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COMPARATIVE TESTS OF PITOT-STATIC TUBES

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SUMMARY

Comparative tests were made on seven conventional pitot-static tubes to determine their static, dynamic, and resultant errors. The effect of varying the dynamic opening, static openings, wall thickness, and inner-tube diameter was investigated. Pressure-distribution measurements showing stem and tip effects were also made. A tentative design for a standard pitot-static tube for use in measuring air velocity is submitted.

This report covers an investigation conducted under the auspices of the National Research Council.

INTRODUCTION

Curious, but understandable and significant, are the facts that no two conventional designs of pitot-static tube agree and that at least one commercial modification of a conventional design is capable of showing an error of more than 15 percent of dynamic pressure at zero yaw in a uniform air stream. These facts are curious because the pitot-static tube is generally regarded as being the standard instrument for measuring the velocity of high-speed air. They are understandable because prior to 1925 little detailed information was available regarding the characteristics of pitot-static tubes and the reasons for the characteristics. The facts are significant in that they suggest the desirability of settling the design questions pertaining to the pitot-static tube and of evolving a single standard design (bearing the name of no laboratory or individual) to be generally adopted to replace the many varying conventional designs now in use.

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The astonishing 15 percent dynamic-pressure error of the commercial modification of a conventional design of pitot-static tube, mentioned above, was observed at the aeromechanics laboratory of the Worcester Polytechnic Institute in 1930; several attempts to convince the manufacturer of the existence of this error have been unsuccessful. In this paper, this commercial instrument is referred to as "Tube A."

In undertaking and planning the investigation, the writers were powerfully influenced by the information contained in reference 1. A careful study of this reference will be helpful in following the arguments of this paper. A considerable number of other investigators have studied the problem during the past 30 years. A list of references dealing with such research is given at the end of reference 2.

With the foregoing facts in mind it was decided: (1) to construct models of seven conventional types of pitot-static tube and to subject them, as well as Tube A, to individual tests under identical conditions in order to get an experimental comparison of static, dynamic, and resultant errors; (2) to see if the measured discrepancies, if any, could be explained by the conclusions of reference 1; (3) from the experience gained in carrying out objectives (1) and (2), to suggest for general adoption some definite design of pitot-static tube for high-speed-air measurements.

In order to test the models under identical conditions it was decided to make use of a wind tunnel, the dynamic pressure at any point in the region of which was directly proportional to the static pressure at a chosen section in the air circuit. Indeed, by proper selection of the point in the working region and the section of the air circuit, the proportionality constant could be made very nearly unity, if desired. Controlling the reference pressure at the chosen section of the air circuit would control the dynamic pressure at the chosen test position in the working region. The static pressure at the chosen test position could be made very nearly atmospheric, if desired, by using an open jet for the working region.

The difference between the reference pressure at the chosen section of the air circuit and the impact-pressure indication of the model permitted the performance of the dynamic opening of the model to be studied with more accuracy than would be possible by measuring the impact-pres-

sure indication directly, assuming the reference pressure to be chosen so as to make the above-mentioned proportionality constant nearly equal to unity. The experimental principle involved is that it is better to measure A-B directly than to determine A-B by separate measurements of A and B, especially when A and B are nearly equal. As the impact-pressure and the static-pressure errors were measured separately, the sources of the errors could be more easily traced than if the errors had been combined.

The errors caused by imperfect alinement of the instrument relative to the direction of motion of the air stream were found by studying the performance of the models under conditions of extreme yaw, as well as under conditions of zero yaw. In some applications, the mechanical alinement of the instrument relative to the enclosing walls of an air stream does not insure proper alinement relative to the true motion of the air.

In the attempt to check part of the work in reference 1 with the aid of the wind tunnel to be used in the investigation, some basis would be provided for applying the conclusions of the earlier tests to check the results of the present tests. It was decided to check the pressure-distribution effects produced by the stem and the tip.

Because some facts might be learned by even such crude attempts as flow visualization, a careful survey of the working region of the air stream was to be made by any pressure-distribution or flow-visualization methods available.

The series of tests indicated by the foregoing general considerations were:

(1) Survey of working region and selection of test position.

(2) Tip-effect test for a hemispherical tip similar to that described in reference 1.

(3) Stem-effect test like that in reference 1.

(4) Tests with fabricated or simulated tube models, hemispherical tip and movable dummy stems.

(5) Tests to find impact- and static-pressure errors for models with zero yaw and variable dynamic pressure.

(6) Tests like those in (4), but holding the dynamic pressure constant at a high value and varying the yaw.

(7) Rough attempts at flow visualization for cases of interest.

The detailed technique adopted was influenced by the theoretical considerations to be presented later.

How many of the ideas contained in this paper may have received prior attention the authors themselves do not know. They hope to have contributed some data of practical interest and value to add to the existing store of knowledge on the subject.

The authors wish to express their sincere appreciation to Dr. G. W. Lewis, Director of Research, National Advisory Committee for Aeronautics, to Professor Lionel S. Marks of the Harvard Engineering School, and to the many others who so generously gave advice, encouragement, and assistance in the work. The work was carried out under a grant of the National Research Council.

NOTATION OF SYMBOLS

E, error in dynamic pressure, inches of water.

e, error in dynamic pressure, percent.

$h_v = \frac{1}{2} \rho V^2$, true dynamic pressure, inches of water.

h_v', indirectly measured dynamic pressure, inches of water.

$h_d = h_v + h_s$, true impact pressure, inches of water.

h_d', indirectly measured impact pressure, inches of water.

h_s, true static pressure, inches of water.

h_s', measured static pressure, inches of water.

h_r', measured static pressure at reference section*, inches of water.

$\epsilon = h_r' - h_d'$, by definition and measured directly.

$\delta = -(\epsilon + h_s')$, by definition.

THEORETICAL CONSIDERATIONS

Theory of comparative-errors determination.- If A and B are two pitot-static tubes to be compared, we have:

$$E_b - E_a = (h_v')_b - (h_v')_a$$

$$= (h_d' - h_s')_b - (h_d' - h_s')_a$$

Now h_r' is to be the same for both tubes, so

$$E_b - E_a = (h_d' - h_s' - h_r')_b - (h_d' - h_s' - h_r')_a$$

But $\delta = -(\epsilon + h_s') = h_d' - h_r' - h_s'$, and $E_b - E_a = \delta_b - \delta_a$ and it is to be noted that ϵ and h_s', and hence δ, can be measured experimentally. Expressing errors in percent, we have:

$$e_b - e_a = \frac{100\ (\delta_b - \delta_a)}{h_v}$$

But h_r' may be made equal to h_v, very nearly, and we then have:

$$e_b - e_a = \frac{100\ (\delta_b - \delta_a)}{h_r'} \quad \text{(very nearly)}$$

Elimination of air circuit characteristics.- Experiment verifies the theoretical supposition that measured impact and static pressure are directly proportional to the reference pressure h_r'. Using this information, one

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* The reference section refers to a section of the tunnel [illegible] from the test section where the static pressure is [illegible]ional to the dynamic pressure at the test section.

can show that the relative errors of any two tubes, as found from $\delta_b - \delta_a$, are determined solely by the tube characteristics and not at all by characteristics of the air circuit.

Let $h_d' = K_d\, h_r' + C_d\, h_r'$, where $K_d\, h_r'$ is the true impact pressure at the test position, and $C_d\, h_r'$ is the error in impact pressure caused by lack of symmetry or some other tube fault. Similarly let $h_s' = K_s\, h_r' + C_s\, h_r'$.

The constants K_d and K_s are determined solely by the nature of the air circuit, while C_d and C_s are determined entirely by the nature of the pitot-static tubes.

We may now write:

$$h_v' = h_d' - h_s'$$

$$= K_d\, h_r' + C_d\, h_r' - K_s\, h_r' - C_s\, h_r'$$

but $\delta_b - \delta_a = (h_v')_b - (h_v')_a$

Substituting and subtracting, the terms containing K vanish and we have:

$$\delta_b - \delta_a = h_r' \left[(C_d - C_s)_b - (C_d - C_s)_a\right]$$

which shows that $\delta_b - \delta_a$ is independent of air-circuit characteristics.

When determining $\delta_b - \delta_a$ by experiment, it is required that all h_s' and ϵ readings be taken at the same point in the air circuit. If a longitudinal traverse of the working region of the air stream shows negligible variation in ϵ, the test procedure may be simplified to provide only that all h_s' readings be taken at the same point in the working region.

Theory of absolute-errors determination.- Thus so fa only comparative errors have been discussed. While it seems to be impossible to measure accurately the true solute errors for pitot-static tubes by the indicat

of procedure, we can get some indication of such absolute error, for cases of zero yaw, if we are willing to assume that h_d' is equal to h_d and if we can adjust the experimental arrangement so that h_s is very nearly zero, and so that h_r' is very nearly equal to h_v. Under such circumstances, we would have:

$$E = h_v' - h_v = h_d' - h_s' - h_v$$

Also $$h_d - h_v = h_s = 0$$

so $$h_v = h_d$$

Hence $$E = h_d' - h_s' - h_d = - h_s'$$

and $$e = - 100 \frac{h_s'}{h_r'} \text{ very nearly}$$

Note also that

$$\epsilon = h_r' - h_d' = h_v - h_d = - h_s' = 0$$

if $$h_r' = h_v$$

If yaw is present, we have:

$$E = h_v' - h_v = h_d' - h_s' - h_v \quad \text{and} \quad h_v = h_d$$

as before. But now $h_d' \neq h_d$; actually, $h_d' = h_r' - \epsilon$.

Therefore,

$$E = h_r' - \epsilon - h_s' - h_v$$

But $h_r' - h_v = 0$ very nearly, hence $E = - (\epsilon + h_s')$

and $$e = 100 \frac{\delta}{h_r'}$$

Although experiment may not actually prove that $h_d' = h_d$, if zero-yaw experiments for several pitot-static tubes with different types of symmetrical tips show that for a given value of h_r' the value of ϵ is always the same,

we will have some evidence that any impact-pressure errors which exist are not functions of the shape of the tip, and if we know of no other factor besides the shape of the tip which might influence the impact error, we might assume with some justification that such error is really zero.

Effect of density changes.- For a given actual air velocity, the value of h_v will depend on the air density, since h_v is the dynamic pressure in inches of water. Assuming that h_r' is taken very nearly equal to h_v and that ϵ and h_s' are directly proportional to h_r', it follows that ϵ, h_s', and h_r' will depend on the air density just as h_v does. Ratios such as ϵ/h_r' or h_s'/h_r' or δ/h_r' will, however, not be affected by density changes because the numerator and the denominator change in the same proportion. Consequently, for the purposes of this investigation, the data obtained from tests made on different days did not need to be corrected for density changes.

Theory of superposition of flow effects.- Assuming potential flow, which would occur in the case of a fluid of zero viscosity, it is possible to determine from theory the pressure distribution upstream of an infinite circular cylinder and also along the upstream boundaries of a long blunt-nosed body.

The stem of a pitot-static tube corresponds to a portion of such an infinite cylinder and the nose-head assembly corresponds to the blunt body. At the static openings of the conventional pitot-static tube, then, the available theory teaches one to expect a positive pressure effect from the presence of the stem and a negative pressure effect from the presence of the nose. The presence of boundary-layer effect along the boundary of the head, and the absence of a portion of the infinite cylinder, may be expected to alter the magnitudes, but not the signs, of the pressures computed from theory. The resultant pressure at the static openings, for ideal flow, may be taken as the algebraic sum of the separate pressure effects of nose and stem.

In reference 1, the pressure distribution caused by the nose was first determined by experiment. The distribution of pressure caused by the stem was then found, very nearly, by arranging the nose to be at a considerable dis-

tance from the static openings, and varying the position of the stem relative to the static openings. In these experiments, the positive pressure effects of the stem, for large distances between static openings and stem, was found to be greater than that computed from theory, in which an infinite cylinder was assumed. This result may have been caused by a boundary-layer effect, which caused a cumulative positive pressure at the head boundary. Otherwise, one would expect the measured pressure to be less than that calculated.

EQUIPMENT

The wind tunnel shown in figure 1 was used to provide the air stream. This tunnel furnished an open jet of air, 20 inches in diameter, and had a maximum dynamic pressure of about 4 inches of water.

The axes of the entrance and exit cones of the tunnel were carefully checked for alinement, and a jig was used for locating models at the test position.

Ellison inclined draft gages measured all the pressures. Type No. 11440 gave a multiplication of 10:1, with a capacity of 1 inch of water; Type No. 11470 gave a multiplication of 5:1, with a capacity of 3 inches of water.

The essential specifications for seven types of pitot-static tube were obtained by correspondence and reference to technical literature. These tubes are commonly identified by the following names: Bureau of Standards, Washington Navy Yard, National Advisory Committee for Aeronautics, National Physical Laboratory modified, American Society of Heating and Ventilating Engineers, Prandtl, and National Physical Laboratory old standard. The abbreviations used to designate the models of these tubes will be, respectively: BS, WNY, NACA, NPLmod, ASHVE, Prandtl, and NPL.

A careful and experienced mechanic made the models from specifications using 5/16-inch brass tubing of 0.04-inch shell thickness and 1/8-inch copper tubing. The copper tubing was used for the inside static tube.

The models are shown in figures 2 and 3, and the specifications actually obtained in the models are given in table I. It is very important to observe in table I that in practically no instances were the detailed features of

the prototypes reproduced in the models, a notable deviation being the size of the impact or dynamic openings, this feature being considered of secondary importance at the time the models were made. Especial care was taken, however, to locate the static-hole groupings at the proper position on the head, relative to stem and tip, because one of the main objects of the investigation was an attempt to apply the design suggestions of reference 1 to models of existing designs tested.

TESTS

The majority of observations were taken at a dynamic pressure of 3 inches of water. This value corresponds to a Reynolds Number of 18,000, based on tube diameters, or one of about 3,600, based on the diameters of the majority of the impact or dynamic openings.

A record of the flow pattern in the horizontal plane containing the axis of the jet was obtained by a modification of the Fales technique. (See reference 3.) It was found that a convergence of streamlines was visible in the edges of the downstream half of the jet. The streamlines in the upstream third of the jet appeared to be essentially parallel to the jet axis. It was tentatively decided, therefore, that the test position would be a point on the jet axis, 6 inches downstream of the upstream edge of the open jet.

Using the NPLmod model, the variation of ϵ and h_s' was observed for longitudinal, lateral, and vertical displacements from the selected test position. The longitudinal uniformity was good, but the lateral uniformity, sufficiently poor to require correction procedure in yaw tests; the vertical uniformity was poor enough to require reliable means of locating models at the proper vertical position in the air stream. The maximum observed variation in velocity was only about 1 percent, but it will be seen that such variation, without correction, cannot be tolerated in yaw tests. The lateral variation in h_s' was small. The lateral variation of ϵ is plotted in figure 4.

Tip-effect tests.- The experimental arrangement for investigating the static-pressure effect of a hemispherical tip was very similar to that used in reference 1. A

5/16-inch brass tube was held at the axis of the jet by an arrangement of wires and sleeves, so that it could be moved longitudinally. The upstream end of the tube was fitted with a hemispherical closed tip, carefully finished to shape by means of the special tool shown in figure 2. Rows of 0.038-inch diameter static holes (four holes per row) were made with a longitudinal spacing of about 1/8 inch between rows for the first $2\frac{1}{2}$ inches and with 1-inch spacing for the next 3 inches.

In order to determine the static pressure at any given row of holes, all holes were first filled with a mixture of casein and vaseline and the whole tube was wiped clean and tested for tightness. The given row of holes was then unplugged, moved to the test position, and the region near the open holes was wiped very carefully to remove burs of the plugging mixture. Finally, the dynamic pressure of the 3 inches of water was established and the pressure at the row of open holes was measured by a sensitive manometer attached by tubing to the downstream end of the tube.

The results are shown in figure 5; it is evident that the tip-effect errors become negligible at sections more than 5 or 6 diameters downstream from the base of the tip. The shape of the curve is in good agreement with figure 8 of reference 1 but the ordinates do not agree because the two curves are not plotted with respect to the same reference pressure. The dispersion of test points downstream of the 5-tube-diameter location probably reflects actual flow conditions rather than indicates errors in the readings, because such dispersion does not appear in the upstream region.

An interesting flow variation with change in Reynolds Number, not shown in the data, was observed for the section 1/4 inch downstream from the base of the tip. With the dynamic pressure set at 0, 0.95, 1.17, 1.80, and 3.00 inches of water, the corresponding static pressures were 0, -0.019, 0, 0.03, and 0.013 inch of water. At all other sections investigated, the static pressures seemed to be directly proportional to the dynamic pressure. The inference is that the flow at a section about 1 tube diameter downstream from the base of the hemispherical tip is very unstable.

The maximum-error effect downstream more than 1 tube diameter produced by the hemispherical tip appeared to be about 2 percent of the dynamic pressure. The static pres-

sure induced by the tip is negative, thus causing a positive error in dynamic pressure determination for a pitot-static tube.

If the actual static pressure at the test position was atmospheric, and tests described later indicate this value to be very nearly correct, then there was a slight positive static pressure at sections more than 8 diameters downstream. This phenomenon might be explained by the action of the boundary layer on the head.

Stem-effect tests.- The method of introducing a dummy stem was as follows. One end of a 5/16-inch brass tube was filed so that it could be fitted snugly against the static-pressure tube to simulate a square connection between stem and head. The other end was bent to about a 3-tube-diameter radius to simulate a curved connection between stem and head such as was used in many models shown in figure 2. This end was also filed to fit snugly against the static tube.

The row of static openings on the static tube about 18 diameters downstream of the base of the tip was unplugged and set at the test position. The dummy stem was then set at a desired position relative to this row of static holes. With the dynamic pressure set at 3 inches of water, the pressure at the row of static holes was measured with a sensitive manometer, just as in the tip-effect tests. By the use of a large number of positions of the dummy stem, the pressure variation caused by the presence of the stem (plus the presence of a hemispherical tip 18 diameters upstream) could be plotted. This procedure is similar to that described in reference 1.

The results are shown in figure 5. The square and curved connection cases gave the same results for sections more than 20 tube diameters upstream from the stem axis, and there was not more than 0.2 percent of dynamic-pressure difference in the two cases for any section more than 4 tube diameters downstream from the stem axis. This result showed that a curved connection of 3-tube-diameter radius might be used in place of a square connection without causing serious error, if any construction advantage existed.

The results obtained checked those shown in reference 1 very closely. An interesting point, previously mentioned, is that the observed pressure for sections more

than 6 diameters downstream are greater than those computed on the assumption of potential flow around an infinite cylinder. This feature contributes further evidence to support the hypothesis that the action of the boundary layer at the head is such as to build up a slight positive pressure, as mentioned in the discussion of the tip-effect tests.

The stem-effect error is seen to be about 1 percent of the dynamic pressure at the 10-tube-diameter section and about 1/2 percent of the dynamic pressure at the 16-tube-diameter section.

The asymptotic value of error approached at a great distance appeared to be the same as the asymptotic value approached in the tip-effect tests.

Tests of models simulated by static tube and dummy stem.- From the results of the stem- and tip-effect tests it should be possible closely to predict the error to be expected for any combination of x and y distances. In order to test this hypothesis, actual tests were made with the static tube and dummy stem with the curved end, and the results are shown in table II. A study of this table shows that the actual measured errors agree very well with the stem- and tip-error curves of figure 5. It would seem that this agreement could not be possible unless the true static pressure at the test position were very close to atmospheric.

Significance of h_r', ϵ, h_s', and δ in the projected tests.- From the foregoing discussion, it should now be evident that, with the selected test position, h_r' is essentially equal to the true dynamic pressure, h_v; $-\epsilon$ is nearly equal to the true error in impact head, expressed in inches of water; and h_s' is very nearly equal to the error in static head, expressed in inches of water. Then $-100\ \epsilon/h_r'$ and $-100\ h_s'/h_r'$ become the percentage error in dynamic pressure caused by impact- and static-pressure errors, respectively, while $100\ \delta/h_r'$ becomes the resultant percentage error in dynamic pressure.

In lateral-yaw tests, the lateral variation of ϵ must be taken into account to get the true value of ϵ for the model.

In order to be more accurate, the graphs have been

labeled with the symbols just discussed, but the reader will not be seriously in error if he adopts the foregoing significance in his interpretation of the symbols.

Tests of models at zero yaw.- In order to determine the variation of ϵ and h_s' for zero yaw and varying dynamic pressure (h_r') the model was set up by means of the jig so that the center of the static-opening grouping was at the test position. With this arrangement the tip was not at the test position, but the longitudinal-traverse test data showed negligible variation of ϵ in the region used and, also, a few check tests in which the tip was moved to the test position showed no change in the measured value of ϵ. No further effort was therefore made to keep the tip at the test position for the ϵ measurements.

Values of h_r' were set at about $\frac{1}{2}$-inch increments up to 3 inches and corresponding values of ϵ and h_s' were observed. The results are shown in figure 6. In all cases, h_s' was found to be essentially directly proportional to h_r', while ϵ remained essentially zero for all settings of h_r'. It is evident that the slopes of the straight lines shown in figure 6 represent the percentage errors in dynamic pressure for the models tested at zero yaw. A more complete discussion of these results appears later in this paper.

Tests of models in yawed position.- By means of the arrangement shown in figure 1, it was easily possible to set any desired value of yaw. In the case of each model, after the test at zero yaw had been completed, the model was yawed by 2° increments (4° in the case of Tube A) from the 24° west to the 24° east position, h_r' being held nearly constant at about 3 inches of water, and the corresponding values of ϵ and h_s' were observed.

A few tests were made to see if ϵ and h_s' were directly proportional to h_r' for values of yaw other than zero. The data shown in figure 7 are typical of the results. Within the scope of the investigation, it appeared that ϵ and h_s' were at all times essentially directly proportional to h_r'.

Figures 4 and 8 have been prepared to illustrate the method by which the corrections for lack of jet uniformity and lack of tube symmetry were applied.

Referring first to figure 8, which is a graphical analysis of data taken for the BS model, the values of $-100\ h_s'/h_r'$ are seen to be plotted as the upper set of test points with east yaw and west yaw scales superposed. Since no essential correction need be applied to the h_s' values as far as air-stream nonuniformity is concerned, the slight lack of agreement of east yaw and west yaw test points probably indicates a slight lack of symmetry in the model. The upper dashed line averages the two sets of test points and represents the corrected static-head error against yaw curve.

In figure 8, the lower set of test points represent values of $100\ \epsilon/h_r'$ plotted with east yaw and west yaw scales superposed. Until the ϵ corrections are applied, no symmetry or agreement of the resulting curves are evident.

The following method is used to apply the ϵ corrections. The lateral displacement of the tip of the model for each yawed position is noted in figure 4 and the corresponding value of $-100\ \epsilon/h_r'$, for correction, is read from the ordinate of the curve that is vertically in line with the position of the tip.

The two smooth dotted curves are obtained after applying these corrections. These two curves are averaged by drawing the dashed curve midway between them. This dashed curve represents the negative of the corrected impact-pressure error against yaw relation.

The ordinates of the two dashed curves are now subtracted graphically and plotted to obtain the curve indicated by a full line, which represents the relation between resultant error and yaw.

It will be noted that the operation represented by the relation:

$$100\ \delta/h_r' = -100\ \epsilon/h_r' - 100\ h_s'/h_r'$$

has been accomplished graphically, and that corrections for nonuniformity of the air stream have been applied and that the effects of lack of model symmetry have been "averaged out."

In all instances in which the data indicated some

slight lack of model symmetry, such lack of symmetry was discovered to be present when a careful scrutiny of the tube was made.

The corrected curves obtained for the other models are shown in figures 9, 10, and 11. Discussion of these results will now be undertaken. Errors in percentage of dynamic pressure will be referred to simply as "errors."

PRECISION

The estimation of the absolute error for a single observation using the 1-inch capacity Ellison manometer, is ±0.003 inch of water, which gives an accuracy of ±1 percent of the dynamic pressure. In no case was reliance placed on a single observation. Continuous functions were investigated and many test points along the curve for each functional relationship were found. In the majority of instances the data represent independent observations by two independent operators.

DISCUSSION

Results for the BS model.- Based on the results shown in figure 5, the stem-effect error for the BS model would be expected to be about -0.1 percent and the tip-effect error (had a hemispherical tip been used) would be expected to be about 1.3 percent, making a net predicted error of 1.2 percent. The actual measured static-pressure error at zero yaw was 0.6 percent.

Reference 1 shows that the substitution of a conical tip for a hemispherical tip should make considerable difference in the static-pressure distribution, and in this case the correction for shape of tip, obtained from reference 1, amounts to about 1 percent, giving a predicted value of error of about 0.2 percent as against a measured value of 0.6 percent, which is a good check considering the uncertainty and large magnitude of the tip correction, and the fact that the static holes are grouped in three rows in a region where tip effect is severe and is changing rapidly with position of openings.

When tested in yawed positions, the model showed good "static symmetry" but only fair "dynamic symmetry," as

shown by figure 8. The lack of perfect dynamic symmetry can be explained by the fact that the conical tip was not precisely coaxial with the head, although this defect was so small that it was not discovered until after the yaw tests had been made.

Figure 8 shows clearly the effect of applying the air stream lateral-gradient corrections. Before such corrections are applied, the ϵ curves show no symmetry whatever and appear to wander without purpose; whereas, after the corrections are applied, two smooth curves emerge with a lack of agreement that can readily be attributed to the known lack of symmetry of the model tip.

With an increase in yaw, the BS model shows an increase in static-head error from 0.6 percent at zero yaw to about 14 percent at 24° of yaw, while the error in impact pressure ranges from zero at zero yaw to about -3 percent at 24° of yaw. The resultant error in dynamic pressure, then, ranges from 0.6 percent at zero yaw to about 11 percent at 24° of yaw.

Results for the NACA model.- The predicted stem-effect error (fig. 5) for the NACA model is about -0.25 percent and the predicted tip-effect error is about 0.5 percent, making a predicted resultant error of about 0.25 percent. The actual measured error was about 0.4 percent.

A peculiarity of this model, discovered after the tests had been made, was that the outside diameter of the nose was 0.303 inch instead of 0.312 inch, as intended. The lack of agreement of measured and predicted values might be attributed to this defect. The tool shown in figure 2 was used to keep all hemispherical tips in good condition, and the use of the tool on the NACA model produced only a portion of the complete hemisphere because of the lack of proper diameter of the nose.

Case No. 2, in table II, is a simulated NACA model and in those tests the agreement of predicted and measured errors was better, the values being, respectively, 0.45 percent and 0.60 percent.

When tested in yawed positions, the model showed good static symmetry and relatively poor dynamic symmetry. Careful scrutiny of the tip showed that the dynamic opening was not precisely in the center of the tip, and thus a lack of symmetry in dynamic yaw characteristics was to be expected.

Static-head errors ranged from 0.4 percent at zero yaw to about 15 percent at 24° of yaw; impact-pressure errors ranged from zero at zero yaw to about -23 percent at 24° of yaw; resultant errors ranged from 0.4 percent at zero yaw to about -8 percent at 24° yaw. The model could be yawed as much as 8° without increasing the resultant error beyond its value at zero yaw, and the resultant error at 7° appeared to be zero.

Results for Prandtl model.- The predicted stem-effect error for the Prandtl model (fig. 5) is about -1 percent, while the predicted tip-effect error is about 0.5 percent, making a resultant predicted error of about -0.5 percent as against the actual measured error of about 0.2 percent.

Case No. 1 in table II is a simulated Prandtl model, and there the predicted error was -0.3 percent as against a measured value of -0.42 percent, which was a good agreement.

For some time the investigators were puzzled concerning the lack of agreement in predicted and measured values for the actual model, but finally careful examination showed that the static slot was very slightly wider on the one side than on the other. With this trouble removed by bending the upstream portion of the head very slightly, a measured error of -0.5 percent could be obtained. But other measured values between -0.5 percent and 0.5 percent could also be obtained, depending on the nature of the various attempts to aline the nose with the rest of the head. All these results showed that the slot construction is very sensitive to slight defects in alinement.

When tested in yawed positions, the model showed poor static symmetry and excellent dynamic symmetry, as might be expected with a poorly adjusted slot and a tip in good condition.

From zero at 24° yaw, static, impact, and resultant-pressure errors ranged respectively as follows: 0.2 percent to 15 percent, zero to -22 percent, and 0.2 percent to -7 percent. The model could be yawed nearly 20° without exceeding an error of 2 percent in dynamic pressure, and its error at 17° was apparently zero.

Results for WNY model.- The predicted stem-effect error for the WNY model (fig. 5) is about -0.25 percent while the predicted tip-effect error is about zero, as

nearly as one can estimate considering the fact that there are eight rows of holes extending over a region about 7 tube diameters long. The resultant predicted error, neglecting the tip correction, is about -0.25 percent and, taking from reference 1 at tip correction of 0.4 percent, the final predicted error is 0.15 percent as against an actual measured error of about -0.35 percent.

Zero-yaw tests for this model made in November 1933 by two separate investigators, gave a measured error of 0.3 percent in each case. During the winter months the model received considerable use. Check tests in 1934 gave the value -0.35 percent mentioned above. The reason for this discrepancy has not been discovered.

No trouble was encountered in checking the results for any models except the Prandtl and the WNY models.

When tested in yawed positions, the WNY model showed good static symmetry and fair dynamic symmetry. From 0° to 24° of yaw, static, impact, and resultant errors ranged respectively as follows: -0.35 percent to 12 percent, zero to -9 percent, and -0.35 percent to 3 percent. Increasing the yaw beyond 20° apparently caused a decrease in resultant error.

Results for NPLmod model.- The predicted stem-effect error for the NPLmod model (fig. 5) is about -0.6 percent while the predicted stem-effect error is about zero, indicating an expected resultant error of -0.6 percent as against an actually measured error of about -0.5 percent.

In table II, Case No. 5 is the simulated NPLmod model case; the predicted and measured errors are respectively -0.55 percent and -0.58 percent.

When tested in yawed positions, the NPLmod model showed good static and dynamic symmetry. From 0 to 24° of yaw, static, impact, and resultant errors ranged respectively as follows: -0.5 percent to 12½ percent, 0 to -23 percent, and -0.5 percent to 11½ percent.

The interesting feature is that this model could be yawed as much as 14° without exceeding a resultant error of 0.7 percent. At about 13° of yaw, the resultant error was zero.

Results for NPL model.- The predicted stem-effect er-

ror for the NPL model (fig. 5) is about -1.5 percent, while the predicted tip-effect error for a hemispherical tip is about 1 percent, indicating a resultant error without tip correction of about -0.5 percent as against a measured error of about -0.8 percent. After the application of a tip correction from reference 1, the predicted error becomes -1.5 percent.

When tested in yawed positions, the NPL model showed good static symmetry but rather poor dynamic symmetry. As in the case of the BS model, examination of this NPL model showed that the conical tip was not precisely coaxial with the head. From 0 to 24° of yaw, static, impact, and resultant errors ranged respectively as follows: -0.8 percent to 13 percent, 0 to -10 percent, and -0.8 percent to 3 percent. Beyond about 14° of yaw, the resultant error appeared to decrease.

Results for ASHVE model.- The predicted stem-effect error for the ASHVE model (fig. 5) is about -1.2 percent, while the predicted tip-effect error is about zero, for a hemispherical tip, so that the expected resultant error, without tip correction, is about -1.2 percent as against a measured error of about -1.00 percent. The application of an approximate tip correction from reference 1 increases the predicted error to about -1.4 percent.

When tested in yawed positions, the ASHVE model showed fair dynamic symmetry but poor static symmetry. Careful examination of the model disclosed the fact that the x distance for the static-opening grouping on one side of the model was about one third of a tube diameter different from the x distance on the other side of the model. This difference had not been observed until after the test had been made, and it might contribute something to the lack of static symmetry. From 0 to 24° of yaw, the static, impact, and resultant errors ranged respectively as follows: -1.0 percent to about -3 percent, 0 to about -12 percent, and -1.0 percent to about -15 percent.

For this model, static and impact errors were always of the same sign so that resultant errors were not reduced by any partial cancelation of component errors.

Results for Tube A.- The predicted stem-effect error for Tube A (fig. 5) is about -4.4 percent while the predicted tip-effect error is about 0.4 percent for a hemispherical tip, so that the final predicted error without

tip correction is somewhere around -4 percent as compared with an observed error of -14.5 percent for the case of no stem extension. This value leaves a 10 percent error to be explained by the assumption that static openings, which were about three shell thicknesses in diameter, were incapable of recording the actual static pressures where they were located and by the fact that the stem extended about 1.5 tube diameters above the head, thereby causing a larger error than is represented in figure 5. When tested with the extension in place, Tube A showed, at zero yaw, the surprising error of -18 percent.

When tested in yawed positions, Tube A showed fair static and dynamic symmetry, and from 0 to 24° of yaw, the static, impact, and resultant errors ranged as follows: -14.5 percent to 0.5 percent, 0 to -3 percent, and -14.5 percent to -2.5 percent, with the extension removed; -18 percent to -3 percent, 0 to -3 percent, and -18 percent to -6 percent with the extension in place.

VALIDITY OF THE CONCLUSIONS OF REFERENCE 1

One of the major purposes of this investigation was to see if measured discrepancies (for errors of seven models at zero yaw), if any, could be explained by the conclusions of British R. & M. No. 981. At this point it is possible to form an opinion based on the experimental evidence.

A study of the discussion of results just presented shows that, despite the influence of many variables such as shape of the tip and scheme of arrangement of the static openings relative to each other, it was possible in nearly all cases to predict the sign and approximate amount of the error of a model at zero yaw from a knowledge of the location of the static-hole grouping relative to stem and tip.

From a study of table II one may conclude that, when the influences of secondary variables are removed, the agreement of predicted and measured errors at zero yaw becomes almost exact.

The investigators conclude, therefore, that the conclusions of reference 1 <u>are</u> valid, and that the errors of the models tested at zero yaw <u>can</u>, in general, be explained

by the governing factors of location of static openings relative to stem and tip and the shape of the tip given therein.

ATTEMPTS AT FLOW VISUALIZATION

Before any further discussion of the tests thus far described, it may be fitting to discuss figures 12 and 13, which show some of the records made by a modification of the Fales technique. (See reference 3.) The photographs must not be regarded as giving true indications of flow in detail, and too sweeping conclusions cannot be drawn from them.

The Fales technique is a method of making the flow about an object visible. The object is secured to a glass plate mounted in the air stream of the tunnel. A mixture of lampblack and kerosene is spread over the glass plate and under the action of the air stream assumes a pattern such as those shown in figures 12 and 13.

Figure 12 shows a Fales record made using a head with hemispherical tip and stem of the same diameter as the barrel of the head. The pronounced stem effect is evident in the record.

Figure 13 is a record of the flow about a model of Tube A with stem and indicates a very large damming effect due to the stem. The arrows indicate the position of the static openings.

SYSTEMATIC CONTROL OF VARIABLES IN YAW TESTS

As long as the angle of yaw is held at zero, it appears that the x and y distances are the major variables controlling errors in measuring the dynamic pressure. When the angle of yaw is varied, however, it can be seen from figures 9, 10, and 11 that there is the widest variation of error-yaw characteristics with varying designs of tubes. In order to understand the reasons for such variation, it will evidently be necessary to list the controlling variables under conditions of yaw, to restrict some permanently to constant values, and systematically to vary the others one at a time, through practical ranges.

In many applications of the pitot-static tube, the amount of yaw is unknown. Mechanical alinement of a pitot-head does not insure zero yaw in turbulent or swirling flow.

It seems reasonable to suppose that an instrument which is designed to perform well under conditions of moderate yaw in a uniform straight-line flow will also perform well when set mechanically at supposed zero yaw in an air stream having some erratic tendencies as far as swirl and turbulence are concerned.

The problem, then, seems to be to design an instrument which not only performs well when the yaw is known to be zero but which also performs with only slightly less accuracy at unknown angles of as large a magnitude as may prove to be feasible.

The discussion of the general problem of performance under conditions of yaw will be simplified by the definition of the following additional symbols.

θ, angle of yaw, in degrees.

Y, plane of yaw; i.e., plane containing head axis and streamline that impinges on tip of head.

i, diameter of impact opening, in inches.

s, diameter of each static hole, in inches.

t, shell thickness of outer tubing, in inches.

d_1, external diameter of interior tube, in inches.

d_s, external diameter of stem, in inches.

α, form of connection between stem and head.

β, form of tip.

τ, form and grouping of static holes.

ν, kinematic viscosity of air.

e_0, value of e (error in dynamic pressure) when $\theta = 0$.

e_θ, value of e when $\theta = \theta$.

Δe, $e_0 + \Delta e = e_\theta$.

K, coefficient; definition: $h_v = Kh_v'$.

C, zero yaw coefficient, equal to K when $\theta = 0$.

C', yaw coefficient; definition: $CC' = K$.

Variables controlling the measured value of static head, h_s'.- While it might be said that h_s' is controlled by the true static head, the Reynolds Number, and the shape of the instrument, a more specific generalization would probably require the following statement:

$$h_s' = f_1 \quad h_s, \nu, h_v, d, d_s, \alpha, \beta, \tau, \theta, Y, x, y, s, t, d_i$$

Of these variables, ν, h_v, and d control the Reynolds Number while the others (h_s excluded) define the effective shape of the instrument.

The factors, s, t, d_i, and τ affect the flow through the instrument head, under conditions of yaw. If yaw exists, the pressure distribution around the head will not be symmetrical with respect to the head axis, so that a pressure differential causing flow into some static openings and out of others will exist. The energy losses associated with this flow will depend on the nature of constriction in this region of flow and will help to determine the pressure, which is recorded as h_s'. The nature of the constriction will depend upon s, t, d_i, and τ.

For air velocities between 10 and 100 miles per hour, it will be nearly true to say that:

$$h_s' = f_2 \, [h_s, d_s, \alpha, \beta, \gamma, \theta, Y, x, y, s, t, d_i]$$

and if, in addition, $\theta = 0$, and $d_s = d$, and $\beta =$ constant, it may be said that:

$$h_s' = f_3 \, [h_s, x, y]$$

which has been demonstrated in the work so far described.

Variables controlling the measured value of the impact pressure h_d'.- The measured impact pressure is probably controlled by the Reynolds Number and the effective shape of the tip. This function might be expressed as follows:

$$h_d' = f_4 \; [h_v, \nu, d, \beta, i, \theta, h_s]$$

Of these variables, the first three control Reynolds Number and the next three control the effective shape.

For zero yaw, if air speeds range from 10 to 100 miles per hour and if the tip form including impact opening is symmetrical with respect to the head axis, it is probably safe to say that:

$$h_d' = f_5 \; (h_v, h_s) = h_v + h_s$$

Variables controlling the measured value of the dynamic pressure h_v'.- If the statements made in the previous sections are correct, then the variables controlling the value of h_v' can be found from the relation:

$$h_v' = h_d' - h_s'$$

Thus, in general,

$$h_v' = f_6 \; [h_v, \nu, \alpha, \beta, \gamma, \theta, Y, x, y, d, d_s, i, s, t, d_i]$$

For zero yaw, if air velocities range from 10 to 100 miles per hour, if $x > 8$, $y > 16$, and true tip symmetry exists,

$$h_v' = f_7 \; (h_v, y)$$

If α, β, γ, Y, x, y, h_v, ν, d, d_s, and θ are held constant, then it follows that,

$$h_v' = f_8 \; (i, s, t, d_i)$$

In an effort further to systematize the discussion of pitot-static tube performance, it may now be useful to consider the significance of certain coefficients.

Theory of pitot-static coefficients.- Using the pre-

viously defined symbols, we may write,

$$h_v = K\, h_v' = CC'\, h_v'$$

and

$$e_\theta = \left[\frac{h_v' - h_v}{h_v}\right] 100 = \left[\frac{h_v' - K\, h_v'}{K\, h_v'}\right] 100 = \left[\frac{1 - K}{K}\right] 100$$

Therefore, $$K = \frac{100}{100 + e_\theta}$$

But $$e_\theta = e_0 + \Delta e, \quad \text{and} \quad K = CC'$$

Therefore, $$CC' = \frac{100}{100 + e_0 + \Delta e}$$

Now, if $$C = \frac{100}{100 + e_0} \quad \text{and} \quad C' = \frac{100}{100 + \Delta e}$$

then,

$$CC' = \frac{100}{100 + e_0 + \Delta e + \dfrac{(e_0)\,(\Delta e)}{100}} = \frac{100}{100 + e_0 + \Delta e} \quad \text{nearly,}$$

for small values of e_0 and Δe.

We may now write:

$$C = \frac{100}{100 + e_0} = \frac{(100)^2 - 100\, e_0}{(100)^2 - e_0^2} = 1 - \frac{e_0}{100} \quad \text{nearly,}$$

and, similarly, $C' = 1 - \frac{\Delta e}{100}$, nearly, for small values of e_0 and Δe.

Now e_0 and Δe can be measured experimentally by the technique described and, from these values, C and C' can be computed easily.

Example: Suppose $e_0 = -1$ and $\Delta e = -6$ as found by experiment. Then $C = 1.01$ and $C' = 1.06$ and CC' will be $1 + 0.01 + 0.06 + 0.006 = 1.076$; whereas the true value

of K will really be $\frac{100}{0.930} = 1.078$.

The significance of these coefficients lies in the fact that the error effect of any given amount of yaw is expressed simply and separately by the coefficient C', while the error inherent in the design at zero yaw can be expressed simply and separately by the coefficient C. If the yaw is zero, then C' becomes unity.

With this preliminary discussion, it now becomes possible to make a further attack on the problem.

Restriction of variables for test purposes.- It has been stated that if α, β, γ, Y, x, y, h_v, ν, d, and d_s are fixed, then, for any fixed value of θ,

$$h_v' = f_8 [i, s, t, d_i]$$

The choice of the basic fixed values for the many quantities to be held constant, while one of the foregoing four variables is being varied, must depend upon judgment. Certain practical guiding principles do exist, however, so that it is possible to make logical choices. The remainder of this article will be devoted to making, and attempting to justify, selections of basic constant values for d, d_s, α, β, γ, Y, x, y, h_v, ν, i, s, t, and d_i.

1. Let $d = d_s = 5/16$ inch.- Factors considered: strength and rigidity; obstructions to the average air stream; space requirements for interior tubes and static openings; commercial sizes of tubing available; construction advantages of having stem and head made integral; possibility of use of a stem extension to take care of cases in which unusual rigidity is required.

2. Selections for α.- Factors considered: gland requirements in inserting instruments in closed ducts; simplicity of construction; elimination of sources of leakage; rigidity.

3. Selections for β - hemispherical tip.- Factors considered: ruggedness; simplicity of construction and duplication; ease of maintenance by use of forming tool (see fig. 2); longitudinal head space occupied by tip.

4. Selections for γ - eight static holes with equal

radial spacing.- Factors considered: Ease of duplication and construction; consistency of performance; simplicity; probability of elimination of effective bur (a very tiny misalinement of the upstream and downstream portions of the head appears to produce a serious, effective bur in the Prandtl slot design); h_s' not to be a function of Y. (A considerable number of supplementary tests, not listed in this report, were helpful in showing that not less than eight holes can be used if the last requirement is to be obeyed.)

5. Selections for Y, the plane yaw.- In all tests described in this report the plane of yaw is normal to the stem of the instrument. In supplementary tests, the effective plane of yaw was varied by constructing an instrument so that the upstream portion of the head, containing the static openings under test, could be rotated about the head axis, with respect to the downstream portion of the head. The results appeared to show that eight or more equally spaced static holes would be essentially insensitive to the location of the plane of yaw, for a given value of θ.

6. Let $x = 8$, and $y = 16$.- Factors involved in the selection: certainty of duplication of instrument performance, leading to rejection of idea of canceling tip and stem effects; minimum distance between the tip and static openings, and minimum over-all head length consistent with the previous requirement; desirability of even values for coefficient C under three possible types of application: without stem, with stem, with stem extension.

7. Let $h_v = 3$ inches of water and allow V to vary through normal atmospheric ranges.- Reasons: previously described work shows that the effect of Reynolds Number variation is secondary within the velocity limits used, and the value of 3 inches is the largest value that can be recorded accurately with the manometers used.

Values for i, s, t, and d_i can logically be selected only after additional experimental information has been obtained.

EFFECT OF UNFIXED VARIABLES

Effect of size of impact opening on impact pressure error.- Six different sizes of impact openings were used,

and the test results are plotted in figure 14. The general conclusion is that, for any given angles of yaw, the impact-pressure error decreases as the impact opening is enlarged and that, for angles of effective yaw exceeding 8°, this effect is very pronounced.

Effect of size of static openings on static-pressure error.- Six different sizes of static-pressure openings were used and the test results are given in figure 15. For the given test conditions one general conclusion is that for any given angle of yaw, the static-pressure error is not greatly affected by variations of size of static opening above 0.02 inch. Very small openings probably introduce energy losses associated with the flow through the head, thus cutting down the static-pressure errors as shown.

Effect of size of shell thickness and size of interior tube on static-pressure error.- The results plotted in figures 16 and 17 were obtained by the use of dummy tips so constructed that t and d_i could be varied and show the effect of the shell thickness and the interior-tube diameter. Both figures show that if the clearance between the inner wall of the shell and the outer wall of the interior tube becomes too small, the energy losses, associated with the flow through the head, become large enough to diminish the static-pressure errors. A complete theoretical interpretation of the static-pressure-error variations observed in figures 15, 16, and 17 would probably be complex if not impossible. No attempt is made to present the results of even such crude attempts, in this direction, as have been made.

Selection of suitable values for s, t, i/d, and d_i.- Figure 15 indicates that a static opening having a diameter of 0.040 inch would not be objectionable. In any case, relatively large changes in s or t, from these selected basic values, would make no change in the performance of the instrument. This feature would be a distinct advantage from the important consideration of duplication of instruments to give the same performance. That the static-opening diameter corresponds to the No. 60 drill and that s and t can be made numerically equal, are minor, but appealing factors.

The important consideration of duplication of instrument coefficients, even with moderate variation in certain dimensions, indicates that the constrictions, necessary to

produce low static-pressure errors under yaw conditions, should not be tolerated, because it would be too delicate a task to control the amount of constriction and, because as far as the necessary small static holes for such purposes are concerned, they are too difficult to drill and become too easily obstructed.

A necessarily large, but definite, static-pressure error must consequently be balanced by the negative impact-pressure error furnished by the tip. A study of figures 14, 15, and 16 shows that up to 12°, or more, of yaw, this balance can be expected very nearly if i/d be chosen as 0.2, which would make $i = 1/16$ inch.

Figure 17 tends to show that d_i should be made as small as possible, although up to 12° of yaw almost any selection up to 0.14 inch would be adequate.

There will be no objection to selecting d_i so that the bore of the interior tube is equal to i, or 1/16 inch, which can be done by using 1/8-inch copper tubing of 21 gage thickness. Therefore, it would seem reasonable to make $d_i = 0.125$ inch.

A check on rigidity for an outer tube diameter of 5/16 inch and a thickness of 0.040 inch shows that a brass tube would furnish a rigidity (EI) factor of about 5,000, and the absolute drag coefficient (C_D) per foot of length, would be about 1.2. From this value the expected pitch or dive angle for the head could be computed for any given air speed and method of mounting. For extreme applications, a stem extension, different tube material, stem reinforcement by means of a 1/4- by 1/4-inch steel strip soldered in rear of the tube, or any combination of these arrangements could be used.

In steady flow, the vibration problem should not occur but, in those cases where it does, the solution of the difficulty can probably be found by changing the effective EI or method of mounting to avoid a critical frequency.

The considerations of ease and certainty of duplication, ease of tip maintenance, aerodynamic obstruction, stem and head rigidity, small error from longitudinal pressure gradient in the air stream, known coefficients, yaw insensitivity, adaptability in service, ease of construction, and other factors have led with some logic to

the selection of the dimensions and shape factors mentioned.

A check-up will reveal that the order of selection has been as follows:

$$d, \alpha, \beta, \gamma, x, y, s, t, i, d_i.$$

These selected values are tabulated in summarized form in table III, and a drawing of the corresponding instrument is shown in figure 18.

PERFORMANCE OF PROPOSED TENTATIVE STANDARD INSTRUMENT

Figure 19 was drawn by combining the results obtained with $i/d = 0.2$ (fig. 14) with the results obtained for $s = 0.040$ inch (fig. 15).

The actual instrument finally built and tested had the brass fitting (for attaching the stem extension, shown in fig. 18), soldered on, and had the four-hole static-hole arrangement used in obtaining the data for figure 15. The actual performance of this instrument was almost precisely as predicted, showing negligible effect from the presence of the brass fitting.

The number of static openings was then increased to eight. Under this condition the dynamic performance was, of course, the same as before, but there was a slight change in the static performance, in that static-pressure errors between 12° and 20° of yaw were about 0.5 percent of the dynamic pressure higher than those predicted and measured for the four-hole static-hole arrangement. This value was considered a good check, and it was not considered worth while to alter figure 19 to show this small change.

The data obtained in the tests of the actual instrument are given in table IV, and the values of the C and C' coefficients for the finally evolved instrument (eight-hole static-hole arrangement) are given in table V.

It may be noted that the dynamic pressure is given correctly, within 1 percent, up to 14° of effective yaw by applying the proper value of C and considering C' equal to unity. This fact is important because, when the amount

of effective yaw is unknown, application of the correct value of C' becomes impossible.

CONCLUSIONS

It is believed that the general objectives have been accomplished. In addition, several secondary elements have been encountered and subjected to study.

Much work on the topic of the pitot-static tube remains to be done. The N.A.C.A. is now conducting a research on this subject with special emphasis on the influence of Reynolds Number variation.

Eventually, it is probable that an instrument will be devised which, in general characteristics and performance, will be superior to any now in existence, including the tentative standard herein proposed.

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Worcester, Mass., July 25, 1935.

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TABLE I

SPECIFICATIONS OF MODELS

	BS	WNY	NACA	NPLmod	ASHVE	Prandtl	NLP	A
Outside diameter of stem, inches	5/16	5/16	5/16	5/16	5/16	5/16	5/16	0.432
Outside diameter of head, inches	5/16	5/16	5/16	5/16	5/16	5/16	5/16	0.272
Shape of nose	Con	Con	Hem	Hem	Con	Hem	Con	Con
Outside diameter of nose, inches in tube diameters	0.138 .44	0.135 .44	0.303 .97	5/16 1.00	0.100 .32	5/16 1.00	0.178 .57	0.156 .57
Length of nose taper, inches in tube diameters	1.50 4.7	1.00 3.2			0.45 1.44		1.33 4.26	0.90 3.3
Pitch of taper	1-5.7	1-6			1-2.2		1-10	1-7.7
Inside diameter of nose, inches in tube diameters	0.116 .38	1/16 0.20	1/16 0.20	1/16 0.20	1/16 0.20	1/16 0.20	1/16 0.20	0.118 .43
Diameter of static holes, inches	0.038	0.038	0.038	0.038	0.020	slot 0.031	0.038	0.055
Shell thickness at static holes, in.	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.02
Number of rows of static holes	3	8	2	1	3	slot	3	1
Number of static holes per row	7	6	4	7	2	slot	7	4
Distance between rows of holes, in. in tube diameters	0.2 .64	0.28 .90	0.05 .16		0.07 .22		0.20 .64	
*x in inches in tube diameters	0.65 2.08	2.07 6.7	0.95 3.0	1.93 6.2	2.56 8.2	0.90 2.9	0.75 2.4	0.80 2.9
*y in inches in tube diameters	12.9 41.8	7.85 25.2	8.00 25.6	4.80 15.4	2.56 8.2	3.00 9.6	2.00 6.4	0.73 1.7
*L in inches in tube diameters	15.1 48.6	10.9 35.1	9.07 29.0	6.87 22.0	5.58 17.9	4.03 12.9	4.08 13.1	2.70 -

*Length x is the distance from the center of the static-hole grouping to the base of the nose, or tip; y is the distance from the center of the static-hole grouping to the axis of the stem; L is the distance from the stem axis to the end of the tip.

TABLE II

TESTS OF MODELS SIMULATED BY STATIC TUBE AND DUMMY STEM

Case number	x in tube diameters	y in tube diameters	Tip-effect error from figure 5, percent	Stem-effect error from figure 5, percent	Resultant predicted error, percent	Actusl measured error, percent
1	2.8	9.6	0.70	-1.00	-0.30	-0.42
2	2.8	25.6	.70	-.25	.45	.60
3	2.8	17.5	.70	-.40	.30	.32
4	2.8	13.2	.70	-.65	.05	0
5	5.9	15.4	0	-.55	-.55	-.58
6	5.9	13.0	0	-.65	-.65	-.68
7	5.9	9.3	0	-1.00	-1.00	-1.00
8	5.9	19.2	0	-.40	-.40	-.35
9	8.0	17.0	-.05	-.45	-.50	-.60

TABLE III

SUMMARY OF RECOMMENDED GOVERNING SPECIFICATIONS
FOR STANDARD PITOT-STATIC TUBE

(See figure 18 for reference drawing)

1. OUTER TUBING..5/16 inch by 18 gage brass tubing (18 gage is a shell thickness of 0.040 inch).

2. INNER TUBING..1/8 inch by 21 gage copper tubing (21 gage is a shell thickness of 0.0285 inch, or about 1/32 inch, i.e., an inside diameter of 1/16 inch).

3. SHAPE OF TIP..Hemispherical.

4. DYNAMIC OPENING..1/16 inch diameter hole, drilled accurately coaxial with head.

5. LOCATION OF STATIC OPENINGS..Eight tube diameters downstream from base of tip, and sixteen diameters upstream from the stem axis.

6. NATURE OF STATIC OPENINGS..Single row of eight holes, made with a No. 60 drill (0.040 inch diameter), with equal peripheral spacing in a plane normal to the head axis.

7. INNER-TUBE SPACER..A brass spacing ring, soldered to the copper tube and fitting snugly the inner surface of the beass tube, is to be used, as shown in figure 14, to keep the axis of the inner tube coaxial with the head at the static opening location.

8. CONDITION OF OPENINGS..Static and dynamic openings are to be clean and free from bur, as nearly as can be determined by careful visual examination supplemented by the sense of touch.

9. CONDITION OF TIP..Perfect condition of the tip is to be maintained by means of the forming tool, similar to that shown in figure 2.

10. STEM..The stem is to be connected to the head as shown in figure 18. The length of the stem is limited by service conditions. When necessary, a stem extension may be used to give proper rigidity to the instrument.

TABLE IV

Data obtained with instrument proposed as a tentative standard using first the four-hole arrangement and finally the proposed eight-hole arrangement of static openings. h_r' was held at 3 inches of water.

Angle of yaw in degrees	h_s' with 4 holes and with stem extension	h_s' with 4 holes and without stem extension	h_s' with 8 holes and without stem extension	h_s' with 8 holes and with stem extension
24W	-0.327	-0.339	-0.340	0.675
20W	-.214	-.229	-.245	.486
16W	-.130	-.154	-.165	.264
12W	-.068	-.086	-.100	.122
8W	-.019	-.037	-.040	.027
4W	.021	.003	.005	-.006
0	.034	.017	.017	-.002
4E	.021	.000	.005	.020
8E	-.020	-.040	-.045	.042
12E	-.070	-.090	-.100	.120
16E	-.131	-.151	-.165	.265
20E	-.211	-.230	-.250	.438
24E	-.323	-.341	-.340	.645

TABLE V

Values of coefficients C and C', for proposed tentative standard instrument, found by analyzing the data given in the last two columns of table IV. See text for method of analysis and meaning of the coefficients.

Method of application	Value of C
Without stem or extension	1.000
With stem, but without extension	1.005
With both stem and extension	1.010
Angle of yaw in degrees	**Value of C'**
0	1.000
2	.999
4	.996
6	.991
8	.988
10	.990
12	.995
14	1.005
16	1.023

These coefficient values should be reliable within ±0.2 percent

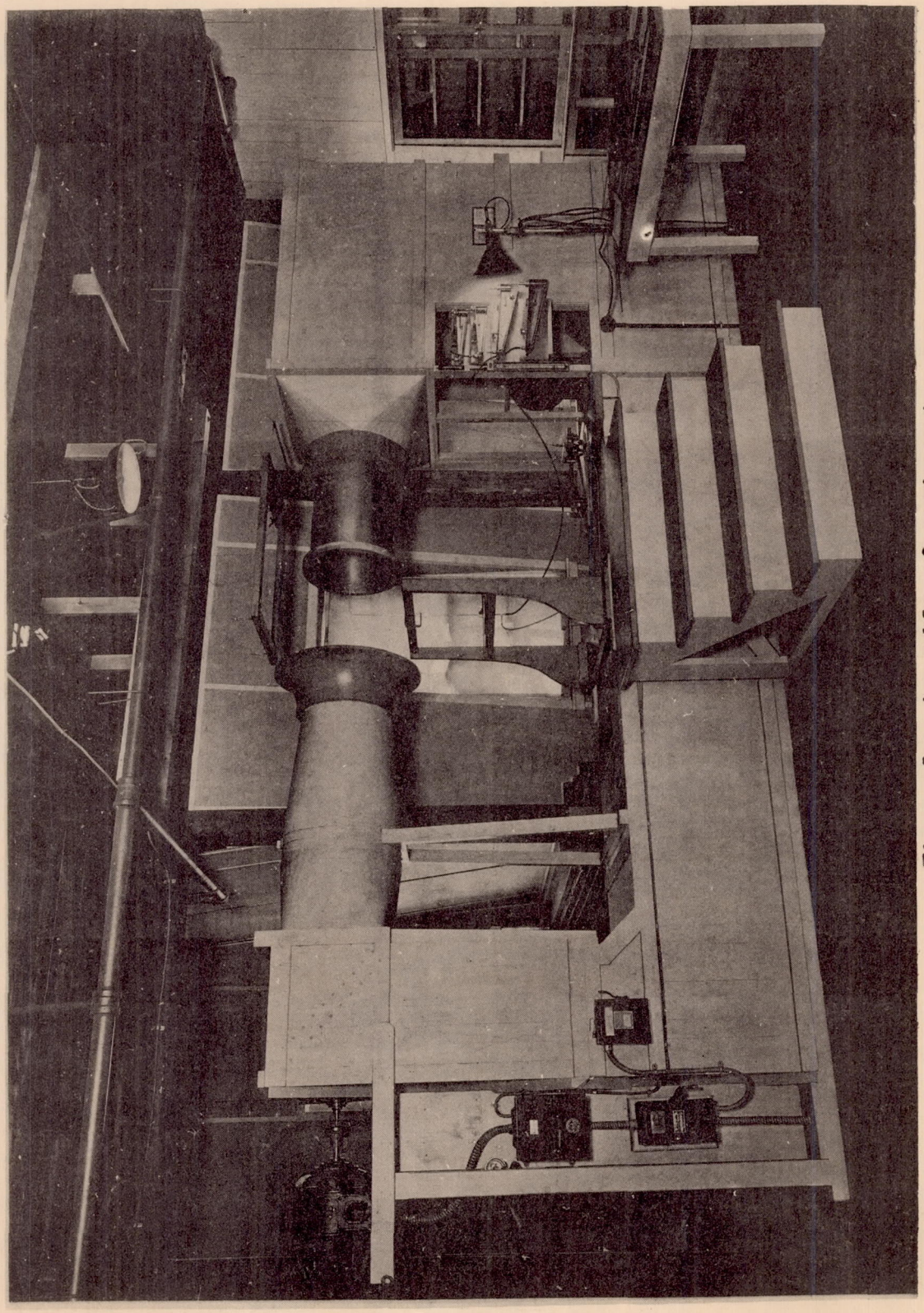


Figure 1.- Assembly of equipment.

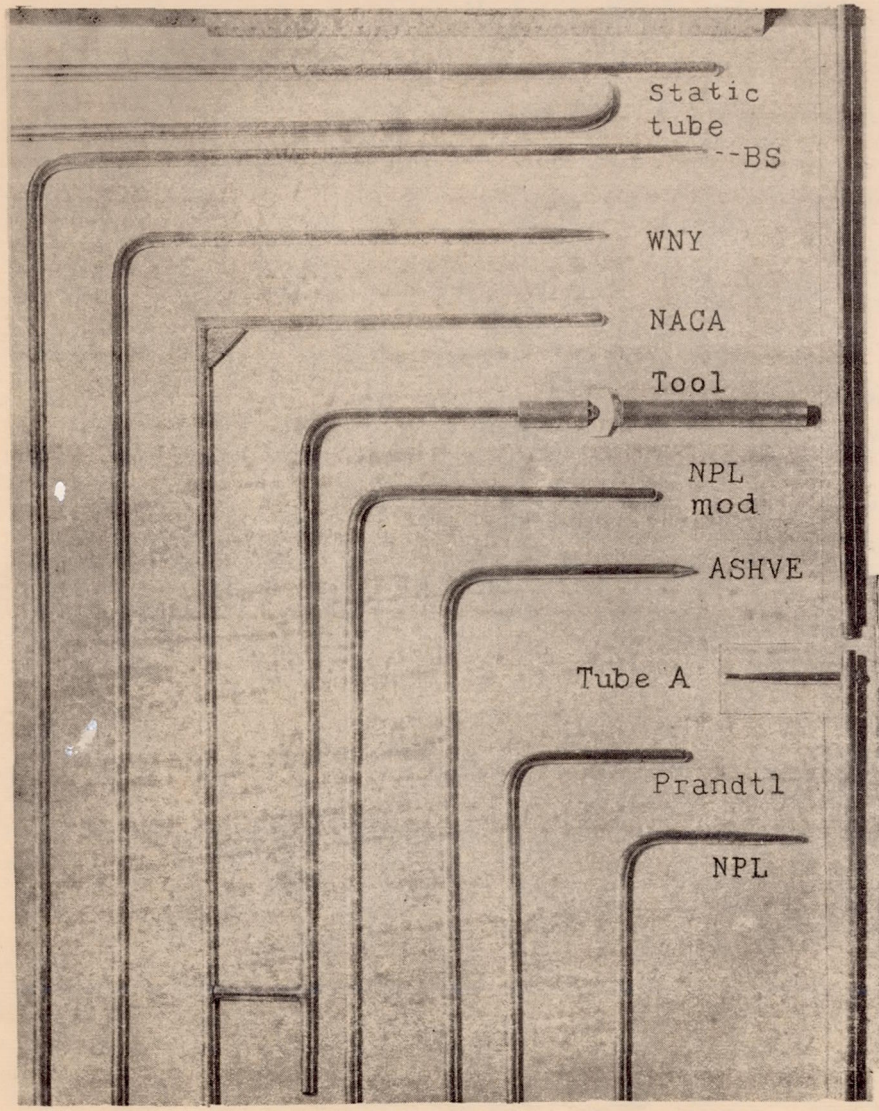


Figure 2.- Models used in investigation.

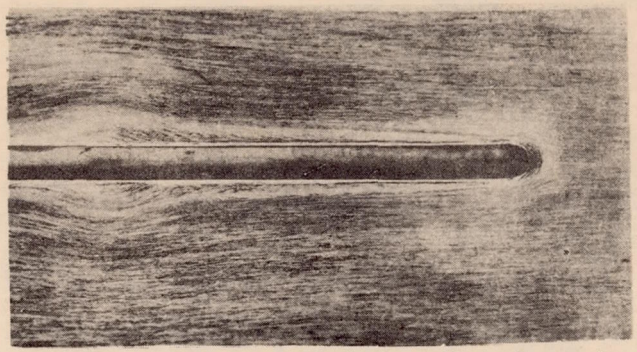


Figure 12.- Fales record for flow by a head with hemispherical tip and with a stem (in position shown) of same diameter as that of the head.

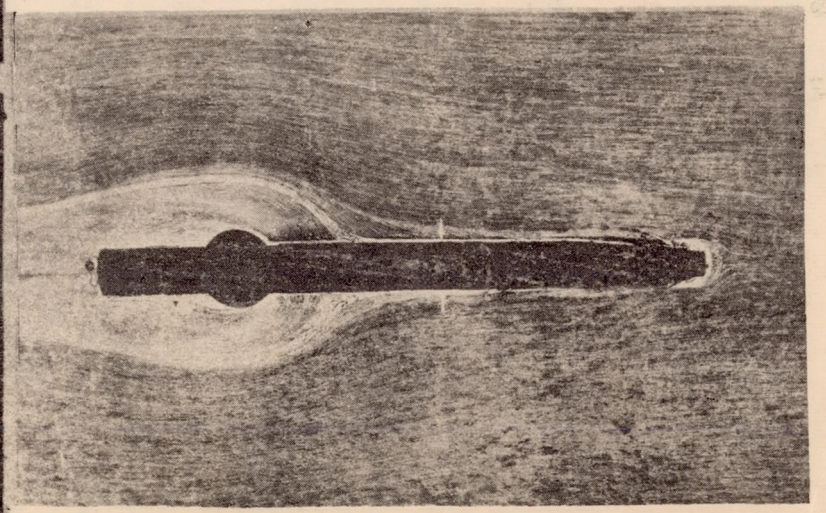


Figure 13.- Fales record for flow by a model simulating conditions in tube A .

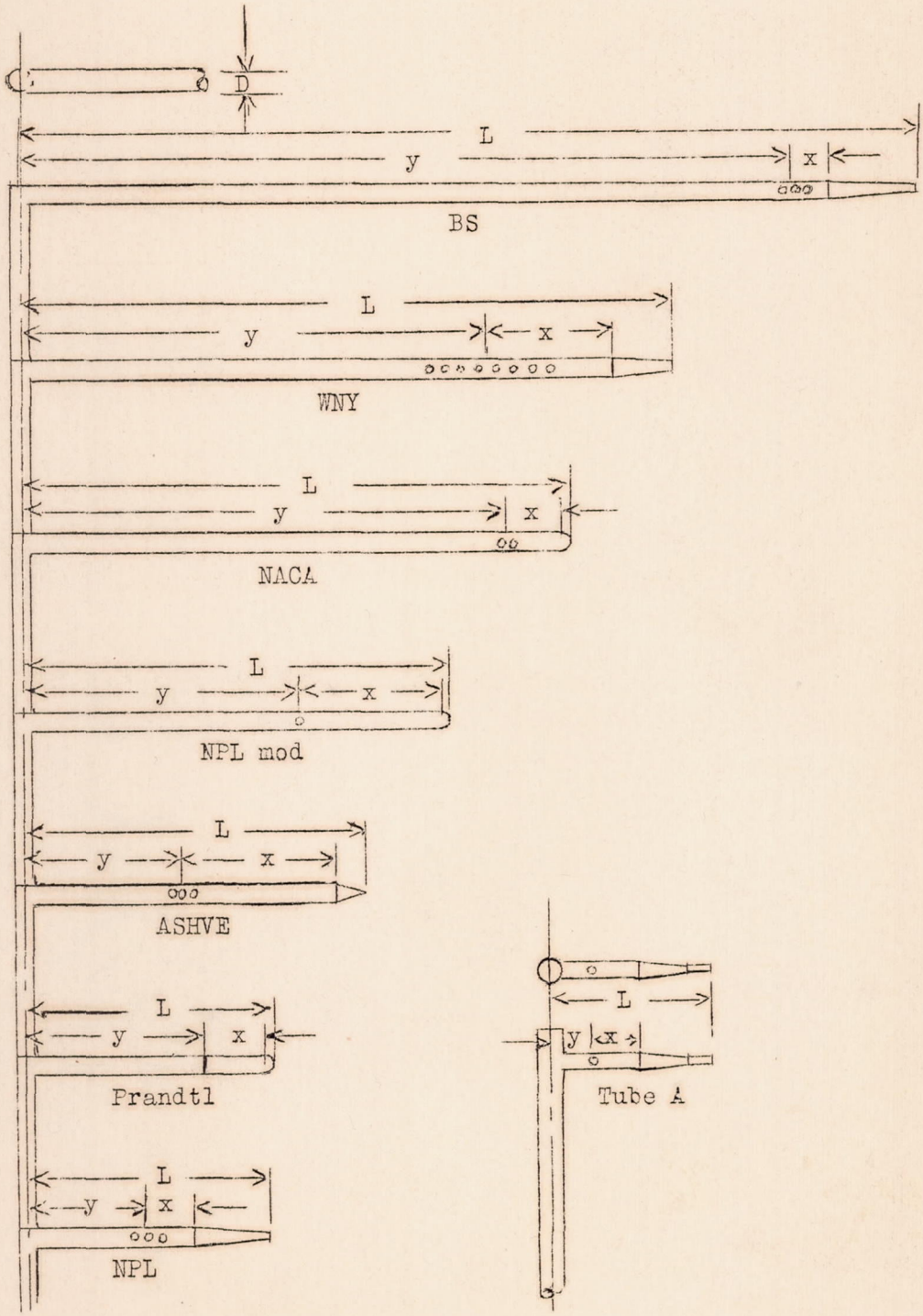


Figure 3.- Diagram of models used in investigation.

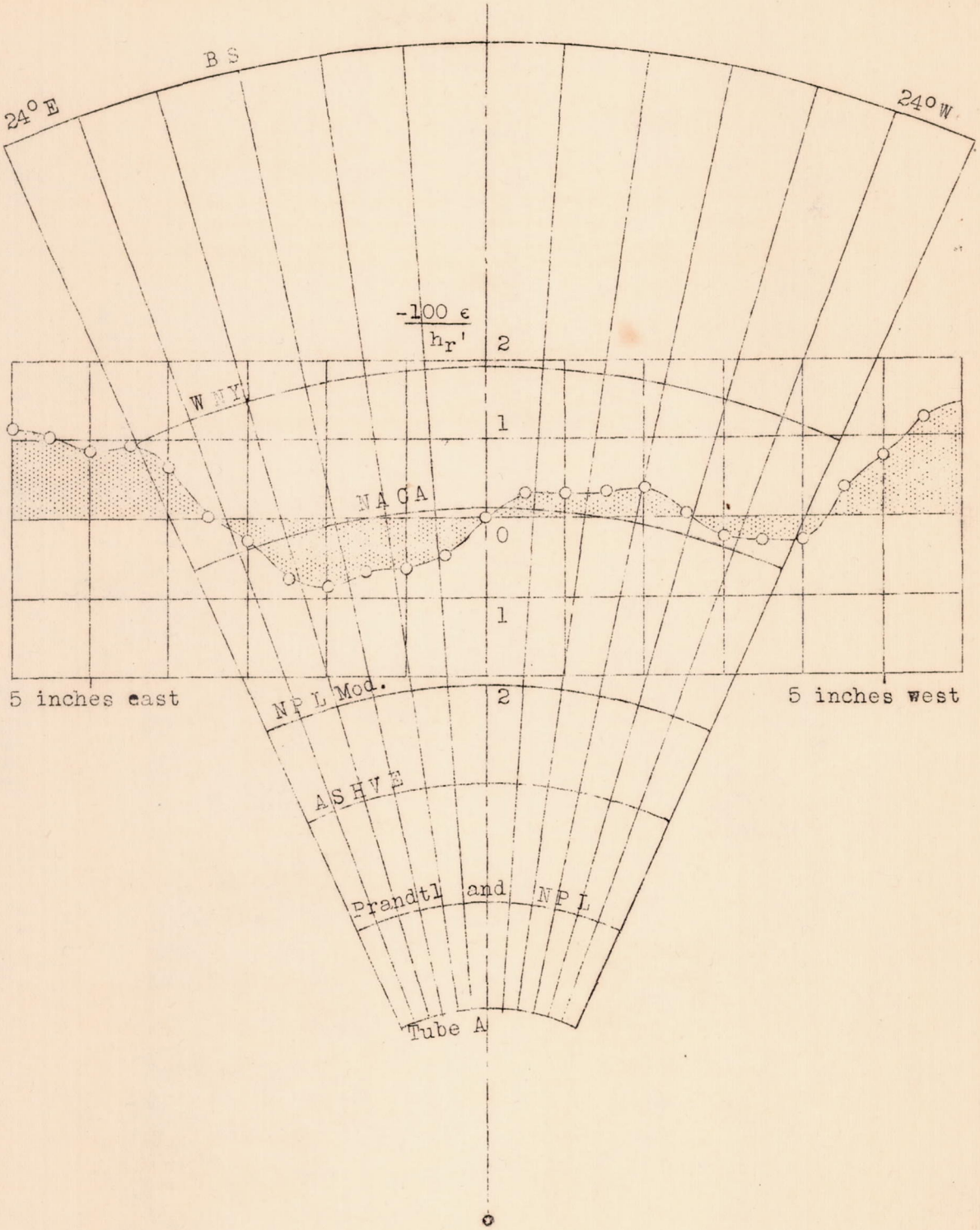
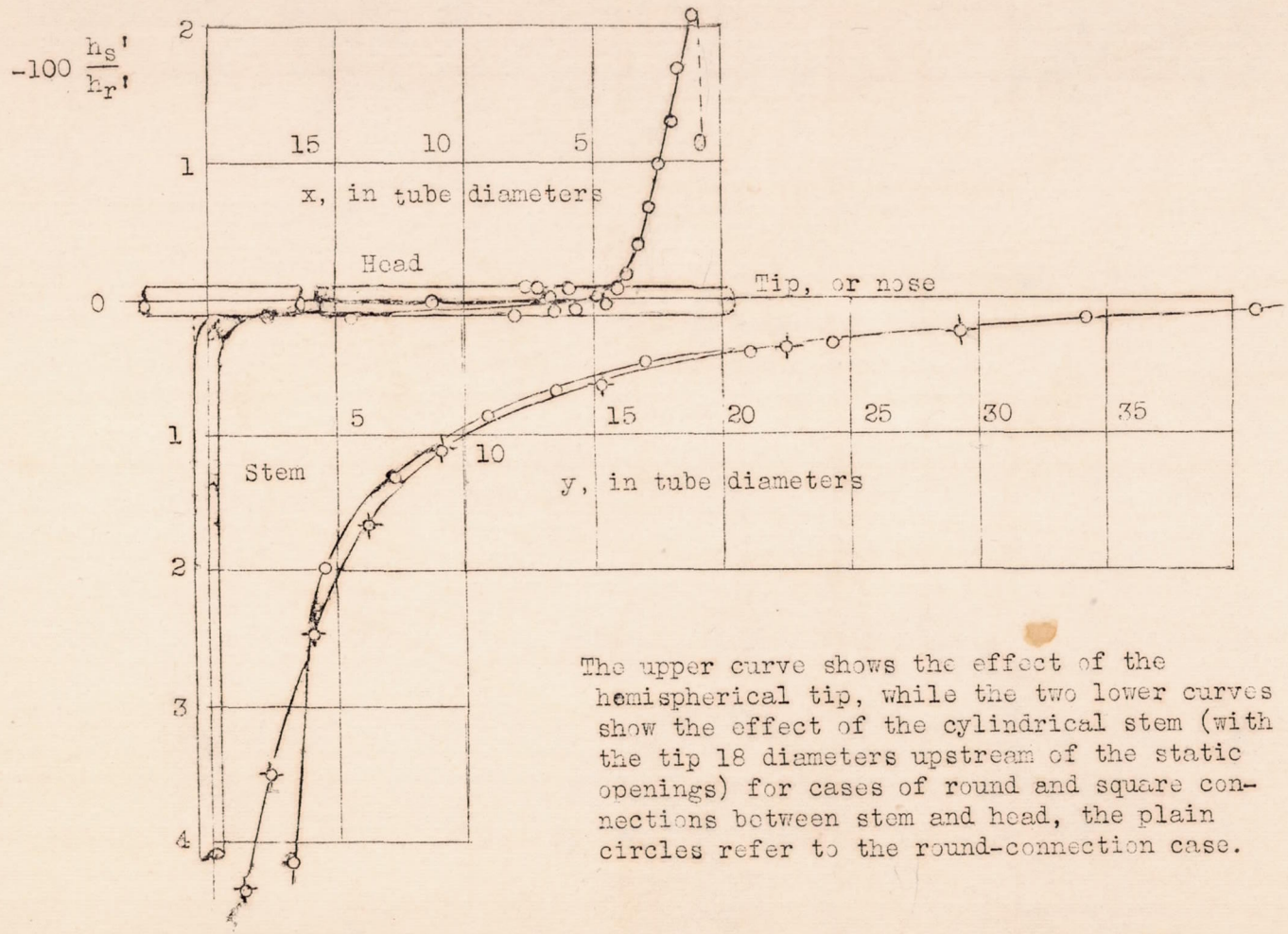


Figure 4.- Chart used in correcting for nonuniformity of air stream.



The upper curve shows the effect of the hemispherical tip, while the two lower curves show the effect of the cylindrical stem (with the tip 18 diameters upstream of the static openings) for cases of round and square connections between stem and head, the plain circles refer to the round-connection case.

Figure 5.- Static pressure errors caused by presence of stem and tip.

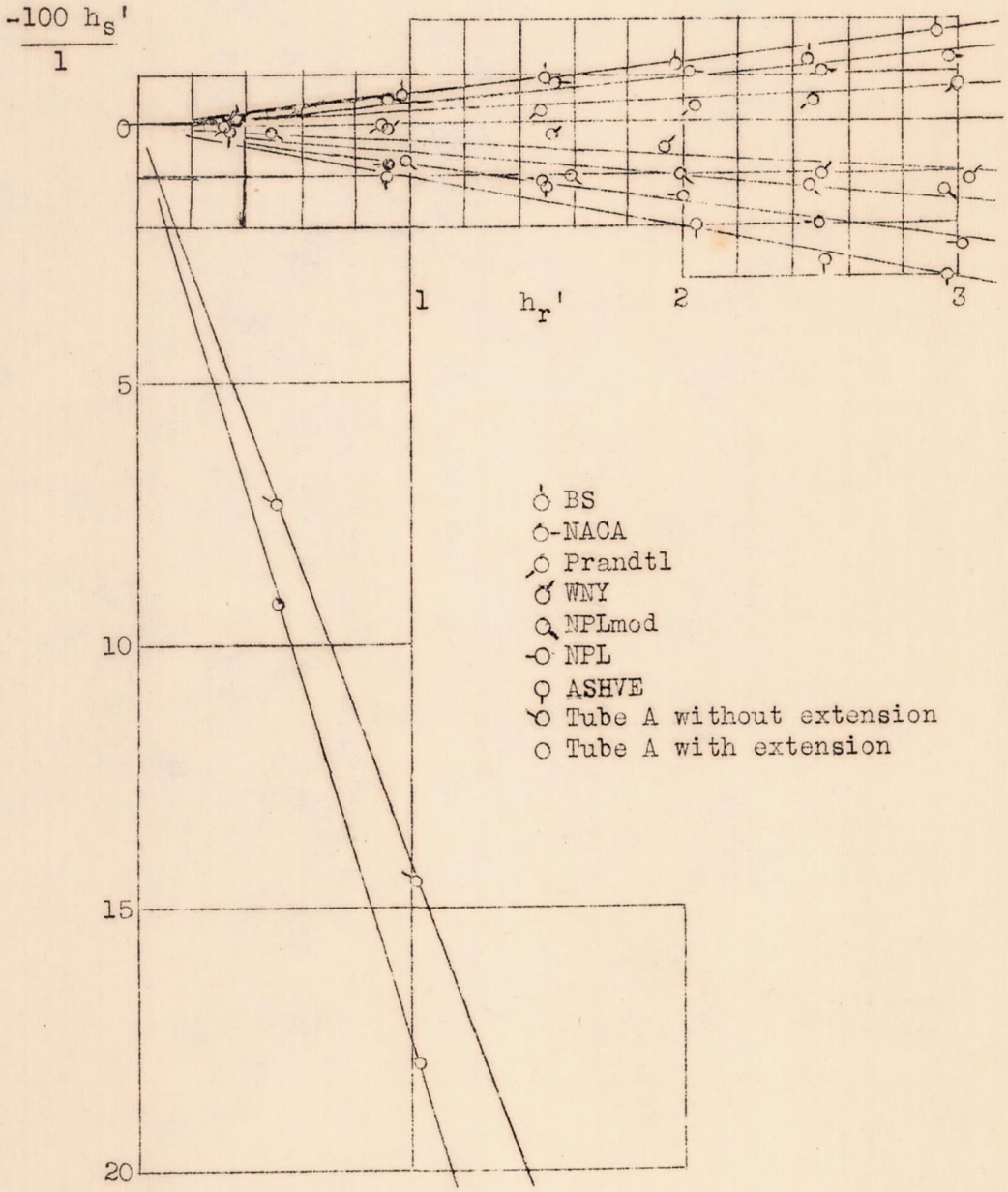


Figure 6.- Graphical method used for more accurate determination of errors for zero yaw.

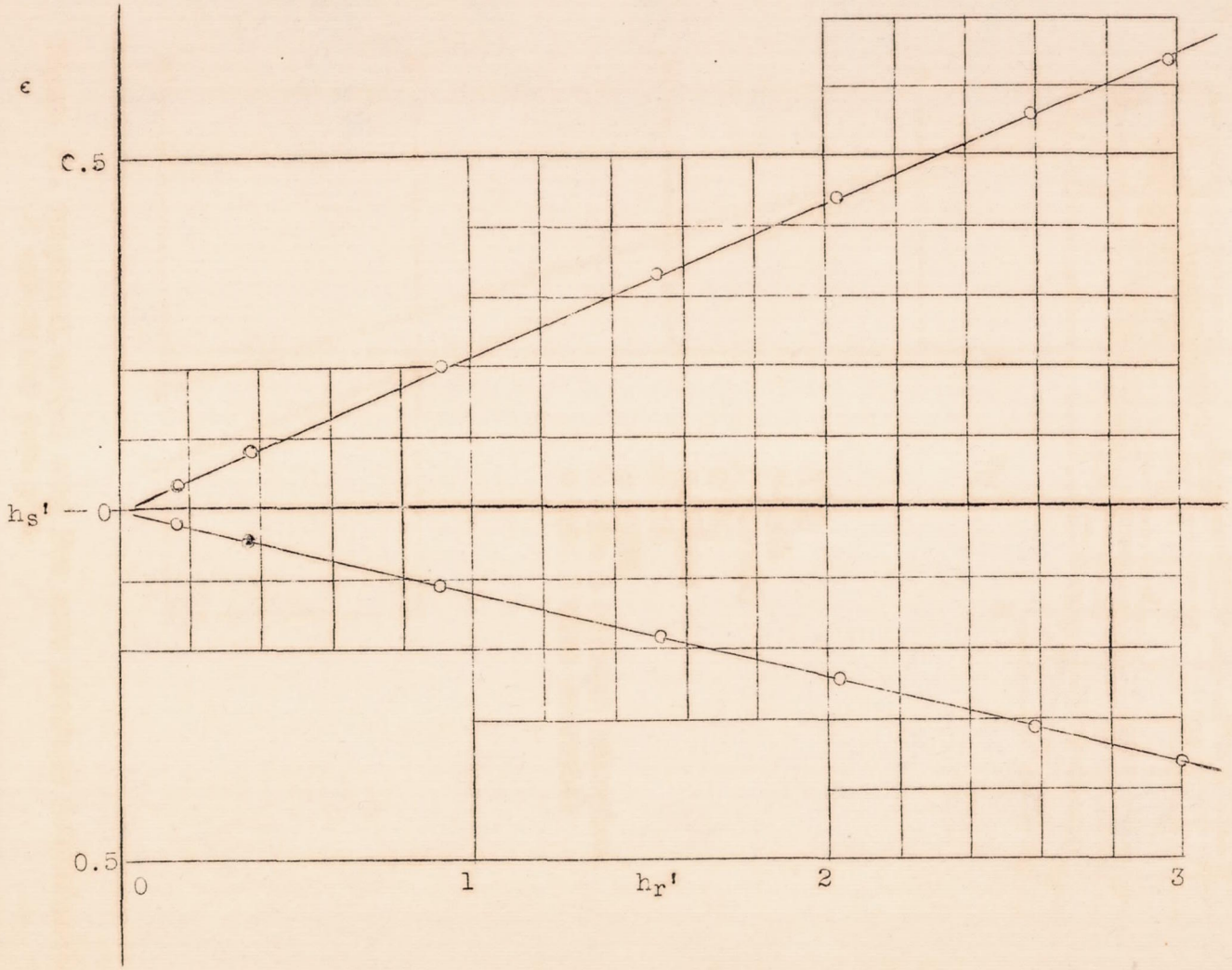


Figure 7.- Variation of ε and h_s' with h_r' for NPLmod tube at about 24° of yaw

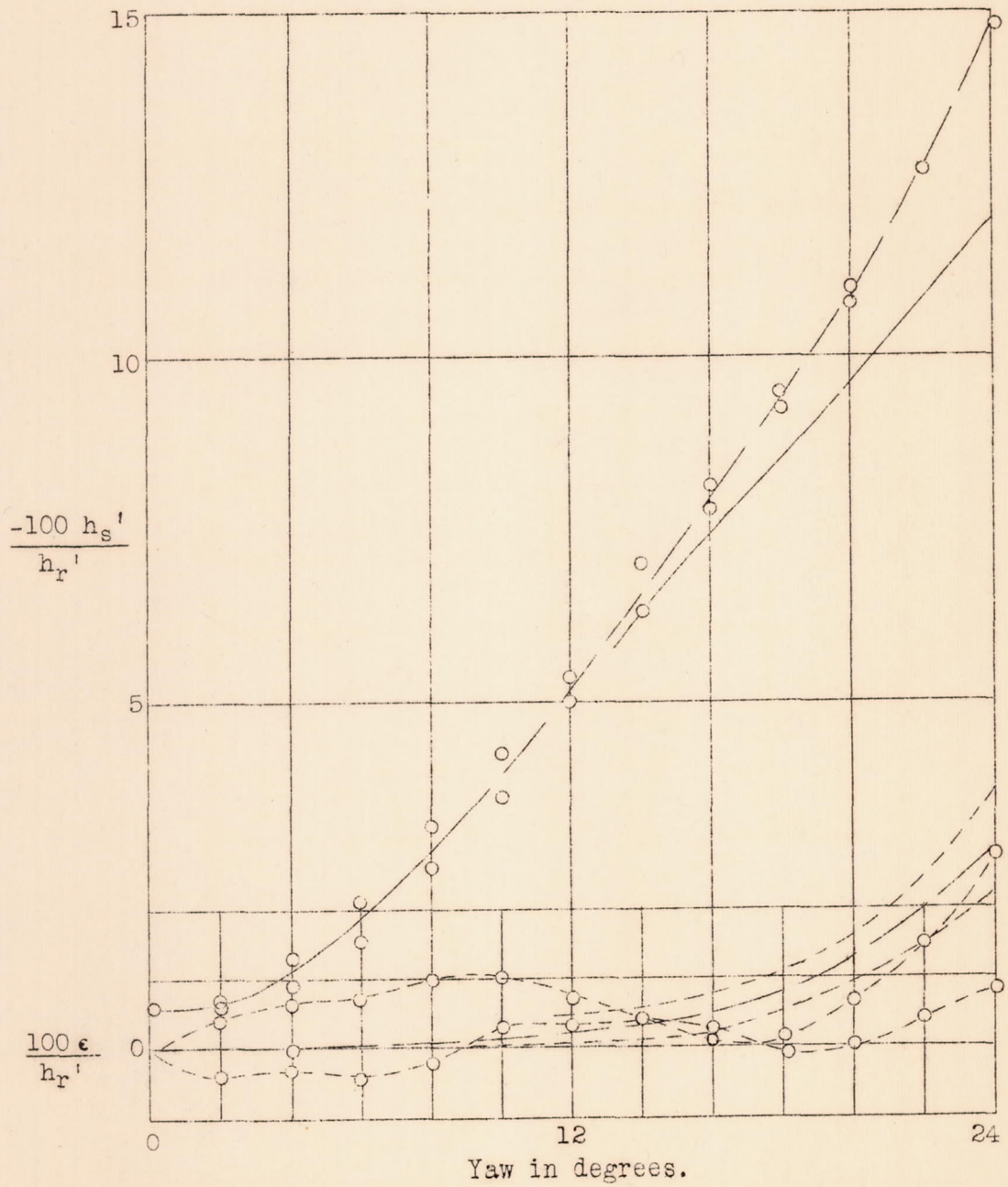


Figure 8.- Graphical method of analysis used to obtain corrected yaw-error curves. Data from BS model.

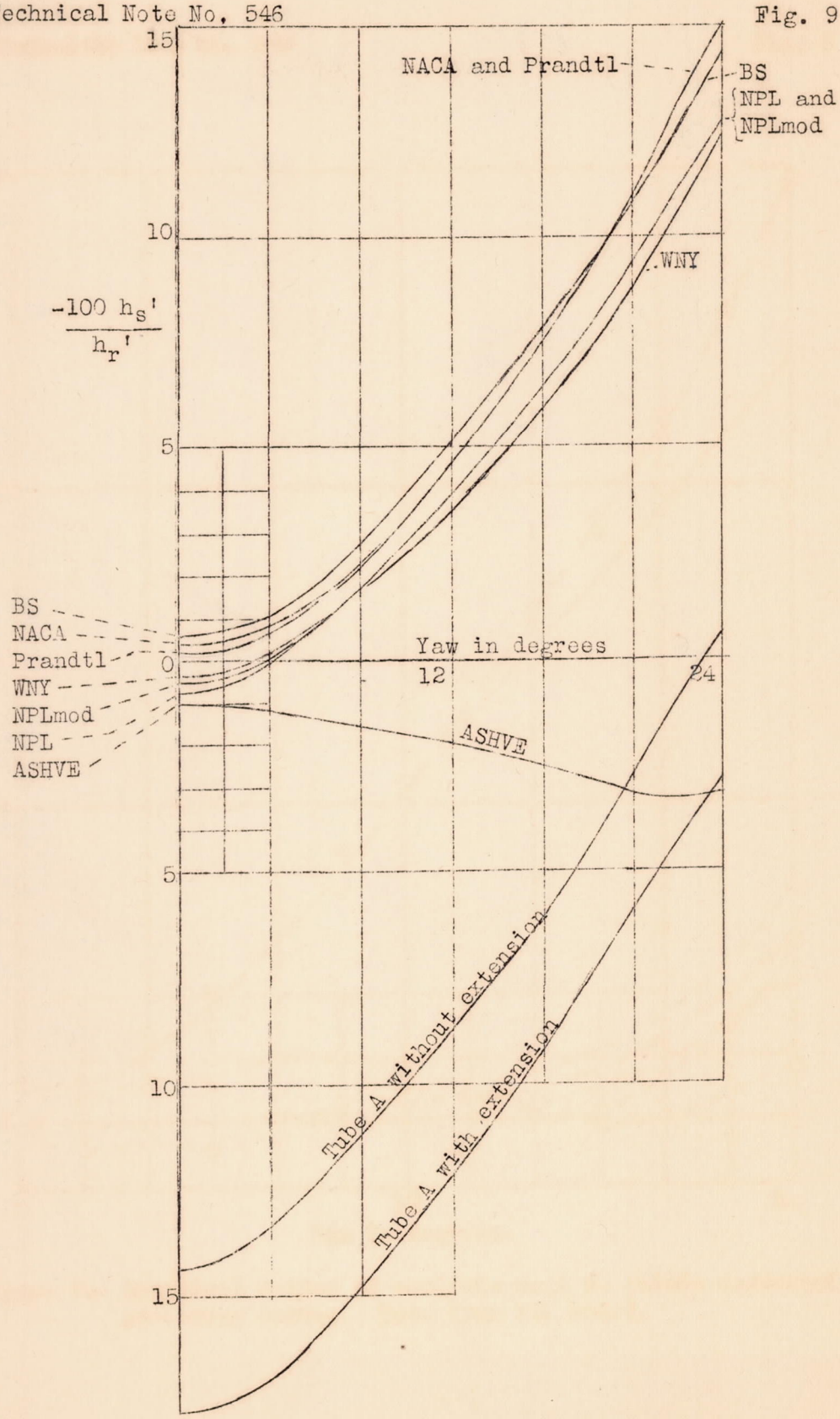


Figure 9.- Variation of static-pressure errors with yaw for eight types of pitot-static tube.

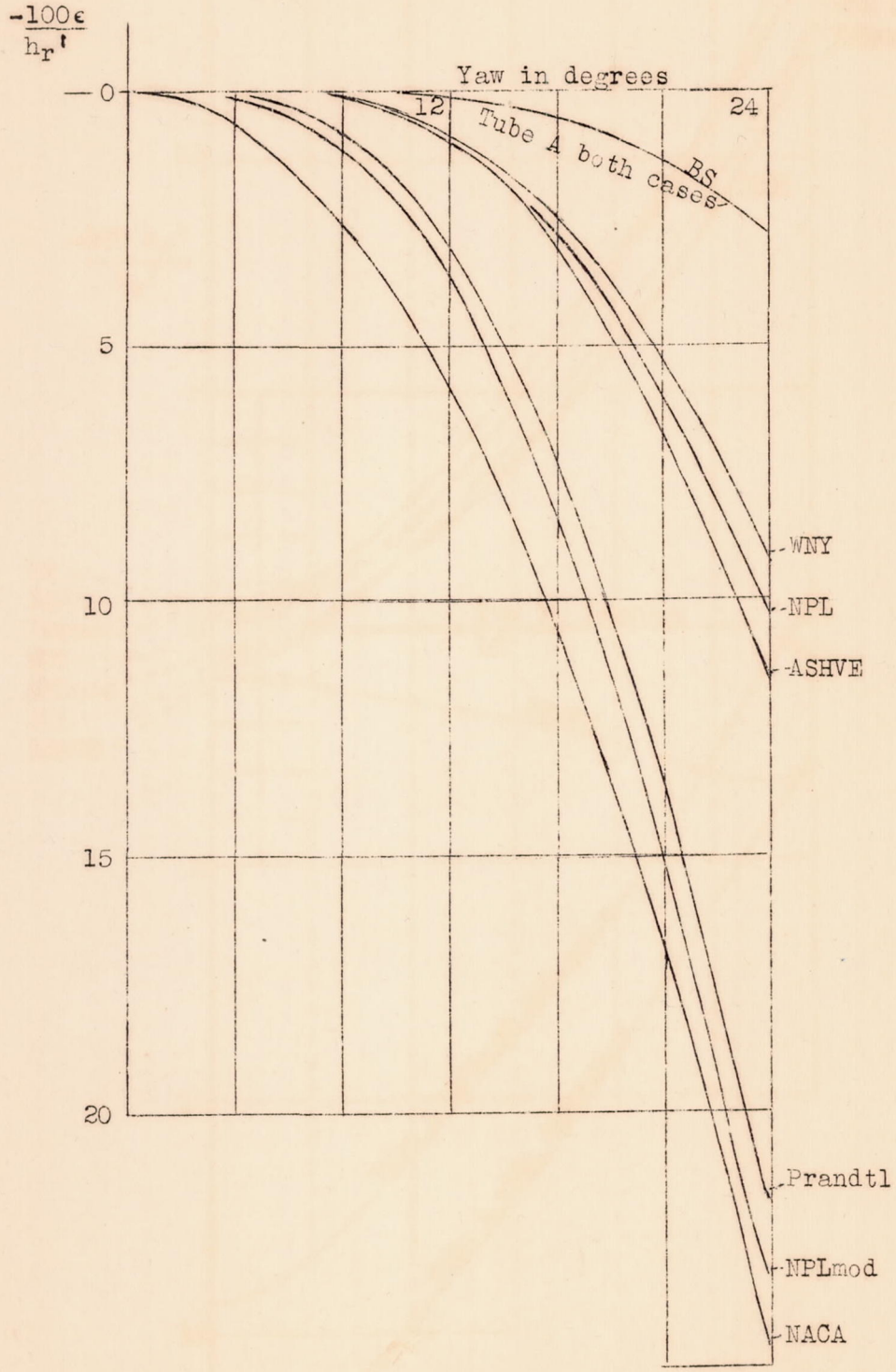


Figure 10.- Variation of impact-pressure errors with yaw for eight types of pitot-static tube.

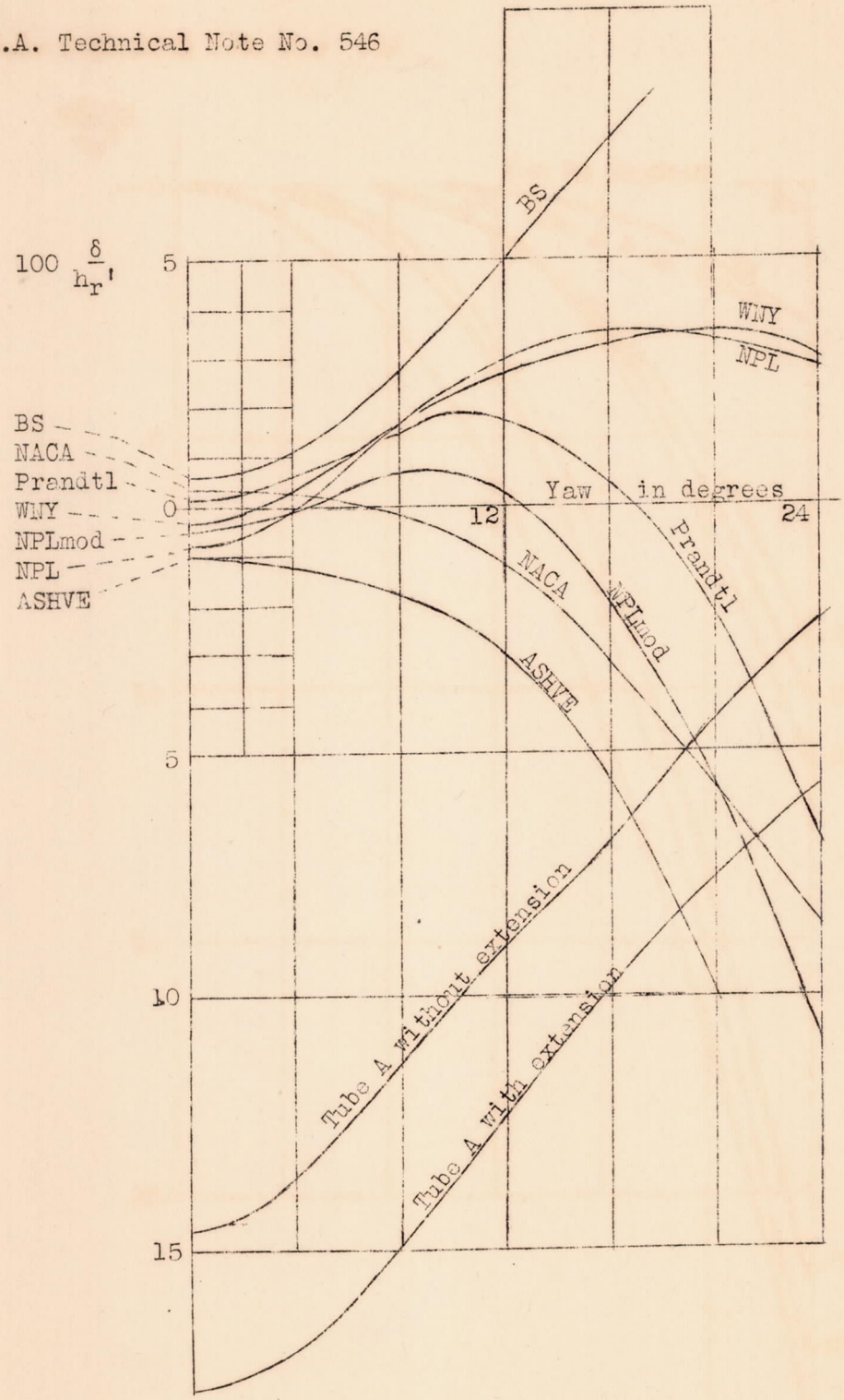
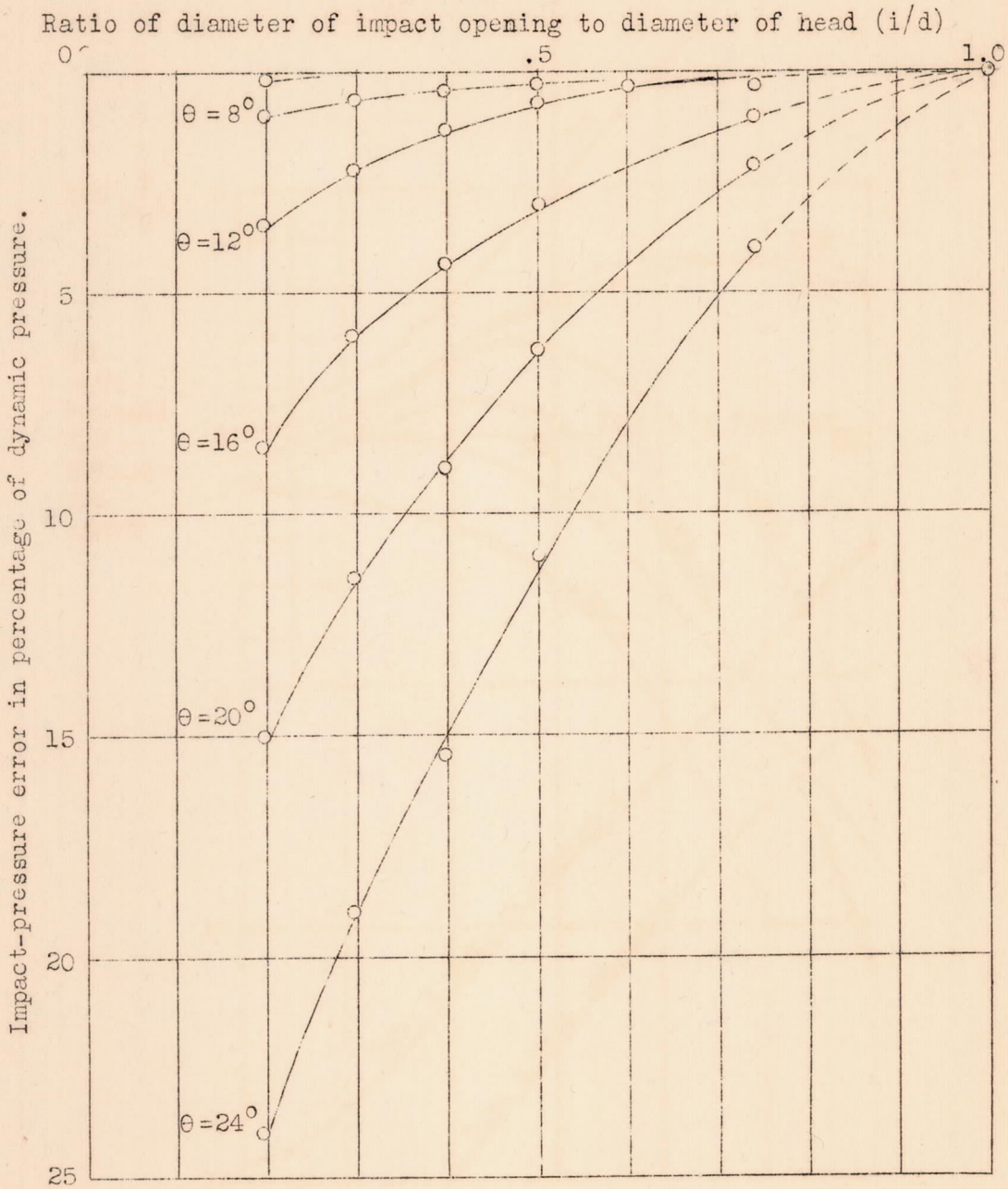


Figure 11.- Variation of resultant velocity pressure errors with yaw for eight types of pitot-static tube



Angle of yaw, θ ,varied as shown.
Diameter of head, d ,5/16 in.
Hemispherical tip.
Dynamic pressure, 3 in. of water.

Figure 14.- Effect of size of impact opening on impact-pressure error.

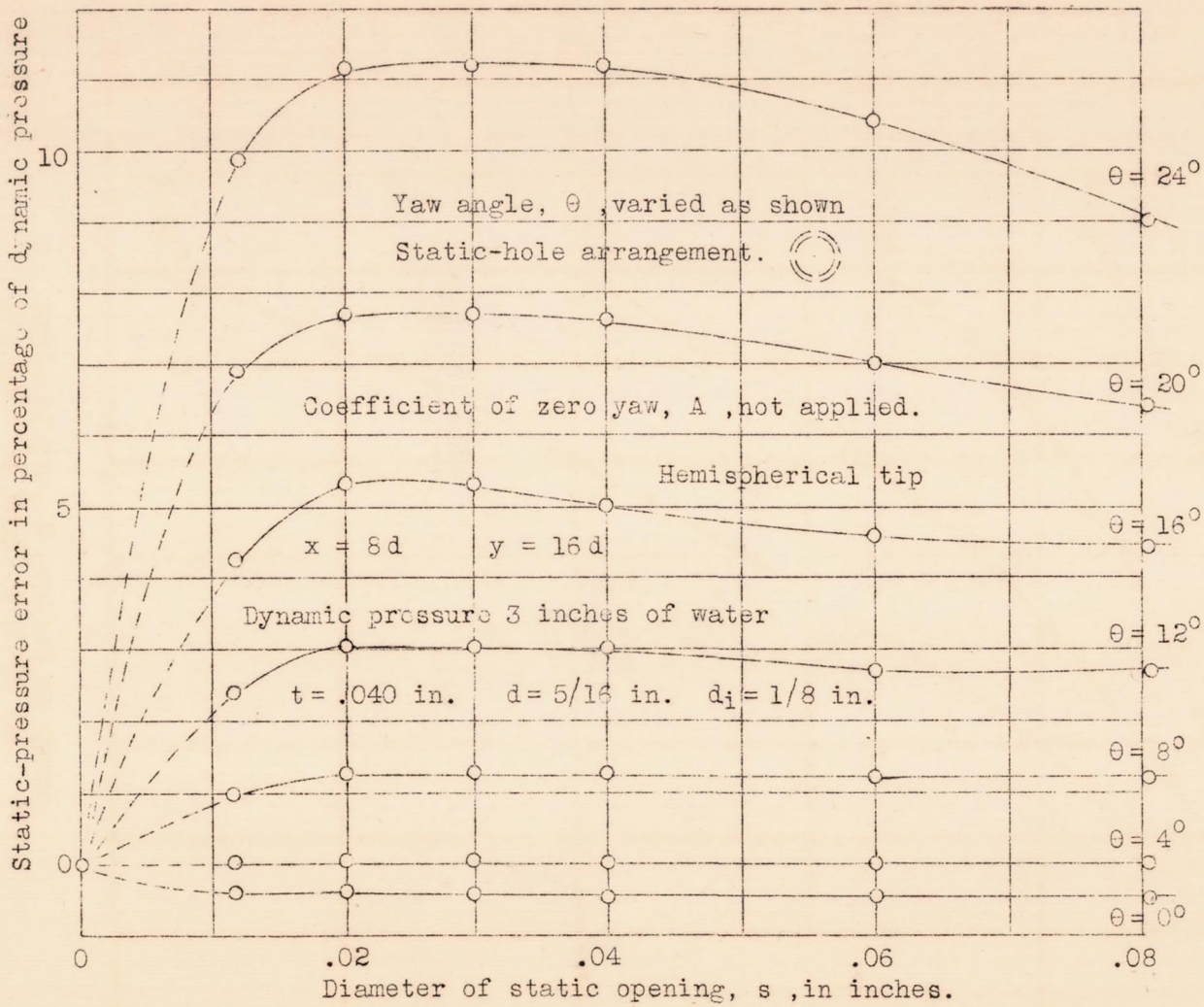


Figure 15.- Effect of size of static openings on static-pressure error.

Angle of yaw, θ, varied as shown; ◯ static hole arrangement; diameter of each static opening, s, is 0.040 in.; diameter of head, d, is 5/16 in.; hemispherical tip; x, distance from static openings to base of tip is 8 d; y, distance from static openings to stem axis is 16 d; diameter of interior tube is 1/8 in.; zero yaw coefficient, A, not applied; dynamic pressure is 3 in. of water.

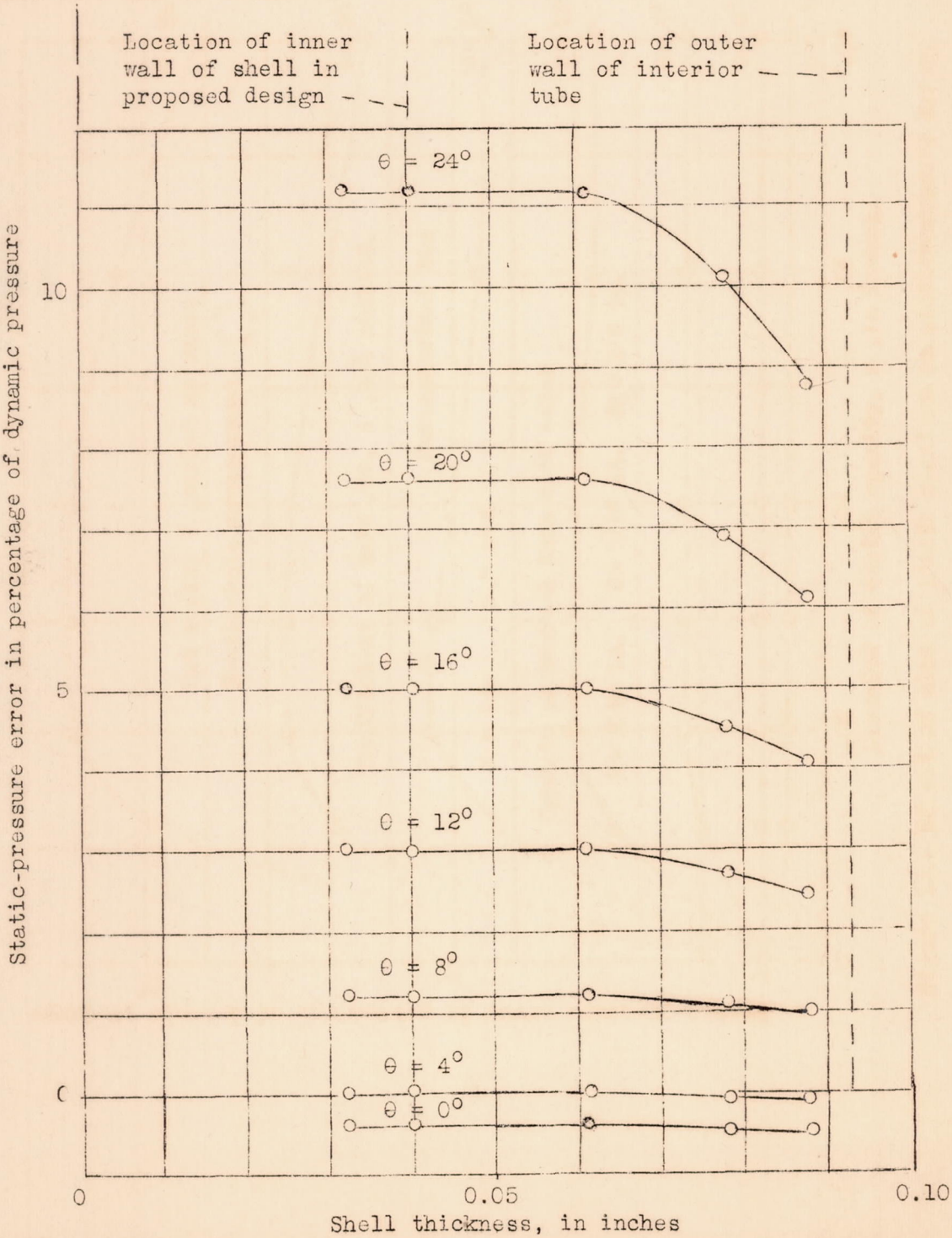


Figure 16.- Effect of shell thickness on static-pressure error.

All conditions the same as in figure 16, except shell thickness held at 0.032 in., and d_i varied as shown.

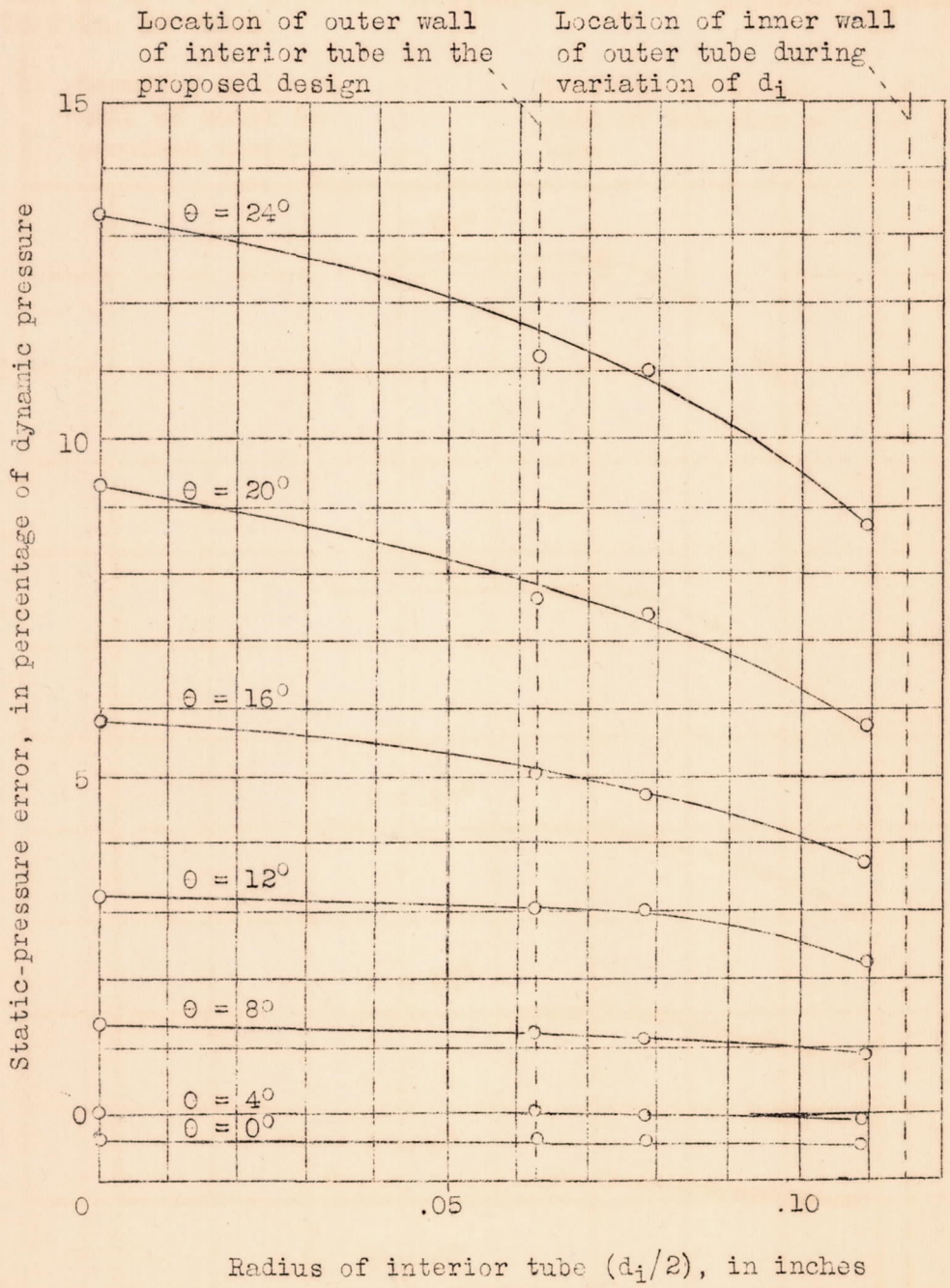


Figure 17.- Effect of diameter of interior tube (d_i) on static-pressure error.

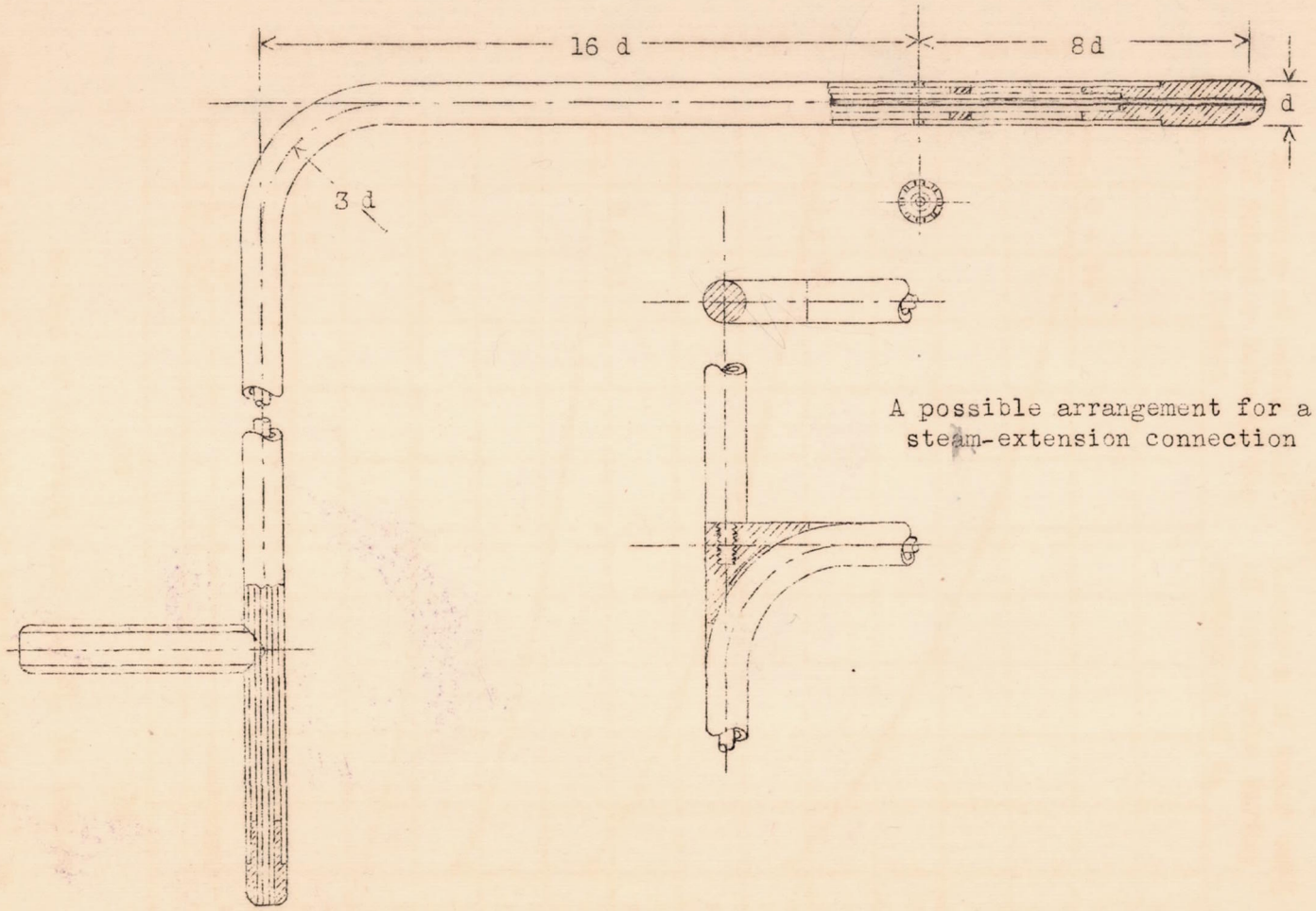


Figure 18.- Proposed tentative standard pitot-static tube.

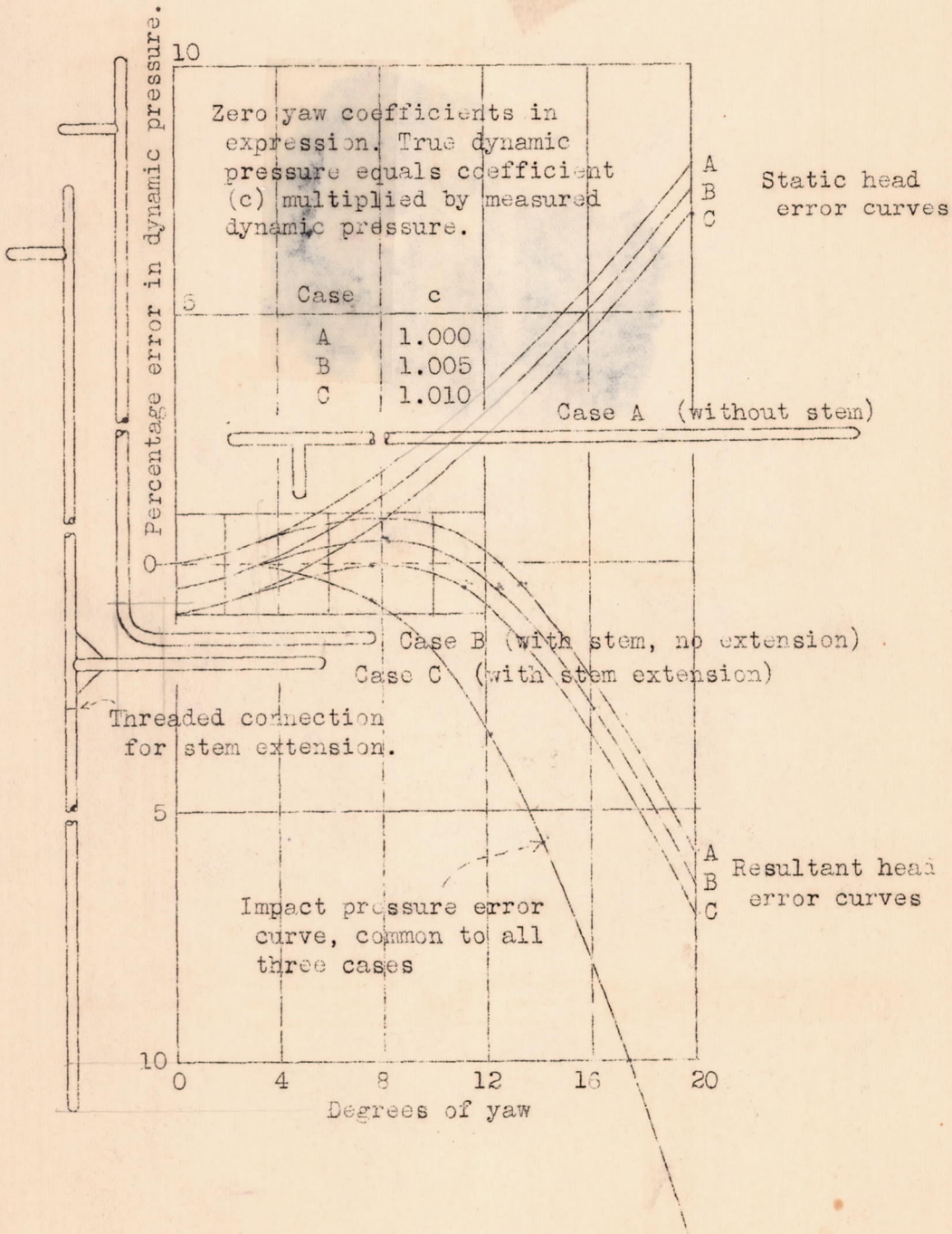


Figure 19.- Relation between percent error and degrees of yaw for proposed tentative standard pitot-static tube in its three types of application.