necessary to have the tube contracted to such an extent that the mercury will take about twenty minutes to fall from the top of the tube to the height indicating the true pressure of the atmosphere at the time."

The whole distance through which the mercury fell in Welsh's experiments was most probably about 5 centimetres and the actual limits of the time of fall as proposed by him were 18 to 25 minutes.†

In testing the marine barometer for the correct constriction, the time taken by the mercury to fall from 1·5 to 0·5 in., or 51 to 17 mb., above the actual barometric height, is noted. According to the specification still in force at the Meteorological Office, this interval of time which is known as the " falling time " should lie between 3 and 6 minutes.‡ On examination, these limits of the " falling time " are found to be essentially the same as stipulated by Welsh.

(ii) *The Lag and the Lagging Time.*—In the process of adjusting the barometric height to the atmospheric pressure, the mercury has to overcome the viscous resistance offered to its flow by the constriction in the marine barometer. That the factor of lag in this instrument was known to Welsh is evident from his remark that " the standard barometer is always, to a certain extent, in *advance* of the marine barometer," when the latter is left quite at rest as on land. His estimate of the lag amounts to about 0·3 mb. in extreme cases. Welsh, however, came to the conclusion that " the tremor of the ship is beneficial rather than otherwise to the performance of the barometer."

In 1878, Buchan, in a report to the Meteorological Council, condemned the use of marine barometers at the telegraphic reporting stations. It is not surprising that Buchan did so, because Dr. Chree§ has since shown that the mean lag of such barometers is 0·3 mb. when the barometer is rising and about half this amount when the barometer is falling.

The lag is due to various other causes besides the viscous resistance to the flow of mercury through the capillary. The action of a highly curved meniscus at the top of the tube has already been mentioned. Stokes|| points out that—

> " The effect of sluggishness properly so-called is, however, mixed up with another which, if sensible, is not easily allowed for, namely, that an irregularity in the capillary depression depending on the variability of the angle of contact of mercury and the glass. This effect would certainly be sensible if the tube or mercury were at all dirty,¶ and may, perhaps, be not insensible even when the mercury and the glass are in the best condition."

---

* *Sailing Direction*, by Maury : Washington, Vol. I, 8th Edition, 1858, p. 374.

† Welsh says that " in order to reduce pumping so that the probable error of an observation from this cause may not exceed 0·01 in., the contraction should be to 20 minutes at least."

‡ The Kew Committee laid down these limits at the request of the Meteorological Committee to ensure " a higher standard of excellence." See *Report of the Kew Committee* for 1868–1869, p. 5.

§ *Geophysical Memoirs*, No. 8, 1914.

|| *Report of the Meteorological Council to the Royal Society*, March, 1880, pp. 28–32.

¶ An interesting example of the effect of dirt in the barometer, No. 1033, formerly used at Roches Point, Ireland, may be noted here. An inspection in January, 1922, confirmed the fact that the barometer read as much as 1 mb. too high. The convex meniscus of the mercury vanished altogether between the 1,000 and 1,020 mb. graduations. The tube was fouled in this part and the top of the mercury column even showed a slightly concave meniscus over this range. The internal diameter at the top of the tube of the barometer, No. 1033, was about 8 mm. According to Fig. 2 the capillary depression in this case is about 0·7 mm., which is approximately the length of a scale division of the Kew pattern barometer graduated in millibars. Thus, a positive error of the order of a millibar is easily accounted for by the complete disappearance of the capillary depression which depends on the surface tension between the mercury and the glass.

The curved meniscus of mercury in the cistern is also a source of lag, especially when the cistern is small. Again, the magnitude of the lag also " varies according to the rate* at which the mercury is rising or falling," and is said to range from 0·0 to as much as 0·7 mb.

Of all the factors of lag, that due to the viscous resistance offered to the flow of mercury by the constriction is the most important. At the request of the Meteorological Council, Stokes undertook an investigation of the sluggishness with a view to determining the magnitude of the lag and the results were published in 1880 (loc. cit.).

Let z_0 and h_0 be the initial readings of the marine and Fortin barometers respectively and z and h the corresponding values after an interval of time t. For simplicity we shall assume that the atmospheric pressure is falling at a uniform rate m so that $h = h_0 - mt$. If the resistance of the capillary portion to the motion of mercury is the sole cause of the sluggishness, then the rate at which the mercury in the marine barometer will adjust itself to the height of the Fortin is proportional to the difference between the heights of the mercury columns in the two barometers at any instant, or, in symbols—

$$-\frac{dz}{dt} = q\,(z - h) = q\,(z - h_0 + mt) \qquad . \quad . \quad . \quad . \quad . \qquad (9)$$

where q is a constant for a particular marine barometer its reciprocal denoting a time which has been called by Stokes the lagging time, L.

Equation (9) may be written—

$$\frac{dz}{dt} + qz = q\,(h_0 - mt)$$

Multiplying both sides by e^{qt}, integrating, and dividing by e^{qt}, we get—

$$z = h + \frac{m}{q} + \left(z_0 - h_0 - \frac{m}{q}\right) e^{-qt} \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (10)$$

where e is the base of Naperian logarithms.

If z_1 and z_2 are the readings of the marine, and h_1 and h_2, the readings of the station barometer corresponding with times t_1 and t_2, then—

$$\frac{z_1 - h_1 - \dfrac{m}{q}}{z_2 - h_2 - \dfrac{m}{q}} = e^{-q\,(t_1 - t_2)}$$

Putting $t_2 - t_1 = T$ and remembering that $q = \frac{1}{L}$ and $h_2 = h_1 - mT$, we have—

$$T = L.\ \log_e \frac{z_1 - h_1 - m/q}{z_2 - h_1 + m\,(T - 1/q)} \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (11\text{A})$$

If the barometer is rising the above becomes—

$$T = L.\ \log_e \frac{z_1 - h_1 + m/q}{z_2 - h_1 - m\,(T - 1/q)} \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (11\text{B})$$

It will be seen from equation (10) that with a falling barometer, when t is large—

$$z = h + \frac{1}{q} \cdot \frac{dh}{dt} = h + \lambda$$

where $\lambda = L.\ \frac{dh,}{dt}$ or the amount of lag in the marine barometer . . . (12)

* *The first number of the meteorological papers published by the Board of Trade*, 1857, p. 181.

It is evident therefore that after " a good few minutes " since the atmospheric pressure has commenced to change at a constant rate $\frac{dz}{dt} = \frac{dh}{dt}$. Hence the lag can be calculated if the rate of change of atmospheric pressure and the lagging time are known. It is clear, therefore, that if dh/dt is constant, the height given by the marine is the same as the height of the station barometer, L minutes previously. Stokes concludes his paper with the remark that :—

> " the sluggishness arising from viscosity, as the mercury flows through the capillary part of the tube, affects a barometer on shipboard equally with one on land, and *that* can be easily allowed for if the lagging time is known."

Dr. Chree (loc. cit.), however, refutes this statement on the ground that observations on land are not in agreement with Stokes's theory. The point will be discussed further in Section 6.

(iii) *The Driving Head.**—In order to understand fully the behaviour of the marine barometer, the mechanism of the flow of mercury through tubes of capillary dimensions must be studied. Let us suppose that the atmospheric pressure is falling. Owing to the lag, the height z of the marine barometer would be greater than the height h of the standard barometer. This excess head is responsible for driving the mercury through the capillary. We know from Poiseuille's equation that if l is the length of the capillary and r is its radius, the rate of flow of mercury Q through the capillary and the driving head are related as follows :—

$$Q = \frac{\pi r^4}{8 l \eta} \cdot H \qquad \ldots\ldots\ (13)$$

where η is the viscosity of mercury, provided that the motion of mercury is steady and along the stream lines under the pressure of the driving head H, and there is no slipping of mercury past the walls of the capillary tube. In the Kew pattern barometer when the mercury passes out of the capillary, the level of mercury in the cistern rises. From Section (1) it is clear that the fluctuation of the level of mercury in the cistern of a barometer with a highly contracted scale is greater than in the case of a barometer with a more open scale. Therefore, the condition obtaining in a barometer with a very contracted scale, a defect generally due to the diameter of the cistern being small, is not conducive to the steady flow of mercury through the capillary. It should be noted, however, that the head which is actually utilized in driving the mercury through the capillary is given by :—

$$H = g\,\rho\,(z - h) \qquad \ldots\ldots\ (14)$$

where both z and h are measured on the same contracted scale of the Kew pattern barometer. This is done in the testing of the falling time of a marine barometer.

(iv) *The " falling time " and the dimensions of the capillary.*—For simplicity let us assume that after a fall the atmospheric pressure becomes steady,† so that $dh/dt = 0$. The excess volume in the upper part of the tube of the marine barometer is

$$v = \pi a^2 (z - h) \qquad \ldots\ldots\ (15)$$

This volume must pass through the capillary before the actual barometric height is attained. The rate of flow of mercury—

$$Q = -\frac{dv}{dt} = -\pi a^2 . \frac{dz}{dt} \qquad \ldots\ldots\ (16)$$

* An interesting paper in this connexion by W. N. Bond has been published in *Proc. Physic. Soc.*, London, p. 187, Vol. 34, August 15, 1922.

† It will be seen from equation (11A) that *even* when the atmospheric pressure is falling at the rate of 10 mb./hr. the falling time of the existing marine barometer will only be underestimated by about 2 per cent. Ordinarily the correction due to h being not constant during the falling time experiment, is negligible.

Thus from equations (16), (13) and (14)—

$$-\frac{dz}{dt} = \frac{g\rho}{8\eta} \cdot \frac{r^4}{la^2} \cdot (z - h) \qquad \ldots \ldots \quad (17)$$

From equations (17) and (9) it will be seen that—

$$L = \frac{8\eta}{g\rho} \cdot \frac{la^2}{r^4} \qquad \ldots \ldots \quad (18)$$

Again—

$$dt = -\frac{8\eta}{g\rho} \cdot \frac{la^2}{r^4} \cdot \frac{dz}{z - h} \qquad \ldots \ldots \quad (19)$$

If z_1 and z_2 are the heights of the marine barometer corresponding with times t_1 and t_2, then by integrating—

$$T = t_2 - t_1 = \frac{8\eta}{g\rho} \cdot \frac{la^2}{r^4} \cdot \log_e \frac{z_1 - h}{z_2 - h} \qquad \ldots \ldots \quad (20)$$

where e is the base of Naperian logarithms. It should be observed, however, that T becomes infinite when $z_2 = h$. In this connexion it must be remembered that equation (20) holds for all practical purposes only when the variable pressure on the mercury column due to capillarity is small compared with the level of mercury above the actual barometric height. Suppose the mercury meniscus is falling from 1065 to 1060 mb. If capillarity were absent this range would have corresponded with 1066 to 1061 mb. approximately (*see* Fig. 2). The amended equation when this pressure due to capillarity is taken into account becomes :—

$$T = \frac{8\eta}{g\rho} \cdot \frac{la^2}{r^4} \cdot \log_e \frac{z_1 + \tau - h}{z_2 + \tau - h} \qquad \ldots \ldots \quad (21)$$

where τ is the additional effective head due to capillarity. The point will be further discussed in Section (6).

In an actual test the time of fall of mercury from 1·5 to 0·5 in. above the actual barometric height is noted. Equation (20) therefore becomes :—

$$T = \frac{8\eta}{g\rho} \cdot \frac{la^2}{r^4} \cdot \log_e 3 = 1{\cdot}09861\, L \qquad \ldots \ldots \quad (22)$$

The values of the various quantities in equation (22) have been quoted in Section 1. The coefficient of viscosity of mercury* at 289a is ·0158 C.G.S. units. Hence,

$$T = \frac{la^2}{r^4} \cdot 10^{-5}, \text{ approx.} \qquad \ldots \ldots \quad (23)$$

$$\text{or more accurately, } r^4 = 1044 \cdot \frac{la^2}{T} \cdot 10^{-8} \qquad \ldots \ldots \quad (24)$$

In this connexion two more points of interest should be noted :—

(*a*) It is evident from equation (22) that the falling time is dependent on the viscosity as well as on the density of the mercury. Consequently, the falling time of every marine barometer has a temperature coefficient. If the temperature of the barometer is θ° C. above the standard, it can be shown easily that within ordinary ranges of temperature, the following relation holds :—

$$T_{(s+\theta)} = T_s\,(1 - {\cdot}004\theta) \qquad \ldots \ldots \quad (25)$$

where T_s is the falling time at the standard temperature and $T_{(s+\theta)}$, the falling time at a temperature θ° C. above the standard. The increase of falling time in winter or the decrease in summer will amount to about 5 per cent. for a departure of 12° C. from the standard temperature of the barometer.

* It is assumed throughout that the mercury and glass are clean and there is no tendency for the mercury to cling to the walls of the glass tube.

(*b*) If the speed of efflux of the mercury into the cistern is considerable, the potential energy of the driving head has not only to overcome the viscous resistance of the capillary, but also to supply the kinetic energy of the flow. It is important, therefore, that the dimensions of the capillary should be so chosen that the kinetic energy of flow is as small as possible and almost the whole of the available potential energy of the driving head is utilised in just overcoming the viscous resistance to the flow of mercury through the capillary. The point will be discussed further in Sections (5) and (6).

§ 5. The Choice of the Capillary.

Hitherto the introduction of the capillary in a marine barometer to ensure a given falling time has been a matter of skilful manipulation and trials, as is evident from the following note* by Mr. F. J. W. Whipple :—

> " The modern practice varies amongst different instrument makers. One maker uses a tube about 1 mm. bore and depends entirely on the constriction for producing the lag ; the general method is to have about 30 cm. of tube with bore about 0·4 mm. and adjust the falling time *by making a constriction.* Apparently it is possible to take a tube with bore about 0·3 mm. and adjust its length to get the right falling time. This seems to have been the original practice, and one firm with high reputation regards it as the best."

The empirical methods now followed in workshops often necessitate the drawing out and even twisting of the capillary to bring the falling time within the specified limits. So far only one of the London instrument makers has succeeded in introducing a straight piece of capillary in the marine barometer.

Experiment 1—For a preliminary test of the validity of equation (24), the falling time of one of these marine barometers, No. M.O. 2147, which had a straight piece of capillary, was measured, and then the tube was cut into three pieces. The capillary was found to be of more or less uniform bore and 42·5 cm. in length. The bore of the tube at the top was 7 mm. Thus the following data were obtained for the barometer :—

$$T = 4 \text{ min. } 15 \text{ sec. at } 289\text{a.} \quad l = 42{\cdot}5 \text{ cm.} \quad a = 0{\cdot}35 \text{ cm.}$$

On substituting these values in equation (24) the radius of the capillary is found to be $r = 0{\cdot}215$ mm. A thread of mercury in the capillary, 33·7 cm. in length, was carefully emptied into a small crucible and weighed. The weight of the mercury was found to be 0·685 g. The radius of the capillary according to this experiment is 0·218 mm. Thus almost complete agreement between the calculated and the experimental values of the bore of the capillary was obtained. The method followed in the construction of the barometer No. M.O. 2147, however, has been entirely of an empirical character. Hitherto no general principle has been suggested which will enable the maker to turn out marine barometers having the required falling time within narrower limits for any given cross-section of the tube at the top.

At the suggestion of Mr. R. Corless, the present investigation was undertaken with a view to giving definite instructions to instrument makers as to the choice of the capillary. From equation (24) it will be seen that—

$$\text{For } T = 3 \text{ min., } r^4 = 5{\cdot}8 \cdot la^2 \cdot 10^{-8} \qquad (26)$$

$$\text{For } T = 6 \text{ min., } r^4 = 2{\cdot}9 \cdot la^2 \cdot 10^{-8} \qquad (27)$$

---

* *Geophysical Memoirs*, No. 8, 1914, Appendix 11, p. 185.

Fig. 3 is based on equations (26) and (27). The isopleths of the bore of the capillary are derived in the usual way by giving different values to l and a and computing the corresponding values of r. A glance at these graphs suffices to show the importance of measuring the bore of the capillary accurately. In actual workshop practice the bore of the tube at the top should be carefully determined. When this is done the right length and bore of the capillary to be used for a given falling time can be easily chosen from Fig. 3. The following is an example of the use of Fig. 3 for practical purposes.

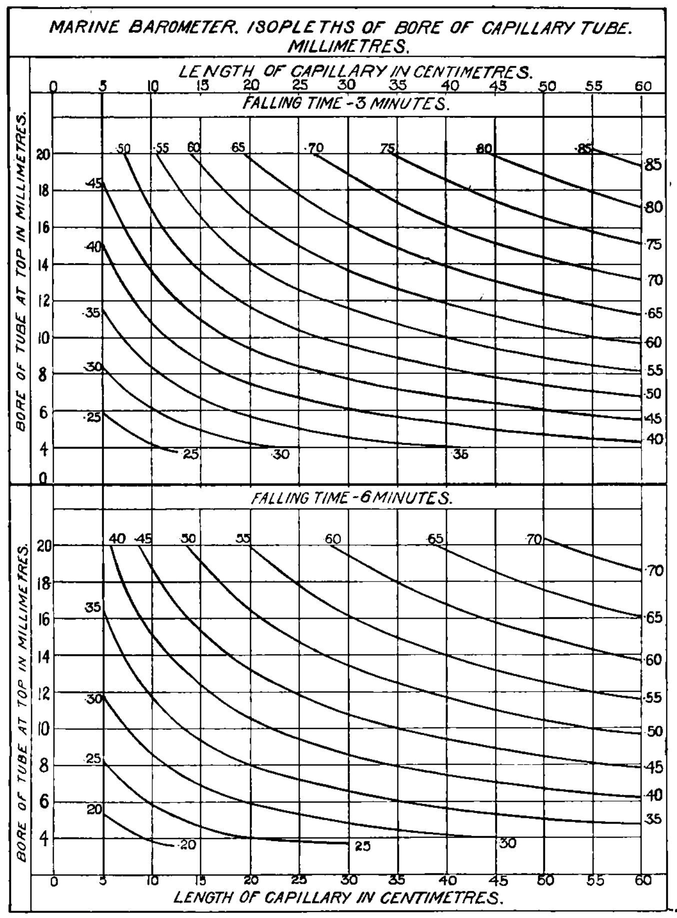


FIG. 3.

The falling time of a barometer of which the bore of the tube at the top is 7 mm., is required to lie between three and six minutes. From Fig. 3 we find that the bore of the capillary must lie between 0·43 and 0·36 mm. if a length of 30 cm. of the capillary is to be used. The permissible limits of the capillary bore are thus fixed. The preliminary measurements of the bore of the capillary and that of the tube at the top remove much of the uncertainty in the construction of marine barometers. The method also admits of a more rigid specification of the falling time. We shall now consider the appropriate bore and length of the capillary for the experimental barometer, so that its falling time is within the limits prescribed by the Meteorological Office.

In the case of a marine barometer having a tube the bore of which at the top is 8 mm., equation (24) becomes :—

$$r^4 = 167 \frac{l}{T} \cdot 10^{-8} \qquad \text{. . . . (28)}$$

Fig. 4, which is based on the equation (28), illustrates the relation between the bore and length of the capillary and the falling time. From the previous section it is clear that a marine barometer should be provided with a long and narrow capillary, so that the flow of mercury through it is steady, and consequently the barometer is less liable to " pumping." It will be seen, however, from the graph, that isopleths are more and more crowded together as the length of the capillary increases. It is thus clear that the advantage of having a wider bore of the capillary by using a longer length becomes inappreciable after a certain limit in length is reached. It is also noteworthy that the effect of diminishing the bore in increasing the falling time is very marked until a falling time of about four minutes is reached. Incidentally, it may be pointed out that Dr. Chree (loc. cit.) has suggested the use of a marine barometer having a falling time of less than three minutes, on the ground that the lagging time should not be greater than is absolutely necessary. It will be observed later that the lag in a properly constructed barometer is very small even when the falling time is as much as five minutes. Moreover, from Fig. 4, it will be seen that

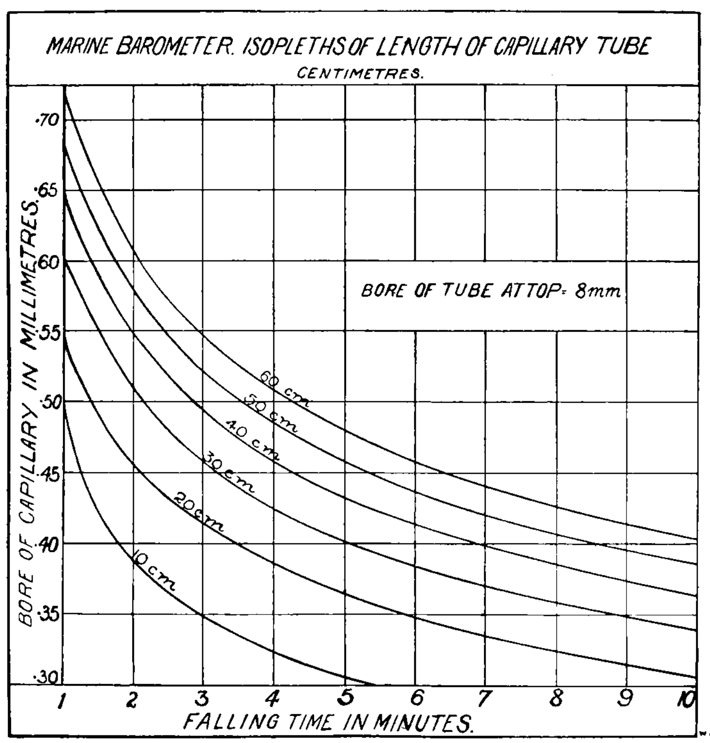


FIG. 4.

owing to the steepness of the graph, especially in the neighbourhood of 0 to 3 minutes, makers whose object it is to turn out standardized barometers on a large scale, are likely to find difficulty in working to this recommendation.

An examination of the graph shows that when $2a = 8$ mm., the best values of the three quantities r, l and T, are the following :—

$2r = 0{\cdot}4$ mm.* $\quad l = 300$ mm. $\quad T = 5$ min. 13 secs.

* Capillaries of 0·4 mm. bore are easily available.

[*To face page 217.*]

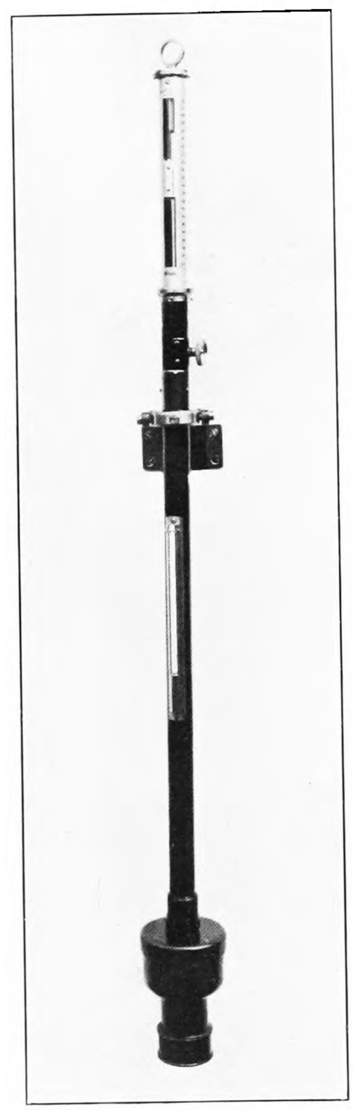


FIG. 5.—The Experimental Barometer (M.O. 2209).

These dimensions of the capillary (CD in Fig. 6) are therefore chosen for the experimental barometer. The loss of the potential energy of the driving head in imparting the kinetic energy of the flow of mercury through the capillary is inversely proportional to the length of the capillary and the square of its cross-section. It is found that in the case of the experimental barometer the error due to this source is negligible.

The most important point to note in this connexion is that the method enables the maker to bring the falling time within much narrower limits than the existing specification without mutilating the capillary in any way, as was evidently the practice in the construction of the marine barometer in earlier days.

§ 6. The Experimental Barometer M.O. 2209.

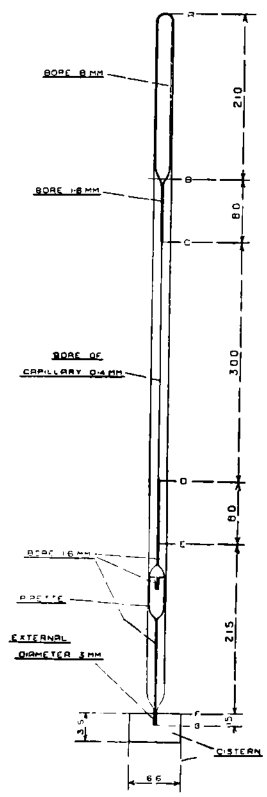
In order to ascertain whether the method of construction of the Kew pattern barometer advocated in the preceding paragraphs is applicable to actual workshop conditions, an order was placed by the Meteorological Office with Messrs. S. and A. Calderara, of Springfield Gardens, Clapton, London, E.5. The following table summarises the essential points of the instructions to the maker and the degree of accuracy with which the work has been executed.

Table I.—Dimensions of the Experimental Barometer—Proposed and Actual.

Items.	Proposed.	Actual (The measurements are correct within ·01 mm.).
Scale millibars only; length, 900–1,100 mb.	148·2 mm. (computed)	148·2 mm. (measured).
Bore of tube at top $2a$	8 mm. ± ·06 mm.	8·03 mm. at the top. 8·03 mm. „ middle. 8·05 mm. „ bottom.
External diameter of dipping tube $2b$	3 mm.	3 mm.
Internal diameter of the cistern $2c$	66 mm.	66 mm.
Depth of the cistern d	35 mm.	35 mm.
Length of capillary l	300 mm. ± 50 mm.	310 mm.
Bore of capillary $2r$	0·40 ± ·025 mm.	0·40 mm. at one end, and 0·41 mm. at the other.
The alteration of the level of mercury in the cistern by the plunger.	4 mm.	3·7 mm. (5 mb. on the scale).

The information as regards the calibration of the component parts of the tube and the diagrammatic sketch of the cistern (Fig. 7) have been supplied by Messrs. Calderara. It will be noticed that in the table no reference whatever has been made to the falling time, and therefore, the maker had no knowledge of its actual value. Fig. 5 is a photograph of the experimental barometer, the tube of which is shewn in Fig. 6. We shall presently see how far the " falling " and " lagging " times of the barometer agree with their theoretical values.

(i) *The cistern plunger.*—References have already been made to this device in Sections (2) and (3). The screw, as shown in Fig. 7 at the bottom of the cistern, propels the plunger either up or down, thus altering the capacity of the cistern.



TUBE
MARINE BAROMETER
FIG. 6.

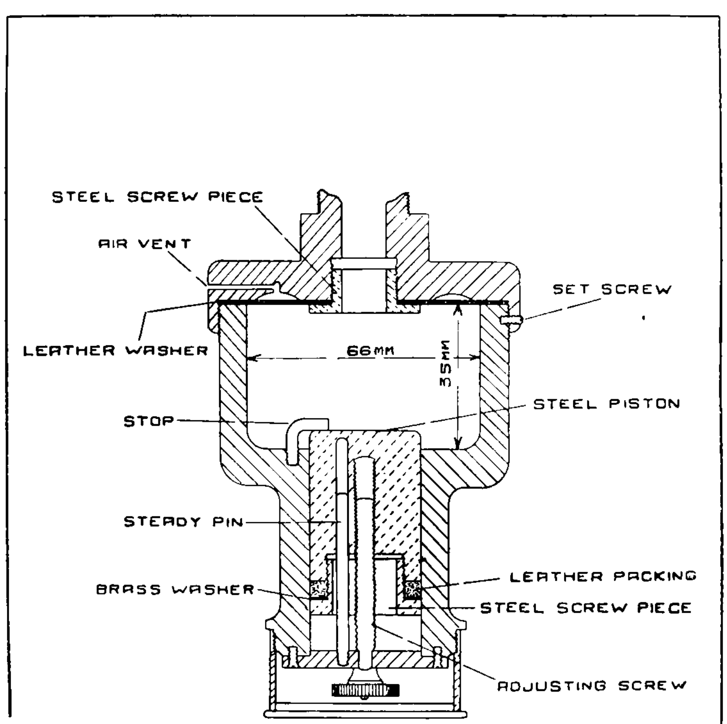


FIG. 7.—Cistern of the Experimental Barometer (M.O. 2209) showing the Plunger.

The stop prevents the plunger from pressing against the dipping tube. It is quite easy to calibrate the screw thread against the barometric scale. In the experimental barometer, a full turn of the milled head alters the barometric reading by ·03 mb. approximately.

Although the standard temperature, at 1,000 mb., of the Kew pattern barometer, is meant to be 285a, actually it is very rarely so. Moreover, in the case of the individual barometer there is a gradual change of the standard temperature with time. In practice it is found that the departure in individual barometers may be as much as 2½° C. on either side of 285a, apart from the variation of the standard temperature along the scale of the same barometer. A fixed standard temperature has many advantages, e.g., in the efficient use of the Gold* Correction Slide. With this kind of plunger it is possible to adjust the standard temperature to 285a to a degree of nicety which at present is not within the reach of the maker. The screw head is enclosed in a metal cover and could easily be made inaccessible to the unskilled observer.

(ii) *The determination of the "falling time" of M.O.* 2209.—It should be mentioned at the outset that the narrow portions of the tube besides the capillary (*see* Fig. 6) will not add more than a second to the "falling time" of the barometer. The data in Table I justify the assumption that both a and r are constants. Equations (20) and (21) for both the proposed and actual dimensions of the tube of the experimental barometer reduce to—

$$T = 285 \, . \, \log_e \frac{z_1 - h}{z_2 - h} \qquad \qquad (29)$$

$$T = 285 \, . \, \log_e \frac{z_1 + 1 - h}{z_2 + 1 - h} \qquad \qquad (30)$$

assuming the upper limit of τ in equation (21) to be one millibar. It certainly is much less than a millibar and depends on the angle of contact, which is a variable quantity. At least the average value of τ especially when the column of mercury is falling, may probably be determined experimentally. Incidentally, it may be noted that the constant of equation (29), by a curious coincidence, happens to be numerically the same as the standard temperature of the Kew pattern barometer.

The labour of computing the theoretical values of the time of fall according to either equation (29) or (30) could be saved by interpolating from a graph based on the data set out on the following table :—

Table II.—Time of Fall of Barometer No. M.O. 2209 at 289a in London.

Ratio of Heads and Time in Seconds.

Ratio of heads z_1/z_2.	1·05	1·25	1·45	1·65	1·85	2·05	2·25	2·45	2·65	2·85	3·05
Time, secs.	13·9	63·6	105·9	142·7	175·3	204·6	231·1	255·4	277·7	298·5	317·8

* In the new design of this instrument provision has been made to allow for the error arising out of the fact that the standard temperature of the barometer is not exactly 285a. *See* "Barometer readings in absolute units and their correction and reduction."—E. Gold. *Q.J.R. Meteor. Soc.*, July, 1914.

In testing the falling time of the experimental barometer, the following method was adopted. The barometer was tilted* so as to fill the top part of the tube with mercury. The instrument was then allowed to return to the normal vertical position. The upper edge of the vernier was set at 1,070 mb. and the observation of time commenced at the moment when the mercury meniscus stood at 1,070 mb. The upper edge of the vernier was then set at 1,065 mb. and the time was noted when the mercury meniscus dropped to exactly 1,065 mb., and so on. Thus, the time of fall from 1,070 mb. to the successive graduations in steps of 5 mb. was noted until sufficient readings had been obtained to draw a graph, as in Fig. 8. The lengths of the two broken vertical lines in Fig. 8 represent pressures 51 and 17 mb. above the actual barometric height. The falling time in each case is given by the length of the broken horizontal line. The experimental data are set out in the following table, along with the corresponding theoretical values derived from equations (29) and (30) :—

TABLE III.—BAROMETER No. M.O. 2209. TIME OF FALL IN SECONDS. Observed and Calculated.

Barometric Scale Millibars.	*Experiment* 2.			*Experiment* 3.			*Experiment* 4.		
	Observed.	Computed according to Equation 29.	Computed according to Equation 30.	Observed.	Computed according to Equation 29.	Computed according to Equation 30.	Observed.	Computed according to Equation 29.	Computed according to Equation 30.
1070 to 1065	22	27	27	20	25	24	16	19	19
1060	53	57	56	45	52	51	37	40	40
1055	87	91	89	75	82	80	58	63	62
1050	127	130	126	110	115	113	85	87	86
1045	169	174	169	150	153	150	112	114	112
1040	222	226	220	194	197	193	141	143	141
1035	289	291	281	244	249	243	175	176	173
1030	369	374	359	304	312	303	212	213	209
1025	482	491	468	382	394	381	254	256	250
1020	666	695	645	499	508	486	305	306	299
1015	—	—	—	685	703	657	366	366	357
1010	—	—	—	—	—	—	436	444	430
1005	—	—	—	—	—	—	533	551	530
1000	—	—	—	—	—	—	678	724	683
" Falling time " (experimental).	5 min. 12 s.			5 min. 11 s.			5 min. 10 s.		
Date	10th May, 1924.			12th May, 1924.			24th May, 1924.		
Time, G.M.T. ..	11 hr. 30 min.			10 hr. 30 min.			10 hr. 30 min.		
Barometer as read ..	1015·2 mb.			1009·9 mb.			994·0 mb.		
Barometric tendency	Falling ½ mb. per hr.			Rising ¾ mb. per hr.			Falling 1½ mb. per hr.		
Attached thermometer	288·6a.			289·0a.			291·0a.		
Observer	S. N. Sen.			R. G. Veryard.			C. H. Wood.		

It will be seen from equations (11) that the error in the time of fall due to the atmospheric pressure being not constant, is negligible. The discrepancy between the observed and the theoretical times of fall at the beginning of the experiment is certainly due to the difficulty in observing the top of a rapidly moving mercury column. The observed values of the time of fall in Table III, however, are very near to the computed values either according to equation (29) or equation (30). The discrepancy

* The operation should be repeated two or three times before commencing observations of the time of fall.

between the experimental and computed values towards the end of each experiment is most probably to be attributed to the difference between equations (29) and (30). In these experiments it was not considered advisable to employ finer methods of observation, as the instruments required for this purpose may not be within the reach of either the observer or the maker. *It is noteworthy that the agreement is most satisfactory up to* $(z_1-h) / (z_2-h) = 3$ *in all the experiments.* This is the vital part of the graph in the estimation of the "falling time." The purely physical aspect of equation (30) should be further investigated by employing finer methods of observation.

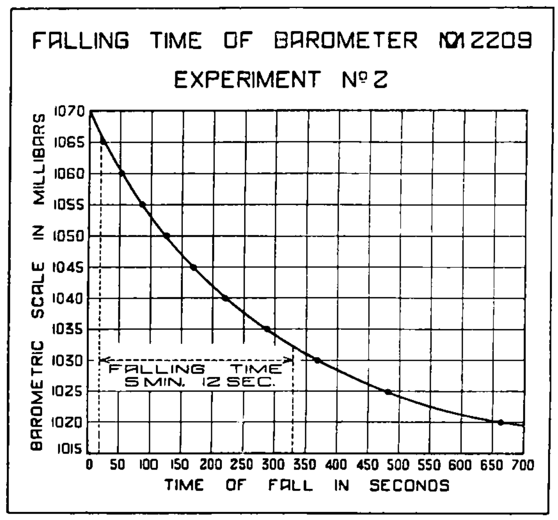


FIG. 8.

It will be noticed that the "falling time" of the experimental barometer is 5 min. 13 s., according to equation (29), and 5 min. 2 s. according to equation (30). The experimental values of the "falling time" as set out in Table III, are well within these limits. In this connexion, the importance of the accurate measuring of the actual barometric height (i.e., as read, and uncorrected for temperature, etc.) should be emphasised.

(iii) *The lagging time of M.O.* 2209.—The barometers M.O. 875 and M.O. 2209 were hung side by side and the latter was adjusted by means of the cistern plunger to the reading of M.O. 875 on a day when the barometer was steady. The temperature coefficients of both barometers are expected to be of the same order of magnitude.* R. G. Veryard has taken simultaneous observations of the two barometers in the Test Room of the Instruments Division of the Meteorological Office for over a month under rising and falling barometric tendencies. The standard barometer was always tapped before taking an observation, but both untapped and tapped readings were taken of the experimental barometer.

From equations (22) and (29) the lagging time of M.O. 2209, according to Stokes, is 4 min. 45 sec. The tapped readings of the experimental barometer suggest that the lag in this instrument is small and could be almost eliminated by Stokes' method. A summary of the observations prepared by R. G. Veryard is given in Table IV. The first column of the table gives the barometric variations as obtained from a barograph. The last column was obtained as follows :—On each occasion the lag in millibars was calculated according to equation (12), and set out in column 2. This amount was subtracted from the tapped reading of the experimental barometer, M.O. 2209, when the barometer was falling, but added when the barometer was

* The variation of standard temperature along the scale of M.O. 875 within the range of pressures observed is of the order of 0·4 ° C.

rising, because the standard barometer is always in advance of the marine. This amended reading of M.O. 2209 was then subtracted from the corresponding reading of M.O. 875 and the residual difference between the readings of the two barometers was set out in column 8 of Table IV.

TABLE IV.—OBSERVATIONS OF LAG IN M.O. 2209.

Barometer M.O. 2209 was adjusted to the reading of the Standard Barometer M.O. 875, when the atmospheric pressure (1018·0 mb.) was steady.

Falling time of M.O. 2209, $T = 5$ min. 13 s.

Stokes' relation :—$L = 0{\cdot}91\,T$, where L = Lagging time.

Lagging time of M.O. 2209, $L = 4$ min. 45 s.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		M.O. 2209.			M.O. 875.	M.O. 2209.	
Barometric Variation.	Lag correction according to Stokes' Formula.	Untapped Readings.	Tapped Readings.	Differences (3–4).	Tapped Readings.	Tapped Reading corrected for lag from column 2.	Differences (7–6).
mb./hr.	mb.	mb.	mb.	mb.	mb.	mb.	mb.
−1·5	−·12	1000·9	1000·7	+·2	1000·6	1000·58	−·02
−1·2	−·10	994·8	994·6	+·2	994·5	994·50	0·00
−1·1	−·09	1001·7	1001·5	+·2	1001·4	1001·41	+·01
−1·0	−·08	1012·85	1012·75	+·1	1012·7	1012·67	−·03
− ·9	−·07	1024·8	1024·65	+·15	1024·6	1024·58	−·02
− ·8	−·06	1018·65	1018·55	+·1	1018·5	1018·49	−·01
− ·5	−·04	1007·75	1007·70	+·05	1007·70	1007·66	−·04
− ·4	−·03	1021·15	1021·1	+·05	1021·05	1021·08	+·03
− ·3	−·02	1015·3	1015·25	+·05	1015·2	1015·23	+·03
− ·2	−·02	1021·75	1021·65	+·1	1021·65	1021·63	−·02
− ·1	−·01	1024·6	1024·6	0·0	1024·6	1024·59	−·01
Steady ..	·00	1022·0	1022·0	0·0	1022·0	1022·0	0·0
+ ·1	+·01	1022·15	1022·2	−·05	1022·2	1022·21	+·01
+ ·3	+·02	1005·25	1005·3	−·05	1005·3	1005·32	+·02
+ ·5	+·04	1025·25	1025·3	−·05	1025·3	1025·34	+·04
+ ·5	+·04	998·25	998·3	− 05	998·3	998·34	+·04
+ ·6	+·05	1012·25	1012·3	−·05	1012·3	1012·35	+·05
+ ·8	+·06	1008·45	1008·5	−·05	1008·5	1008·56	+·06
+1·0	+·08	1012·5	1012·6	−·1	1012·65	1012·68	+·03
+1·3	+·11	1002·05	1002·3	−·25	1002·35	1002·41	+·06

The outstanding differences noticed in column 8 of Table IV are within the range of probable error in such observations. No physical meaning could be attached to these differences, and, therefore, the lag in the experimental barometer appears to be in accordance with Stokes' theory. The high lag observed by Dr. Chree (loc. cit.) is probably due to the fact that the marine barometers he examined had " strangled " capillaries or " constrictions." It should be noted that the motion of mercury through constrictions tends to become intermittent. A familiar example is the passage of mercury through the constriction in maximum thermometers. Bond's paper (loc. cit.) is very interesting in this connexion.

It appears from the observations that the difference between tapped and untapped readings varies from 0·05 mb. to 0·20 mb., corresponding with barometric changes from 0·5 to 1·5 mb. per hour. These divergencies are probably due to the clinging tendency of mercury.

(iv) *Improvements in the barometer, M.O.* 2209.—The points of improvement in the experimental barometer will now be given and also a recommendation for further improvements in the marine barometer :—

(*a*) The scale is contracted only $1\frac{1}{2}$ per cent., as against 3 to 10 per cent. in ordinary barometers.

(*b*) It is seen from Figs. 1, 2 and 4, that the dimensions of the various parts of the tube have been chosen from the more or less stable parts of the graphs. Thus the chance of irregular behaviour of the barometer is reduced to a minimum.

(*c*) The additional air space in the cistern in the inverted position of the barometer is only 2 mm. in depth. There is, therefore, less risk of the air gaining admission to the tube.

(*d*) The potential energy of the driving head which becomes unavailable owing to the fluctuations of the level of mercury in the cistern is less than half of what it is in ordinary barometers. The motion of mercury through the capillary is therefore more steady than in ordinary barometers.

(*e*) The falling time is in accordance with Stokes' theory. The lag is much less than in ordinary barometers and the lagging time is probably in accordance with Stokes' equation.

(*f*) The dimensions of the capillary have been so chosen that the flow of mercury through it is steady.

(*g*) The standard temperature at 1,000 mb. can always be adjusted to 285a by means of the cistern plunger.

(*h*) It is expected that the specification laid down will limit the variation of the standard temperature along the scale to within $\pm 0 \cdot 2$ °C. of the standard temperature at 1,000 mb.

(*i*) The estimated range of variation* of the capillary depression at the top of the experimental barometer is of the order of $\pm 0 \cdot 17$ mb. and in the cistern about $\pm \cdot 03$ mb., so that in actual practice with a rising or falling barometer, the doubt in a single observation is about one vernier division when the barometer is tapped. Thus an accuracy of ·01 per cent. in the reading is probably secured when both cistern and tube are tapped.

(*j*) *Recommendation.*—In view of the much reduced lag in the experimental barometer, the question of repeating Welsh's experiment with barometers having a longer falling time than six minutes, should be considered as probably the effect of pumping could, for all practical purposes, be eliminated. The construction of the marine barometer could then be simplified by making approximately the whole of the tube between the wide top part of the tube and the Gay-Lussac air trap (*see* BE in Fig. 6) a capillary. The falling time of the barometer would then be in the neighbourhood of 8 minutes (*see* Fig. 4), if a capillary of 0·4 mm. bore, as in M.O. 2209, is used. No doubt the lag would be more than in M.O. 2209, and on land it would be of the order of a millibar corresponding with a barometric change of 10 mb/hr. The defect, however, is not at all serious under ordinary meteorological conditions and on board ship the readings would probably be more satisfactory than at present. Moreover, the greater lagging time would make the amplitude of oscillation† of mercury due to heaving, much smaller than that in existing barometers.

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* See *Dictionary of Physics*, Part III, " Barometers and Manometers," Tables III and IV, pp. 160–161, by F. A. Gould.

† " Comparison of ship's barometer readings with those deduced from land observations ; with notes on the effect of oscillatory motion on barometer readings," by E. Gold, *Q. J. R. Meteor. Soc.* Vol. 34, 1908, p. 97.

§ 7. The Station Type.

The Kew pattern barometer now in use on land has no constriction in the tube. In some barometers of the station type, however, the middle portion of the tube, about 50 cm. in length, has a bore of the order of 0·7 mm. From the previous sections it is clear that in order to obtain the best results the bore of the middle portion of the tube must not be less than 1·6 mm. The falling time of this type would be of the order of three seconds, and, hence, the lag would amount to about ·01 mb., if the atmospheric pressure is changing at the unusual rate of 10 mb/hr. In consideration of the fact that barometers of this type are not expected to read more accurately than to the nearest 0·1 mb., the lag introduced by the narrow portion in middle of the tube is of no practical consequence.

In conclusion, one more important point should be noted. The time period of the Kew pattern barometer swinging freely on its gimbals, is generally between 1·2 and 1·6 seconds. The swinging of the marine barometer, owing to the rolling and pitching of the ship, is capable of introducing large errors in the observation of the atmospheric pressure at sea. The mounting of the marine barometer is therefore an important consideration. The subject has been studied by many* and it is not proposed to discuss it here.

A provisional specification of the essential points in the construction of the Kew pattern barometer is set out in the Appendix.

The author has much pleasure in expressing his thanks to Mr. F. A. Gould, of the National Physical Laboratory, for his valuable criticisms.

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* Duffield and Littlewood, *Phil. Mag.*, July, 1921, p. 166.; Schuster *Proc. R. Soc.*, 1916, Vol. XCII. Ser. A, p. 517: Giblett, *Phil. Mag.*, Vol. XLVI, October, 1923, p. 707; Dines, J. S., *Q. J. R. Meteor. Soc.*, Vol. XLII, Jan., 1916, p. 1.

APPENDIX

Provisional Specification of the C.G.S. Kew Pattern Barometer

1. To be graduated in millibars and have a standard temperature of 285a. The mercury* must be pure and free from air bubbles. The glass tube† must be thoroughly cleaned. To be provided with an N.P.L. certificate.

2. *The Tube.*—(*a*) Must be of good flint glass and all parts of it thoroughly annealed. To be provided with an air trap as in Fig. 6. To be firmly fixed to lid of cistern. The joint to be mercury tight At top the tube to be between 20 and 21 cms. in length. The bore next to graduations to be 8 mm. ± ·05 mm. throughout.

(*b*) The falling time from 52 mb. to 18 mb. above the actual barometric height to be 5 min. ± 15 secs. [To save trouble and expense, the maker is recommended to adhere to the following dimensions of the capillary :—length, 300 mm. ± 20 mm. and bore 0·4 mm. ± ·01 mm.] *This paragraph does not apply to the station type.*

(*c*) The bore of the rest of the tube to be *not* less than 1·6 mm. diameter. The dipping part of the tube must be a uniform cylinder whose external diameter does not exceed 6 mm. The dipping tube to project about half-way in the cistern. The barometer is to be so assembled that there is a clearance of about 3 mm. between the lid of the cistern and the free surface of mercury in the cistern when the barometric reading is about 1,010 mb. the plunger being in its mid-position.

3. *The Cistern.*—To be a cylinder of rustless steel (having no action on mercury) with a flat screw-on lid. There must be fiducial marks both on the outside of the cistern and the lid showing the correct position of the cistern with respect to the tube. The internal diameter to be 66 mm. and depth 35 mm. The inside wall to a depth of 10 mm. from top of cistern to be well polished and to be a uniform cylinder. To be provided with a cistern plunger which must be perfectly mercury-tight as in Fig. 7. The screw propelling the plunger to be such that the barometric reading could be altered through a range of 5 mb. To be provided with a vent hole as in Fig. 7. The washer must render the cistern mercury-proof, but offer no sensible obstacle to atmospheric pressure. Lightness in construction desirable.

4. *The Case.*—To be of standard‡ brass tubing 25 to 26 mm. in external diameter, the whole to be protected by black japan. Two parallel slots to be cut in the tube to hold the vernier. The lower end of the case to screw on to the cistern lid, the relative position of the scale and the cistern being fixed by means of a clamp screw. To have a slit cut in the case of approximately the same size as the thermometer bulb and just behind the bulb. Lightness in construction desirable.

5. *The Scale.*—To be graduated in millibars, the range being 870 mb. to 1,100 mb., readable by vernier from 1,065 to 870 mb. The graduations for every 5 mb. to be longer than the ordinary graduations, but shorter than the graduations for every 10 mb. To be figured at every 10 mb. and blackened. The graduations to be fine lines of uniform thickness and depth throughout. To be silvered, lacquered and protected by means of glass tube resting on a brass cap screwed on to the brass tubing.

6. *The Vernier.*—To be screwed to a tubular piece of metal which is operated smoothly by a rack and pinion. To be toothed at top and have a straight edge at the bottom. The straight edge to be in exact alignment with the lower edge of the metal piece at the back of the vernier. To cover 39 divisions of the main scale reading to 0·1 mb. The graduations to be blackened and figured for every tenth millibar ; the scale to be silvered and lacquered. The milled head screw for actuating the vernier to be as close as possible to the gimbal suspension.

7. *The Attached Thermometer.*—To have a straight cylindrical bulb mounted on a brass frame covering the bulb. The brass frame is to be screwed about the middle of the barometer tube. To have a range from 260 to 320a graduated for every degree Centigrade on the thermometer and figured at intervals of 5° C., which is to correspond with about a centimetre on the thermometer stem. To be exact at 285a, the tolerance allowed over the rest of the scale is to be in accordance with the N.P.L. practice. The brass frame is to be so shaped that it offers ample protection to the thermometer stem.

8. *The Gimbals.*—To be so made that the barometer may be easily rotated on the bearing. The height of the gimbal fitting to be 50 cms. above the top of the cistern lid.

9. *The Accessories.*—The barometer to be provided with an index plate just above the attached thermometer, suitable wooden case with fitting, suspension arms, brackets and screws. The arm of the station type not to be less than 15 cms., and of the marine type the arm to be not less than 30 cms. in length. The arm to be made of hard brass and to be reinforced by means of ribs.

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* Welsh, J., *Phil. Trans.*, 1856.

† Laby, T. H., *J. Sci. Inst.*, Aug., 1924, p. 342, and Mauley, J. J., *Proc. Physic. Soc.*, London, Vol. 36, 1924, pp. 288–293.

‡ Having a coefficient of linear expansion of ·0000189.