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# RESEARCH MEMORANDUM

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## INVESTIGATION OF TWO PITOT-STATIC TUBES AT SUPERSONIC SPEEDS

By

Lowell E. Hasel and Donald E. Coletti

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Langley Field, Va.

[redacted]

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RESEARCH MEMORANDUM

# INVESTIGATION OF TWO PITOT-STATIC TUBES AT SUPERSONIC SPEEDS

By Lowell E. Hasel and Donald E. Coletti

## SUMMARY

Tests have been conducted in the Langley 9-inch supersonic tunnel of two pitot-static tubes to measure at several angles of attack the body static pressures and indicated Mach numbers. A cylindrical tube with an ogival nose section 8 body diameters long was tested at a free-stream Mach number of 1.94. A service pitot-static tube was tested at free-stream Mach numbers of 1.93 and 1.62.

The axial pressure distribution on the cylindrical body was independent of position at zero angle of attack provided that the measurements were made 8 or more body diameters behind the end of the nose section. The radial pressure distribution on the forward side of the cylindrical tube was in fair agreement at small angles of attack with that calculated by an approximate theory.

The service pitot-static tube gave results which were nearly independent of small angles of attack in pitch but which varied appreciably with yaw angle. The indicated Mach number at zero angle of attack for a test Mach number of 1.93 was 1.95; for a test Mach number of 1.62, the indicated Mach number was 1.62.

## INTRODUCTION

The design of suitable tubes or other devices for measuring the pressures corresponding to supersonic flight Mach numbers of airplanes and missiles appears of importance at the present time. Such a device should be capable of measuring the free-stream static pressure and the stagnation pressure after a normal shock. Accurate stagnation pressures are easily obtained; however, the ability to measure the static pressure appears more uncertain. It is indicated from theoretical calculations that if an ogival-nose, cylindrical body is placed in a supersonic air stream at zero angle of attack, the static pressures on the body will at some station downstream of the nose return to free-stream static pressure. The length of the cylindrical body required for the static pressure to return to free-stream pressure is dependent primarily upon nose shape and Mach number. In an attempt to determine this length,

experimental tests on an ogival-nose, cylindrical pitot-static tube have been made in the Langley 9-inch supersonic tunnel at a Mach number of 1.94. Static pressures were measured on the cylindrical body 4, 8, 12, 16, and 20 body diameters behind the end of the nose section.

The service pitot-static tube is also essentially an ogival-nose, cylindrical tube and the possibility of using it to indicate supersonic flight Mach numbers is of importance. Tests have been made on such a pitot-static tube at Mach numbers of 1.93 and 1.62.

## SYMBOLS

| | |
|---|---|
| $M$ | free-stream Mach number |
| $M_1$ | indicated Mach number |
| $\alpha$ | angle of attack, degrees |
| $\alpha_{av}$ | average angle of attack, degrees |
| $\psi$ | angle of yaw, degrees |
| $\theta$ | angle of rotation, degrees |
| $p$ | free-stream static pressure |
| $H$ | free-stream stagnation pressure |
| $p_s$ | static pressure on surface of pitot-static tube |
| $H_p$ | stagnation pressure measured by pitot-static tube |
| $p_c$ | static pressure on surface of cone |
| $V$ | free-stream velocity |
| $V_T$ | free-stream-velocity component parallel to axis of pitot-static tube |
| $V_r$ | free-stream-velocity component perpendicular to axis of pitot-static tube |

## APPARATUS AND TEST METHODS

The Langley 9-inch supersonic tunnel in which these tests were made is a closed return tunnel in which the pressure and humidity can be controlled. The size of the test section is approximately nine inches square. The Mach number is changed by means of sets of removable nozzle blocks which form the top and bottom surfaces of part of the subsonic entrance section, the two-dimensional supersonic nozzle, and the test section.

A sketch of the ogival-nose, cylindrical pitot-static tube is shown in figure 1. For convenience, the ordinates of the nose section have been included. The stagnation pressure orifice at the nose has a diameter of 0.020 inch and has edges which are relatively sharp. Two static orifices of the same diameter are located 180° apart at each of five stations on the cylindrical portion of the body. The tubes connecting the orifices to the mercury manometer (used to record the pressures visually) extended out the rear of the model and did not cause any interference with the static orifices. The model was supported in the tunnel by fitting inside a conical sleeve as shown in figure 1. The sharp leading-edge tip of the support was 1 inch downstream of the last orifice station.

The service pitot-static tube was a Manning-Bowman & Co. tube, specification No. 94-27876-A. It was tested as received except for minor alterations at the rear which were necessary to facilitate mounting it in the tunnel. These changes were made internally and had no effect on the measured static pressures. A sketch of the tube illustrating the method of support is shown in figure 2.

The same general test methods were used for both models. As stated previously, the models were supported from the rear. The angle of attack was determined within ±0.015° by reading on a graduated scale the position of a light beam which was reflected from a small mirror mounted at the extreme rear of each model. The angle-of-attack range was from -3.3° to 4.8° for the cylindrical tube and ±7° for the service tube. Since it was desired to determine the pressure distribution as a function of the radial location $\theta$ (see fig. 1), as well as of axial location, the static-pressure data for the cylindrical tube were obtained from a series of tests because the small size of the model restricted the number of radial static-pressure orifices which could be installed. Pressure readings were made at 30° radial intervals by rotating the model about its longitudinal axis from $\theta = 0°$ to $\theta = 180°$ and running through the complete angle-of-attack range at each radial position of the orifices.

The service pitot-static tube was tested in both pitch and yaw attitudes with the drain holes to the stagnation-pressure chamber open and closed to determine their effect upon the measured stagnation pressure. The drain holes are installed in service instruments to remove the water which may accumulate in the chamber during flight and are not found in laboratory instruments. The holes were sealed with duratite compound and then sanded to give a smooth outside surface.

## PRECISION OF DATA

The accuracy of the data to be presented is dependent on the accuracy of the static and stagnation pressure readings. These pressures were visually recorded from a mercury manometer. The chief error to be found in this method of recording pressures is that introduced by incorrect reading of the heights of the mercury columns. It has been found that the maximum probable reading error may make the static-pressure readings in doubt by $\pm 0.2$ percent, and the stagnation pressures in doubt by $\pm 0.04$ percent. Since the indicated Mach numbers were computed from the ratio of stagnation to static pressures, a cumulative error in the two pressure measurements could introduce a maximum error of $\pm 0.005$ in the indicated Mach number. However, the scatter at each axial station of the static pressures measured on the body at $\alpha_{av} = 0.02^{\circ}$ (fig. 3) is greater than the $\pm 0.2$ percent of $p_s$ predicted from the precision of the pressure measurements. Further evidence that the scatter is greater than predicted is present in figure 4, which shows the result of two tests made with the orifices in the same radial plane but differing in angular rotation by $180^{\circ}$. The data show a small difference in static pressure on the opposite sides of the tube although the measured angle of attack is very close to $0^{\circ}$. Furthermore, rotating the tube $180^{\circ}$ does not shift the direction of the pressure difference. It seems probable therefore that there is a small misalinement of the free stream in the pitch direction with respect to the measured $0^{\circ}$ angle of attack of the tube. More important is the difference of about 1 percent in the average pressure obtained from the two runs. No satisfactory explanation can be found for this variation. Hence these data together with the data shown in figure 3 provide another indication of the precision of the data presented in this report. These errors are relative and may be indicative of the spread of data which could be expected if the tubes were tested in a uniform stream.

Available free-stream surveys made in the vicinity of the tubes are shown in figures 5 and 6. It should be mentioned that the two tubes were not located at identical stations in the tunnel during the tests and, therefore, stream surveys for each tube location are shown at the

higher Mach number. Since no surveys have been made at the exact location of the cylindrical tube, the survey located closest to the tube is shown. These surveys were made in a plane perpendicular to the angle-of-attack plane $\theta = 90^\circ$ and $270^\circ$ and passing through the axis of the tubes at $\alpha = 0^\circ$. The survey shown in figure 5 was made 0.16 inch from the axis of the tube. The surveys were made to obtain at various stations in the stream the static pressure $p_c$ on the surface of a $5^\circ$ half-angle cone having 0.020-inch orifices located 0.97 inch behind the tip. In addition, the stagnation pressure behind a normal shock $H_p$ obtained with a square-nose pitot tube whose orifice diameter was 16 percent of the frontal diameter was obtained at the same stations where $p_c$ was obtained. The free-stream Mach numbers were determined from the ratio of $H_p/p_c$ by use of the calculated results presented in reference 1. A series of careful measurements by methods using photographic enlargements indicated that the cone half-angle was $5.00^\circ \pm 0.01^\circ$. The error introduced by this small variation in cone angle is negligible. Thus, the maximum probable error in stream conditions, as indicated by the stream surveys and as plotted in figures 5 and 6, may be $\pm 0.005M$ and $\pm 0.75$ percent of $p$.

The plot of free-stream Mach numbers shown in figure 5 indicated that the nose of the pitot-static tube is in a region of slightly higher Mach number ($\Delta M = 0.008$) than the static orifices. The main error which this Mach number distribution can introduce is in the indicated Mach number obtained from the ratio of $H_p/p_s$ since with a constant free-stream stagnation pressure the measured values of $H_p$ decrease with increasing Mach number. The values of $H_p$ used to compute the indicated Mach numbers in figure 8 have been increased by 1.005 which is the theoretical ratio of the change of $H_p/H$ when $M$ changes from 1.948 to 1.940. It is realized that the correction does not eliminate entirely the effects of the Mach number distribution because the flow characteristics over the nose are a function of Mach number and do affect the static-pressure distribution. However, it is thought that such effects are small for the small variation present in free-stream Mach number.

The humidity in the tunnel was kept sufficiently low so that the effects of condensation in the supersonic nozzle were negligible for all the data presented.

## PRESENTATION AND DISCUSSION OF RESULTS

### Cylindrical Pitot-Static Tube

The static-pressure distributions obtained on the surface of the cylindrical pitot-static tube at several angles of attack at $M = 1.94$ at a Reynolds number of 4,000,000 per foot are shown in figure 7. These results are presented in the form of the ratio $p_s/p$ where $p_s$ is the measured static pressure and $p$ is the free-stream static pressure based on an approximate mean free-stream Mach number of 1.94.

The data show that the pressures measured at the most forward orifice location, which is 4 body diameters behind the end of the nose section (12 diameters from the front end), are, in general, lower than the pressures measured farther back on the body. These lower pressures could be caused by the effect of the ogival nose section or a variation in the free-stream static pressures in the vicinity of the orifices. In figure 3 the variation of the static pressures measured at $\alpha_{av} = 0.02^{\circ}$ is compared with the free-stream static-pressure distribution. The shaded area indicates the probable limits of accuracy of the survey as previously discussed.

A comparison of the two curves indicates that the free-stream pressure distribution could be influencing the measured pressures since the slopes of the two curves are in the same direction and of approximately the same value. The effect of the ogival nose section on these static pressures cannot be predicted accurately without detailed calculations or the installation of more static orifices in the nose section although it appears from available calculations that the pressures in this vicinity may be expected to be below free-stream pressure. Since the effects of the nose section and free-stream static-pressure distribution are probably additive and the effect of each cannot be evaluated, the data obtained 4 body diameters behind the end of the nose section should be considered to be of doubtful value.

The static pressures measured 8 diameters behind the end of the nose section appear generally to be in fairly good agreement with those measured farther downstream on the tube except in the radial region near $\theta = 270^{\circ}$. The pressure variation at 12, 16, and 20 diameters behind the end of the nose section appears to be of a random nature and not entirely a function of free-stream variations. It is not understood why the change in the pressure distribution 20 diameters behind the nose section on figures 7(e) and (f) should differ with that at corresponding positive angles on figures 7(b) and (c). Neglecting these irregularities in the data, the static pressures measured on the cylindrical body appear to be independent of axial location provided

that the measurements are made at least eight diameters behind the end of the nose section. While the axial location of the orifices behind the eight-diameter station is not important, it is apparent from figure 7 that most of the static-pressure variation is due to radial location of the orifices and that the variation could be reduced by measuring the pressures close to the plane of angle of attack. ($\theta = 0^\circ$ and $180^\circ$.)

An approximation to the radial pressure distribution around the body may be made by use of incompressible potential theory for the flow about a circular cylinder. According to the simple sweepback concept, the free-stream velocity $V$ may be divided into two components, $V_T$ parallel to the tube axis and $V_r$ perpendicular to the tube axis, and

$$V_T = V \cos \alpha$$

$$V_r = V \sin \alpha$$

The pressure distribution on the cylinder at a given angle of attack is a function of the crosswise velocity component $V_r$ which is small for small angles of attack. Therefore the following incompressible-flow equation (reference 2) can be used to compute the pressure distribution where $\theta$ (see fig. 1) denotes the radial location on the cylindrical surface:

$$p_s = p + \frac{1}{2}\rho V_r^2(1 - 4 \sin^2\theta) \tag{1}$$

The theoretical pressure distributions obtained by this method have been plotted in figure 7. The agreement between the theory and experimental data on the forward side of the body is fairly good at the low angles of attack. As would be expected, since the crosswise velocity component increases with increasing angle of attack, the pressures near the plane of angle of attack increase as the angle of attack increases while those pressures near $\theta = 90^\circ$ and $270^\circ$ generally decrease. According to the approximate theory, the pressures on the rear side of the tube, $\theta = 180^\circ$ to $\theta = 90^\circ$, should be the same as the corresponding pressures on the front side of the tube, $\theta = 0^\circ$ to $\theta = 90^\circ$. However the approximate theory does not take into account the laminar-boundary-layer separation which takes place in the vicinity of $\theta = 90^\circ$. At the small angles of attack the effect of this separation is not readily apparent since the crosswise velocity component is small; however, at the larger angles of attack the pressure recovery near $\theta = 180^\circ$ does not equal the theoretical value. Reference to equation 1 shows that at $\theta$ equal to $30^\circ$, $150^\circ$, $210^\circ$, or $330^\circ$, the pressures should be independent of the angle of attack.

However, since it has already been shown that the Reynolds number affects the pressures on the rear of the tube, only the two pressures on the front, $\theta = 30^\circ$ and $330^\circ$ for positive angles of attack ($\theta = 150^\circ$ and $210^\circ$ for negative angles of attack) might be expected to agree with the theory. This expectation is verified by the data which show a variation of the mean pressures at these locations of less than 1 percent of the reference static pressure for the entire angle-of-attack range.

The indicated Mach number obtained from the ratio of $H_p/p_s$ as measured on the cylindrical body tube at two angles of attack is shown in figure 8. Since for these tests, the indicated stagnation pressure $H_p$ is independent of the angle of attack for small angles, the indicated Mach numbers of these tests are a function only of the static pressures on the body. The indicated static pressures were, in general, lower than free-stream static pressure and as a result the indicated Mach numbers are generally higher than the approximate mean free-stream Mach number of 1.94. If the static pressures were measured at the most suitable radial location, as discussed above, the Mach number variation could be reduced.

## Service Pitot-Static Tube

The results of tests in the conventional pitch and yaw attitudes of a service pitot-static tube at $M = 1.93$ at a Reynolds number of about 4,000,000 per foot are shown in figures 9 and 10, respectively. The tests were made in both attitudes with the pitot chamber drain holes open and closed. The results are presented as ratios of measured stagnation and static pressures to free-stream stagnation pressure $H_p/H$ and $p_s/H$. Figure 9 shows that in the pitch attitude both measured pressures are nearly independent of angle of attack. These pressures were also independent of whether the drain holes were open or closed. Near $\alpha = 0^\circ$ the measured static pressures are about 4 percent lower than the free-stream static pressure. The indicated Mach number obtained from the ratio of $H_p/p_s$ is 1.95 for angles of attack up to $\pm 3^\circ$ and decreases as the angle of attack is further increased. The yaw results shown in figure 10 indicate that in this attitude ($\alpha = 0^\circ$) the static pressure is dependent on the yaw angle. The variation as predicted by the use of equation (1) is also shown. Since the orifices are located at values of $\theta$ varying from $60^\circ$ to $120^\circ$, an average value of the sine of $\theta$ corresponding to $75^\circ$ was used for these calculations. As a result of the static-pressure variation the calculated Mach number varies from 1.95 at $\psi = 0^\circ$ to 2.07 at $\psi = 7^\circ$.

Results of a similar set of tests made at $M = 1.62$ at a Reynolds number of about 4,400,000 per foot are shown in figures 11 and 12.

Two main differences from the previous set of data are evident. The agreement between free stream and measured static pressures is much better and, secondly, the drain-hole condition changes the measured stagnation pressure by about 0.7 percent. The resultant effect of the drain holes on the indicated Mach number is negligible. The indicated Mach number in pitch agrees very well with the free-stream Mach number of 1.62. In the yaw attitude the indicated Mach number varies from $M = 1.62$ at $\psi = 0^{\circ}$ to 1.69 at $\psi = 7^{\circ}$.

No attempt has been made to correct the data on the service pitot-static tube for the variation in stream conditions shown in figure 4. The combined effect of the Mach number distribution and blunt nose may be of some importance; however, the magnitude of the effect is not known.

## CONCLUDING REMARKS

Tests have recently been made in the Langley 9-inch supersonic tunnel of two pitot-static tubes. A cylindrical tube with an ogival nose section 8 body diameters long was tested at $M = 1.94$. Static pressures on the cylindrical body and the stagnation pressure at the tip were recorded for a series of angles of attack. The results show that with this configuration at this test Mach number static pressures may be measured with fair accuracy 8 body diameters or more back of the nose section and that the axial orifice location behind this point was not critical. The radial pressure distribution can be predicted by an approximate theory at small angles of attack. The data indicate that if, at small angles of attack the average of the static pressures on both sides of the tube near the plane of angle of attack were measured, the resultant pressure would be close to free-stream static pressure and reasonable accuracy of the indicated Mach number could be expected.

The second pitot-static tube was a service instrument. It was tested at free-stream Mach numbers of 1.93 and 1.62 through a range of pitch and yaw angles. Tests were made in both attitudes with the pitot chamber drain holes open and closed. The indicated Mach numbers at $\alpha = 0^{\circ}$ were 1.95 and 1.62. The indicated Mach number in pitch was independent of angle of attack up to $3^{\circ}$. The

variation of the indicated Mach number with yaw angle was greater, and it is shown that the variation of static pressure with the yaw angle can be predicted theoretically.

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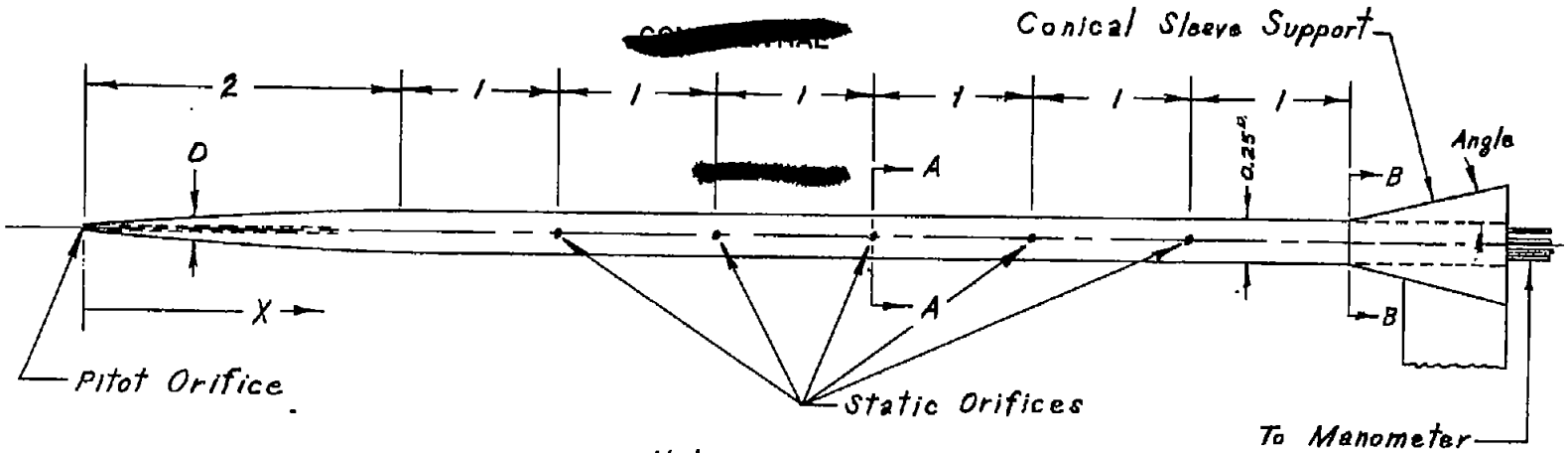
Langley Field, Va.

## REFERENCES

1. Staff of the Computing Section, Center of Analysis (Under Direction of Zdeněk Kopal): Tables of Supersonic Flow around Cones. Tech. Rep. No. 1, M.I.T., 1947.

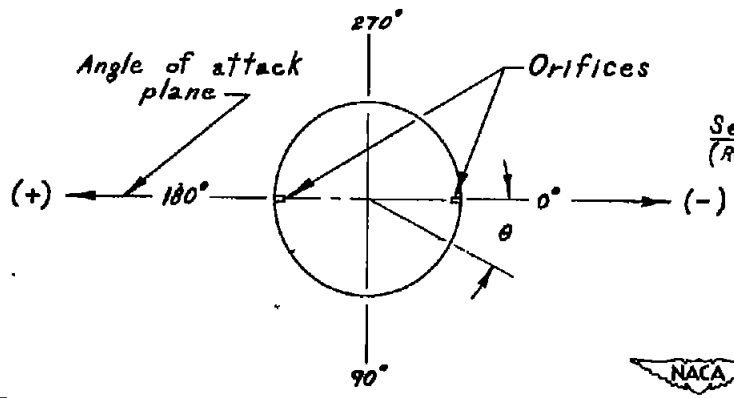
2. Glauert, H.: The Elements of Aerofoil and Airscrew Theory. American ed., The Macmillan Co., 1943.

[redacted]

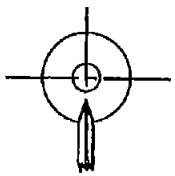



Note:
All orifices 0.020" Dia.
All dimensions in inches.

| X | D |
|---|---|
| 0 | 0.03 |
| 0.10 | 0.05 |
| 0.25 | 0.08 |
| 0.50 | 0.12 |
| 0.75 | 0.16 |
| 1.00 | 0.19 |
| 1.25 | 0.21 |
| 1.50 | 0.23 |
| 1.75 | 0.24 |
| 2.00 | 0.25 |



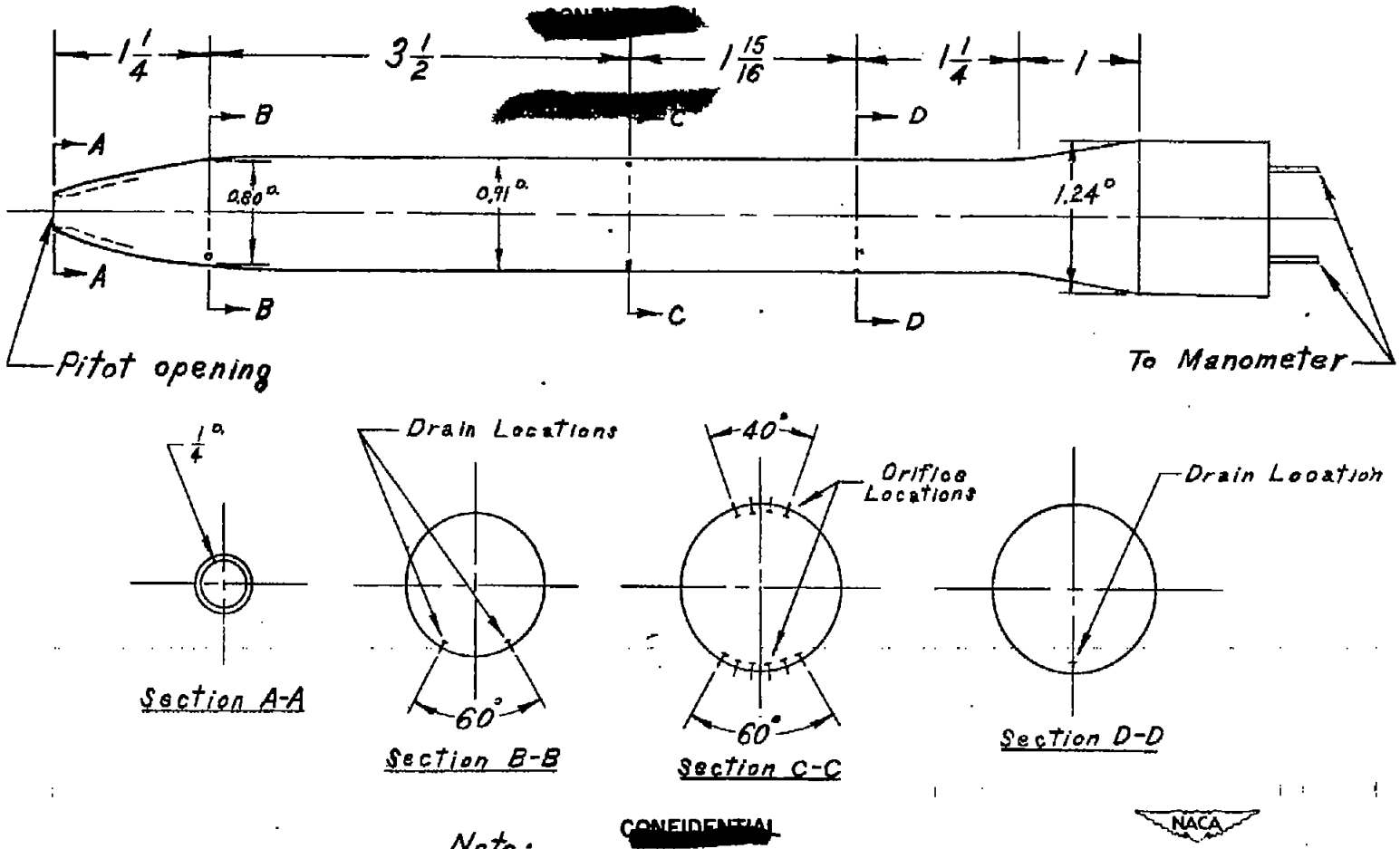

Section A-A
(Enlarged scale)



Section B-B
(Reduced scale)

[redacted]

Figure 1.- Sketch [redacted] cylindrical pitot-static tube.




[redacted]

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Note:
All orifices and drain holes are 0.05" dia.
All dimensions in inches.

Figure 2.- Sketch of a [redacted] pitot-static tube.

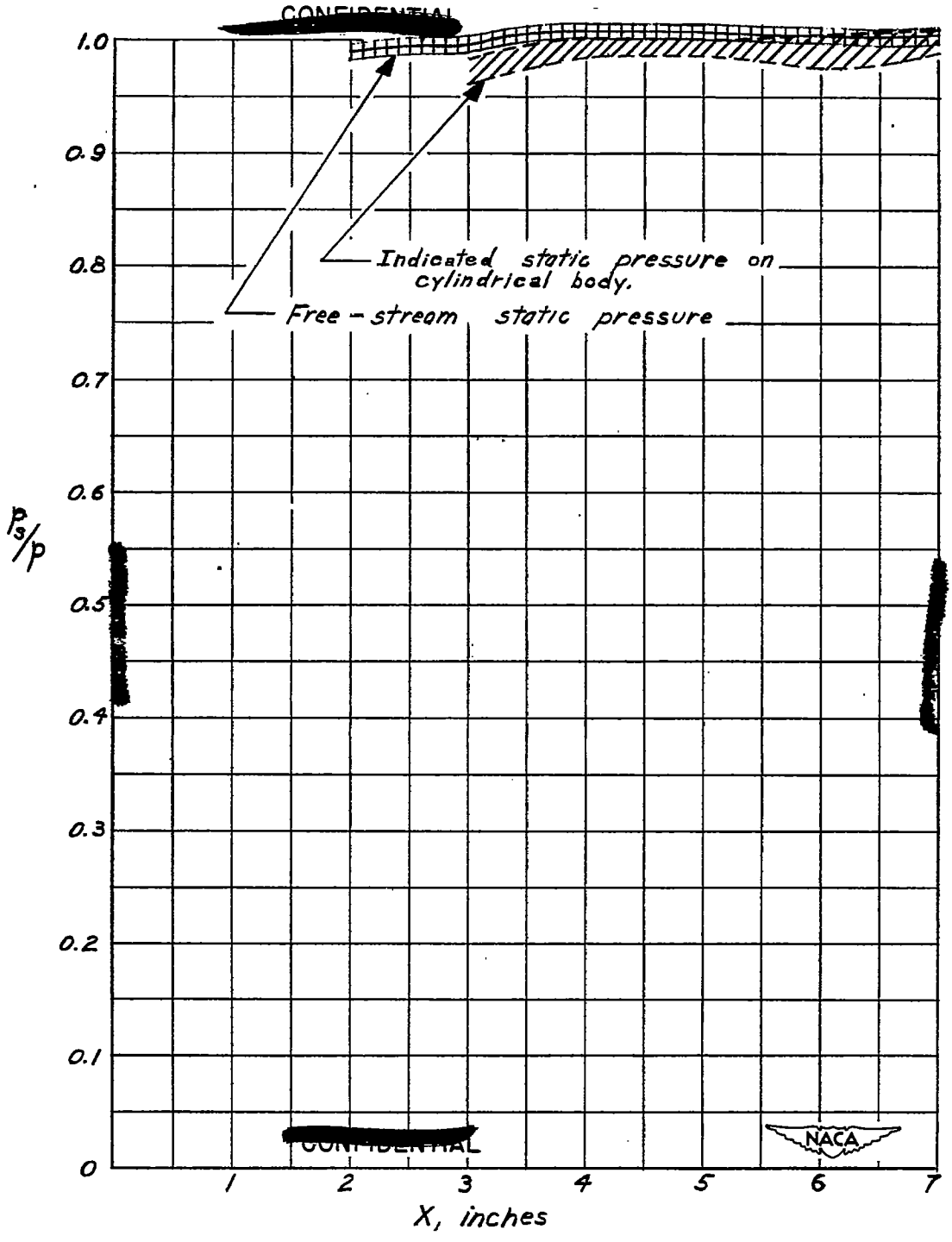



Figure 3.- Comparison between free-stream static pressure and the static pressure measured on cylindrical pitot-static tube at $\alpha_{av} = 0.02°$; $M = 1.94$.

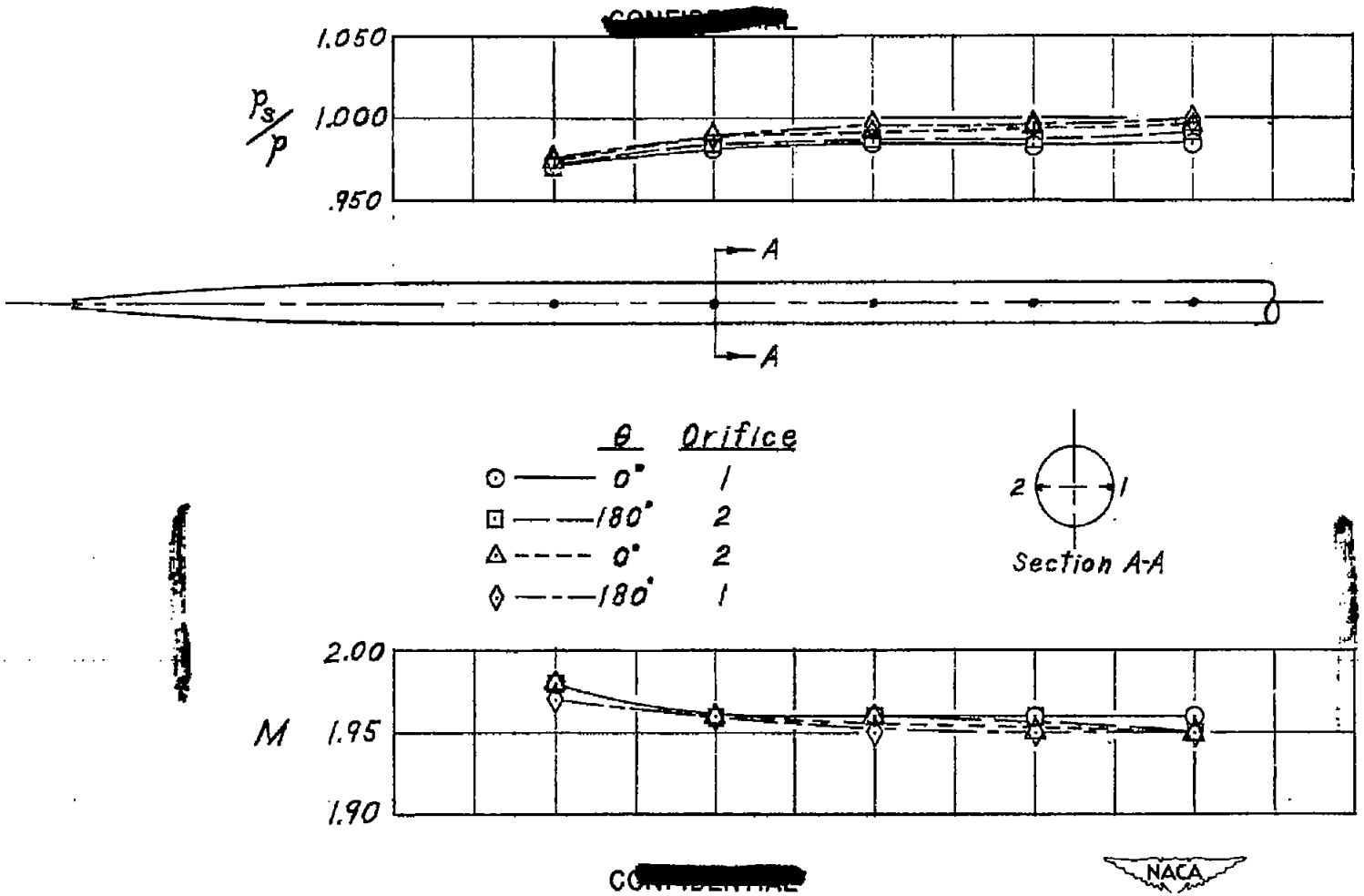
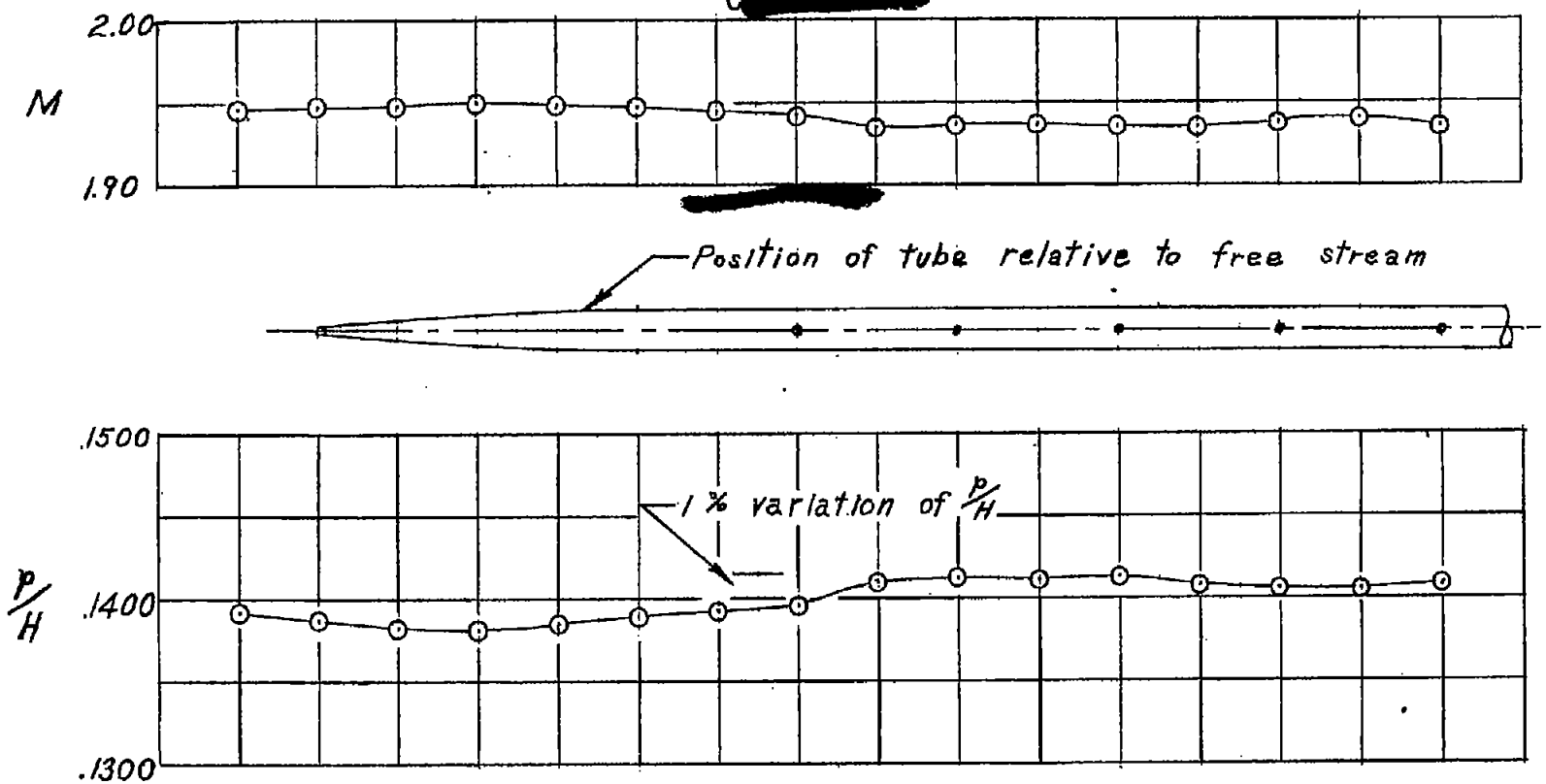


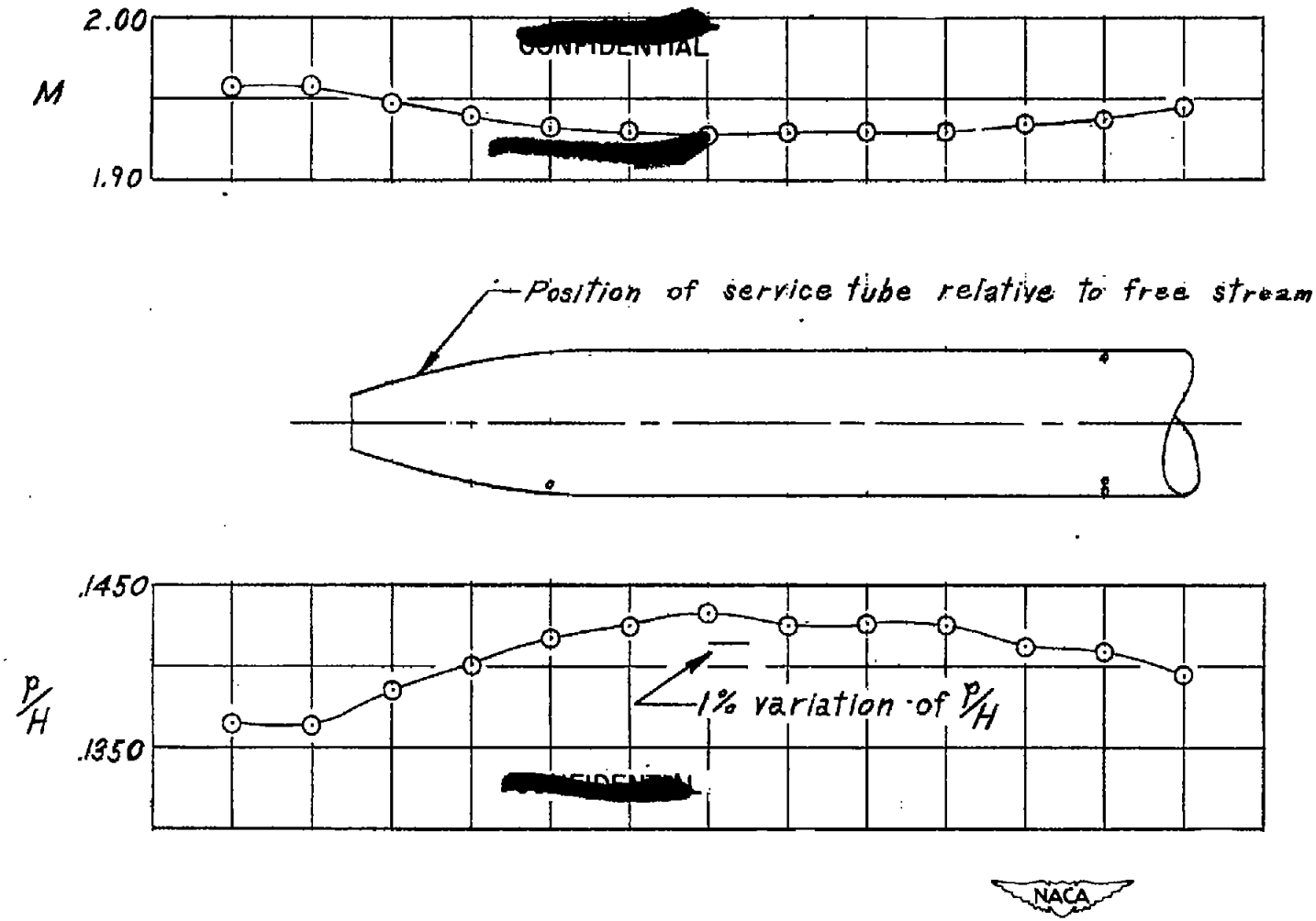

Figure 4.- Comparison of the results of cylindrical tube with static orifices in same radial plane; M = 1.94.

[redacted]




[redacted]

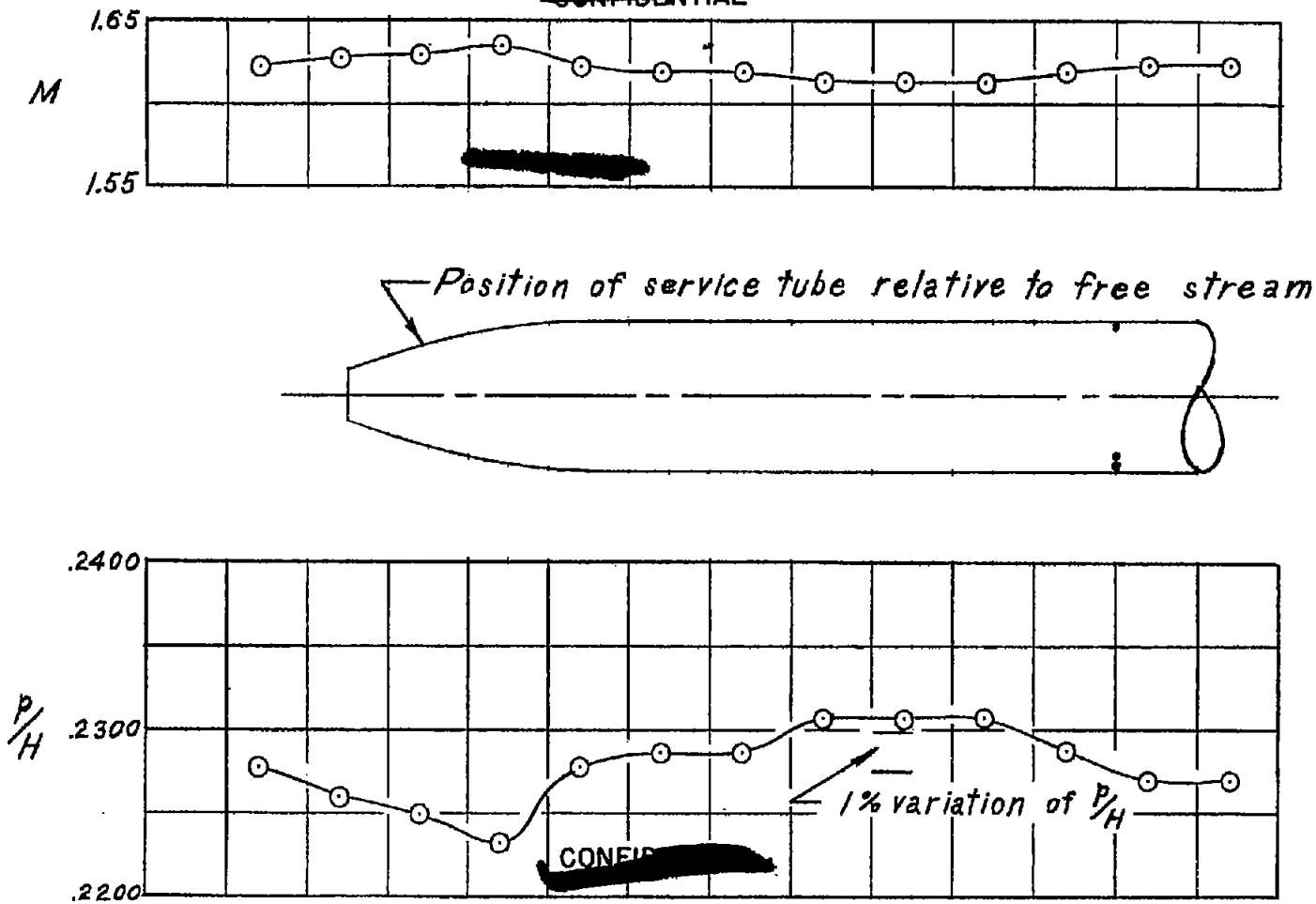
Figure 5.- Free-stream [redacted] conditions for cylindrical tube; M = 1.94




(a) M = 1.93 [redacted]

Figure 6.- Free-stream conditions for service tube.

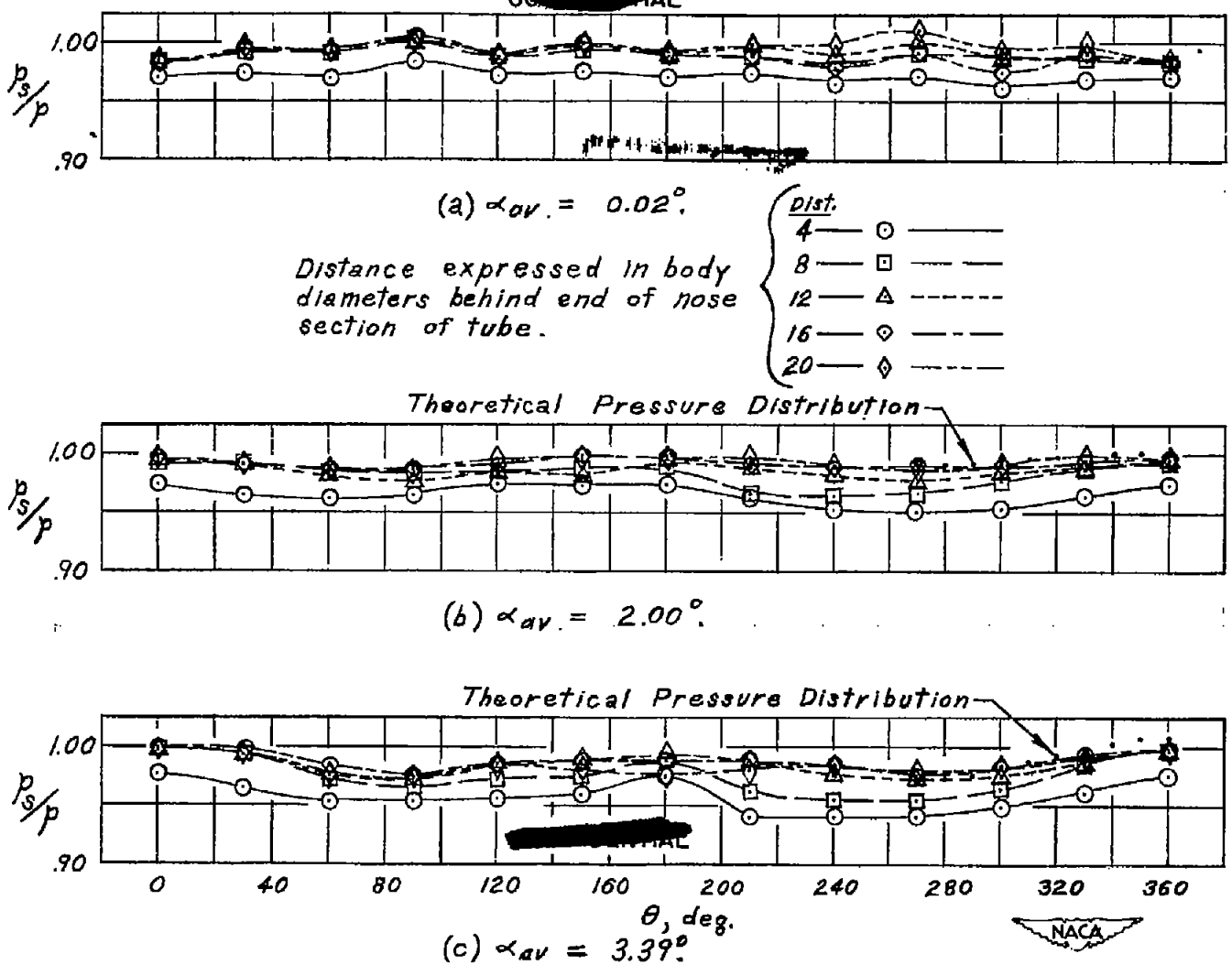
[redacted]




(b) M = 1.62

F[redacted] - Concluded.

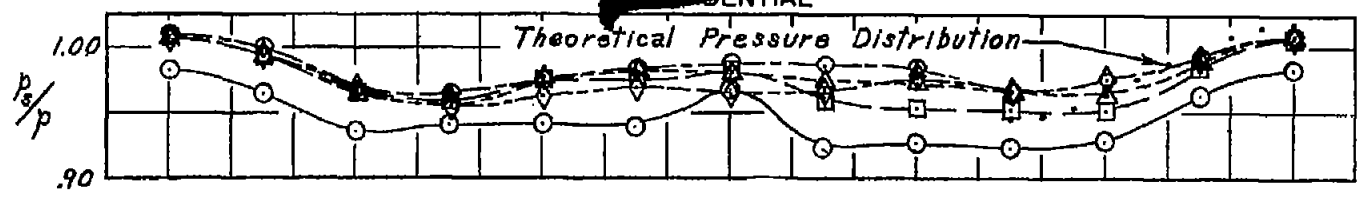
[redacted]




[redacted]

Figure 7.- Static-pressure distribution on cylindrical tube; M=1.94.

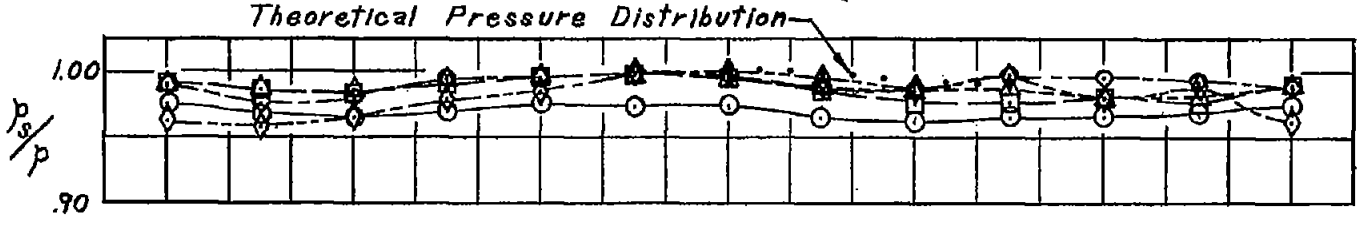
[redacted]



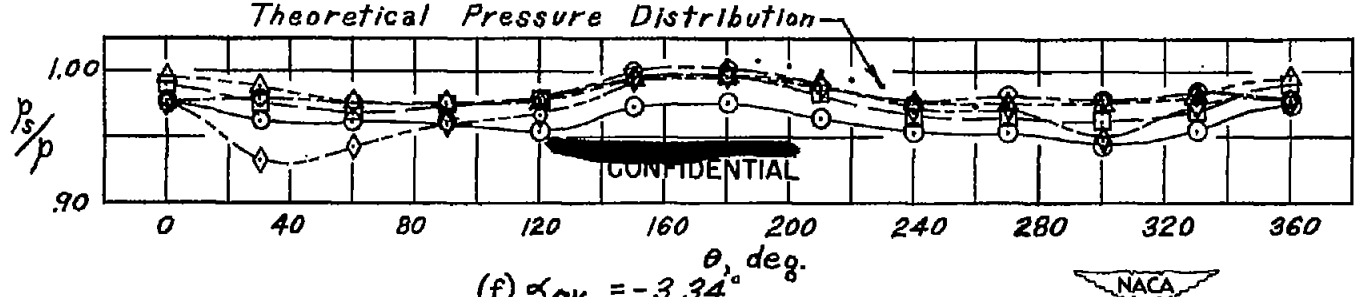

(d) $\alpha$ [redacted]

Distance expressed in body diameters behind end of nose section of tube.

| Dist | |
|---|---|
| 4 | ⊙ ——— |
| 8 | ⊡ — — |
| 12 | △ - - - - |
| 16 | ⊙ — - — |
| 20 | ◊ — - - — |




(e) $\alpha_{av} = -2.01°$

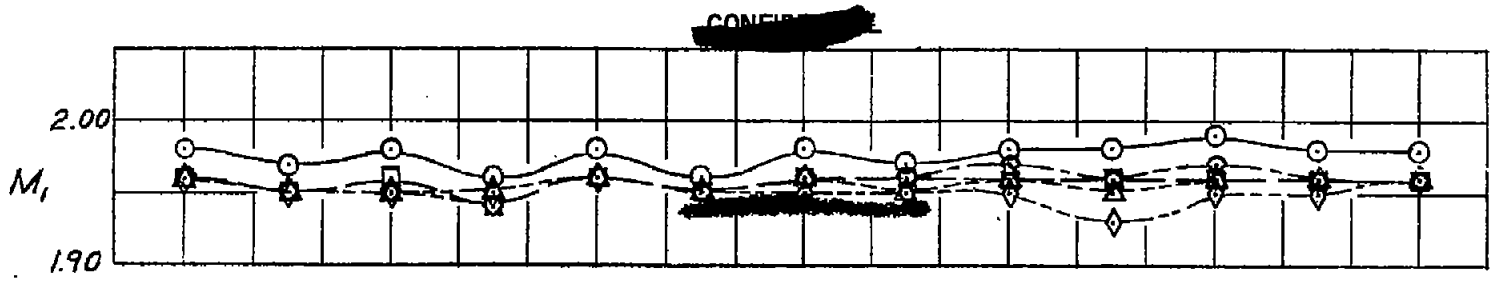



[redacted]

(f) $\alpha_{av} = -3.34°$

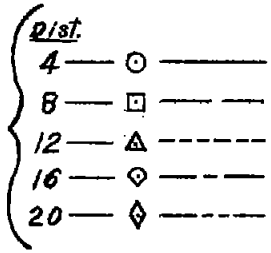
[redacted]

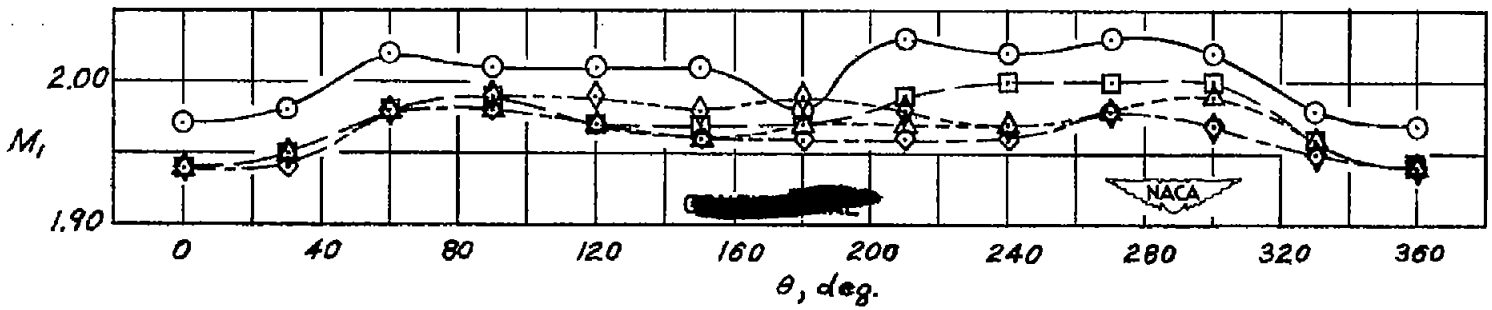
Figure 7.- Concluded.




(a) $\alpha_{av} = 0.02°$.

Distance expressed in body diameters behind end of nose section of tube.

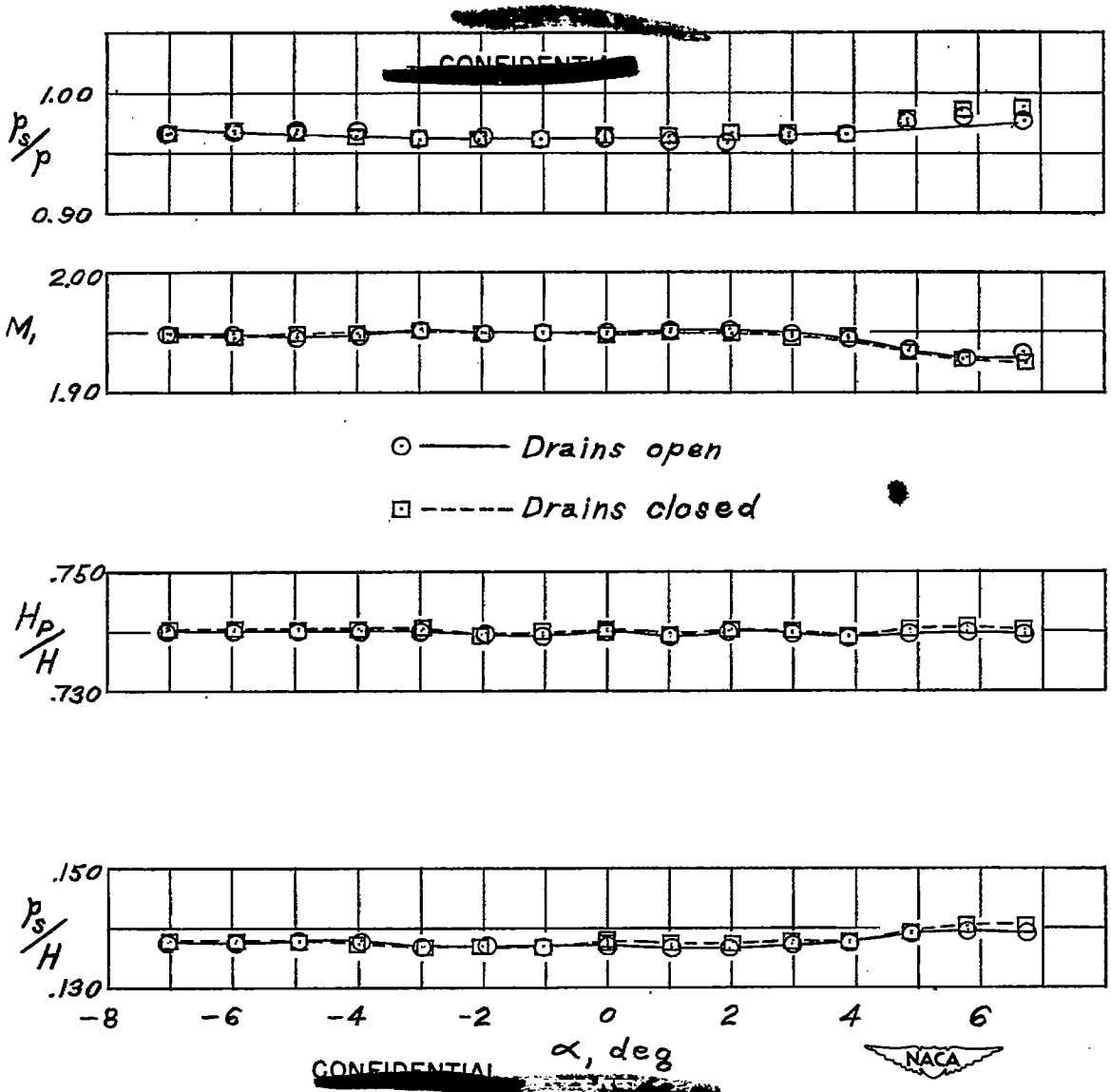



(b) $\alpha_{av} = 4.79°$.

Figure 8.– Mach numbe[redacted]ation on cylindrical tube, M=1.94.

[redacted]




[redacted]

Figure 9.– Supersonic characteristics of a service pitot-static tube in pitch; M = 1.93.

[redacted]

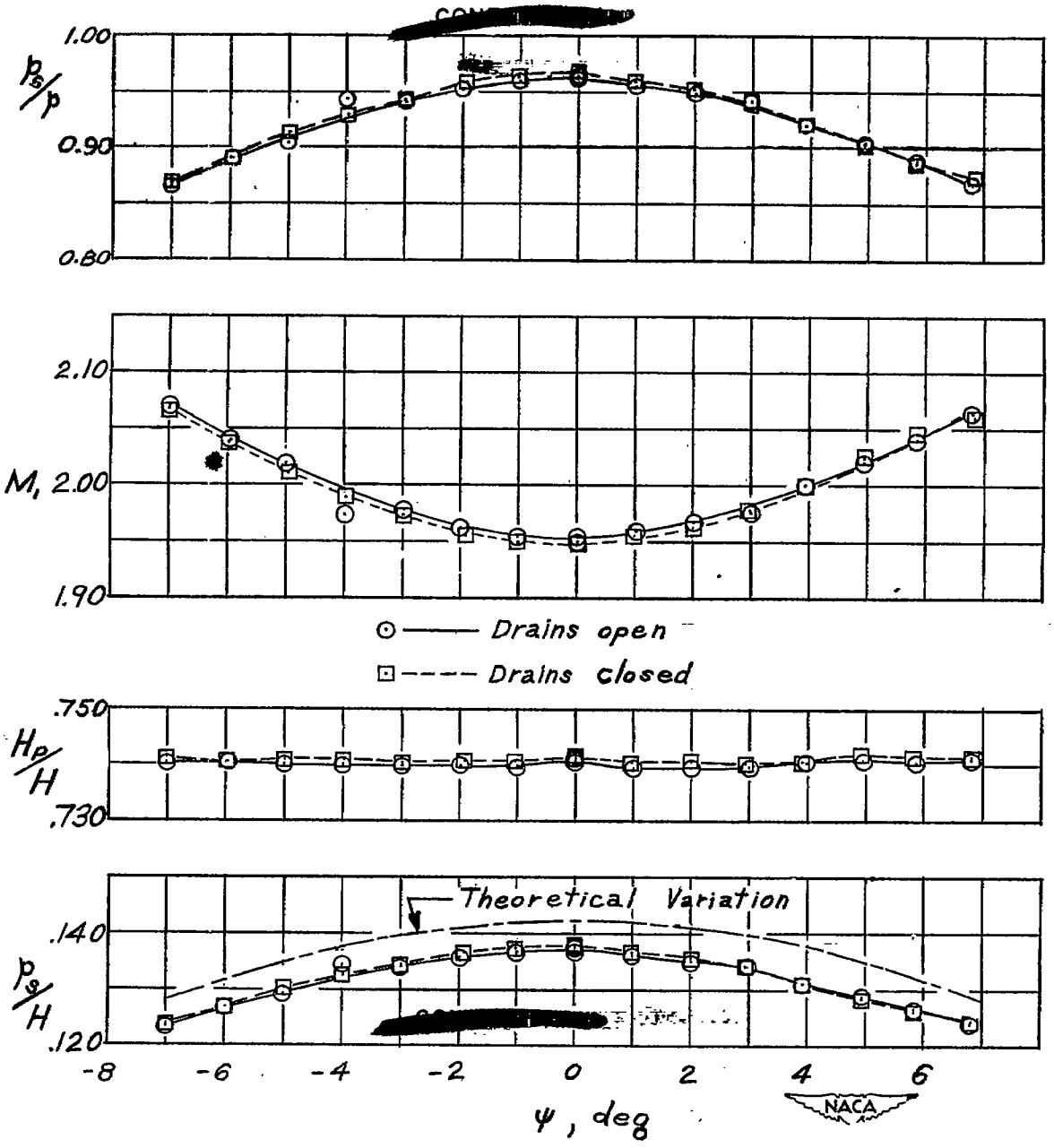
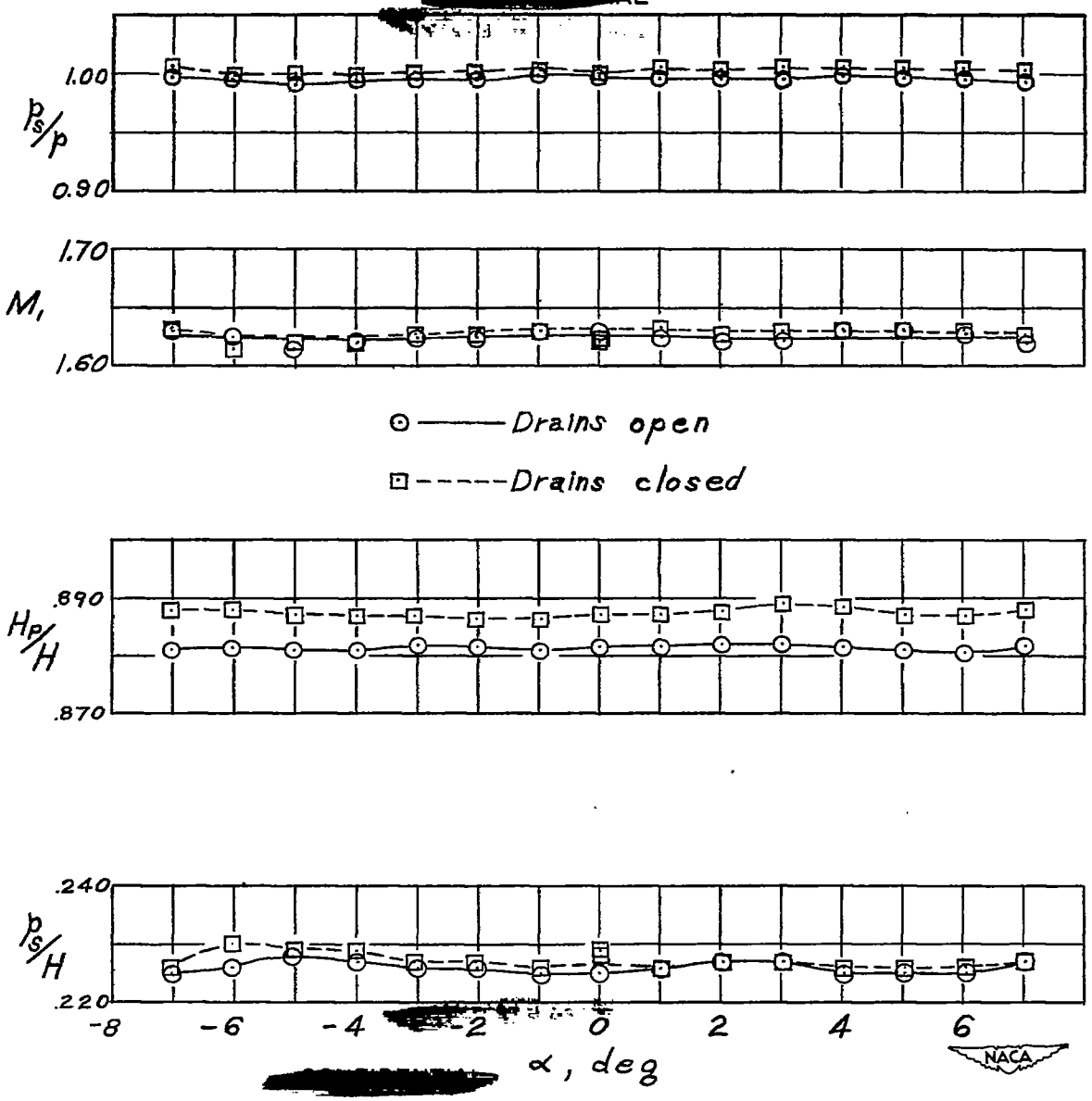



Figure 10.- Supersonic characteristics of a service pitot-static tube in yaw; M = 1.93.

[redacted]




[redacted]

Figure 11.- Supersonic characteristics of a service pitot-static tube in pitch; M = 1.62.

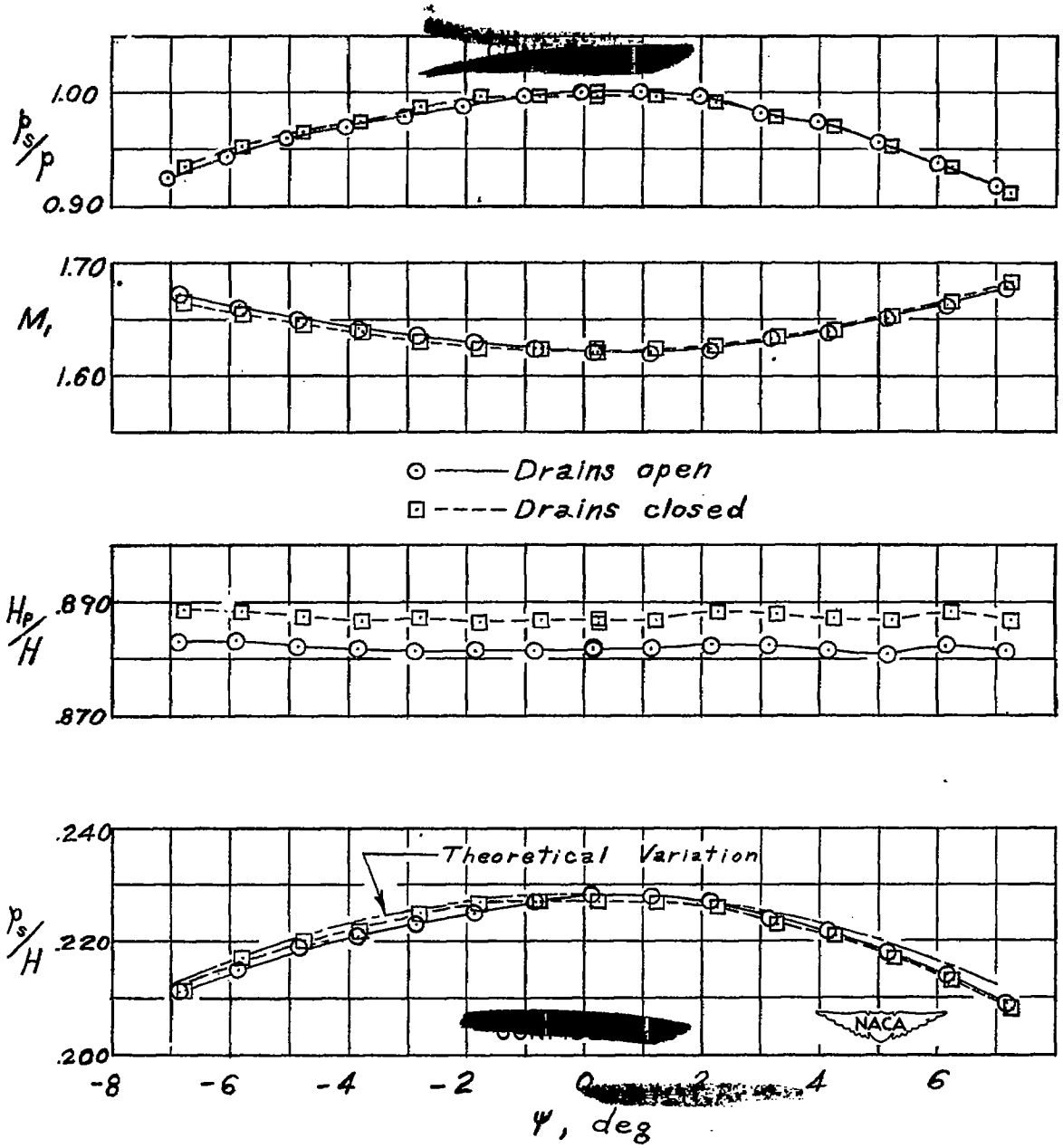



Figure 12.- Supersonic characteristics of a service pitot-static tube in yaw; $M = 1.62$.