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A Discussion of Pitot-Static Tubes and of their Calibration Factors with a Description of Various Versions of a New Design

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Summary.

The report describes experiments devised to investigate some of the previously unexplained peculiarities of normal types of pitot-static tube. Revised basic calibration factors for various instruments are recorded.

In the process use was made of a special design of standard *static-pressure* tube and the experiments led to new alternative types of *pitot-static* and plain *static-pressure* instruments. These have nose profiles of modified-ellipsoidal shape.

In the report particular attention is given to the implications of the term 'calibration factor', to the special features and limitations of various types of instrument, to the details and precautions of experimental technique for reliable investigations and to the inclusion of generally associated information and comment.

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1. *Preliminary Notes.*

Whilst the above summary describes briefly but correctly the content of the report, it has to be emphasized that the detailed discussions given in the text are regarded as being at least as important as the factual record of the investigation; in any case most of them are essential to a proper appreciation of the significance of the experimental results. As they run through the text from beginning to end they may be more difficult to correlate than the fairly logical sequence of the experimental development. Partly for this reason the report is divided into five main parts and extensive cross-references between sections have been included. For further assistance Section 2 emphasizes the distinction between the purposes of the investigation (Section 2.1) and of the report itself (Section 2.3) and also describes the main framework of the report (Section 2.2).

The five main parts of the report are as follows:

General Considerations—Sections 2 to 7.
Experimental Procedure and Equipment—Sections 8 to 21, 35, 36.
Calibrations of Tapered- and Hemispherical-Nose Tubes—Sections 22 to 28.
New Design of Pitot-Static Tube—Sections 29 to 46.
Principal Conclusions and Concluding Remarks—Sections 28, 46, 47, 48.

A very brief summary of each is given in Section 2.2.

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2. *Scope of* (a) *Investigation* (b) *Report.*

In this section we are concerned to point out the overall differences between as well as the general scope of investigation and final report respectively.

2.1. *Origin and Purpose of the Investigation.*

The original designs of so-called Standard Pitot-Static Tubes incorporated heads with tapered or hemispherical noses (as in Fig. 1). These nose shapes give rise to marked suction peaks downstream of which the boundary layer is prone either to separate from the surface or at least to become significantly disturbed (e.g. as in Plates 1, 2, 3). As boundary-layer behaviour is dependent on Reynolds number, stream turbulence, etc., some slight uncertainty in respect of calibration factor has always been accepted. From time to time however, at first at very low and later at higher Reynolds numbers, some unexpectedly large variations have appeared.

It was the most recent of these disconcerting surprises that stimulated the present investigation. It related to a copy of the first N.P.L. standard pitot-static tube with a tapered nose. It was generally similar to T.N.1A in Fig. 1 and is described in Section 20.3. The prototype was devised about 1912[1, 2] and very careful measurements then and later indicated that the basic calibration factor (Section 6.1) was 1·000. Some fairly recent incidental work at the Royal Aircraft Establishment however raised the suggestion that for this copy of the (no longer available) prototype the factor was about 0·994 at 50 ft/sec (5/16 in. tube in atmospheric air) falling to 0·99 at 150 ft/sec and over[3].

For some time there had been an ill defined suspicion that the basic factor was actually slightly less than unity but not to this extent. Consequently an attempt had to be made to locate at least the main possible cause of the apparent discrepancy. The reasons for this having been discovered (Sections 24, 25) it was convenient to examine a variety of features of detail of the two types (with tapered and hemispherical noses) and to revise the basic calibration factors.

The investigation was then extended to cover the design and examination of a new type (both pitot-static and plain static-pressure) which should be free from many of those faults of detail discovered in the others.

2.2. *Framework of the Report.*

As already stated in Section 1 the report has been broadly divided into five main parts (there is a small amount of overlap) the general framework being based on the experimental development indicated in Section 2.1. A brief summary of the five parts is as follows: (The *scope and purpose of the report* is explained in Section 2.3).

(1) *General Considerations* (Sections 2 to 7).

This covers such matters as history of design of pitot-static tubes, experience in usage and the resulting situation, meaning and potential meaning of calibration factors.

(2) *Experimental Procedure and Equipment* (Sections 8 to 21, also 35 and 36).

In this are described the equipment employed including a variety of the pitot-static tubes, a special design of *static-pressure* tube (Fig. 2) used as a basis of comparison for most of the experimental work, techniques, precautions, accuracy and so on.

(3) *Calibrations of Tapered- and Hemispherical-Nose Tubes* (Sections 22 to 28).

This includes discussions of the calibrations of the well known types of instrument (Fig. 1) and of the resulting implications.

(4) *New Design of Instrument* (Sections 29 to 46).

At this stage the need for an alternative design (not necessarily to the exclusion of the others) became evident. The reasons for and the basis of the new nose profile (Fig. 8) are detailed and several versions (Fig. 10) have been carefully examined even (as far as possible to date) at very low Reynolds numbers.

(5) *Principal Conclusions and Concluding Remarks* (Sections 28, 46, 47, 48).

2.3. *Scope and Purpose of the Report.*

Referring to Section 2.1 the work as a whole illustrated well some of the many difficulties associated with the design, construction, calibration and use of pitot-static and static-pressure tubes. Because of this it appeared that far more use could be made of it than merely to record the experimental investigation and its results. Such a record would not have been effectively informative unless the reader were provided with sufficient detail for a full appreciation of its implications and this would be even more important for anyone wishing to extend the work. The numerous details and points of consideration of the present investigation have very general application and the many pitfalls are not by any means well known—nor have they been well advertised. Consequently the scope and purpose of the report is extended beyond the range of experimental investigation and (somewhat freely) into the realm of discussion and comment. The investigation provides the framework and background for the extension.

The main objects of the record are therefore:

(i) to describe experiments devised to investigate some of the previously unexplained peculiarities of normal types of pitot-static tube,

(ii) to specify the revised basic calibration factors of various instruments,

(iii) to present a new design of pitot-static tube with details of its main aerodynamic characteristics,

(iv) in the framework of the above:

    (a) to discuss the implications of the term 'calibration factor',

    (b) to point out some of the special features and limitations of various types of instrument,

    (c) to illustrate some of the difficulties of devising satisfactory standards,

    (d) to describe the details and precautions of experimental technique for reliable investigation,

    (e) to record a variety of considerations relevant to static-pressure and pitot-static tubes not otherwise conveniently made known even if available at all.

3. *General Introduction.*

It is desirable from time to time to re-examine anything which may have become very much taken for granted and the calibration factor of a pitot-static tube is a typical example. Before settling down to an investigation such as the one described in these notes one has to consider very carefully what it is that one accepts as the meaning of the term 'calibration factor' and what is its relationship both in theory and in practice to the actual instrument. We start therefore by referring to the Bernouilli relation (its simple elementary form is adequate here) and considering the consequences of its practical application.

In a very simple case of virtually steady flow of an almost perfect fluid the relation between the local static pressure p_0 and the local speed of movement U_0 can reasonably be expressed '$p_0 + \rho U_0^2/2$ is constant along a streamline'; ρ is the density of the fluid but the word 'streamline' is used with some reserve (Section 4 is relevant here). It is an easy deduction from the basic theory that if in such a case one causes the flow in a small 'streamtube' to 'come (locally) to rest' by making it impinge on the end of a tube of solid material, the pressure inside that tube can be expected to be equal to the $p_0 + \rho U_0^2/2$ of the undisturbed flow at the selected location[1, 12]. Therefore if one can also measure the value of p_0 one can deduce that of $\rho U_0^2/2$ and so also of U_0.

Many investigations have been directed towards devising suitable instruments—mainly a problem of measuring this static pressure—and, in practical application, the so-called 'standard' instruments (in reasonably good flow conditions) have in general served their purpose well enough. They have none of them however been completely satisfactory especially when having to be accepted as laboratory standards. For example experience has shown that all types are subject to some unknown degree of uncertainty (cf. Section 2.1). This could be ascribed vaguely to various possible causes but only in recent years has the development of the science reached a stage when one could hope to identify them more specifically.

It is to be noted that the original basic investigations (e.g., Refs. 2, 5, 7) were effected in flow conditions which were definitely far from being as near the ideal as would be desired and were made at a time when knowledge of the more abstruse features of actual fluid motion was far from adequate. (That is not to imply that background knowledge is now amply sufficient.)

If furthermore the equipment and techniques had been available then as they are now it would have been better to have devised instruments for the near-ideal case and either to have modified the design or corrected the observations for the not-so-good conditions. This may not have reduced the number or extent of subsequent difficulties but it would have prevented the basic foundations from remaining for so long, so to speak, 'in the air'.

We find ourselves in the light of modern requirements, embarrassed by the uncertainties of the current situation. There are many of them and there is a need to locate their causes and either to eliminate them or at least to establish their associated limits of error. In this connection a number of relevant aspects are being followed up in various establishments. Having expressed the general situation we can now proceed first to a discussion of calibration factors and then to the investigation and its developments.

4. *General Notes on Terminology.*

Four terms are in common use in connection with the subject matter of present concern—total pressure, pitot pressure, static pressure, dynamic pressure—with the meanings of which a reader is generally but unwarrantably presumed to be thoroughly familiar. Within a certain limited range of virtually steady-flow conditions of a nearly perfect fluid there is no special difficulty—the formal definitions are usually adequate; but in respect of most actual flow conditions and experimental processes the terms are often used either in place of specially invented expressions or without redefinition appropriate to the circumstances. This practice must be tolerated being so extensive and in any case it is often not unreasonable even when academically unjustified. Nevertheless it is necessary to be fully aware that the usual definitions are not always strictly appropriate when these terms are encountered.

The subject is too extensive and too complicated to be discussed further here. Fortunately we are at present mainly concerned with near-ideal flow. In consequence of this, having made the point, it is sufficient for our immediate requirements to conclude by saying that the implication of these and of any other terms employed in these notes will it is hoped, if not in themselves self-evident, be made quite clear by the context.

5. *General Notes on Pitot-Static Tubes, and their Calibration.*

In general the head of a pitot-static tube comprises (basically) two concentric tubes; it is affixed to a stem which is at right angles to it and extends to one side only. This head is mainly cylindrical but the outside of the upstream portion of it (the nose) is specially shaped to a profile depending on the type of tube (*see* Figs. 1 and 10). Where a design differs appreciably from this it will not be difficult to make an appropriate interpretation of subsequent remarks.

For most purposes the calibration of individual tubes is not usually necessary as long as the prototype has been investigated. For precise measurements however, as will be seen later, the formal calibration of a prototype may or may not be adequate; furthermore, although an appropriate calibration might be called for in principle, it might not be conveniently obtainable in practice.

A calibration factor which is not 1·000 (Sections 6.1 and 6.2) usually implies that the design has not quite achieved the object in mind. This in itself is not necessarily a handicap but it is important to understand the exact implication of any specified factor. These factors cannot be described or defined in very brief terms; in any case there are various methods of approach.

It is necessary to assume here that the tube is suitably coupled to a suitable manometer—otherwise the manometer becomes part of the instrument and this aspect is a subject in itself. Then again in the consideration of the factors, etc., we shall not be concerned at all with situations where the speed of flow is high enough for shock waves to be generated or cavitation to arise; nor shall we consider abnormal conditions such as lack of homogeneity of the fluid.

6. *Calibration Factors of Pitot-Static Tubes.*

6.1. *Basic Calibration Factor of a Pitot-Static Tube.*

It is best to consider first the use of such a tube (Section 5) held stationary in a uniform, steady, turbulence-free stream.

With the head pointing directly upstream we may write for the difference between the pressure p_a in the annulus and the true local static pressure p_0 in the stream

$$p_a - p_0 = (1-K)\rho U_0^2/2.$$

$(1-K)$ is an error factor in respect of the annulus in such a stream; the value of K is (and should be) approximately or exactly unity but in general it has to be determined quantitatively and experimentally.

For the difference between the pressure t_c in the centre bore (sometimes called the total-pressure duct) and the local $t_0(=p_0+\rho U_0^2/2)$ of the stream (this is in many instances the local total pressure) we may write—

For liquids

$$t_c - t_0 = E\rho U_0^2/2$$

and for gases in a state sufficiently removed from the critical state

$$t_c - t_0 = \left(E + \frac{M^2}{4} + (2-\gamma)\frac{M^4}{24} + \dots\right)\rho U_0^2/2\,.$$

For vapours (e.g. steam) and also for liquids the M terms are not of this form; in respect of liquids they can fortunately be completely ignored anyway.

M is the ratio of U_0 to the local speed of sound in the fluid, γ is the ratio of the specific heat of the fluid at constant pressure to that at constant volume. In each case ρ, p_0, U_0 and t_0 refer to local conditions in the stream before insertion of the tube.

For the pitot-static combination therefore the pressure difference between the centre bore and the annulus may, for our present illustration, be written

$$t_c - p_a = \left[E + K + \frac{M^2}{4} + (2-\gamma)\frac{M^4}{24} + \ldots\right]\rho U_0^2/2 .$$

In this equation the brackets enclose an *overall calibration factor*. The part E is an *error factor* in respect of the centre bore. It depends mainly on the shape of the nose and is significant at very low Reynolds numbers. With the possibility of very slight deviation in some cases it is zero at normal Reynolds numbers. The M terms are only of interest at relatively high rates of flow (Refs. 1, 12).

Our present interest is mainly with K. With appropriate detailed specification of the conditions (as listed below) $1-K$ is a *Basic Error Factor* in respect of the annulus and K is a *Basic Calibration Factor*. In practice K is the same as the *Formal Calibration Factor* of the pitot-static tube. The latter assumes (*see* above) that E is zero at normal Reynolds numbers but it must not be forgotten that strictly speaking it is related only to the annulus (*see* also paras. 1 and 2 of Section 6.2).

The conditions in which K is a *Basic Calibration Factor* in this sense are as follows:

(a) Extremely steady flow with virtually zero turbulence.

(b) The stream to be of such large lateral dimensions that blockage effects resulting from the relative magnitude of the projected area of the tube are quite insignificant.

(c) The head to be, in effect, in the middle of the stream.

(d) The stream to be, in effect, laterally uniform.

(e) The stream to be, in effect, straight flowing and with parallel flow, i.e. longitudinally uniform.

(f) The head to be carefully aligned to the local flow direction.

(g) The instrument to be supported, without vibration, in such a way that the supports do not distort the stream enough to affect the separate pressures.

For some instruments K remains usefully constant for a wide range of Reynolds number; for others it varies more or less continuously.

6.2. *Other Calibration Factors of a Pitot-Static Tube.*

Notwithstanding its general use as a formal calibration factor (Section 6.1) it is important to note that K is not a magic number which caters for all circumstances. Admittedly, in practice, the circumstances can often differ considerably from the specification of the previous section before significant errors arise but it is necessary to appreciate in what respects the factor is basic and not universal.

Where the conditions deviate sufficiently from the near-ideal it is necessary either to apply certain corrections or to modify the factor (say to K') whichever may be the more appropriate and convenient. This applies equally to the error factor E and of course $(E+K)$ may be regarded as a calibration factor if so desired.

It is therefore necessary to point out at least some of the many influences in respect of which some adjustment may be required:

(a) Turbulence or other unsteadiness.
(b) Blockage in general (i.e. Duct Constraint) including wall proximity.
(c) Lateral and longitudinal velocity and pressure gradients including the influences of curvature of the stream.
(d) Misalignment.
(e) Vibration.
(f) Wear or minor damage.
(g) Support interference—cf. also item (b).
(h) Variations in the critical Reynolds number of the stem in so far as it depends on the other influences; the existence of this critical may result in a corresponding pronounced change in the value of the factor—consequently the Reynolds number of the change depends on the circumstances.
(i) K (or K') and E are usually quoted, either specifically or by implication, on a Reynolds number basis. It must be noted however that with some designs it may be practically impossible to manufacture sufficiently accurate copies (1/1 scale or otherwise) for the prototype calibration on this basis to be transferred without some error in respect of calibration and/or scale effect.
(j) It is similarly to be noted that changing the actual size of a tube of a given shape (in a given stream) leads to a change in the relative scale of any turbulence that may be present. This very much influences any adjustment required in respect of item (a). Furthermore, instantaneous local Reynolds numbers related to the distances of various points on the surface from the tip will be no longer comparable and this could lead to significant indirect effects.
(k) It may be necessary to consider whether ρ and U_0 in the equation are to refer to the position of the tip or to that of the holes in the side of the head or (if one is so minded) to any other position.
(l) It will also probably be necessary to consider what is implied by ρU_0^2 when the flow conditions differ from those appropriate to Section 6.1; for example is ρU_0^2 to imply a true-mean-square speed or the mean square of a resolved component of local velocity or the square of a mean value of speed or velocity component and so on. In the process one may also have to ask whether ρ is to be regarded as a mean local value of density.

It is regrettably an inescapable conclusion that in the present state of knowledge calibration factors of or appropriate corrections for pitot-static tubes once the conditions depart appreciably from such as may be called very good conditions are by no means either well defined or easily determined.

7. *Calibration of a Static-Pressure Tube.*

It will be clear that very rarely can any *pitot-static* tube be employed (as a pressure-difference instrument) without the need (if maximum accuracy is required) for sundry corrections—in respect of tube design, turbulence, etc., etc. There is however no difficulty in applying a correction which depends on $\rho U_0^2/2$, i.e. nearly enough on the pressure difference. For this reason it is not necessarily a requirement of a good *pitot-static* tube that the annulus pressure should correspond exactly to a true static pressure.

On the other hand, when using a simple *static-pressure* tube (instead of the annulus of a pitot-static tube), whatever other corrections may be necessary, it is often very inconvenient to be compelled to know also the local value of $\rho U_0^2/2$. (Such a tube is normally only the outer shell, more or less, of a pitot-static tube. This simplification is of importance if the instrument has to be made in very small sizes or for ease of construction in general). One would therefore like to design so that $1-K$ in Section 6.1 (or it may be $1-K'$ in Section 6.2) is zero.

The consideration of the plain static-pressure tube is therefore automatically included in the present investigation. $1-K$ provides the correction in principle (Section 6.1) and the new instruments to be described later (Section 44.4) go a long way towards ensuring that it shall be extremely small throughout a very large range of Reynolds number.

EXPERIMENTAL PROCEDURE and EQUIPMENT

8. *Method of Attack in the Investigation.*

In principle the ultimate check on the calibration factors of a pitot-static tube as such, whether for measuring $\rho U_0^2/2$ or any other functions of a similar nature (as indicated in Section 6.2) would involve some extremely reliable, accurate and elaborate method of establishing and measuring true relative velocities. This is very difficult even in simple cases whether the fluid or the instrument is moving and is especially so in the presence of turbulence, etc. The whirling-arm and the moving-fluid techniques of previous investigations have both involved a considerable number of corrections. Many of these were applied, some were not then known to exist, others were not amenable to either calculation or estimation. (Nevertheless it is now reasonable to deduce that the findings were in fact appreciably less uncertain than might have been feared.)

In the circumstances then it is worth getting as far as one can by a simpler alternative method. For present purposes the focus of interest is on the annulus side of the tube and hence indirectly in the combined pitot-static tube. In any case there are other reasons for this approach; most of the worst difficulties are known to be associated with this side, the number and magnitude of the corrections involved can (in the basic case) be made very small and the actual measurements can, with care, be made to an extremely high degree of precision and reliability.

We are therefore constrained in the first stages to find a static-pressure tube which, although possibly quite inconvenient for general use and probably not a universal laboratory standard anyway, might be shown to be as close to a true standard as one can expect to achieve for the time being and with which other instruments can be compared.

Furthermore, in order to establish the basic information, it is necessary to eliminate the complications of various uncertain influences; stream turbulence is one of these. Fortunately it is now possible to carry out such investigations in streams with completely negligible turbulence levels. Even so it is also necessary to examine the boundary-layer conditions of any instrument these being the main link of influence between cause and effect.

9. *Standard Ellipsoidal-Nose Static-Pressure Tube.*

In the attempt to find such a tube as is mentioned above in Section 8 one automatically decides upon a tube without a stem because stem interference is known to be appreciable. It is then necessary to choose between (a) one which extends so far upstream of the pressure holes in the side that the shape of the upstream end is not critically important and (b) one of relatively short length with a suitably designed nose, e.g. a longish ellipsoid. Because there are so many arguments against the former the final choice fell upon the latter. It was found that such a tube had already been in use at the R.A.E. for some time and it was expedient to use one of more or less the same dimensions[3, 4]. Details are given in Fig. 2, its total length being just over 5 ft.

It was not sufficient to guess that such a tube must be as nearly as need be a 'standard' and further consideration both mathematical and experimental was required. Of the numerous mathematical calculations the most precise (ignoring the displacement thickness of the boundary layer) were subsequently carried out at the R.A.E.[4]. Calculations at the N.P.L. indicated that for the more usual Reynolds numbers the effect of boundary-layer thickness should be quite negligible.

It is not necessary to describe in great detail the incidental experimental tests at the N.P.L. It was first established that in an air stream of very low turbulence the boundary layer remained laminar and unseparated at all wind speeds from 30 to 130 ft/sec. (Plate 1 is interesting in this connection—*see* also Section 18). It was later found to remain laminar up to at least 180 ft/sec.

Next it was found that holes of 0·05 in. diameter were nearly small enough—they resulted in a very slightly higher measured pressure at the lowest speeds than was obtained with 0·02 in. holes. The influences of the finer details of the geometry of the holes were checked to ensure that no error could arise for these reasons; slight countersinking had an effect much the same as that of increasing the diameter; slight protuberances such as might arise from heavy or careless drilling had to be avoided. A very slight vibration which could sometimes arise at a high wind speed was found not to have the slightest effect. The pressure drop between the two sets of holes (6 in. apart—located in turn in the same position in the tunnel) was found to agree closely with the calculated difference.

In the present state of knowledge it is hardly possible to be completely dogmatic about any measurement of static pressure in a moving fluid. Taking everything into consideration however it was concluded that the measured pressure in the specified flow conditions using the downstream set of holes was as nearly as could be correct (*see* also Sections 15 and 16). It turned out later that this corresponded almost exactly with the theoretical calculations.

10. *Experimental Arrangement—Primary Investigation.**

Most of the experimental work was carried out in the N.P.L. 7 ft 16-sided wind tunnel. This was particularly suitable for the purpose; the flow was extremely steady with a very low turbulence level u'/U_0 of about 0·1%, u' being the r.m.s. value of the longitudinal variations. The local axial static-pressure gradient at the time was also small being 0·0026 of $\rho U_0^2/2$ per ft (pressure decreasing, i.e. stream accelerating along wind). Observations covered a speed range of 30 to 130 ft/sec. For convenience however a few results obtained later in a similar manner and in an equally suitable 13 ft × 9 ft tunnel and which increased the maximum speed to 160 ft/sec are included under the heading 'Primary'.

The general layout is illustrated in Fig. 3. The standard static-pressure tube and the various pitot-static tubes were supported in turn, the one by wires and the others in a metal support as shown. They were set up with the holes located in one specific position in the tunnel (X in Fig. 3) and the heads all carefully aligned to the wind.

The metal support is only sketched in outline in Fig. 3. The horizontal clamp was $8\frac{1}{2}$ in. long, 1 in. deep, $\frac{1}{2}$ in. thick and faired in plan at the upstream end; the vertical stem was 2·1 by 0·7 in. 'streamline' section. The length of stem of the pitot-static tubes varied from one to another between 1 and 2 ft but for all of them the exposed length above the clamp was $11\frac{1}{2}$ in.

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* The arrangements for tests in yaw and pitch are described in Section 35.

11. *Datum Tube.*

Pressures were measured against that in a datum tube (*see* Fig. 3). This had a hemispherical nose, was $\frac{3}{8}$ in. in outside and $\frac{1}{4}$ in. in inside diameter. The holes (0·02 in. diameter) were 7 and 16 tube diameters from nose and stem respectively (*see* general sketch of a tube in Fig. 6). The exact dimensions of a datum tube are not very important provided that its design and especially its location are such as to result in a completely reliable datum pressure. This was fully confirmed. For a special precautionary note see Section 17. In particular when the pressure in it was compared with that in a somewhat similar tube which was set up in the experimental position not only was absolute consistency observed but it was incidentally also found that there was no scalee ffect whatever in the pressure difference between the two positions. The datum tube was set up on the same horizontal level as the tubes being examined (*see* Fig. 3 and Section 12) and clear of any interference effects of other instruments, etc.

12. *Manometer and Connections.*

The tube under examination and the datum were connected to a well made and specially cleaned 13 in. Chattock Manometer. In a method deliberately so arranged that the pressure differences to be measured are small it is most important to avoid casual errors, due to lack of care, which could easily swamp the readings. Of these the most important could be due to differential 'buoyancy' error on the two sides. It is usually quite impracticable to ensure uniform temperature throughout the whole of the building and tunnel unit. Consequently one has to run the tubes close together, avoid relative local heating and cooling effects as much as possible in respect of each part of the system, arrange the vertical heights of the tubes to be equal (this determines the vertical position of the datum tube) and so on. Full attention was given to all such matters.

Where pressure differences are large a number of corrections can if necessary be applied. When they are small these are often unimportant; the main concern is then to ensure that the screw of the manometer is in fact reliable for the required range of small movements. This was carefully established.

The final test in all these respects is given by the consistency of day to day repeat observations for a variety of temperature conditions. This was completely satisfactory. The lowest useful wind speed for the accuracy required here was set at 30 ft/sec by the effective minimum response of the manometer which under these conditions was approximately 0·00003 ($3/10^5$) in. of water.

13. *Reduction of the Observations in the Primary Investigation.**

The presentation of the results is illustrated in Figs. 4, 5 and 6. All actual measurements having been taken relative to the datum pressure p_d the first aim was to obtain a corrected plotting of these against wind speed. Typical single runs for the pitot-static tubes are shown in Fig. 4. Superimposed are two curves relating to the ellipsoidal-nose static-pressure tube of Section 9 (these measurements also being relative to datum pressure p_d). The significance of the two curves is explained later in this section.

As the work proceeded a more or less automatic cross-correlation process (e.g. by comparison of various curves) determined where observations or calculations should be checked. The various small corrections were applied as required and the exact tunnel calibration was itself based on the results of the investigation.

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* The procedure in respect of the tests in yaw and pitch is described in Section 36.

The batch of curves associated with the various minor modifications of the ellipsoidal-nose standard are not here reproduced. They comprised however a set of closely spaced curves all nearly parallel to the dashed curves of Fig. 4. This parallelism itself greatly assisted the process of checking and of deciding just what curve represented true local static pressure (relative to the datum) in the experimental position (X in Fig. 3) as measured by the ellipsoidal-nose standard. The long-dash curve of Fig. 4 is the curve for the true value of the static pressure in this position when the tunnel is occupied only by the ellipsoidal-nose standard but this is *not* our p_0. The short-dash curve is the true value when occupied *in addition* by the metal support that was used for holding one by one the various pitot-static tubes (*see* Fig. 3); this is in effect our p_0. We say 'in effect' for reasons given below. In Section 14.2 it will be indicated how in both cases the respective static pressures would have remained unaltered if the ellipsoidal-nose standard had been removed.

Reverting first to Fig. 4, intercepts between the curves for the pitot-static tubes and one or other of the dashed curves show to what extent the measured pressures, when using the annulus side of an instrument, exceed the true static pressure and lead at once to error factors as defined in Section 6.1.

With the long-dash curve as a basis we should be regarding the metal support as an integral part of the pitot-static tube. In this case, the instrument now being so much more bulky, we should have to consider if a special correction might be required on account of any potential tunnel constraint discussed in Sections 14.1 and 14.2. If however (as we do) we use the short-dash curve as representing the value of true local static pressure p_0 we automatically eliminate both the support and its blockage effect, if any, from the analysis. We thus obtain the *basic error factors* $(1-K)$ of Section 6.1 (in respect of the annulus) for the pitot-static tube on its own imagined to be supported by (e.g.) wires which involve no interference of any kind. These are plotted in Figs. 5 and 6 (left-hand scale). The corresponding values of the *basic calibration factors* K of the various instruments follow immediately and are indicated by the right-hand scales.

In these notes the analysis must necessarily relate to the latter condition mainly because this particular form of support is by no means generally employed. Besides, it is undesirable to imply that such a support can be freely adopted; the aim should always be for minimum extra obstruction because of possible complications. Hence the inclusion of item (b) in Section 6.2. Some extra support is often required if only in the form of interference-free wires but pitot-static tubes frequently have very long stems. In the present investigation we should have expected to arrive at the same results if the stems of the tubes had been long enough to have been supported directly in a wall of the wind tunnel probably steadied by a few thin guy wires. In this connection see Section 14.2.

14. *Interference and Tunnel Constraint.*

14.1. *General Notes on Interference.*

It has been found to be necessary to discuss the reduction of the observations in some detail and reference has had to be made to the obstruction caused by objects placed in a ducted stream. The influence of interference and obstruction is a matter of concern in both investigation and application and it is now known to be more insidious than it was once thought to be. For the record then as well as for the purposes of the present report it appears to be worth including some more general remarks about these often forgotten but always potentially important features.

When the instrument is set up in a stream of very large dimensions (usually referred to as a 'free stream') 'tunnel constraint' or 'blockage' is of course quite negligible. We are however left with an interference resulting from any (arbitrary) support that may be employed. The effects on the recorded pressures are primarily the local changes in the pressure field due to the support but there may be secondary effects; for example in the case of a pitot-static tube (even though the local static pressure may be unaltered) a change of local flow direction might lead to more complicated changes in the flow pattern around the head these also affecting the recorded pressures; the secondary influence could at times be greater than the primary one. When the effect is to increase the local static or surface pressure it is often called a 'back pressure' but it is to be observed that the back pressure of the usual stem is a matter of design and not of interference (*see* Section 44.1).

It is desirable to think of the support (and of the stem as well for that matter) as comprising not only the solid material but also the wake shed from it when it is immersed in the stream; this is because the degree of interference (and incidentally of blockage effect where there is any) depends on a variety of parameters besides the frontal area. In a duct of significantly restricted dimensions the flow pattern around the instrument and its support becomes altered and the change is associated, in general, with a change in the pressure at the holes.

This additional effect is due to what is now usually called as follows:

(a) 'solid blockage' of the duct by the *head* of the instrument—this one is in effect a frontal-area blockage and is easily appreciated,

(b) solid blockage arising from the stem and its support which is not so straightforward and

(c) 'wake blockage' due to the various wakes which is much less obvious.

Together they lead to overall 'blockage effects' superimposed on the free-stream interference effect. In some cases, but more particularly where the drag of bodies is concerned, wake-blockage effects can become unexpectedly important. Quantitative information about all these effects is very limited but if the situation is appreciated it is at least possible to do something about it.

14.2. *Interference in the Primary Investigation.*

The effect of the presence of the metal support (Section 10) without pitot-static tube was to *reduce* the pressure at the experimental position (X in Fig. 3) by about $0 \cdot 001\ \rho U_0^2/2$. It was measured by the ellipsoidal-nose standard and is the separation of the two dashed curves in Fig. 4. Tests showed that it was an acceleration of speed effect, i.e. that the direct influence of any associated deviation or curvature of the stream was quite insignificant. Consequently if K refers to the pitot-static tube alone and the special factor K' (Section 6.2) to the combined tube and support we have $K' = K + 0 \cdot 001$. The difference is extremely small and its magnitude in these circumstances is a very reasonable free-stream interference effect of the support. Interference and blockage are not necessarily of the same sign but in this instance they probably are. It therefore seems fair to conclude that both are extremely small and that this particular support could usefully be employed, as an integral part of the instrument, in a duct appreciably smaller than 7 ft in diameter (*see* Section 13).

Tunnel constraint in respect of the head of the instrument and even of the ellipsoidal-nose standard is easily seen to be quite negligible but the frontal area of the stem is large enough (in view of the accuracy to which we are endeavouring to identify the factors) to raise the question of any potential solid and wake blockage effects associated with it. (Free-stream interference is not at issue here—*see* Section 14.1.) The arguments just laid down in respect of the support could be regarded as disposing of the possibility and a consideration of probable flow pattern leads to the conclusion that blockage effects due to the stem are unlikely to be of any importance. There is anyway some confirmation of this in Figs. 5 and 6 where the extension of the speed range (with overlap) to 160 ft/sec in the larger

13 ft × 9 ft wind tunnel (*see* Section 10) for four of the instruments shows that if there is an effect it is very small.

As has been explained in Section 13 the values of K for the pitot-static tubes on their own—the main concern of the present investigation—are not affected by the use of the metal support because of the technique of experiment and analysis. All in all then it is concluded that the values quoted as free-stream basic calibration factors K have not been vitiated by any effects of tunnel constraint.

Even so there remains another point to be covered. The effective stem-length of the pitot-static tubes was between 1 and 2 ft. The question that arises is whether the deduced factors would apply if the stems were long enough to pass through the wall of the tunnel. Here again one can say that a consideration of probable flow pattern suggests that this would make no measurable difference.

Interference and blockage have been discussed at some length not so much because they were expected to be important in this actual investigation but more in order to emphasise their potential importance in other investigations and in the general application of pitot-static (and static-pressure) tubes for purposes of measurement and to demonstrate the content of Section 6.2 which specifies that calibration factors must always be viewed in relation to the circumstances.

15. *General Remarks on Accuracy of Results.*

The consideration of final accuracy involves two distinct aspects. The one relates to the reliability of the conclusion that local free-stream static pressure exists inside the Standard Static-Pressure Tube (Section 9). The other concerns the accuracy of actual measurement and analysis. Both of these involve the study of much detail additional to what has been quoted earlier. Much of this is too tedious to be reproduced here but some general remarks are necessary before attempting to specify the errors.

As regards measurement the situation was greatly assisted by the fact that the observations during the primary investigation never exceeded 2 % of the dynamic pressure of the stream and were usually much less.

Cross correlation and repeat observations all tended to reduce the possible errors and day-to-day variations were found to be in themselves negligibly small. A close search for consistent errors in respect of the measurements resulted in complete satisfaction that there were none that could not be brought into account as in Section 16. A very powerful test—one might say an essential one—is to consider what differences might arise after a period of weeks or months during which the equipment has been completely dismantled and then again put together with sundry rearrangements. This was in fact done albeit not deliberately. It was found that the maximum scatter from this cause was 0·02 % of $\rho U_0^2/2$ which must therefore be included in the list of possible errors (Section 16). Overlap measurements in the two large wind tunnels showed even less scatter.

It may fairly be argued that an extension of such a test should be applied to the Standard Static-Pressure Tube of Section 9. In this case it would involve constructing a variety of such tubes, all significantly different in design and/or size, in each of which however one could feel equal confidence. The scatter of the results obtained would be a useful indication of reliability. To this extent the possibility of a consistent error remains for further investigation but indirect evidence from experiment (here recorded and otherwise) tends to show that this can be expected to be very small.

The primary investigation has been mainly in mind in relation to the remarks made so far in this section. They are followed up in more detail in Section 16 and specific reference to the accuracy of the other results will be included later as and where convenient, e.g. Section 17 and elsewhere.

16. *Accuracy of the Results of the Primary Investigation.*

The various unresolved possible errors of the measurements (which were corrected where possible) can now be listed quantitatively as follows, being expressed as a percentage of $\rho U_0^2/2$:

Wind Speed	30	50	80 and over
(a) Wind-speed calibration and reproducibility	$\pm 0 \cdot 02$	$\pm 0 \cdot 01$	$\pm 0 \cdot 01$
(b) Actual manometer readings	$\pm 0 \cdot 07$	$\pm 0 \cdot 03$	$\pm 0 \cdot 01$
(c) General repeatability after complete dismantling	$\pm 0 \cdot 02$	$\pm 0 \cdot 02$	$\pm 0 \cdot 02$
(d) Sundry	$\pm 0 \cdot 02$	$\pm 0 \cdot 02$	$\pm 0 \cdot 02$
	$\pm 0 \cdot 13$	$\pm 0 \cdot 08$	$\pm 0 \cdot 06$

These are for individual points; they are most unlikely to be cumulative and with slight local smoothing of various parts of the curves one may say that the *possible* errors in the final curves of the observations are generally about $0 \cdot 05\%$ of $\rho U_0^2/2$ and therefore too small in the circumstances to be worth specifying either more precisely or more academically. At 30 ft/sec however the uncertainty may be rather greater. These values are just about the same as those considered to be appropriate to the reliability of the Standard Static-Pressure Tube (Section 9).

Combining the two the final accuracy in the primary investigation of the values obtained for the basic static-pressure errors of the pitot-static tubes, $(1-K)\, \rho U_0^2/2$ in Sections 6.1 and 7, is estimated to be approximately $\pm 0 \cdot 1\%$ of $\rho U_0^2/2$ at 40 ft/sec and over but possibly $\pm 0 \cdot 2\%$ at 30 ft/sec. The accuracy of the basic calibration factors of the tubes (K in Section 6.1) is therefore correspondingly $\pm 0 \cdot 001$ and $\pm 0 \cdot 002$.

17. *Accuracy of the Comparisons in a Turbulent Stream—N.P.L.* 18 *in. Wind Tunnel.*

It will be necessary to refer later to some calibrations in the turbulent stream of the N.P.L. 18 in. wind tunnel. In these the annulus pressures of various pitot-static tubes were compared with one another following the same general procedure as was used in the primary investigation. The characteristics of the stream in this tunnel can be fairly well specified. The steadiness and uniformity (statistical) are extremely good; the longitudinal pressure drop is $0 \cdot 02$ of $\rho U_0^2/2$ per ft, pressure again decreasing along wind; the levels of turbulence are $u'/U_0 = 0 \cdot 2\%$ (longitudinal) and $w'/U_0 = 0 \cdot 3\%$ (lateral) (*see* Section 10), i.e. moderate. There are some acoustic resonances present but the turbulence arises mainly from eddies shed from a honeycomb straightener followed by a contraction. One may therefore (for present purposes) quote the lateral dimension of the scale of turbulence as being in the main about $\frac{1}{4}$ in. i.e. *not* large compared with the diameter of the various tubes (5/16 in.).

In these calibrations the annulus pressures of various instruments were compared with one another following the same general procedure as was adopted in the primary investigation (Sections 10, 11). In this connection it is convenient to record here a special requirement regarding the datum when a small wind tunnel is being employed in this way; it is an important matter because, in the interests of accuracy, one has to arrange that the datum pressure is not unduly different from the annulus pressures. It must be positively established either that there is no interference on the datum due to the instruments being examined or else that the interference is the same for any two instruments that are being compared with one another.

Some of the results obtained in the 18 in. tunnel are as accurate as are those of the primary investigation (Sections 16 and 32). Where however it was a matter of obtaining a turbulence effect the accuracy cannot always be specified very precisely; it is not a question of measurement so much as of interpretation. Such conclusions as are drawn in this respect are therefore, pending further investigations, to be regarded as being qualitative rather than precisely quantitative (Sections 24.5 and 27).

18. *N.P.L. (Aerodynamics Division) Water Tunnel.*

Reference will be made later to some visual observations of axisymmetric flow around rods of diameter 1·5 in. profiled to different shapes, but not much need be said in description of the water tunnel employed for this purpose. The flow was sufficiently steady in a working section of dimensions 13 in. by 10 in. and illumination was by means of a single thin sheet of light.

The flow patterns illustrated by photographs of the movement of tiny aluminium particles immersed in the stream (*see* Plates 1, 2, 3) refer to a diametral plane upstream of the models but only to one radial plane alongside. The greater part of each model was not illuminated and is therefore not easily visible on the Plates. This part of the work was very efficiently performed by Mr. P. S. Pusey.

19. *Types of Pitot-Static Tube Examined—General.*

These comprised four of the type known as the Original Tapered-Nose N.P.L. Standard[1, 2], six with an actual or nominal hemispherical nose[1, 5, 6] one of them being generally known as the Alternative (Short-Head) N.P.L. Standard[1, 6] and some with specially shaped nose profiles here referred to as modified-ellipsoidal. For convenience of appreciation they are identified to this extent thus: T.N.-, H.N.- and M.E.N.- respectively.

The head designs are illustrated in Figs. 1 and 10 (*see* also Fig. 8). All were nominally 5/16 in. in diameter except H.N.3/8 which was 3/8 in. Most of them were fitted with cutaway spacers in the annuli (*see* Figs. 1 and 10 and Section 31) to ensure that the inner and outer tubes were coaxial. Two important dimensions are the distances of the side holes (in units of tube diameter) from the base of the nose and from the axis of the stem respectively (*see* insert Fig. 6). Consequently it is sometimes useful to include these in the abbreviated designations of the tubes, e.g. H.N.3/8 (7D, 15D).

It may be asked why so many of the tubes have 7 side holes instead of the more obvious 8. This is merely because the Alternative Hemispherical-Nose Standard had 7; this in turn was related to the three sets of 7 in the Original Tapered-Nose Standard; beyond that one can only assume that 7 was regarded as a magic number. It is not considered to have any practical significance whatever even in yaw and pitch.

20. *Descriptions of the Tapered-Nose Pitot-Static Tubes.*

Although basically of Original N.P.L. Standard design (Refs. 1 and 2 and Fig. 1) certain special features of the individual tubes have to be noted.

20.1. *T.N.1A and T.N.1B—Description.*

These were new and accurately made copies except for very small differences in some of the internal dimensions which would not be expected to have any significant effect whatever (*see* Ref. 7). The tips were left as sharp-edged as possible.

20.2. *T.N.2—Description.*

This copy, manufactured in the 1920s, (*see* Ref. 6) had become subject to wear and damage to an extent not very obvious but now appreciated as being significant. It took the form of some distortion of the 'facing' aperture and in particular a rounding of the sharp edge at the tip.

20.3. *T.N.3—Description.*

This was not such a carefully made copy as the others but its main difference consisted of a spread of the thin tip into the form of a very slight flare. This was the tube used at R.A.E. and referred to in Section 2.1 and Ref. 3.

21. *Descriptions of the Hemispherical-Nose Pitot-Static Tubes.*

These tubes are illustrated in Fig. 1. The rounded ends of any such tubes constructed at the N.P.L. are generally well made hemispheres carefully matched to the cylindrical portions of the heads. Others however do not invariably agree so closely with the standard specification; it is also important to bear in mind that the diameter of the hole at the tip is not always half the outside diameter of the tube.

21.1. *H.N.4* (6*D*, 8*D*)*—Description.*

This was a new and well made copy of the Alternative Standard (Short-Head) Tube mentioned in Section 19.

21.2. *H.N.C.* (6*D*, 8*D*)*—Description.*

This commercial instrument was a modification of the Alternative (Short-Head) Standard (Section 19). The main modification comprised a curved junction between head and stem of mean radius $2\frac{1}{2}$ times the outside diameter of the tube (Fig. 1). It was also different from the specified standard in that the radius of the nose was rather greater than that of the tube. This led to the nose being a truncated hemisphere so that, in effect, a ridge was formed around the base of the nose.

21.3. *H.N.8* (6*D*, 15*D*)*—Description.*

This one was the actual instrument described in Ref. 5 and the prototype of a design generally known as the Long-Head Version of the Alternative Standard. The nose portion had been somewhat scored in the course of long usage.

21.4. *H.N.9* (8*D*, $15\frac{1}{2}D$)*—Description.*

A new and well made tube with an even longer head (Fig. 1). It was also different in having a slightly smaller 'facing' hole.

21.5. *H.N.3/8* (7*D*, 15*D*)*—Description.*

This was another new long-head tube of larger diameter (0·370 in.). The special feature of interest of this tube was that the profile in the immediate neighbourhood of the junction between the basic hemisphere and the cylindrical head was slightly faired off to a larger radius. This provided a contrast to the ridge of H.N.C. mentioned above.

21.6. *H.N.G.* ($4\frac{1}{2}D$, $15\frac{1}{2}D$)*—Description.*

This tube was a fairly close copy of the German Standard Pitot-Static Tube. The design is distinctive in that the side holes are unusually close to the tip and the junction between head and stem is well curved to a mean radius of $5\frac{1}{2}$ tube diameters, i.e. about double that of the British commercial tube H.N.C. (Fig. 1).

CALIBRATIONS of TAPERED- and HEMISPHERICAL-NOSE TUBES

22. *Calibrations of the T.N. and H.N. Pitot-Static Tubes—General.*

Following on from Section 13 we are now able to consider the calibrations illustrated in Figs. 5 and 6 which show the variations (if any) with wind speed. These curves are derived from all the measurements which were obtained in the two low-turbulence streams (7 ft and 13 ft × 9 ft, Section 10). Individual points are not generally recorded because no more smoothing of the curves has been introduced than has been necessary to accommodate the small variations arising with repeat observations (*see* Section 15).

The left-hand scale of ordinates represents the static-pressure error factor of the annulus, $(1-K)$ in Section 6.1, scaled in the figures as a percentage of the dynamic pressure; that on the right is the deduced *basic* calibration factor K for the complete pitot-static tube (without metal support—*see* Section 13). Generally the annulus pressure is higher than the true so that these factors are nearly always less than $1 \cdot 0$.

23. *Visual Observations of the Boundary-Layer Flow.*

Before discussing the actual calibrations it is convenient to refer here, without going into great detail, to the corresponding visual observations carried out in the water tunnel (Section 18). Some of the many photographs taken are reproduced in Plates 1, 2, 3.

23.1. *T.N. Tubes—Separation of Flow from the Tip.*

From an examination of photographs such as those in Plates 1 and 2 one may deduce that, for a 5/16 in. diameter tapered-nose tube in atmospheric air, the separation of flow from the tip (with subsequent reattachment of the flow) becomes definitely evident at some 'equivalent air speed' below 5 ft/sec. As the speed rises to say 12 ft/sec the size of the so-called nose bubble increases but the boundary layer otherwise remains steady. At about 18 ft/sec the 'bubble' begins to break away spasmodically (*see* Plate 2) and run rearwards. The resulting fluctuation effect extends further and further along the tube until at 40 to 50 ft/sec it appears to become swamped in severe general boundary-layer turbulence.

On the face of it one might expect to encounter some peculiar scale effects below say 40 ft/sec or a Reynolds number (based on external diameter) of 600. They are known to be present below 20 ft/sec (Ref. 1); the question that arises is how conclusively they can be identified but this is not attempted in these notes and the results of these visual observations must only be regarded as being qualitative. In any case it has to be borne in mind that such a flow pattern is dependent to a greater or lesser degree on stream turbulence.

23.2. *H.N. Tubes—Visual Examination of the Boundary Layer.*

Plate 3 provides three typical photographs illustrating the boundary-layer development of the (truly) hemispherical-nose tubes.

With increasing speed a 'nose bubble' was found to be detectable near the base of the hemisphere at an 'equivalent air-speed' (for a 5/16 in. tube in atmospheric air) of about 20 ft/sec. This resulted in very little disturbance of the boundary layer at the side holes up to 40ft/sec or so. Higher speeds still however were associated with progressively increasing boundary-layer turbulence. Above about 100 ft/sec the bubble itself virtually disappeared.

24. *Actual Calibrations of the Tapered-Nose Tubes.*

24.1. *T.N.1A* and *T.N.1B* (*New*)—*Calibration Factors.*

The calibrations of these two accurate copies of the original standard agree to within 0·1% of $\rho U_0^2/2$ (Fig. 5) and it is deduced that the true value of K (Section 6.1) for this particular design is about 0·995 to 0·996 (±0·001, Section 16).

Scale effect in the range is very small (and may be zero). On the face of it (Fig. 5) there appears to be a tendency for the value of K to fall off below 50 ft/sec. One cannot be certain at present if this is a genuine variation but what is interesting is that the apparent change for T.N.1B is about double that for T.N.1A and it looks as if the T.N.1B curve is inclined to run off into the curve for the worn tip T.N.2. An examination of the tip of T.N.1B showed that it was in fact very slightly rounded. In this connection see Section 24.3.

24.2. 1912 *Whirling-Arm Results—Discussion.*

The original meticulously careful calibration in 1912 of the prototype tapered-nose standard on a whirling arm[2] at speeds of 30 to 50 ft/sec pointed to a factor K of 1·000. Later experiments (in both air and water) indicated an absence of scale effect up to much higher relative air speeds. The present revised value is therefore not in complete agreement.

Relevant to some remarks in Section 8 the 1912 observations and results have been very carefully examined and an attempt has been made to estimate the numerous very small corrections which were (definitely or probably) *not* brought into account. Many of these are associated with the interpretation of the readings of a Chattock manometer; others with such factors as support interference, swirl effects, etc.; with regard to all of these, over the years, general experience has provided much qualitative information although it is no longer possible to establish the actual corrections in respect of those items where they might have been identified fairly precisely. Being so numerous they might of course be expected to a very large extent to cancel one another.

A detailed description of the process is far too long and tedious to be included in these notes but the net additional corrections, as they panned out, can be summarised thus:

Certain	$-0{\cdot}002\ \rho U_0^2/2$
Probable	$-0{\cdot}002\ \rho U_0^2/2$
Possible	$-0{\cdot}004$ to $+0{\cdot}003\ \rho U_0^2/2$
Turbulence could be + or − .	

Regarding the last item we are thinking of the results of possible flow separations (probably neither steady nor axisymmetric) rather than of what might for the moment be called the normal turbulence effect.

In the circumstances this still does not enable one to come to a definite conclusion but it does appear that the basic calibration factor that would result with appropriate extra corrections to the factor 1·000 actually obtained would probably be rather less than 1·000 by a few parts in 1000.

24.3. *T.N.2* (*Worn Tip*)—*Calibration Factor.*

The error for the much used T.N.2 is seen to be about double what it is for the brand new tubes T.N.1A and T.N.1B and there is a definite scale effect (Fig. 5). The increased pressure at the side holes and the scale effect are both consistent with the rounding of the tip; such rounding is known to influence the surface boundary layer; the magnitude of the effect in this case shows the great importance of the sharp edge and accounts for much of the previous uncertainty mentioned in Sections 2.1 and 3 but as will be seen later the rounding is not the cause of the immediate source of concern (Section 2.1; *see* also the final remarks in Section 24.1). The value of K for this worn tip T.N.2 is round about 0·99.

24.4. *T.N.3 (Flared Tip)—Calibration Factor.*

Surprisingly enough at first glance, in spite of its relative lack of precision of manufacture, the calibration of this tube agrees fairly closely with those of T.N.1A and T.N.1B (Fig. 5). It will be noted also that the apparent fall-off at the lowest speeds is the same as for the particularly sharp-edged T.N.1A but not as much as for T.N.1B; in this connection see Section 24.1. Clearly the slight flare of the thin-walled tip merely tends to enhance the effective sharpness of the edge at the tip.

This being the tube used at R.A.E. (Ref. 3 and Section 2.1) part of the reason for the very low value of the factor found in the R.A.E. tests is therefore that its true basic factor is (by laboratory standards) significantly less than 1·000 anyway. This however is not sufficient to account adequately for the discrepancy and further reference to it is made in Sections 24.5 and 25 where the effect of turbulence is considered.

24.5. *Tests on Tapered-Nose Tubes in a Turbulent Stream.*

In respect of T.N.2 and T.N.3 the short-dash curves of Fig. 7 relate to some measurements taken in the turbulent 18 in. wind tunnel (Section 17). They were obtained by comparison of the annulus pressures against those of tubes with known values of K. It is interesting to note that the same answer is obtained in these circumstances whether the comparison is with a hemispherical-nose tube or with one (to be described later) having a modified-ellipsoidal nose. By this process however the error appears to be greater by about 0·2% of $\rho U_0^2/2$ than the true error found by the technique of the primary investigation. If the effect of the turbulence had been the same for all types of tube the curves would have coincided with the full-line curves and the true values of the basic error factors, $(1-K)$ in Section 6.1, would have been obtained.

It is deduced that the direct effect of this particular turbulence is probably much the same for all types of tube but that the indirect effect is noticeably more pronounced on a tapered-nose tube. This indirect effect is that due to the reduction of the separation region at the tip in the presence of turbulence; this results in an associated increase in the pressure at the side holes. Introduction of turbulence is therefore in this respect equivalent to a rounding of the sharp edge at the tip (Section 24.3). This then is another source of apparent lack of consistency (mentioned in Sections 2.1 and 3) besides being one of uncertainty such as applies in some degree to most types of tube.

It is to be emphasised that the factors indicated by the tests in a turbulent stream are neither K (Section 6.1) nor (without further information) K' (Section 6.2); for the time being they can only be regarded as apparent factors.

25. *Discussion of R.A.E. Tests on T.N.3.*

We can now consider the source of stimulation of the present inquiry (Section 2.1). The upper long-dash curve of Fig. 7 is that obtained in the turbulent 5 ft wind tunnel at R.A.E. using tube T.N.3 (Sections 20.3 and 24.4); the observations have been slightly adjusted to make them comparable with N.P.L. results. It is seen that the error at 130 ft/sec appears to be 0·85% of $\rho U_0^2/2$. It is shown in the same figure (full-line curve) that a basic error of 0·5% of $\rho U_0^2/2$ is now to be expected at this speed anyway.

In this particular tunnel at the R.A.E., however, because of its turbulence, one would expect some indirect effect on the boundary-layer separation leading to an increase in annulus pressure (*see* Section 24.5). This is just what is found; the *extra* apparent error of $0 \cdot 35\,\%$ of $\rho U_0^2/2$ is therefore not surprising. It is less at lower speeds where turbulence is less intense and the R.A.E. curve runs down to the short-dash N.P.L. curve.

It may be mentioned in passing that the U.S.A. tests back in 1935[7] on a tapered-nose tube at the higher wind speeds in a highly turbulent stream indicated an apparent factor of 0·992 but one should not attempt to draw too firm a conclusion from this at present.

26. *Actual Calibrations of the 'Hemispherical-Nose' Tubes.*

These calibrations are basic (*see* Sections 6.1 and 13) and appropriate to a stream of very low turbulence level; they are presented in Fig. 6. Most of them show a scale effect and some have a critical speed (in the speed range considered). See also Section 44.1.

26.1. *H.N.*4 (6*D*, 8*D*)—*Calibration Factor.*

H.N.4, with a carefully profiled hemisphere but with a large 'facing hole' has a scale effect but no definite critical in this range. The basic calibration factor for the Alternative (Short-Head) Standard Instrument (Sections 19 and 21.1) should now be taken to be as indicated by this curve in Fig. 6, i.e. in the region of 0·994 and not as heretofore by the constant factor 1·000.

26.2. *H.N.C.* (6*D*, 8*D*)—*Calibration Factor.*

This is interesting in that the commercial modifications (Section 21.2) have resulted in a constant basic factor of 0·996 to 0·997, i.e. there is no significant scale effect in this range of wind speed (*see* also Sections 27 and 28.2).

26.3. *H.N.*8 (6*D*, 15*D*)—*Calibration Factor.*

The calibration factor of this design was originally quoted in Ref. 5 as 1·006 based on experiments in streams of strong (and mainly large scale) turbulence, i.e. turbulence quite unlike that in the 18 in. wind tunnel—for which *see* Section 17. By comparison with a good Short-Head Alternative Standard (Sections 19 and 21.1) all the evidence of the past suggests that for a good Long-Head Alternative Standard (Section 21.3) the factor should certainly not be less than 1·000. The factor for H.N.8 is now found to be round about 0·996 to 0·997 which illustrates the extent to which ordinary long-term wear at the nose can affect the calibration factor.

26.4. *H.N.*9 (8*D*, 15½*D*)—*Calibration Factor.*

The very-long-head H.N.9, carefully profiled and with a relatively somewhat smaller 'facing hole' has scale effect with a fairly well defined critical (Fig. 6).

26.5. *H.N.*3/8 (7*D*, 15*D*)—*Calibration Factor.*

H.N.3/8 with the relieved profile around the base of the hemisphere (Section 21.5 and Fig .1) also has scale effect and a rather more well defined critical (Fig.6).

26.6. *H.N.G.* (4½*D*, 15½*D*)—*Calibration Factor.*

Mainly because, in this German design, the side holes have been placed as near to the tip as reasonable consistency will permit the factor is nearer to 1·000 than it is for any of the other tubes (Fig. 6). It has a scale effect similar to that quoted for it (Fig. 7) but the basic factor is found to be about 0·002 less.

27. *Discussion of the Calibrations of the Hemispherical-Nose Tubes.*

Each and every test raised some further point of inquiry and it became clear that much more experimentation would be required in order to analyse adequately the peculiar scale effects, etc. Nevertheless enough features of general or tentative interest are present to be worth recording and some are particularly interesting.

Comparatively small changes in the shape of the nose profile (including such as result from superficial damage or from alterations in facing-hole diameter) clearly have a significant influence in respect of both scale effect (gradual and critical) and of the magnitude of the factor (Fig. 6). It appears further that scale effect (as well as back-pressure effect—*see* Section 14.1) may also be to some extent dependent on the shape of the head-stem junction, e.g. mitred or curved.

The critical-speed region appears to be related to the flow condition where the boundary layer behind the 'nose bubble' (Section 23.2) becomes noticeably disturbed. In comparison with H.N.9 and H.N.G. (Fig. 6) an 'aerodynamically improved' profile as in H.N.3/8 shows signs of aggravating this critical; the deterioration caused by damage to the nose (H.N.8) or by the use of a large facing hole (H.N.4) tends the other way; 'worsening' the profile to the extent of H.N.C. removes scale effect altogether in this speed range although it may be present at lower speeds. Incidentally it may be expected that the greater the scale effect at these Reynolds numbers the greater it will be at lower ones.

The differences in the actual calibration factors in Fig. 6 cannot be put down entirely to differences in profile shape because the *xD*, *yD* dimensions (*see* insert) are so important in this respect (Section 44.1).

Some tests were carried out in a turbulent stream (small-scale turbulence—Section 17) but in view of the tentative nature of the conclusions it is not necessary to record them in detail (but *see* Fig. 7). Generally they confirm that turbulence has two effects, one contributing directly to the recorded pressures, the other indirectly by modifying the boundary layer on the head.

28. *Main General Conclusions regarding Current Designs of Pitot-Static Tube.*

28.1. *Tapered-Nose Tubes.*

It has been shown that in respect of the tapered-nose tubes the calibration factor is dependent to a significant degree on a very minor but nevertheless important detail of geometry namely the sharpness of the edge at the tip. It is clear that the form and structure of the boundary layer is noticeably influenced by this particular detail. Fig. 5 suggests that any relief of the sharpness of the edge also tends to introduce a scale effect in the speed range considered and it might be expected, following the water-tunnel observations of Section 23.1, that this might be more important at lower speeds.

This type of instrument has naturally never been regarded as being other than delicate. Surprisingly therefore one of them with considerable geometrical error (T.N.3) agreed very closely with the well made tubes. This is because the noticeable flare of the tip maintained an effectively 'sharp edge' and the other faults were then unimportant.

The revised value of K for the original design specification (T.N.1A and T.N.1B) for the normal range of wind speed (or Reynolds number) is $0 \cdot 995$ to $0 \cdot 996$ (Section 24.1). In this range it appears to be free from scale effect. It may be expected however that both calibration factor and scale effect may be influenced, in a manner which is not simple and well defined, by turbulence and other peculiarities of the stream. At very low Reynolds numbers, say below 10 ft/sec for a 5/16 in. tube in atmospheric air, past experience has indicated that the readings are often unreliable.

28.2. *Hemispherical-Nose Tubes.*

The 'hemispherical' nose pitot-static tube turns out to be not quite so robust as has been generally assumed. The shape of the individual profile has a (probably indeterminate) relation to the calibration factor but it is mainly important because of its influence on scale effect; where scale effect can be eliminated it is not difficult to modify the factor if so desired—*see* Section 44.1 and also 14.1. (It is incidentally pointed out in Ref. 8 that the minimum surface-pressure—or the 'peak suction'—which is located just upstream of the base of the hemisphere is sensitive to very small deviations from a true hemisphere.) For the accuracy with which we are basically concerned here small variations of the profile, whether in manufacture or as a result of damage, are significant and a prototype calibration as such has no reliable value.

It has nevertheless been found that an average value for a moderate number of instruments is often accurate enough in practice when applied to all those of the same catalogue number for example H.N.C. (Section 21.2). For the individual instrument examined here the value of K is $0 \cdot 996$ to $0 \cdot 997$ (good flow conditions). For some time the recommendation for all similarly manufactured tubes has been $0 \cdot 995$ in very good flow and a round figure of $1 \cdot 000$ for turbulent flow (cf. Section 44.2).

As with the tapered-nose tubes the hemispherical-nose instruments cannot be relied upon for accurate measurement at very low Reynolds numbers. It is to be noted however that the commercial tube H.N.C. is relatively free from scale effect over the range of the present tests (Fig. 6). It may be therefore that the deviation from the true hemisphere (truncation of the hemisphere—Section 21.2) is a beneficial one.

The values of K for the various tubes examined are more effectively obtained from Fig. 6 than from a table.

28.3. *Main Consequence.*

The brief and main consequence of all this appears to be that the 'already bad' aerodynamic nose-profiles of both the T.N. and H.N. tubes are either not 'bad' enough or not 'good' enough to ensure the requisite consistency and reliability. One is therefore led to consider whether it is possible to design an instrument such that the geometry is not critically important and scale effect, if any, is at any rate consistent and amenable to determination either experimentally or theoretically. Whatever alternative designs may be produced however there appears to be no likelihood that any one design will be universally satisfactory. Consequently it should not be assumed that the T.N. or H.N. tubes or in fact any other type of pitot-static combination should be completely abandoned; all have their own particular relative advantages and special uses.

NEW DESIGN of PITOT-STATIC TUBE

29. *Consideration of a New Design.*

As already indicated in Section 28.3 a new design can be considered from two points of view.

In the one the aim would be to find a profile such that severe separation at the nose was always present swamping the effects of any other influence such as stream turbulence. This however would probably involve the incorporation of an easily damaged sharp edge leading to further potential disadvantages such as wake blockage. In any case one would have grave doubts of being able to maintain a consistent flow pattern at very low Reynolds numbers.

In the other one might endeavour to ensure a thin attached boundary layer on a profile which is not particularly sensitive to accuracy of manufacture and, *ipso facto*, to minor damage while still being reasonably robust. Such a design would be at its best in good flow conditions but one could hope to establish reasonable corrections for its use in other circumstances.

For freedom from flow separation and for consistency it is necessary to ensure, in the surface pressure distribution, a 'peak suction' (conveniently and descriptively so-called) of 'low' magnitude, say about 10% of $\rho U_0^2/2$. For a plain static-pressure tube it would appear that an ellipsoidal nose with a major/minor axis ratio of 4/1 would be suitable; in this connection see Plate I which resulted from tests in the water tunnel (Section 18). If however such a head is drilled out axially so as to accommodate a so-called 'total-pressure duct', to which we are referring here in general as a centre bore, there results an easily damaged sharp edge. This difficulty was conveniently and opportunely resolved by the results of an American investigation (Ref. 8) and consequently this second basis for a new design was adopted.

30. *The New Design of Pitot-Static Tube—General.*

The manner in which a half ellipsoid can be conveniently modified for the purpose in mind is illustrated in Fig. 8. In section the two quarter ellipses are separated by a rectangle and have their minor axes appropriately reduced.

The curves of Fig. 9 (which are reproduced from Ref. 8) record the minimum surface pressures $p_{s\,\mathrm{min}}$ for various values of the parameters b and d. They show in fact the variations in the 'peak suction' (*see* Section 29). Starting, for example, from a 4/1 ellipsoidal nose ($a = 2D$, $d = 0$) it is seen that the value of d resulting in the 'smallest' peak suction for the modified shape is about $0{\cdot}15D$. The diameter of the flat could be increased to $0{\cdot}25D$ still leaving the magnitude of the peak less than that of the unmodified ellipsoid. With this kind of modification therefore not only can the risk of flow separation, etc., be even further reduced in comparison with the plain ellipsoid but the radial section adjacent to the 'facing hole' can be made a right-angled corner instead of a much sharper one. Bearing in mind however the foregoing remarks it will be clear from Fig. 9 that there is not a great deal of latitude in the choice of the actual proportions of the nose shape.

The next points to consider are the type and location of the side holes. Drilled holes are preferred to a slot in the interests of mechanical strength—the profile at and near these holes must be very well defined and not liable to be easily altered in the slightest degree. To prevent dimpling the drilling of the holes must be carried out with very light pressure.

Location is not so easily settled. As with all such tubes the holes must not be so far forward that their position is significantly critical; nor so far back that the head becomes rather long or alternatively, because of back pressure due to the stem (Sections 14.1 and 44.1), the calibration factor departs unduly from a value of 1·000. (A stem as generally understood is of course not always necessary.) Then again the further the holes from the nose the greater the risk of boundary-layer variations at the selected position consequent upon changes in the ambient flow conditions. It is not difficult to decide upon a reasonable general compromise but with suitable investigation one might identify positions more suitable for some specific kinds of measurement than for others. (*See* end of Section 46).

With such a design it might be anticipated that the calibration would be consistent and reliable with relatively little scale effect in respect of the annulus pressures. Furthermore, if the tube is manufactured with reasonable care, the calibration of the prototype should be almost exactly applicable to subsequent instruments of the same design and specific calibration should be unnecessary. (Geometrical accuracy is discussed in Section 45.)

On the reverse side of the picture, because of the relatively small centre bore, the response might turn out to be rather more sluggish than with other designs and the effect of large angles of misalignment more severe.

31. *Some Versions of the New Design.*

A number of versions of the new design, both pitot-static and plain static-pressure, have been constructed and reference will be made to about half a dozen of them. These all have a nominal outside diameter D of 5/16 in. and are illustrated in Fig. 10. The characteristics of two of them have been fairly extensively investigated. Using the method of abbreviated designation proposed in Section 19 the instruments are as follows:

31.1. *M.E.N.*1 ($5 \cdot 9D$, $8 \cdot 1D$).

A short-head pitot-static tube with a mitred junction between head and stem. $D = 0 \cdot 310$ in.

31.2. *M.E.N.C.* ($5 \cdot 9D$, $8 \cdot 2D$).

A commercially manufactured short-head tube with a curved junction of radius $3\frac{1}{2}D$ between head and stem. Otherwise it differs from M.E.N.1 only in small details. $D = 0 \cdot 314$ in.

31.3. *M.E.N.*4 ($5 \cdot 9D$, $16D$).

This is a long-head pitot-static tube. In this case compared with M.E.N.1 the distance of the stem from the side holes has been substantially increased. $D = 0 \cdot 312$ in.

31.4. *M.E.N.*6 ($4 \cdot 0D$, $10 \cdot 5D$).

A short-head instrument. Compared with M.E.N.1 there are 8 side holes instead of 7 (*see* Section 19); they are situated 2 tube diameters closer to the nose and overall the head is slightly longer. $D = 0 \cdot 310$ in.

The next two are plain mitred-junction static-pressure tubes slightly longer than M.E.N.1, M.E.N.C. and M.E.N.6. They have 8 side holes.

31.5. *M.E.N.SP*2 ($4 \cdot 0D$, $12 \cdot 1D$).

A plain static-pressure tube with a core (representing the centre tube of the pitot-static combination) in the neighbourhood of the side holes (Fig. 10). $D = 0 \cdot 308$ in.

31.6. *M.E.N.SP*3 ($4 \cdot 0D$, $11 \cdot 1D$).

Another plain static-pressure tube slightly shorter than M.E.N. SP2 and without the core mentioned above (*see* also Fig. 10). $D = 0 \cdot 308$ in. (For the potential significance of this see Section 44.4.)

Finally another pitot-static tube.

31.7. *M.E.N.7C* ($4 \cdot 0D$, $12 \cdot 3D$).

A conversion of the M.E.N. SP2 design (Section 31.5) into a complete pitot-static tube with an additional modification that the junction is curved to a radius of $2\frac{1}{2}D$. $D = 0 \cdot 308$ in.

31.8. *General Notes—M.E.N. Instruments.*

In all cases the length of the nose is $0 \cdot 6$ in. The nose profiles are based on Figs. 8 and 9 in conjunction with the remarks in Section 30. The 'end flat' (Fig. 8) has a diameter of $0 \cdot 052$ in.

Calculated co-ordinates for $D = 0{\cdot}308$ in. are recorded (with obvious notation) in Table 4; for comments on tolerances see Section 45. In relation to Fig. 9 a/D is about 1·94 and d/D about 0·168 so that one would expect the 'peak suction' (head aligned to wind) to be between 10 and 15 % of $\rho U_0^2/2$.

It was arbitrarily decided that the centre bores of the pitot-static tubes (with the exception of M.E.N.7C) should have the same diameter as has the end flat, i.e. 0·052 in. (No. 55 drill) and that they should extend for $\frac{1}{4}$ in. or so before enlargement (large-scale section in Fig. 10). The centre-bore diameter for M.E.N.7C is 0·046 in. (No. 56 drill).

Spacers are fitted (Fig. 10) in order to ensure that the inner tube or core shall not be far from coaxial in the region of the side holes. The spacers are of course not complete rings but an easy method of construction is to attach a suitable sleeve and then file it down to a near triangle. For sweated joints a non-corrosive flux with good cleaning properties is used (e.g. Tricene for brass and copper). Mitred joints are brazed.

32. *Basic Calibrations of the M.E.N. Instruments.*

Whether the tubes are pitot-static or plain static-pressure the calibrations are all based on the error factor $(1-K)$ of Section 6.1. These basic error factors have been found to be as follows:

M.E.N.1	(5·9, 8·1)	0·006
M.E.N.C.	(5·9, 8·2)	0·003
M.E.N.4	(5·9, 16)	0·001
M.E.N.6	(4·0, 10·5)	0·001 to 0·002
M.E.N.7C	(4·0, 12·3)	−0·001
M.E.N.SP2	(4·0, 12·1)	0·000 to 0·001
M.E.N.SP3	(4·0, 11·1)	0·000 to 0·001

Added, in anticipation, (Section 44.2) is

M.E.N.—	(6, 18)	0·000

The corresponding basic calibration factors K (with an anticipated accuracy of ±0·001—Section 16) are therefore

M.E.N.1	(5·9, 8·1)	0·994
M.E.N.C.	(5·9, 8·2)	0·997
M.E.N.4	(5·9, 16)	0·999
M.E.N.6	(4·0, 10·5)	0·998 to 0·999
M.E.N.7C	(4·0, 12·3)	1·001

Also, in anticipation,

M.E.N.—	(6, 18)	1·000

and if M.E.N.SP2 were converted into a pitot-static tube

M.E.N.—	(4, 12)	0·999 to 1·000

In the main these were obtained by means of various comparisons with those pitot-static tubes for which the factors had already been identified and not by direct comparison with the Ellipsoidal-Nose Standard of Section 9. It was incidentally discovered that the instruments could be accurately so calibrated (for basic error) even in the somewhat turbulent stream of the 18 in. tunnel (Section 17); the turbulence effect balanced out when tubes of not very different nose shapes were being compared. A special note regarding the datum pressure is also recorded in Section 17.

As deduced from these comparisons the quoted values only relate to a speed range of about 40 to 180 ft/sec. It was possible however to make an indirect test for scale effect down to much lower wind speeds. It took the form of a careful comparison between 3/16 and 5/16 in. tubes over the range 10 to 60 ft/sec. It demonstrated, with hardly any scope for doubt, that the above basic factors can be taken to apply down to a Reynolds number corresponding to 6 ft/sec (in atmospheric air) for a 5/16 in. diameter instrument—and perhaps lower still. The calibrations are discussed at length in Sections 44.1–4.

33. *Other Tests on the New Instruments.*

It must be clear from what has been said previously that it is by no means sufficient merely to know the basic calibration factor of a pitot-static tube. Information about many aspects is desirable but the effect of misalignment in particular is very important. Then again, although the use of these tubes at very low Reynolds numbers may not be easy and convenient, it is desirable to know at what values of the number an error arises when using the centre-bore pressure as a measure of $p_0 + \rho U_0^2/2$ in circumstances where the fluid viscosity is significantly important (*see* Section 6.1). Both of these aspects have been investigated.

34. *Misalignment of M.E.N. Tubes—General.*

For purposes of calibration it is more convenient to think in terms of yaw and pitch of the instrument than of the wind and the definitions of yaw and pitch in the present instance are illustrated by the inserts in Figs. 11 and 12. In yaw the change of wind direction is equivalent to rotating the tube about the stem or about an axis parallel to it; in pitch to rotating it about an axis perpendicular to the plane containing both the head and the stem.

If perfect symmetry of manufacture is achieved the effects of positive and negative yaw should be the same. This is not the case in pitch (except in respect of the centre-bore pressure) and it is necessary in principle to differentiate between positive and negative declinations.

Of interest are not only the characteristics of the pitot-static tubes as such but also those of the centre bore and of the annulus side separately.

35. *General Arrangement for Tests in Yaw and Pitch.*

A photograph of the mechanism employed for traversing the new design pitot-static tubes in yaw and pitch is reproduced in Plate 4. The carrier consisted of a strongly built curved rack (radius of curvature 22 in.) which (for pitch) was moved along a curved rectangular channel by a suitable pinion drive. The stem of the tube was offset a couple of inches from the central plane of symmetry of the rack so that it could conveniently be rotated (with its clamp) for change of yaw.

The arrangement was such that for all angles of misalignment the tip of the nose remained in almost exactly the same position. The side holes moved in a plane perpendicular to the wind direction by an amount up to $\frac{1}{2}$ in. or so. The variation of true static pressure over this area was extremely small the tests being carried out in a good quality wind stream and the curved channel being designed to provide minimum interference. Sections 14.1 and 14.2 are of interest here. It may be pointed out that total pressure can vary much more rapidly from point to point across a straight-flowing stream than static pressure so that it is generally safer to fix the position of the facing hole although in this instance it probably would not have mattered.

The channel itself extended for 25° upstream and 45° downstream of the plane perpendicular to the stream and passing through the centre of rotation. Its outside sectional dimensions were $1\frac{1}{4}$ in. (radially) by $1\frac{3}{4}$ in. The rack only projected out of one or other of the ends of the channel at large angles of pitch. This small extra obstruction was unavoidable but in any case, as will be seen later, it could not have been of any importance. To prevent vibration of the tube a pyramid of fine wires was attached to the middle of the exposed length of stem and to some minimum-obstruction arms screwed to the carrier.

The equipment was mounted on one of the side walls of the 7 ft low-turbulence wind tunnel (*see* Section 10) and was operated by shafts passing through that wall. The datum tube consisted of the centre bore and annulus side in turn of tube H.N.4 of Section 21.1. This was set up approximately in the same tunnel cross-section and about 2 ft horizontally away from the head of the tube being examined. See also Section 11.

36. *Reduction of the Observations in Yaw and Pitch.*

At various angles of yaw and of pitch (separately) the centre-bore pressures t_c were measured against that in the centre bore of the datum tube and likewise the annulus pressures p_a against annulus pressure of datum. These measurements were then first plotted against nominal misalignment from the direction of the tunnel axis giving curves of the general nature of those in Fig. 12. For these tests it was not necessary to know accurately beforehand the true local wind direction. This was given for each instrument by the setting about which its two t_c curves (for the centre bore in yaw and pitch respectively) were found to be symmetrical and there was no difficulty in locating it with sufficient accuracy. This provided the first correction for the four curves of that instrument. The curves for the annulus in *yaw* could have been used to influence the identification of direction in one plane but this was found to be unnecessary. It was confirmed that any slight errors in setting zero pitch while varying yaw and *vice versa* were insignificant.

At this point the curves of centre-bore pressure were further corrected by the simple process of shifting them bodily (this time in the direction of the ordinates axis) until the corrected measurement (with correct alignment of the instrument) became zero. The second correction for the annulus consisted of a bodily shift in the same direction by an amount determined by the basic calibration factors found by previous tests (Section 32). (These tests in yaw and pitch were not extended to the stage at which the factors could be deduced directly.)

Wind speeds employed were as follows:

*M.E.N.*1—80 and 110 ft/sec with a more limited number of observations at 40 ft/sec.

M.E.N.C—80 ft/sec with only a few observations at 110 and 40 ft/sec.

In the first case the agreement between the two higher speeds was so close that all the observations at 80 and 110 ft/sec were used for defining the final curves. All the finally corrected curves in Figs. 11 and 12 are smoothed curves, the scatter of the actual points being very small. In yaw the smoothing was carried a little further by taking means for positive and negative deviations so as to remove some slight local dissymmetries which could be due to errors of manufacture as well as of measurement.

37. *Tabulated Results for M.E.N. Tubes in Yaw and Pitch.*

The final results for yaw and pitch in the more usual speed range are given in Tables 1 and 2. For the purposes of convenient reproduction of the curves the values quoted in the first three columns of each are given to the nearest $0 \cdot 1\%$ of $\rho U_0^2/2$ and those in the fourth to the third decimal place. The actual accuracy however, especially for large deviations, is not professed to be as good as this.

Column (a) shows the amount by which the measurement of the pressure in the centre bore exceeds the local value of $p_0 + \rho U_0^2/2$ (which in this instance may justifiably be called the local total pressure). Similarly for column (b) in respect of the annulus and of true static pressure p_0. The differences are recorded in column (c) and indicate the amount by which the pressure difference between the two sides exceeds $\rho U_0^2/2$ (in this case the local dynamic pressure).

Column (d) is the ratio of the pressure difference to $\rho U_0^2/2$ and at zero yaw and pitch the value is the Basic Calibration Factor of the tube (Section 6.1). In conditions of misalignment the other values may if so desired be regarded as modified calibration factors (Section 6.2).

38. *Effect of Misalignment on M.E.N. Tubes.*

Referring to Figs. 11 and 12 the differences between the characteristics of the two tubes are seen to be small.

The pressures in the annuli, as usual, decrease significantly with only a few degrees of yaw or pitch. In pitch (Fig. 12) there is of course some dissymmetry because of the unsymmetrical back-pressure influence of the stem (Section 14.1); it is perhaps not surprising that it is slightly greater for the mitred-junction tube M.E.N.1. It is not expected that the use of seven holes instead of eight or their disposition around the circumference would be important but the point has not been investigated (*see* also Section 19).

As would be expected the pressure in the centre bore falls off more rapidly with misalignment than it would in tubes having a relatively large d/D ratio.

The pressure-difference characteristic first increases and then falls off rather rapidly and the variation over the useful range is rather less for the curved-junction tube M.E.N.C. This characteristic is very much dependent on centre-bore diameter and the effect is well illustrated in Fig. 13 which includes for comparison the corresponding characteristics for various other designs. The 'usable' range of yaw (up to misalignment at which the curve falls away with undue steepness) is less for the small-centre-bore instruments H.N.G., M.E.N.1 and the U.S.A. standard ($d = 1/16$ in., $D = 5/16$ in.) but over the respective 'usable' ranges the tolerances (or possible errors) are beneficially very much less.

On balance it would appear that tube M.E.N.C. (Section 31) is slightly more advantageous than M.E.N.1 in respect of unavoidable misalignment but it has not been established that this is entirely due to the curved junction.

39. *Scale Effect in respect of Yaw and Pitch at Normal Reynolds Numbers.*

Before discussing the implications of the misalignment characteristics a little may be said about scale effect. The observations at 40 ft/sec were only intended to provide a guide as to whether it might be present and they were consequently limited in number. A very small difference was found between 40 and 80 ft/sec, the tendency being towards a slightly flatter curve at the lower speed. The magnitude was such as to indicate that there might possibly be some scale effect in the normal working range but that if so it was very small. See also the end of Section 36.

40. *Application of the Misalignment Characteristics.*

These characteristics can only be used after due consideration of the circumstances. Suppose for example that one wishes to measure $\rho U_0^2/2$ fairly accurately at a point where the flow is smooth and steady and its direction is known but where it is not convenient to align the tube correctly to the wind direction. Then provided that the misalignment is not greater than say 15° a correction (or an appropriate modified calibration factor—*see* Sections 6.2 and 37) can be obtained from curves such as Figs. 11 and 12.

If in an otherwise similar case the angular deviation can merely be said to be not greater than a certain amount, a mean correction may be applied or a mean factor selected. Table 3 illustrates this. For example, taking the results at their face value and using M.E.N.1 for measuring $\rho U_0^2/2$, if misalignment is presumed to be constant but to lie somewhere between $\pm 5\frac{1}{2}°$ in yaw or between $-12°$ and $+5°$ in pitch one should assume a factor of 0·998 and accept a possible error on $\rho U_0^2/2$ of $\pm 0{\cdot}4\%$. This of course is rarely quite so easy to apply in practice; in any case the recorded results do not cover situations in which yaw and pitch exist simultaneously; an intermediate effect (related to the actual misalignment) can, however, be presumed. Also of interest therefore are the magnitudes of the angular deviations that can be tolerated for various permissible errors when one takes an arbitrary value of say 1·000 for the factor. Table 3 also illustrates this.

For misalignment above about 15° the consequential effect increases rather rapidly and it is convenient to point out here that there comes a stage when it is better to use one of the older designs of tube even though it might be less satisfactory in other respects. This can be seen from Fig. 13 (*see* also Section 38). It also applies when the deviations vary with time and are large in magnitude (and in scale—*see* later).

More often it is desired to use the instrument in a stream where the local flow direction is variable with or without a general bias. Sometimes one can measure approximately the maximum significant angular deviation; sometimes one has to make the best guess one can. Where the geometrical scale of the variations (what one might loosely call the eddies) is small compared with the diameter of the tube the effect is to increase the pressure in each side of the instrument. The influence of this type of turbulence is however not included in the present discussion. Where the eddies are relatively large the best one can do in general is to apply a reasonable correction or select an estimated mean modified calibration factor; in this situation the errors might be expected to be about a half of those listed in Table 3. It may be pointed out that only recently have attempts been made to study the case of intermediate-scale eddy turbulence; beyond that one need only state here that scale is undoubtedly an important parameter.

It must be emphasised that Table 3 is primarily illustrative and not comprehensive. Enough has been said however to show how the characteristics may be used at least to reduce the degree of uncertainty even if not to obtain real precision in difficult circumstances. Where not already mentioned or implied similar arguments to the above apply in respect of the two sides of the instrument used independently and of course to the other designs of pitot-static tube also.

41. *Tests on an M.E.N. Pitot Tube at Very Low Reynolds Numbers.*

Following references in Sections 6.1 and 33 we come now to a consideration of the scale effect on centre-bore pressure at very low Reynolds numbers. It is extremely difficult to discover this precisely and with complete certainty but it would be just as difficult to make full use of the exact information anyway because of the extremely small magnitude of any measurements involved. It is important nevertheless to obtain the best information one can.

It was fortunate that MacMillan was carrying out a more general investigation of this nature and was pleased to assist us by including the new head design in his series of tests. The equipment and procedure are adequately described in Ref. 9. It may however be stated briefly here that they were based on the use of a small open wind tunnel with an unobstructed inlet in which virtually still air was smoothly accelerated into the working section. At the same time it was convenient to examine the effect of misalignment, again in respect of the centre bore only. The information is therefore not complete but is nevertheless worth recording.

The tube employed was $0 \cdot 1$ in. in external diameter with an axial $0 \cdot 018$ in. diameter hole in the nose (Fig. 14). It was in fact a pitot tube as distinct from a pitot-static tube. The ratio d/D—$0 \cdot 18$—was rather larger than for the M.E.N. instruments of Section 31.

42. *Effect of Misalignment of the Small Pitot Tube at a Very Low Reynolds Number.*

We deal first with the effect of misalignment on the pressure in the bore of the tube. This is shown in Fig. 14a. The scatter of the actual observations was not enough to prevent a sufficiently satisfactory mean curve from being drawn through them. This curve relates to a Reynolds number of about 43 based on internal diameter. The reason for specifying the number in this way will be explained in Section 43. For the instruments M.E.N.1 and M.E.N.C. used in more or less normal atmospheric air this corresponds to a wind speed of about $1\frac{1}{2}$ ft/sec. At this Reynolds number the pressure in the tube (relative to ambient static pressure) is $1 \cdot 02$ times $\rho U_0^2/2$ when the tube is correctly aligned to the stream. The decrease in the measured pressure when misaligned, 1% of $\rho U_0^2/2$ at 6° and 2% at $7\frac{1}{2}$°, is seen to be considerably greater than it is under more normal conditions (cf. Figs. 11 and 12).

43. *Calibration of the Small Pitot Tube at Very Low Reynolds Numbers.*

Fig. 14b shows the effect on centre-bore pressure of the increasingly important fluid viscosity as the Reynolds number is reduced (Section 6.1). Taking the curves at their face value (but *see* Section 41) the effect is immeasurable above a Reynolds number of about 1300 when it is based on external diameter (i.e. $U_0 D/\nu$ where ν is the kinematic viscosity of the fluid) or about 235 when based on internal diameter (i.e. $U_0 d/\nu$). It rises to 2% of $\rho U_0^2/2$ when these numbers fall to about 240 and 43 respectively, the reading being too large if one is aiming to measure local $p_0 + \rho U_0^2/2$.

For various reasons it would not be expected that exactly the same result would be obtained if the investigation were repeated (*see* also Section 15) but this is unlikely to be important in practice. Nevertheless two curves taken from Ref. 9 for an axisymmetric flat-ended (not flattened) tube with a d/D ratio of $0 \cdot 6$ are of special interest and are included in Fig. 14b. The four curves tend to confirm other evidence that a more nearly unique characteristic covering a variety of nose profiles is obtained if the Reynolds number is worked out on the basis of the internal diameter (*see* Ref. 9). It is not appropriate to enlarge further on this aspect here and it is important therefore not to read into the curves more than is actually presented. Suffice it to add that when selecting a pitot tube to be used for measurements under these conditions one has to consider the geometrical limits of internal diameter in respect of sluggishness of response and external diameter with regard to blockage.

44. *Discussion of the M.E.N. Calibrations.*

44.1. *Introductory.*

The annulus pressure results from a partial (and sometimes complete) balance between a 'suction' due to the proximity of the nose and a 'back pressure' due to the stem (Section 14.1). The $6D$,$8D$

dimensions of the hemispherical-nose tubes H.N.4 and H.N.C. (Fig. 1) were chosen long ago with the object (as we now know somewhat erroneously—Section 26.1) of achieving a factor 1·000. The 6*D*, 15*D* dimensions of H.N.8 (also Fig. 1) were intended to result in a better consistency with a factor 1·006; its true factor is probably not far from 1·000 (Section 26.3) but it is very doubtful if in practice any significant improvement in respect of consistency has resulted. In any case general preference is for the short head (and, it may be added, for a circular stem).

For such reasons it was considered that a 6*D*, 8*D* combination would be a good starting point for the first of the new instruments, i.e. M.E.N.1 and M.E.N.C. (Fig. 10). For the same reasons also it is appropriate, concurrently with a discussion of the calibration factors, to pay special attention to these dimensional parameters.

For later reference it is convenient to note here the *approximate* effects of varying these dimensions in terms of the change of error factor $1-K$ (Section 6.1) for an alteration of length equal to the tube diameter:

Nose effect in respect of the distance of the side holes from the base of the nose (the second dimension remaining unaltered):

0·001 at 6*D*
0·0015 at 5*D*
0·002 at 4*d*

Stem effect in respect of the distance of the side holes from the axis of the stem (the first dimension remaining unaltered):

0·0002 at 24*D*
0·0005 at 15*D*
0·001 at 10*D*
0·0015 at 8*D*
(0·002 at 7*D*)

These are all subject to confirmation.

44.2. *Comments on the M.E.N. Basic Calibration Factors K.*

The various basic factors are recorded in Section 32, most of the values of K being less than 1·000.

It is implied in Section 40 that for general usage of a pitot-static tube as such, whether in good or only moderately good flow, it may be advisable to pick one with a *basic* factor K (Section 6.1) of round about 0·995 but to assume a *working* factor of 1·000 (cf. Section 28.2). If this hypothesis is sound then one should be able to employ tubes like M.E.N.1, M.E.N.C. (Section 32) in this way feeling confident that any resulting errors will not be unreasonable.

When using the M.E.N. pitot-static tubes (in suitable circumstances) for precision measurements it is not necessary that K should be equal to 1·000 (cf. Section 5). The long-head M.E.N.4 (5.9, 16)—Section 31 and Fig. 10—was however an attempt to make $K = 1{\cdot}000$ and it turned out to be 0·999. If a stem at 16 tube diameters from the side holes is moved 2 or 3 diameters further away it can be expected to increase K by 0·001 (*see* Section 44.1). Therefore a mitred-junction instrument with a rather longer head still and which would be designated say M.E.N.—(6, 18) should have a basic factor just about 1·000. This is provisionally included in the list in Section 32.

In due course however, in the light of what had already been investigated and analysed and with the expectation of special consistency in respect of the new design, it appeared that it might be quite practicable by reducing the 6*D* dimension (selected for M.E.N.1, C, 4 and others) to produce a satisfactory instrument with a much shorter head than M.E.N.—(6, 18) (*see* Section 32) and with a basic calibration factor of 1·000. When using a nose profile of good aerodynamic shape such a reduction would at the same time help to delay the incidence of transition in the boundary layer at the side holes station.

In pursuance of this line of thought the instruments M.E.N.6 and M.E.N.SP2 (Section 31 and Fig. 10) were constructed and tested. The value of K for M.E.N.6 (4·0, 10·5) turned out to be rather low, i.e. 0·998 to 0·999 (Section 32). The error factor $(1-K)$ for the static-pressure tube M.E.N.SP2 (4·0, 12·1) was found to be 0·000 to 0·001. This means that if it were completed as a pitot-static tube the value of K would be 0·999 to 1·000 and the instrument would be designated M.E.N.—(4, 12) as listed in Section 32. (See also Section 44.4.)

With an anticipated accuracy of ±0·001 (Section 16) there is probably, pending further investigation, no point in trying to get closer to 1·000 by moving the stem still further away and for the time being one may merely add a few supplementary comments.

In particular, comparing M.E.N.7C (4, 12·3) and M.E.N.—(4, 12) in Section 32, it appears that the probable effect of curving the junction to a radius of $2\frac{1}{2}D$ is to increase K by 1 or 2 in 1000. (This is supported by a comparison of M.E.N.1—K = 0·994—and M.E.N.C.—K = 0·997—but it cannot be said to be confirmed because it is not certain that the difference of 0·003 in the value of K for these two is entirely due to the dissimilarity of the junctions.) Curvature of the junction is therefore equivalent to moving the stem further away.

It is doubtful if the misalignment characteristics (e.g. Figs. 11 and 12) would be much affected by the change from $6D$ to $4D$ other than to result in an appropriate small bodily shift of the curves. At the same time it is unlikely that a reduction to less than $4D$ (except perhaps in special cases) would be desirable and it is possible, although the gradient of the parameter at $4D$ is still small (Section 44.1), that $4\frac{1}{2}D$ might turn out to be a better general minimum. (It may be noted that the decay of 'suction' is slower following the smaller 'suction peak' of the good nose-profile than it is for the larger peak of the hemispherical nose.)

44.3. *Deduced Calibrations of the M.E.N. Pitot-Static Tubes at Very Low Reynolds Numbers.*

With the assistance of Section 43 it is possible to make a reasonable deduction of the values of E (Section 6.1) for the M.E.N. pitot-static tubes. E is given by the ordinates of Fig. 14b minus 1·00. A scale of wind speed has been included in Fig. 14b and in view of the relevant comment in Section 43 it has been related to Reynolds number based on an internal diameter of 0·052 in. when the fluid medium is atmospheric air. For these new instruments the effect requiring the introduction of the error factor E of Section 6.1 becomes measurable at wind speeds below about 8 ft/sec and E increases as the wind speed decreases.

It is doubtful (although the matter has not yet been investigated experimentally) if the back pressure due to the stem introduces any scale effect complication but we assume for the time being that the basic factor K remains constant even below 6 ft/sec (*see* end of Section 32). This leads to the conclusion that the combined factor $(E+K)$ for these instruments (Sections 6.1 and 6.2) increases as the wind speed decreases in accordance with the change in E, e.g. for M.E.N.1 (Sections 31 and 32) from 0·994 at 8 ft/sec to 1·014 at 1·7 ft/sec.

44.4. *M.E.N. Plain Static-Pressure Tubes.*

Although a pitot-static tube with a factor K = 1·000 becomes a static-pressure tube simply by ignoring the centre bore there are times when simplification is desirable—it may be when having to construct in very small sizes or for any other reason. In Fig. 10 two degrees of simplification are illustrated—M.E.N.SP2 (4, 12·1) and M.E.N.SP3 (4, 11·1) the latter being one diameter shorter in the head. Both are included mainly because, as might be indicated by Ref. 7, there is always the possibility that in due course one may be shown to be preferable to the other.

In each case the basic error factors $1-K$ (Sections 6.1 and 7) are 0·000 to 0·001 (Section 32). An independent test on another instrument showed that when aligned to the wind the effect of the presence of the central rod (as in M.E.N.SP2, Fig. 10) is very small. We may deduce therefore that in either case a dimension combination of $4D$, $12D$ is about right (for a mitred-junction instrument) as an alternative to the dimensions of the long-head M.E.N.—(6, 18) of Section 32. At the same time, as indicated in Section 44.2 in connection with complete pitot-static tubes, a curvature of the junction might result in the possibility of a reduction from $12D$ to something rather smaller.

45. *Accuracy of Manufacture of the New Design.*

It has been anticipated all along that the new profile would be much less sensitive to geometrical errors than those of the T.N. and H.N. instruments and it has been thought fit to specify reasonable care in the course of manufacture. Reasonable care implies that if the nose profile is not exactly to the dimensions specified the contour should nevertheless be smooth in the sense that the local curvature should vary smoothly and without reversal from tip to base and beyond. With this requirement it is perhaps better not to attempt to specify dimensional tolerances.

Nevertheless some striking qualitative guidance has arisen in the course of the work. An error of 1% in diameter behind the position of the spacers in Fig. 10 is of no importance. A reduction of 1%in diameter in the form of a shallow 'necking' of the tube between the base of the nose and the side holes was found to have no measurable effect on the calibration. Most surprisingly however when the nose diameter of this tube was then reduced to the neck diameter and its profile modified accordingly all by eye, hand and a file the change in the value of K was much less than 0·001; this on a $4D$, $10D$ tube may be regarded as being quite a severe test.

Even so it is certain that great care should be exercised in the immediate region of the side holes (*see* middle of Section 30) but this is not difficult. One should of course be specially careful at the extreme tip because this is a tricky region in respect of the lathe operation anyway.

For the effect of axial location on the side holes see Section 44.1.

46. *Main Conclusions Relating to the New Design.*

In consequence of the defects found in earlier types the various versions of the new design (e.g. Section 31 and Fig. 10) make use of a nose shape (Fig. 8) such that the calibration is not unduly sensitive to accuracy of profile (*see* Section 45). A calibration of a prototype for specified conditions of use should therefore be transferable to all nominally similar instruments provided that they have been manufactured with reasonable care.

The basic calibration factor K (Section 6.1) depends on the particular version employed. Some specific values are quoted in Section 32 and discussed in Sections 44.1–4 and are appropriate to precision measurements in suitable circumstances (Section 6.1). It is anticipated that the instruments can be fairly reliably employed down to very low Reynolds numbers (Section 44.3).

For general use (streams of moderate and perhaps unknown turbulence and/or the possibility of misalignment of a few degrees) it is tentatively proposed (Section 44.2) that it should be adequate to select a pitot-static tube for which K is less than 1·000 by a few parts in a thousand but to assume a working calibration factor of 1·000.

Static-pressure tubes (without pitot) are described and discussed in Section 44.4.

The new instruments are not recommended for use where the possibility of misalignment, either steady or variable exceeds 15° or so (Sections 38, 40 and Figs. 11, 12, 13) and they may perhaps be found to be rather more sluggish in response than instruments of some earlier large-centre-bore-diameter types (Fig. 1). Otherwise all the evidence and experience so far point to them as being a particularly useful addition, especially as basic standards, to the range already available and there is no more difficulty in the satisfactory manufacture of the special profile. Referring back to a remark in Section 30 their basis of design is such as to facilitate the construction of a version suitable to specific requirements. A new design must be regarded as an addition to the range because no such instrument has universal application; each has its special uses and advantages.

47. *Principal Conclusions Relating to Pitot-Static Tubes.*

Some of the previous sections have already noted various conclusions with relevant comments—in particular 28, 44, 46. This section attempts to pick out the salient features relating to the various types. Most of them (as listed below) are based on the peculiarities of the readings of the pressures in the annuli; consequently, where appropriate, the corresponding features of static-pressure tubes are easily appreciated.

Earlier Types.

(a) Earlier types of instrument have weaknesses of design, both aerodynamic and mechanical, which may easily lead to significant errors where accurate measurement is required.

(b) They cannot be used with confidence at very low Reynolds numbers.

(c) For precision measurement (in conditions where precision is inherently practicable) individual calibration is, for these types, usually desirable.

(d) On the other hand for more general use it is sometimes reasonable to specify an average calibration factor for all those made by a particular production process (Section 28.2).

(e) In the case of the tapered-nose tube the sharpness of the peripheral edge at the tip is of considerable importance (e.g. Section 24.3).

(f) In the case of the 'hemispherical nose' tubes it appears that an instrument with a nose in the form of a truncated hemisphere may be preferable to one which accurately conforms to the formal specification of a complete hemisphere (Sections 21.2, 28.2).

(g) The revised basic calibration factor (Section 6.1) for an accurately constructed 5/16 in. tapered-nose N.P.L. standard instrument is 0·995 to 0·996 from 40 to 160 ft/sec (and probably over an even greater range) with negligible scale effect (Sections 24.1, 28.1).

(h) The basic calibration factors of the 'hemispherical nose' tubes are generally less than they have been thought to be and there is usually scale effect even in the more useful range of Reynolds number (Section 28.2 and Fig. 6).

(i) The factors for these cannot be quoted briefly and it is necessary to refer to text and figures, e.g. Section 26 and Fig. 6.

New Design.

(j) A new design of nose profile (Fig. 8) offers the prospect of an instrument specially suitable for precision measurement (in suitable circumstances) at almost any Reynolds number.

(k) Scale effect probably arises only in respect of the centre bore and then only at very low Reynolds numbers (Sections 32, 44.3 and Fig. 14b).

(l) The basic calibration factors K (Section 6.1) are transferable to similar reasonably well made instruments without need for individual calibrations (Sections 30, 46).

(m) Three versions are suggested with K equal almost exactly to $1 \cdot 000$ (Sections 32, 44.2). The overall dimensions of these are appropriate to more easily constructed, being less complicated, static-pressure tubes (Section 44.4).

(n) Versions with K rather less than $1 \cdot 000$ but assumed to have a *working* calibration factor of $1 \cdot 000$ are proposed for general use (non-ideal conditions) (Section 44.2).

(o) The new design has few disadvantages but in particular it is more sensitive to misalignment beyond 15° or so than those of other types which are made with a large centre-bore diameter (Sections 38, 40 and Figs. 11, 12, 13).

48. *General Concluding Remarks.*

It is with some hesitation that any specific values have been quoted in the previous section. A section on principal conclusions is necessarily very, abbreviated and there is always a risk (confirmed by past experience) of someone picking out a bare statement without adequate reference to the appropriate text and letting it go at that. One of the main objects of these notes however is to emphasise the dangers inherent in such a course.

Pitot-static tubes as such (as their two sides separately) ought not to be used without a careful consideration of what one hopes to measure and also of what one is likely to be actually measuring. With this in mind much of the report is directed to explaining what can be expected of these instruments, where some of their limitations are to be found and what is meant by calibration factors.

It is appreciated that in application it is only on comparatively rare occasions that they can be used to the degree of precision quoted in the main body of this report. This is largely because the conditions so often make extremely accurate measurement impracticable if not impossible. On the other hand errors that do arise are quite as often due to faults of experimentation as to weaknesses in the available instruments. For this reason, as well as for the ease and reliability of future investigations and developments, much attention has been given to the recording of associated information and comment.

There is scope for further tentative modifications of design and these need not be restricted to purely orthodox ones such as changing the nose profile or removing the stem but one requirement in particular has been found to be very important; it is one not satisfied in many pitot-static combinations. This is that where any inconsistency of flow pattern around the tube is possible (as is almost inevitable to some extent) it must be far enough removed from all the pressure holes to be insignificant in its effect. This is a basic feature of any good design. If for special reasons it cannot be ensured then one has to accept not only an error but also an uncertainty as to its probable magnitude.

49. *Acknowledgements.*

Reference has already been made to the special co-operation of Mr. P. S. Pusey (Section 18) and Mr. F. A. MacMillan (Section 41). In addition the authors particularly wish to acknowledge the assistance of Dr. R. C. Pankhurst following a careful perusal of the draft report.

REFERENCES

The number of references recorded below is deliberately limited. They include the minimum number necessary for the text of the report; to these are added just a few which are thought to be useful for the purpose in mind; for example Ref. 7 provides a good indication of the variety of parameters that have to be borne in mind. Most of them of course in themselves contain other references—in particular Refs. 11 and 12 list a large number.

No.	*Author(s)*	*Title, etc.*
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7	K. G. Merriam and E. R. Spaulding	Comparative tests of pitot-static tubes. N.A.C.A. Tech. Note 546. 1935.
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12	R. C. Pankhurst and D. W. Holder	*Wind Tunnel Technique.* Pitmans. 1962.

TABLE 1

*M.E.N.*1 (*Mitred Junction*)

80 and 110 ft/sec (*see* Section 37)

Degrees	Centre bore % of $\frac{1}{2}\rho U_0^2$ a	Annulus % of $\frac{1}{2}\rho U_0^2$ b	Pressure Difference % of $\frac{1}{2}\rho U_0^2$ c	$\frac{\text{P.D.}}{\frac{1}{2}\rho U_0^2}$ d
Yaw				
0	0	0·6	−0·6	0·994
2	0	0·5	−0·5	0·995
4	−0·1	+0·1	−0·2	0·998
6	−0·3	−0·6	+0·3	1·003
8	−0·8	−1·4	+0·6	1·006
10	−1·7	−2·3	+0·6	1·006
12	−3·2	−3·4	+0·2	1·002
14	−5·3	−4·5	−0·8	0·992
17	−9·6	−6·2	−3·4	0·966
20	−15·1	−8·1	−7·0	0·930
25	−27·1	−11·5	−15·6	0·844
30	−42·6	−15·0	−27·6	0·724
37	−66·4	−19·8	−46·6	0·534
Pitch				
−30	−40·0	−13·6	−26·4	0·736
−25	−26·3	−10·4	−15·9	0·841
−20	−14·8	−7·3	−7·5	0·925
−17	−9·4	−5·5	−3·9	0·961
−14	−5·3	−3·8	−1·5	0·985
−12	−3·3	−2·8	−0·5	0·995
−10	−1·8	−1·8	0	1·000
−8	−0·8	−0·9	+0·1	1·001
−6	−0·3	−0·2	−0·1	0·999
−4	−0·1	+0·3	−0·4	0·996
−2	0	+0·6	−0·6	0·994
0	0	+0·6	−0·6	0·994
2	0	+0·4	−0·4	0·996
4	−0·1	0	0	1·000
6	−0·3	−0·8	+0·5	1·005
8	−0·8	−1·7	+0·9	1·009
10	−1·8	−2·6	+0·8	1·008
12	−3·3	−3·6	+0·3	1·003
14	−5·3	−4·6	−0·7	0·993
17	−9·4	−6·2	−3·2	0·968
19	−12·8	−7·3	−5·5	0·945

TABLE 2

M.E.N.C. (Curved Junction)

80 ft/sec (*see* Section 37)

Degrees	Centre bore % of $\frac{1}{2}\rho U_0^2$ a	Annulus % of $\frac{1}{2}\rho U_0^2$ b	Pressure Difference % of $\frac{1}{2}\rho U_0^2$ c	P.D. $\frac{}{\frac{1}{2}\rho U_0^2}$ d
Yaw				
0	0	+0·3	−0·3	0·997
2	0	+0·2	−0·2	0·998
4	−0·1	−0·1	0	1·000
6	−0·3	−0·6	+0·3	1·003
8	−0·8	−1·3	+0·5	1·005
10	−1·7	−2·1	+0·4	1·004
12	−3·2	−3·0	−0·2	0·998
14	−5·2	−3·9	−1·3	0·987
16	−7·7	−4·8	−2·9	0·971
Pitch				
−17	−9·8	−5·4	−4·4	0·956
−16	−8·3	−4·9	−3·4	0·966
−14	−5·7	−3·9	−1·8	0·982
−12	−3·5	−2·9	−0·6	0·994
−10	−1·9	−2·0	+0·1	1·001
− 8	−0·9	−1·2	+0·3	1·003
− 6	−0·4	−0·5	+0·1	1·001
− 4	−0·1	0	−0·1	0·999
− 2	0	+0·3	−0·3	0·997
0	0	+0·3	−0·3	0·997
+ 2	0	+0·1	−0·1	0·999
+ 4	−0·1	−0·3	+0·2	1·002
+ 6	−0·4	−0·9	+0·5	1·005
+ 8	−0·9	−1·6	+0·7	1·007
+10	−1·9	−2·5	+0·6	1·006
+12	−3·5	−3·6	+0·1	1·001
+14	−5·7	−4·9	−0·8	0·992

TABLE 3

Permissible Lack of Alignment (Degrees) (see Section 40)

Error on $\frac{1}{2}\rho U_0^2$ ±%	Taking P.D./$\frac{1}{2}\rho U_0^2$ =	In Yaw (with zero pitch)		In Pitch (with zero yaw)	
		M.E.N.1	M.E.N.C	M.E.N.1	M.E.N.C
0·4	0·998	± 5½		−12 to + 5	
0·4	1·001		±12		−11½ to + 6
0·5	0·999	± 6½		−12 to + 5½	
0·5	1·002		±12		−11½ to +13
0·6	1·000	±13½		−12 to + 6½	
0·6	1·001		±12½		−12 to +13½
0·7	1·001	±13½		−12 to + 7	
0·7	1·000		±13		−12 to +14
0·8	1·001	±14		−12½ to +14	
0·8	0·999		±13		−12½ to +14
1·0	0·999	±14		−13 to +14½	
1·0	0·997		±14		−13 to +14½
1·5	0·994	±15		−15 to +16	
1·5	0·992		±15		−14½ to +16
0·5	1·000	—	±13	— —	−12 to + 6
0·6	1·000	±13½	±13	−12 to + 6½	−12 to + 6½
0·7	1·000	±14	±13	−12½ to + 7	−12 to +14
0·8	1·000	±14	±13	−12½ to + 7½	−12½ to +14
0·9 and 1·0	1·000	±14	±13½	−13 to +14	−13 to +14
1·5	1·000	±15	±14½	−14 to +15	−13½ to +15

TABLE 4

Co-ordinates for 0·308 *in. Instrument with* 0·052 *in. diameter end flat*

Measured from base of nose.
x, y, refer to the quarter ellipse;
x, $(y+0{\cdot}026)$, to the semi-profile.
(*See* Section 31 and Fig. 8)

x	y	$y + 0{\cdot}026$
(Base)		
0	0·128	0·154
0·075	0·127	0·153
0·105	0·126	0·152
0·148	0·124	0·150
0·195	0·121	0·147
0·242	0·117	0·143
0·281	0·113	0·139
0·314	0·109	0·135
0·350	0·104	0·130
0·375	0·100	0·126
0·402	0·095	0·121
0·426	0·090	0·116
0·448	0·085	0·111
0·468	0·080	0·106
0·485	0·075	0·101
0·502	0·070	0·096
0·517	0·065	0·091
0·530	0·060	0·086
0·542	0·055	0·081
0·548	0·052	0·078
0·560	0·046	0·072
0·570	0·040	0·066
0·579	0·034	0·060
0·584	0·030	0·056
0·589	0·025	0·051
0·593	0·020	0·046
0·596	0·015	0·041
0·598	0·011	0·037
0·599	0·008	0·034
0·600	0	0·026
(Tip)		

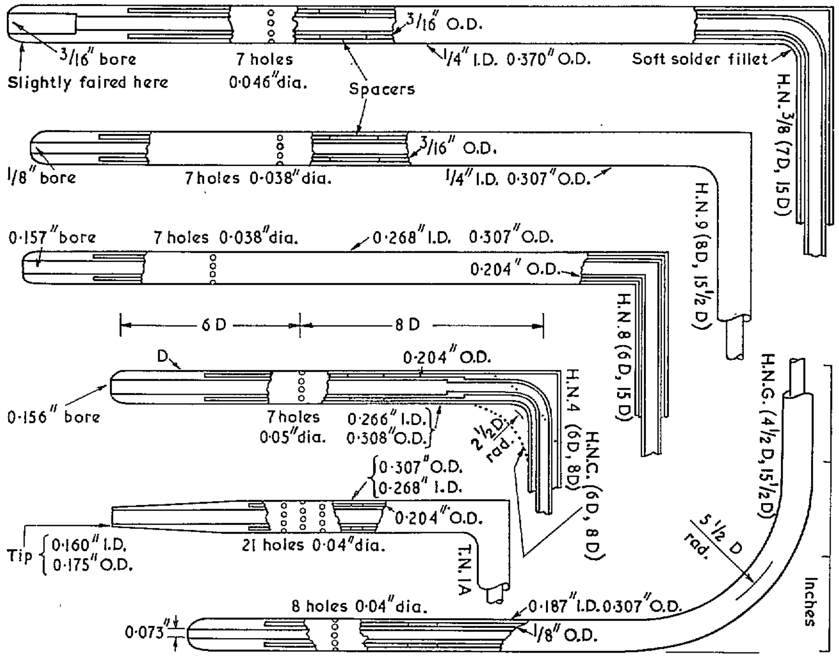


FIG. 1. Various pitot-static tubes.

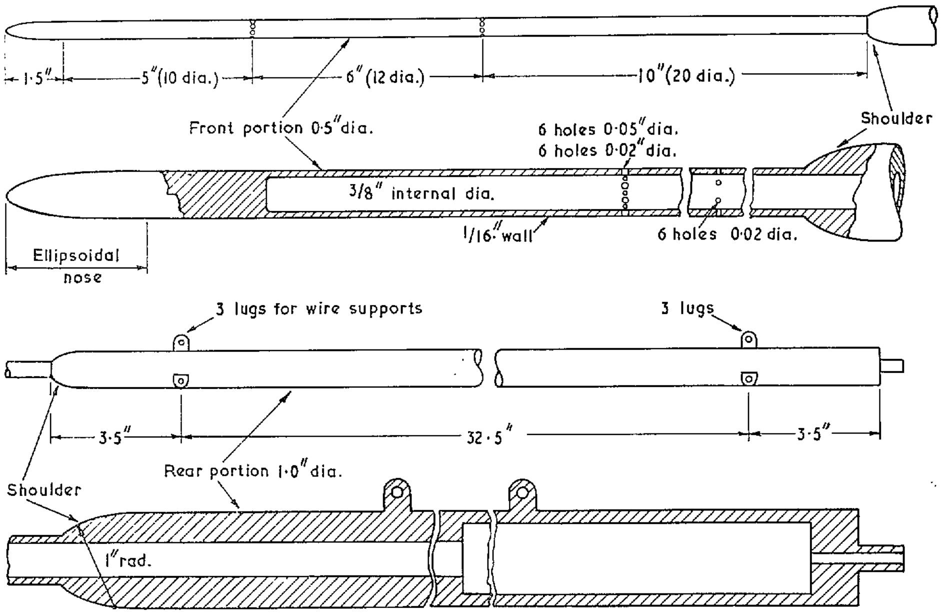


FIG. 2. N.P.L. Ellipsoidal-nose static-pressure tube.

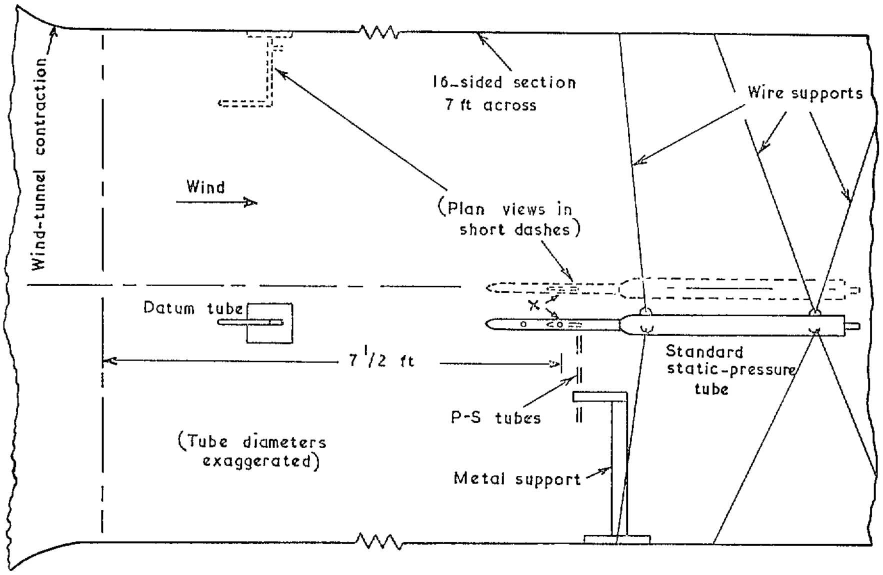


FIG. 3. General arrangement (elevation) in low-turbulence wind tunnel.

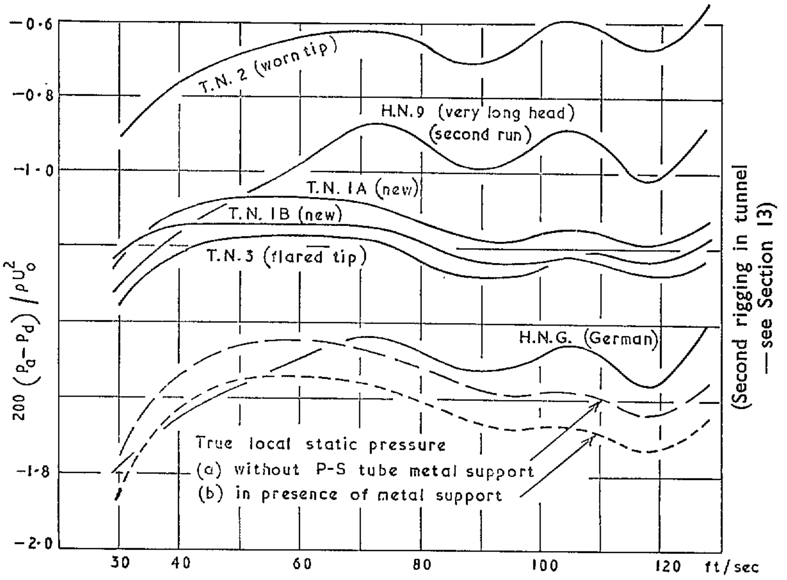


FIG. 4. Recorded annulus pressures relative to datum (Typical curves—low-turbulence wind tunnel).

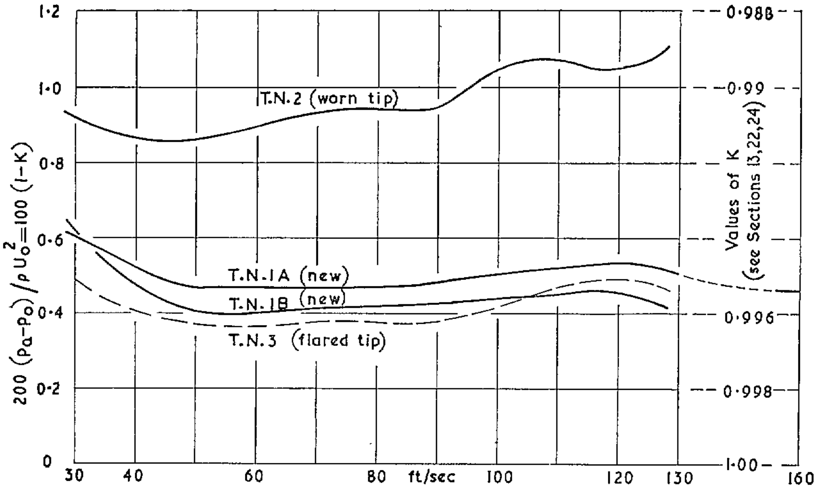


FIG. 5. Tapered-nose P-S tubes in an air stream of low turbulence. Recorded annulus pressures relative to true static pressure. Deduced basic calibration factors *K*.

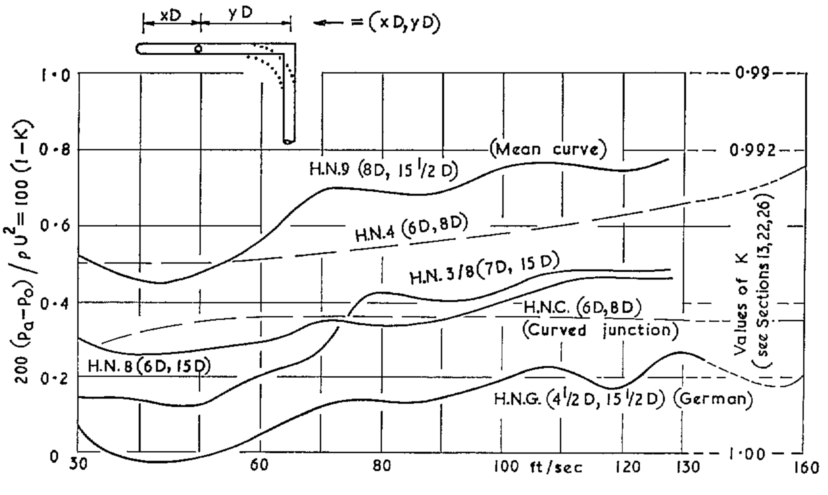


FIG. 6. Hemispherical-nose P-S tubes in an air stream of low turbulence. Recorded annulus pressures relative to true static pressure. Deduced basic calibration factors *K*.

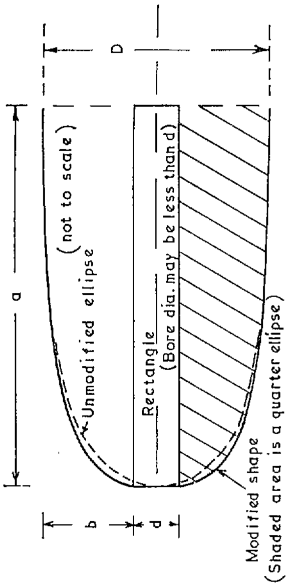


FIG. 8. Sketch of nose section for new design (*see* Section 30).

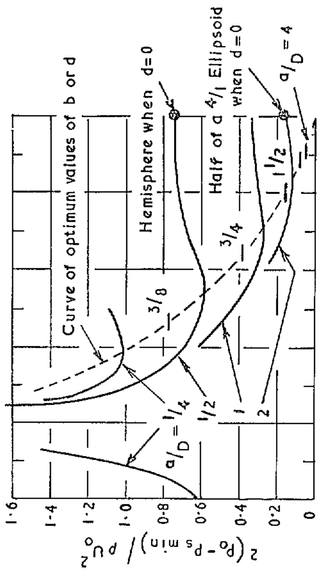


FIG. 9. Minimum surface pressures p_s min (from Ref. 8) (*see* Section 30).

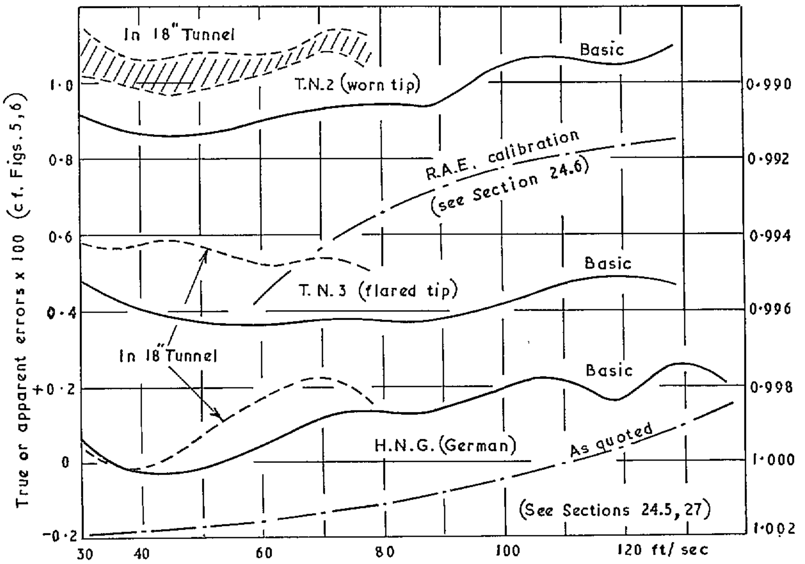


FIG. 7. Comparison calibrations in streams of low and moderate turbulence.

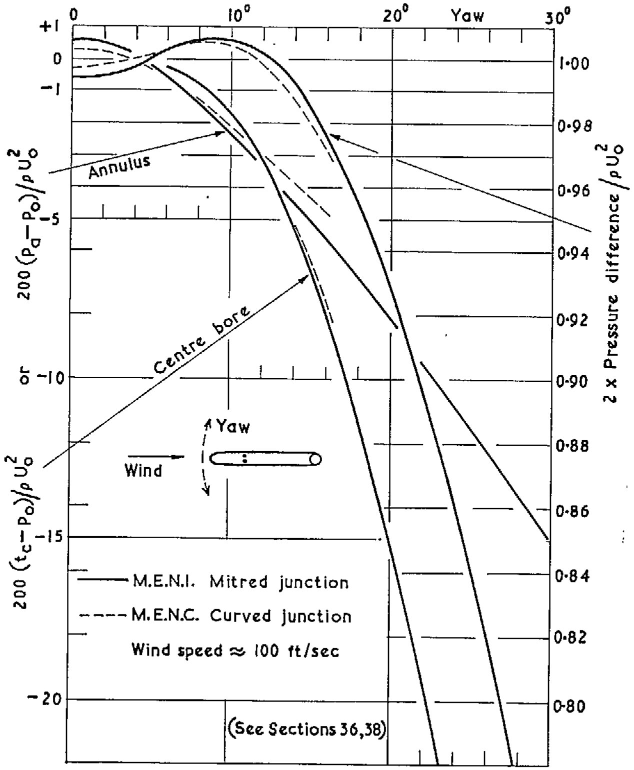


FIG. 11. M.E.N. tubes—effect of yaw.

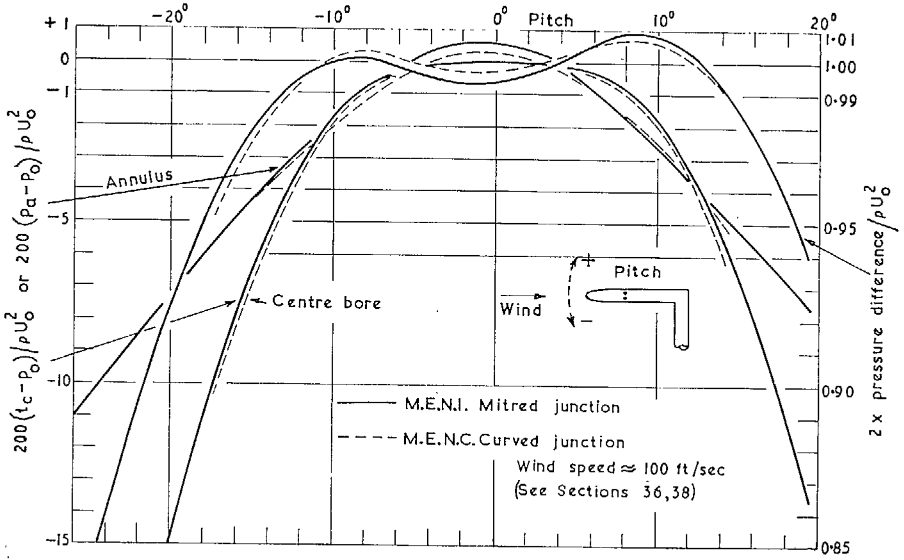


FIG. 12. M.E.N. tubes—effect of pitch of flow.

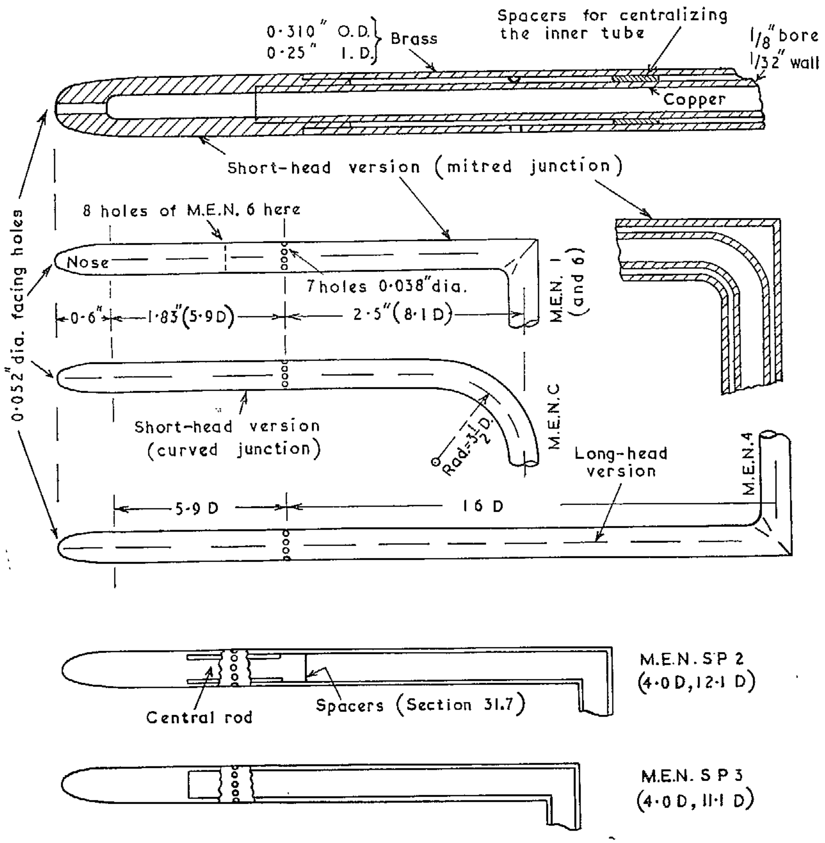


FIG. 10. Tubes with modified-ellipsoidal noses.

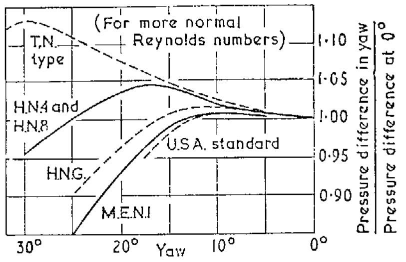


FIG. 13. Comparison of various instruments in yaw (*see* Section 38).

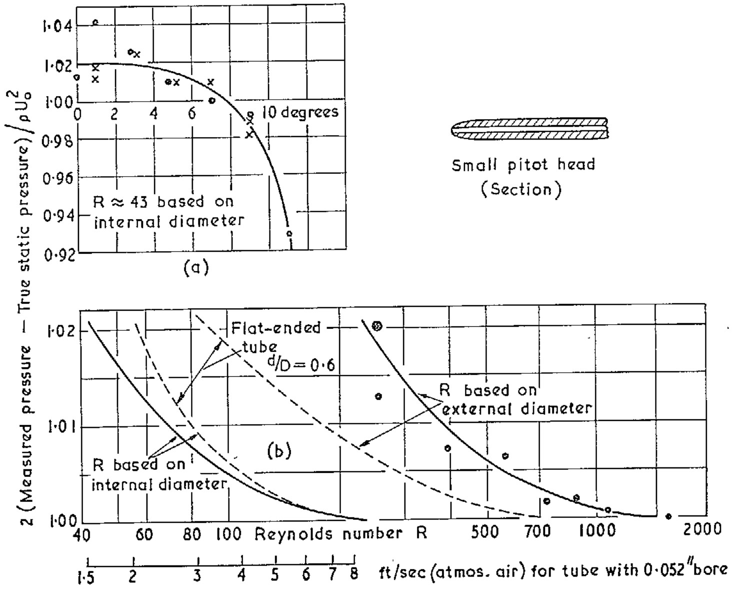
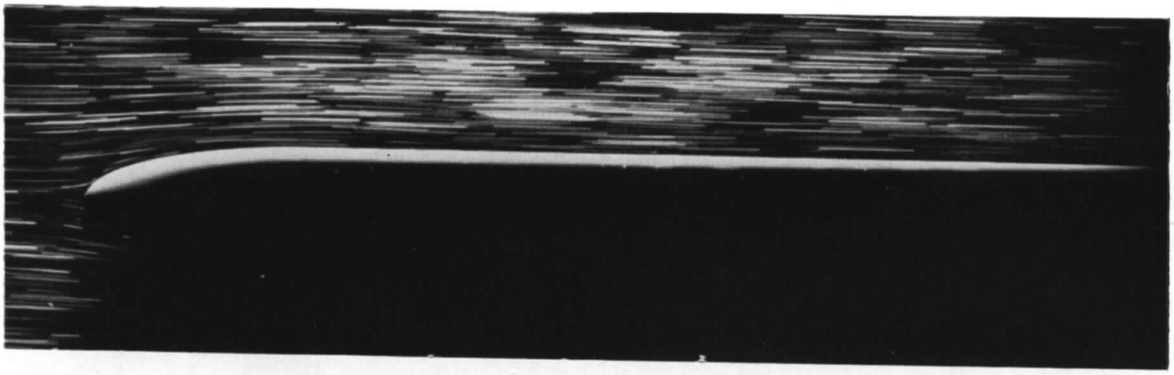
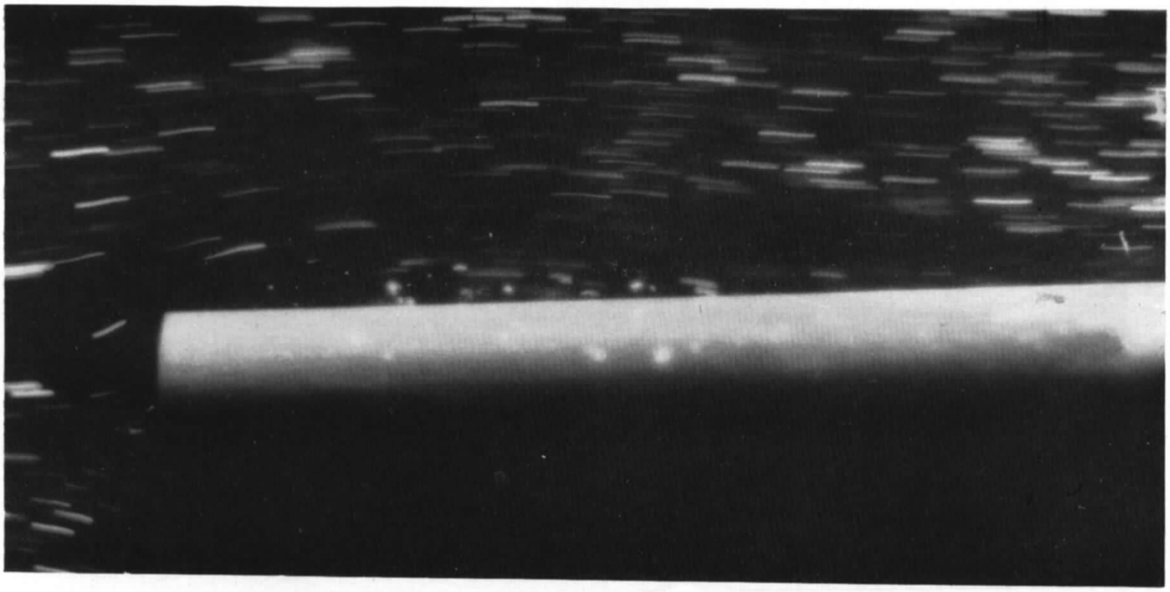


FIG. 14. Centre-bore pressures at low Reynolds numbers.



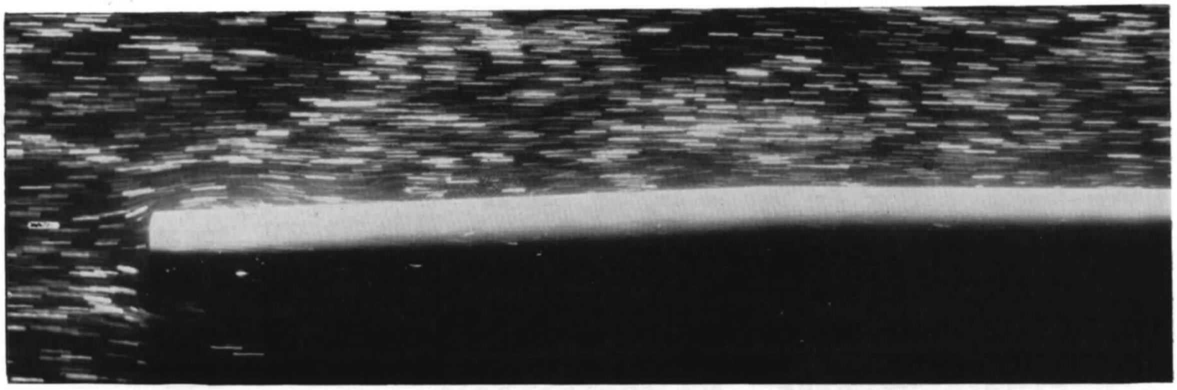
4/1 Ellipsoidal nose. No facing hole
Equivalent air-speed for 5/16" tube = 50 ft/sec

6/1 Ellipsoidal nose. 0·12 D facing hole
Equivalent air-speed = 50 ft/sec

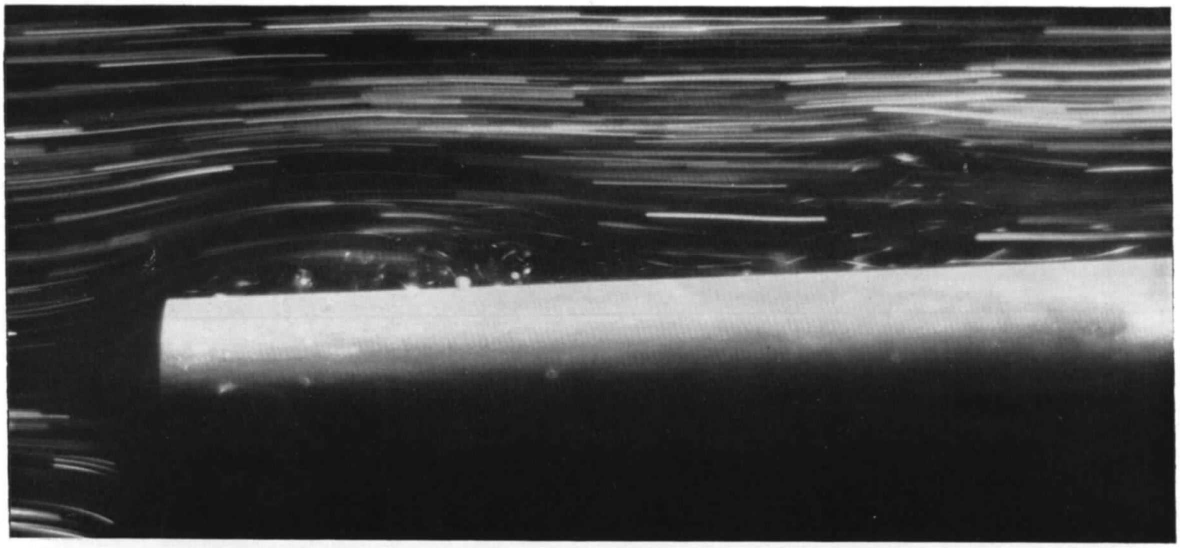


Tapered nose. Equivalent air-speed = 12 ft/sec

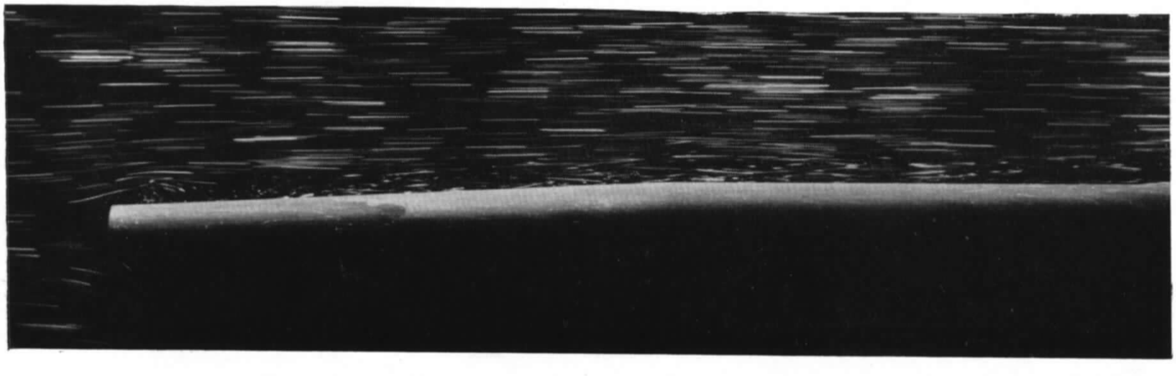
PLATE 1. Ellipsoidal- and tapered-nose models.



Equivalent air-speed for 5/16" tube = 18 ft/sec



Equivalent air-speed = 31 ft/sec

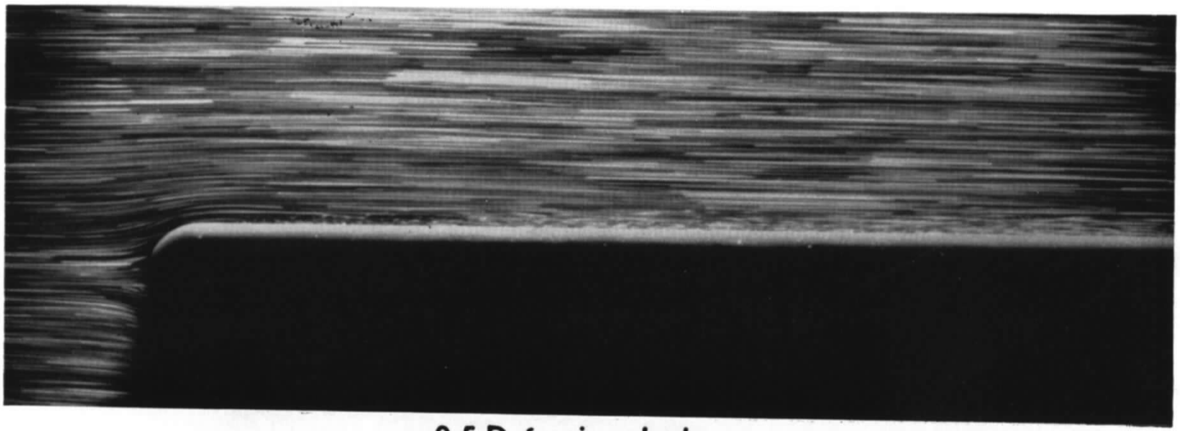


Equivalent air-speed = 87 ft/sec

Plate 2. Tapered-nose models.

0·5 D facing hole
Equivalent air-speed for 5/16″ tube = 31 ft/sec

0·5 D facing hole
Equivalent air-speed = 50 ft/sec



0·5 D facing hole
Equivalent air-speed = 93 ft/sec

PLATE 3. Hemispherical-nose models.

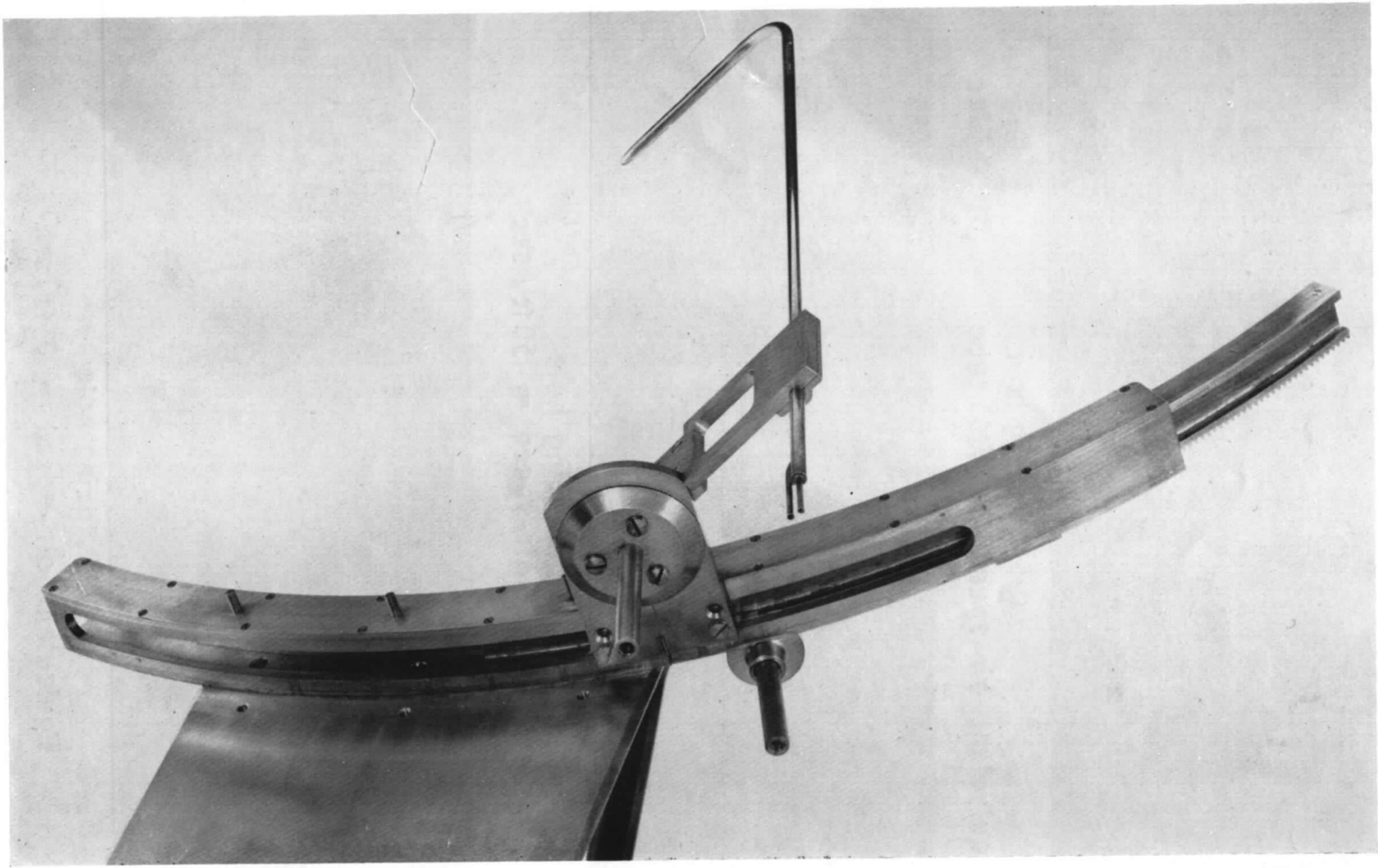


PLATE 4. Mechanism for traverses in yaw and pitch.

(91136) Wt. 66/2301 K5 4/65 Hw.

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