ENGINEERING RESEARCH INSTITUTE
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FINAL REPORT

AN EXPERIMENTAL EVALUATION OF A WEDGE-TYPE FREE-STREAM STATIC-PRESSURE PROBE

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WTM-227

Project M950

AIR RESEARCH AND DEVELOPMENT COMMAND
U. S. AIR FORCE CONTRACT AF 33(038)-20799

May 1952

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ACKNOWLEDGMENTS

The authors would like to express their thanks to M. V. Morkovin, H. P. Liepman and A. M. Kuethe for their contributions to this report. Our sincere thanks is also due to Mr. F. J. Donovan for his able assistance in operating the wind tunnel for these tests. Additional thanks are due to Mrs. Black for assistance in data reduction and the preparation of the graphs and to Mrs. Farrell for typing the report.

FINAL REPORT

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I INTRODUCTION

It is the purpose of this report to present the experimental evaluation of the wedge free-stream static-pressure probe described in Reference 1. This work has been carried out under Air Force Contract No. AF 33(038)-20799.

Reference 1 considered in detail the various aerodynamic sources of error for a wedge probe when used to measure static pressure in a uniform supersonic stream. Since there is no way of knowing the true value of this static pressure, the idea behind the present experiments was to vary the parameters related to the known sources of error and from the resulting spread of measured values to infer if possible the reading obtainable in the absence of aerodynamic errors. In carrying out this program there is the usual difficulty of conducting the experimental evaluation in a slightly non-uniform stream using imperfect pressure recording instruments. Thus, great care has to be exercised to separate insofar as possible from the total error the contributions due to:

a) spatial non-uniformity of the stream in the wind tunnel, i.e., variation of p with x, y and z;

b) the variation of pressure at a fixed tunnel position x_1, y_1, z_1 with time due to slight changes in the boundaries of the supersonic stream including settling chamber conditions;*

*These time variations of local tunnel conditions exist in wind tunnels of all types. In intermittent tunnels their presence makes itself known more strikingly, simply because the whole system is literally shaken up in each run, whereas in continuous tunnels the variations creep in so to speak, often without being observed.

c) the more or less repeatable response of the recording instruments to a given pressure at the wedge orifice.

In order to appreciate the procedures adopted it is desirable to discuss the aerodynamic errors of the wedge probe and the other errors in more detail.

II <u>THEORETICAL DISCUSSION OF THE PROBE AERODYNAMIC ERRORS IN A UNIFORM STREAM</u>

The direct aerodynamic errors combined into a correction δp_o are associated with entropy effects due to shock on the imperfect wedge, boundary layer effects, angle of attack effects, angle of yaw effects, and tip effects at lower supersonic Mach numbers.

Since the original direction of the flow is restored on the flat portion of the wedge the ideal deviation of the local pressure from that in the free stream is due solely to the change in entropy across the shock wave. This entropy change will be small for small flow deflections since the specific entropy varies as the third power of the flow deflection. In the case of a perfect wedge with a total angle of 10°, the matching of the compression and expansion is so close that the pressure ratio across the two in combination is 1.000 at M = 1.45, M = 1.90 and M = 2.85 (see Fig. 1).

For the regions on the wedge flat affected by the curvature of the shock wave, Reference 2 establishes that the first order effects are negligible.

The presence of the boundary layer at the leading edge and at the wedge expansion corner undoubtedly influences the compression and expansion processes locally.

Although there is no theoretical way in which to assess these effects, it is believed that they are mostly local and tend to distort the field upstream of the orifices somewhat as a solid boundary change would do. Then, the results of Reference 2 would again indicate that the pressure at the orifice would remain unaffected, unless the boundary layer changed the effective slope of the wedge flat. A large body of experience indicates that there is no need to suspect the possibility of a vertical pressure gradient through the boundary layer as an additional error source as long as pressures near the sharp corners are not measured.

In order to verify the boundary layer effects two wedges of different sizes were tested and also leading edge bluntness and surface roughness on the wedge faces was introduced. This was done in order to alter the boundary layer conditions sufficiently to detect, if possible, pressure changes of the magnitude expected from a probe with a "normal" boundary layer compared to an ideal probe in non-viscous flow.

The theoretical insensitivity of the probe to angles of yaw was discussed fully in Reference 1 and so was the scheme of manifolding pressure readings from top and bottom orifices in order to render the measured pressure relatively insensitive to angles of attack. The experimental verification of these effects was straight forward as long as the tip effects were not felt near the orifice holes.

The tip effects have to be kept in mind especially when measurements at Mach number 1.45 are considered. As Fig. 2 indicates, the Mach lines in the flow outside of the boundary layer along which the lower pressures from the tip make themselves felt, encroach upon the measuring orifices as angle of attack or angle of yaw increases. Reference 6 established that this encroaching pressure field generates a boundary layer cross flow which may alter the pressure on the wedge beyond the (non-viscous) Mach lines of Fig. 2. Thus, the tip effect may limit the location of the measuring orifice or the usable angle of attack more in the presence of a thicker boundary layer.

III ERRORS CONNECTED WITH NON-UNIFORM STREAM

All know systematic errors associated with tunnel conditions and response of recording instrument are always eliminated as nearly as possible, so that the time error (b) and the recording errors (c) listed in the introduction are treated as random. They are therefore associated with the extent of random non-repeatability of measurements in successive runs. In order to separate them as much as possible from the other errors, many identical runs were made and a statistical analysis applied to the results. Simultaneously, a statistical study of several tunnel wall orifices was made in order to establish some sort of limit on the random errors.

The errors (a) due to spatial non-uniformity of the flow on the other hand, are mainly systematic. They are difficult to assess since both $\delta p_o(x,y,z)$, the pressure increment from static pressure at the orifice of the probe in a uniform stream and the static pressure p to be measured, are unknown. The presence of the probe in a non-uniform flow field causes an additional pressure increment $\delta p_i(x,y,z)$ since the probe forces the streamlines to follow its physical contour.

It is to be noted that this induced incremental pressure field will differ with the probe geometry. Thus, the present wedge probe has a different δp_i from that of the needle static probe, so that their pressure readings may differ in a wind tunnel while they should agree in a uniform supersonic stream such as that encountered by an aircraft moving through air at rest. Stated more precisely;

$$\delta p_{i_{needle}} = \int_{x_1}^{x_o} f(x)\, K_1(x_o - x)dx$$

$$\delta p_{i_{wedge}} = \int_{x_2}^{x_o} f(x)\, K_2(x_o - x)dx$$

$$K_1(x) \neq K_2(x)$$

$$x_1 \neq x_2$$

where x_o is the orifice location, x_1 is the location of the needle tip, x_2 is the location of the wedge leading edge, $f(x)$ is the unknown distribution of tunnel non-uniformities, $K_1(x_o-x)$ is the response at x_o of the needle probe to a Mach wave which gives a unit pressure disturbance at station x, and $K_2(x_o-x)$ is the response at x_o of the wedge probe to a Mach wave which gives a unit pressure disturbance at station x. For a discussion of the corrections which much be applied to a body in a slightly non-uniform stream see Reference 9.

IV EXPERIMENTAL INVESTIGATION

A. Models and Instrumentation

Two wedge static pressure probes of the type mentioned in Reference 1 were designed and built in order to carry out the experimental evaluation. Fig. 3 shows the important dimensions of the large model together with the orifice locations and designations. The small probe which will be designated W_2 is a one-half scale replica of the large wedge probe W_1 except for orifice size which is .042 inch in diameter for all orifices on both probes. Fig. 4 is a photograph of the two probes W_1 and W_2.

All pressures were measured with mercury manometers except for the absolute reference pressure which was measured with a Wallace and Tiernan gage. In addition it was originally planned to measure the pressures at the four orifices B, C, F, and G by means of pressure capsules and special manometers containing acetylene tetrabromide as the indicating fluid. The response time of the tetrabromide manometers turned out to be somewhat too long to allow them to stabilize satisfactorily in the 17 to 18 seconds of run time available. These manometers were therefore immediately cut out of the pressure measuring circuit in order to eliminate their interaction with the mercury manometers and the pressure capsules. The pressure measuring devices used then consisted of mercury manometers for all eight orifices, A through H, and in addition pressure capsules on orifices B, C, F and G. The complexity of the pressure capsule as a pressure measuring device introduces the possibility of additional errors both in technique and in data reduction. Hence, in the discussion that follows reference will be made only to the data taken by means of the mercury manometer since it was obtained for all the orifices and it is believed to be as good as the data from the capsules.

In addition to the pressure data from the probe itself, static pressures at several points on the test section walls upstream of the model were measured. This was done to correlate the randomness in the readings from the orifices on the probe with the randomness in the tunnel flow and the randomness in the pressure measuring technique as mentioned above. The wall orifices used for this statistical study were orifices 467, 567, and 667 which all lie in a plane perpendicular to the flow direction and 12 inches upstream of the test section centerline. Orifice 467 is in the tunnel ceiling 2 inches from the west wall, orifice 567 is in the floor 2 inches from the east wall and orifice 667 is in the floor 2 inches from the west wall (Reference 3).

Besides this pressure data a schlieren photograph of each run was taken. Since the schlieren system measures the density gradient, it was used with a horizontal knife edge in order to show the boundary layer to the best advantage.

B. Test Program

The actual tests themselves were run in two series. The first series of runs was made in October 1951 and all tests were conducted at Mach number 1.90. In this series an attempt was made to compare the two wedge probes with each other and with a conventional hypodermic needle probe. It should be borne in mind at all times that a direct comparison of the actual values of the static pressures measured by the two different types of probes cannot be made since such a comparison assumes one of the probes as more accurate than the other. Any comparison must be made with reservations as to the different response of the needle probe and the wedge probe to tunnel non-uniformities.

Furthermore in order to determine the reliability of the wedge probe it is necessary to attempt to experimentally verify the theoretically predicted properties of the wedge probe such as the independence of the pressure readings to changes in yaw or the response of the wedge probe readings to angle of attack variation. This second measure of the wedge probe's reliability is completely independent of any comparison with the needle probe. The first series of tests also consisted of an evaluation of the effects of leading edge bluntness and surface roughness.

The second series of runs was conducted in December 1951. In this series the emphasis was placed on the large wedge probe and in order to insure the maximum accuracy of the readings obtained each run was repeated a second time in order to check the values of the first run. If the two runs did not check each other within .03 inch of mercury in all eight orifices when the manometers were read by eye immediately following each test, then the same configuration was rerun again and again until this check was obtained.

The second series consisted of three subseries, one each at the three different Mach numbers 1.45, 1.90 and 2.85. In the subseries of runs at Mach number 1.90 an attempt was made to check as accurately as possible the effect of variation of angle of attack on the average of static pressures on the top and bottom of the wedge. In addition the probe was moved fore and aft by small amounts so as to measure the pressure at the same point in space with several different orifice——manometer combinations, and thus to compare one orifice-manometer combination against another. In the subseries of runs made at Mach number 2.85 the effect of variation of angle of attack on the static pressure measured by the wedge was ascertained. The effect of leading edge bluntness was also measured at this Mach number. At Mach number 1.45 tests were again made to check the variation of static pressure on the wedge with angle of attack. The effects of both leading edge bluntness and surface roughness were also investigated.

C. Data Reduction Technique

It is perhaps worth while to mention the method of reducing the data from the photographs taken of the mercury manometer board. Since so few manometer tubes were used it was possible to place the camera very close to the manometer board. As a result the pictures obtained were very large and very readable, thus permitting the use of a reading device which utilizes a dial gage reading to the nearest .001 inch. In order to read the height of a column of mercury from the photograph the first three figures, e.g., 18.8 are read directly from the photograph of the glass scale by eye; then the position of the top of the mercury column in the 0.1 inch division between 18.8 and 18.9 is determined by measuring the ratio of the distance between the top of the mercury column and 18.8 to the distance between 18.8 and 18.9 with the reading device, e.g., 24/62 = .038. The final reading for the sample mercury column is 18.838. No claim is made for the figure in the third decimal place other than that it serves to indicate a plus or minus value. It is felt, however, that this procedure will remove the second decimal place from suspicion in that the second decimal place will be reproducible at will and not estimated by eye.

The height of the mercury column as read in the manner described above does not yet represent the true pressure at the orifice nor is it in a sufficiently general form to permit comparison with other pressures observed on other runs. In order to convert the pressure as read from the manometer photograph into the true pressure it is necessary to correct for:

1) the parallax error introduced by the fact that the manometer tubes do not lie in the plane of the glass scale,

2) the temperatures of the mercury columns in the manometer and the barometer, and

3) the standard reference pressure.

So that the pressures recorded for different runs may be compared with one another, all pressures are non-dimensionalized by taking their ratios to the barometric pressure p_b which is essentially the stagnation pressure.

The reduction of the pressure data is probably best illustrated by an example:

Run 51-12-19-3

Reference tube readings, 14.446 inches, 14.453 inches
Average reference tube readings, 14.450 inches
Manometer tube "B" reading, 18.838 inches
Pressure as read from the photograph, = 18.838 - 14.450 = 4.388 inches
Pressure as corrected for parallax = 4.388 - (.01334)(4.388) = 4.329 inches
Pressure as corrected to 29°F = 4.329 - (.0049)(4.329) = 4.307 inches
Pressure as corrected to zero reference pressure as read on Wallace and Tiernan gage = 4.307 + .010 = 4.317 inches
Barometric pressure after run = 29.610 inches
Barometric pressure corrected to 29°F = 29.491 inches
Pressure ratio, p/p_b = 4.317/29.491 = .1464

For details concerning all corrections except temperature correction see Reference 7. For the procedure used in making temperature corrections see Reference 8.

V TEST RESULTS AND DISCUSSION

A. Statistical Analysis of Measuring Accuracy

1. Tunnel Wall Static Pressures. In order to obtain some idea as to the accuracy with which a static pressure may be measured using a mercury manometer, several static pressure orifices in the test section ahead of the model were connected to the manometer board as mentioned previously.

The results obtained from orifices 467, 567 and 667 at a Mach number of 1.90 are presented below in tabular form:

Day	Number of Runs	467 p/p_b Average	467 Std. Dev.	567 p/p_b Average	567 Std. Dev.	667 p/p_b Average	667 Std. Dev.
12/19/51	9	.1396	.0006	.1416	.0003	.1439	.0006
12/20/51	9	.1394	.0005	.1412	.0002	.1433	.0002
12/21/51	10	.1390	.0002	.1408	.0004	.1430	.0002
12/22/51	9	.1397	.0004	.1412	.0004	.1436	.0003
All 4 Days	37	.1394	.0005	.1412	.0003	.1435	.0005

Since for all three of the orifices the daily average does not differ from the overall average by more than 1.5σ where σ is the standard deviation associated with the overall average for all four days, it would seem that the variation of the static pressure to barometric pressure ratio is a statistical variation. Pearson's χ^2 test has been applied to the overall average and its associated standard deviation for each of the three orifices. The results of this test indicate that the probability that the deviations which would be measured if the tests were repeated would not exceed the deviations actually measured is .8 to .9 for orifice 467; .1 to .2 for orifice 567; and .1 to .2 for orifice 667.

In order to interpret these probabilities we may say that if the probability lies between .1 and .9 the assumed normal distribution law very probably corresponds to the actual distribution law governing the measurements made. Thus, we are led to the conclusion that the probability distribution which applies to the measurement of a static wall pressure at Mach number 1.90 is actually a normal distribution function. Once the kind of distribution is known it is possible to compute the probability that any one measurement will be within a specified range of the true value. Hence, the probability that a given measurement lies within $\pm.0010$ of the mean value is .9634 if we choose the maximum value of $\sigma = .005$.

In terms of Mach number this means that in the vicinity of Mach number 1.90 we will be able to obtain the Mach number within $\pm.005$ in 96.34 per cent of the measurements made. This is an error in Mach number of $\pm.26$ per cent at Mach number 1.90 if the flow is assumed isentropic. If the accuracy of the pressure measurements is independent of the value of the pressure read we will have an error of $\pm.17$ per cent at Mach number 1.45 and an error of $\pm.68$ per cent at Mach number 2.85. The assumption that the accuracy of the pressure measurements is independent of the value of the pressure is undoubtedly justifiable at Mach numbers less than 1.90, but it is known that at Mach number 2.85 this assumption is subject to question, because of the proportionally greater effects of small leaks in the orifice-manometer combination on response time.

2. Wedge Probe Static Pressure. The preceding discussion has dealt with the measurement of a pressure at a fixed point in space and with all measurements made with the same orifice-manometer combination. In order to get some idea of the repeatability involved when a pressure at a fixed point in space is measured with different orifice-manometer combinations a series of tests was run in which the wedge orifices B, C, D and E successively occupied the same point in space. It should be noted that in moving the model in this fashion it is possible to introduce a slight change in angle of attack. Furthermore, the probe will no longer be in precisely the same non-uniform field, i.e., a different portion of the curve $f(x)$ will be used since x_0 and x_1 the limits of integration will be different. Hence, it is to be expected that the standard deviation will be larger even if all the orifice-manometer combinations are precisely the same.

When the pressure ratio on the vertical centerline of the Mach number 1.90 channel was measured with orifice-manometer combinations B, C and D it was found that $(p/p_b)_{mean} = .1452$ with $\sigma = .0010$ based on a total of 9 runs. The pressure ratio .25 inch aft of the vertical centerline was measured with orifice-manometer combinations B, C, D and E and was found to be $(p/p_b)_{mean} = .1445$ with $\sigma = .0009$ based on a total of 11 runs. The pressure ratio .50 inch aft of the vertical centerline measured with orifice-manometer combinations C, D and E was $(p/p_b)_{mean} = .1439$ with $\sigma = .0004$ based on a total of 8 runs. A comparison of this data with the data obtained from orifices 467, 567 and 667 shows that the effect of using different orifice-manometer combinations to measure the pressure at the same point in space approximately doubles the standard deviation. This difference in the standard deviations for the two cases leads one naturally to look for some systematic discrepancy between the orifice-manometer combinations. However, all attempts to locate such a systematic discrepancy failed. We can only conclude therefore, that the randomness of the measurement increases, probably due to slight errors in model position, when we use more than one orifice-manometer conbination.

3. Needle Probe Static Pressure. In order to compare the wedge probe with the hypodermic needle probe a series of six runs was made with the conventional three prong hypodermic needle probe which had been used in the calibration of the M = 1.90 channel (Reference 3). The single orifice of this probe was located on the tunnel centerline, i.e., in the same position as orifice B for the wedge runs. These six runs gave $(p/p_b)_{mean}$ = .1445 with σ = .0003. This value may then be compared to the mean of the values of orifices B and G, p/p_b = .1491 with σ = .0007 and the mean of the values of orifices C and F, p/p_b = .1482 with σ = .0006 from the wedge probe for 19 runs at zero degrees angle of attack. It is necessary to average B and G and to average C and F before taking the mean so that any small angle of attack changes are corrected for. The increase in the standard deviation for the wedge probe as compared to the needle probe does not mean that the needle probe is the better instrument for measuring a static pressure because:

1) both standard deviations are of the same order as the standard deviation which would be expected on the basis of the side wall orifice readings previously given;

2) the response of wedge and needle probes to flow non-uniformities is expected to be different as discussed in section III;

3) the runs used to obtain the average for the needle probe were successive runs while the runs used to obtain the average for the wedge probe were not successive runs but covered a period of several days during which time there were numerous changes in the wedge probe configuration, e.g., changes in angle of attack, axial position, etc.

The fact that the needle probe gives a static pressure less than the static pressure given by the wedge probe is in accord with the findings of Reference 5 where the ratio of static pressure measured on the surface of a needle type of probe to the actual free-stream-static pressure is experimentally determined to be .985 for an orifice 16 diameters from the needle tip which is approximately the location of the orifice on the needle probe used in the October series of runs If this correction is applied to the needle probe value of p/p_b = .1445 we obtain an actual static pressure ratio of p/p_b = .1467 which may be compared to the wedge reading of p/p_b = .1482 which is the mean of the average value of orifices C and F on the October runs at zero degrees angle of attack.

B. Scale Effect

A comparison of the small wedge probe with the large wedge probe at Mach number 1.90 shows that there is no consistant measurable difference between the two probes. The small probe was tested with orifices P and K in the same position with respect to the tunnel as were orifices B and G of the large probe. Average value of p/p_b for P and K on runs 10-13-1 and 10-13-2 are .1494 and .1495 while the average value of p/p_b for orifices B and G on runs 12-19-2 and 12-19-3 are .1482 and .1490. Orifices O and L of the small wedge were not in exactly the same position with respect to the tunnel as orifices C and F of the large wedge because of the 1/2 scale effect. The average value of p/p_b for C and F on runs 10-7-3, 10-7-4, 12-19-2 and 12-19-3 are .1480, .1479, .1480 and .1479. These compare with the average values of p/p_b for orifices O and L on runs 10-13-1 and 10-13-2 of .1485 and .1479. The conclusion to be drawn from this comparison is that no measurable effect on the static pressure readings is caused by decreasing the Reynolds number based on the distance from the leading edge to the first orifice from 0.5×10^6 to 0.25×10^6.

$\delta p_{i_{wedge}}$ changes with a change in wedge size since x_o, x_1 and possibly $K_1(x_o - x)$ are different for the large and small wedge probes. The agreement between pressures measured with the two wedges is therefore an indication that for small tunnel non-uniformities δp_i is negligible.

C. Angle of Yaw Effect

The effect of yawing the wedge probe on the value of the static pressure recorded is graphically represented in Fig. 5. It will be noticed that the pressures read on orifices C and F are completely independent of the angle of yaw from 0° to 10° of yaw.

D. Angle of Attack Effect

The sensitivity of the wedge probe to angle of attack is illustrated in Figs. 6a through 6c where orifices B and G are plotted versus angle of attack. The fact that the probe is sensitive to angle of attack yet insensitive to angle of yaw makes it an ideal instrument with which to measure flow inclination when top and bottom orifices are measured individually. Manifolding of top and bottom orifices will of course give a free-stream static-pressure measurement essentially insensitive to angle of attack.

A very interesting aspect of the curves shown in Fig. 6a and 6b is their very slight non-linearity. It will be noticed that for positive angles of attack the curve of orifice G versus angle of attack has a slope which increases with angle of attack while for negative angles of attack the curve is linear. Similarly the curve for orifice B is linear for positive angles of attack and has a slope which increases with decreasing angle of attack. The reason for this non-linear behavior becomes apparent when we realize that since orifice G is on the lower surface of the probe the flow must be deflected compressively through successively larger angles for successively larger positive angles of attack. For the larger deflections the shock strength becomes larger but not linearly, i.e., the static pressure jump across the shock wave is a slightly non-linear function of the flow deflection angle. This behavior of the separate curves for orifices B and G will be reflected in the curve of the average value of B and G versus angle of attack, making it slightly concave upwards as shown in Figs. 6a and 6b.

One of the possible checks on the accuracy of the wedge probe is the correlation between the theoretical and experimentally observed values of this deviation exhibited in Fig. 7. The theoretical curves are obtained from the curves in Fig. 1 by dividing all the ordinates by the value of the ordinate for zero angle of attack. The experimental points are obtained by dividing the various values of (p average)/p_b by the value of (p average)/p_b at zero degrees angle of attack. In the case of the experimental points it is also necessary to correct the observed geometrical angles of attack by subtracting from the geometrical angle of attack the value of flow deflection which is the value of the flow deflection which is the value of α at which the curves of orifices B and G cross in Figs. 6a through 6c.

The experimental points do not coincide well with the theoretical curve for Mach number 2.85. This is probably due to the inaccuracies inherent in measuring the low static pressures at Mach number 2.85 with mercury manometers. The experimental points at Mach number 1.90 agree very well with the theoretical curve. At Mach number 1.45 the experimental points are in good agreement with the theoretical curve as long as the angle of attack is two degrees or less. However, the points observed at angle of attack slightly greater than three degrees fall considerably below their theoretically predicted value. There are two possible explanations of the phenomenon. First the orifices under consideration may lie in a region which is affected by the reflection from the shock wave of the expansion wave originating at the shoulder. The second and more obvious possibility is that the orifices may be in a region which is influenced by the finite span of the wedge. This second case is discussed in detail in the next section on tip effects.

The first possible explanation of the discrepancies observed may be ruled out for two reasons. First, Reference 2 indicates that the reflected disturbances will be extremely weak. Second, if the first ray of the P.M. expansion fan is constructed by drawing the line from the shoulder of the probe to the point at which the shock wave is first observed to curve in the schlieren picture 52-1-4-13, Fig. 8, and then reflected at the shock wave it will be found that the reflected waves strike the probe aft of the orifice region.

E. Tip Effects

The tip will affect a progressively larger area of the wedge as the angle of attack increases for a given Mach number. Fig. 2 shows the regions of the probe theoretically affected for various angles of attack at Mach number 1.45 for the inviscid case. Fig. 9 is a plot of data from the spanwise orifices A, B and H for the largest negative angles of attack for all Mach numbers. It is apparent from these curves that there is no tip effect at Mach numbers 1.90 and 2.85. However, at Mach number 1.45 it is obvious that orifices A and H are affected.

A plot of the axial pressure gradients measured on the wedge probe at Mach numbers 1.90 and 1.45 are shown in Figs. 10 and 11, respectively. From Fig. 10 it is apparent that there is no measurable tip effect on any of the orifices B, C, D or E. The actual pressure gradient existing in the Mach number 1.90 channel is very small as seen from the fact that the curves are very nearly horizontal. The curves in Fig. 11 present a much more interesting picture.

In order to prevent blocking of the flow at Mach number 1.45 a cantilever strut was used which has its center of rotation outside the test section instead of at the center of the test section as in the case of the full spanning support strut used at Mach numbers 1.90 and 2.85. This displacement of the center of rotation in the support system at Mach number 1.45 causes a translation of the orifices on the model when the angle of attack is varied. With the model at -3° angle of attack all orifices are moved forward approximately .34 inch and downward approximately .25 inch while at +3.4° angle of attack the model orifices are moved backward .43 inch and upward .25 inch. For this reason the abscissa in Fig. 11 is taken to be the actual distance of the orifice from this tunnel centerline. The differences in height of ±.25 inch are not taken into account. If we look first at the curve of axial pressure gradient for zero degrees angle of attack we notice that orifices B, C and D give values of p/p_b of approximately the same magnitude while orifice E gives a decidedly lower value of p/p_b. This lower value of p/p_b at orifice E may be accounted for by:

1) a change in the induced error δp_i since x_o and x_1 have changed

2) the tip effect

3) the actual axial pressure gradient in the test section.

The effect due to (1) is small as pointed out in section V-C. Furthermore, if the change in δp_i is measurable there will be an effect on the orifices, B. C and D with the model in the rearward position.

In order to segregate the effects due to (2) and (3) two extra runs were made with the model shifted rearward by .25 inch. This movement places orifice D which is unaffected by the tip in the position previously occupied by orifice E which may experience some tip effect, i.e., orifice D is now on the test section centerline. The amount of the tip effect felt by orifice E when E is on the centerline is then represented by the displacement on the test section centerline of the dashed curve from the solid curve in Fig. 11. The magnitude of the tip effect at orifice E is seen to be $\delta_{tip}\ p/p_b = .0035$. If now the value read from orifice E in its most rearward position is moved up be an amount +.0035 we obtain the actual value of p/p_b .25 inch aft of the tunnel centerline corrected for the tip effect as shown by the dash dot line in Fig. 11. The slope of this line represents the effect due to tunnel gradient and should be compared to the curve at angle of attack equal to +3.4°. This comparison serves as a check upon the method of correcting for tip effect. Since the curve for angle of attack equal to -3° is in a region of zero axial pressure gradient and yet this curve does possess a definite slope we are led to the conclusion that at an angle of attack of -3° all orifices B through E experience some tip effect for Mach number 1.45.

The slope of the curve for $\alpha = +3.4°$ is due solely to the axial pressure gradient existing in the Mach number 1.45 channel since orifices B, C and D experience no tip effect at $\alpha = 0°$ and the tip effect would be even less severe at positive angles of attack (see also Fig. 2).

F. Roll Effects

One series of tests consisted of rolling the wedge about the horizontal centerline of the wind tunnel at Mach number 1.90 in order to check flow inclination. Zero degrees of roll corresponds to having the plane surface of the wedge probe horizontal with orifice "B" on top. Ninety degrees of roll corresponds to having the plane surface of the wedge probe vertical with orifice "B" on the left hand side when the probe is viewed facing upstream. A plot of the data from orifices "B" and "G" on this series of runs is shown in Fig. 12. The plot has been made on polar coordinate paper so that when a circle is drawn through the data points, (1) the displacement of the center of the circle from the center of the graph paper will be a measure of the flow inclination and (2) the radius of the circle will represent the static pressure ratio $+\delta p_o/p_b$. The coordinates of the displaced center of the circle with respect to the origin of coordinates are $p/p_b = -.0025$ vertically and $p/p_b = -.0010$ horizontally. If use is made of the linear relationship between p/p_b and angle of attack with the constant factor in this linear relation determined from Fig. 6a it will be found that the velocity vector is tilted up at an angle of .32° and to the right at an angle of .10°. The radius of the circle gives a value of $p/p_b + \delta p/p_b = .1500$. These values compare well with the flow inclinations reported in Reference 3.

G. Leading Edge Bluntness and Surface Roughness

In order to determine the effect of a more blunt leading edge two pieces of tape were wrapped around the leading edge of the wedge probe and several runs were made at the three Mach numbers 1.45, 1.90 and 2.85. Fig. 13 shows a typical schlieren photograph at each Mach number with the tape on the leading edge. These schlieren photographs may then be compared to those in Fig. 14 which show runs at the same Mach numbers but with the original "sharp" leading edge. At all three Mach numbers the presence of the tape is sufficient to cause a detached shock wave. There is also in each case a shock which is the envelope of the compressive Mach waves originating from the concave surface formed by the rear of the tape and the sloping face of the wedge. A comparison of the schlierens for the sharp and blunt leading edge at Mach number 1.45 (Figs. 13a and 14a) indicates that there is a very perceptible thickening of the boundary layer in the blunt case. At Mach number 1.90 (Figs. 13b and 14b) the same thickening in the blunt case is apparent but the increase in thickness appears to be less here than at Mach number 1.45. The resolution of the schlieren at Mach number 2.85 (Figs. 13c and 14c) seems to be insufficient to permit a comparison in boundary layer thickness for sharp and blunt case at this Mach number.

Figs. 15, 16, and 17 are plots of the pressures at orifices B, C, D and E for the sharp and blunt leading edge cases as well as the case of the roughened surface to be discussed later on. These curves indicate that at Mach numbers 2.85 and 1.90 there is no measurably consistent difference in the pressure ratios observed for the sharp and the blunt cases. This seems to bear out the statement quoted here from Reference 2.

> "If (as must happen) a thin supersonic air foil has a leading edge not exactly sharp, the shock will be much stronger near this point than elsewhere (perhaps detached): and the resulting comparatively large entropy variations will be propagated along the streamlines to form an 'entropy boundary layer.' Outside a neighborhood of the leading edge the flow will be approximately uniform and of 'progressive wave' character, but with entropy variation. ...Thus the pressure on the surface is unaffected (as in an ordinary boundary layer), while the velocity on the surface is considerably altered... Effectively then the bluntness of the leading edge, as well as producing local effects, increases the vorticity near the whole surface, above that due to viscous stress and heat conduction, but does not affect the pressure."

At Mach number 1.45 there is a measurable difference between the blunt leading edge and the sharp leading edge. The difference in pressure ratio p/p_b between the blunt case and the sharp case is .8 per cent for orifice B, 1.4 per cent for orifice C, 2.6 per cent for orifice D, and 2.9 per cent for orifice E with the pressures for the blunt leading edge being consistently lower than the pressures for the sharp leading edge. The maximum difference of 2.9 per cent in pressure ratios corresponds to a 1.4 per cent difference in Mach number. This difference is discussed in a later paragraph along with the difference due to the roughness effect since both phenomona are similar.

The effect of roughness of the wedge surface was investigated by glueing a piece of sand paper on the sloping wedge surface. This effect was tested only at Mach numbers 1.45 and 1.90. Figs. 18a and 18b are the schlieren photographs of the model with the roughness strip glued on and are to be compared to the corresponding schlieren photographs for the smooth case given in Figs. 14a and 14b, respectively. At both Mach numbers there is an increase in boundary layer thickness with the increase again being the greatest at Mach number 1.45. At Mach number 1.9 there is no measurably consistant difference between the pressures measured for the smooth and the rough cases as shown in Fig. 15. Fig. 17 shows a comparison of the pressure ratios measured at Mach number 1.45 for the smooth and rough cases. The pressure ratios are consistently lower for the rough case the differences being .5 per cent for orifice B, .2 per cent for orifice C, 1.2 per cent for orifice D, and 2.2 per cent for orifice E.

The divergence of the curves for the rough surface and the blunt leading edge from the curve for the smooth surface and the sharp leading edge at Mach number 1.45 as exhibited in Fig. 17 may possibly be explained on the basis of the interaction of the tip effect and the boundary layer effect. If the boundary layer thickness is increased as it is in the case of either the rough surface or the blunt leading edge then the disturbing effect of the tip may be propagated further inward and upstream through the boundary layer. Hence, the orifices pick up more tip effect which is shown by the lower pressure values of the dotted curves of Fig. 17 compared to the solid curve.

Normally, the effect of roughness is understood to increase the rate of growth of the displacement thickness of the boundary layer. If this effect were appreciable, the resulting pressures for blunt leading edge and rough surface would be higher, rather than lower as seen in Fig. 17.

H. Comparison with Conventional Tunnel Calibration

A representative value of p/p_b from the wedge probe for the Mach number 1.45 channel is $p/p_b = .2990$ which compares favorably with the value of $p/p_b = .2980$ observed in Reference 4.

The calibration of the Mach number 1.90 channel reported in Reference 3 gives a value of $p/p_b = .1475$ which is to be compared with $p/p_b = .1491$ from the wedge probe.

At Mach number 2.85 Reference 5 gives a value of p/p_b = .0332 which is to be compared with p/p_b = .0384 as measured with the wedge probe. Here the agreement is not good but it should be remembered that the measurements reported in Reference 4 were made with oil as the manometer fluid so that their accuracy is probably better than the accuracy of the wedge probe measurements.

VI CONCLUSIONS AND REMARKS

The statistical study made at Mach number 1.90 indicates that the probable error for a measurement of the static pressure is .5 per cent. The measurements indicate no tip effect at Mach numbers 1.90 and 2.85. However, at Mach number 1.45 there is a definite tip effect which makes itself felt both directly and through its interaction with the effects due to angle of attack, surface roughness and leading edge bluntness. Except for the instances in which the tip effect interacts with some other effect the wedge probe reacts to variations in such parameters as angle of attack, surface roughness, leading edge bluntness, roll and yaw, in the manner predicted by theory.

Since the wedge probe responds to variations in angle of attack in a linear manner its use as a device to simultaneously measure static pressure and flow inclination makes it a good instrument for the calibration of supersonic wind tunnels. A needle-static-pressure probe cannot give the flow inclination since its reponse to an angle of attack $+\alpha$ is the same as its response to an angle of attack $-\alpha$. Furthermore, the corrections to be applied to the wedge probe due to the presence of a slightly non-uniform stream are much simpler than the corresponding corrections for a needle probe. The fact that the needle probe when used at an angle of attack may experience separation of the flow downstream from the shoulder makes the calibration depend completely on empirically determined coefficients.

The use of the wedge probe for the determination of static pressure in free flight possesses certain advantages over the use of a needle pressure probe. The wedge probe seems less sensitive to boundary layer thickness than the needle probe Since the wedge probe can be made self-correcting for angle of attack variations by manifolding the pressures read on its upper and lower surfaces, it can be made to read the static pressure regardless of the orientation of the aircraft with respect to the free stream within limits. On the other hand, the needle probe is inherently incapable of giving readings independent of its orientation with respect to the free stream. Hence, any slight misalignment of the needle probe with respect to the free stream will give an incorrect reading which can be corrected only by a calibration of the instrument in combination with the aircraft.

In addition, the ability of the wedge probe to respond to flow inclination if the readings on its upper and lower surface are properly interpreted may make it possible to use the wedge probe to give warning when the angle between the flight path and the axis of the aircraft reaches some maximum permissible value.

The importance of the self-correcting properties of the wedge probe with regard to static pressure measured and its ability to obtain two bits of information simultaneously, i.e., static pressure and flow inclination give the wedge probe an advantage over the needle probe, especially in the calibration of supersonic wind tunnels.

It is, of course, impossible on the basis of the experimental evaluation presented above to state definitely that the wedge probe measures static pressure more accurately than the needle probe since such a statement assumes the existence of some device for the measurement of the free-stream static pressure which is more accurate than either type of probe. However, the wedge probe readings appear to be fully as reliable as the needle probe readings.

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4. Culbertson, P. E., "Calibration report on the flow in the U.M.E.R.I. Supersonic Wind Tunnel at nominal Mach numbers 2.84 and 1.44." WTM-213.

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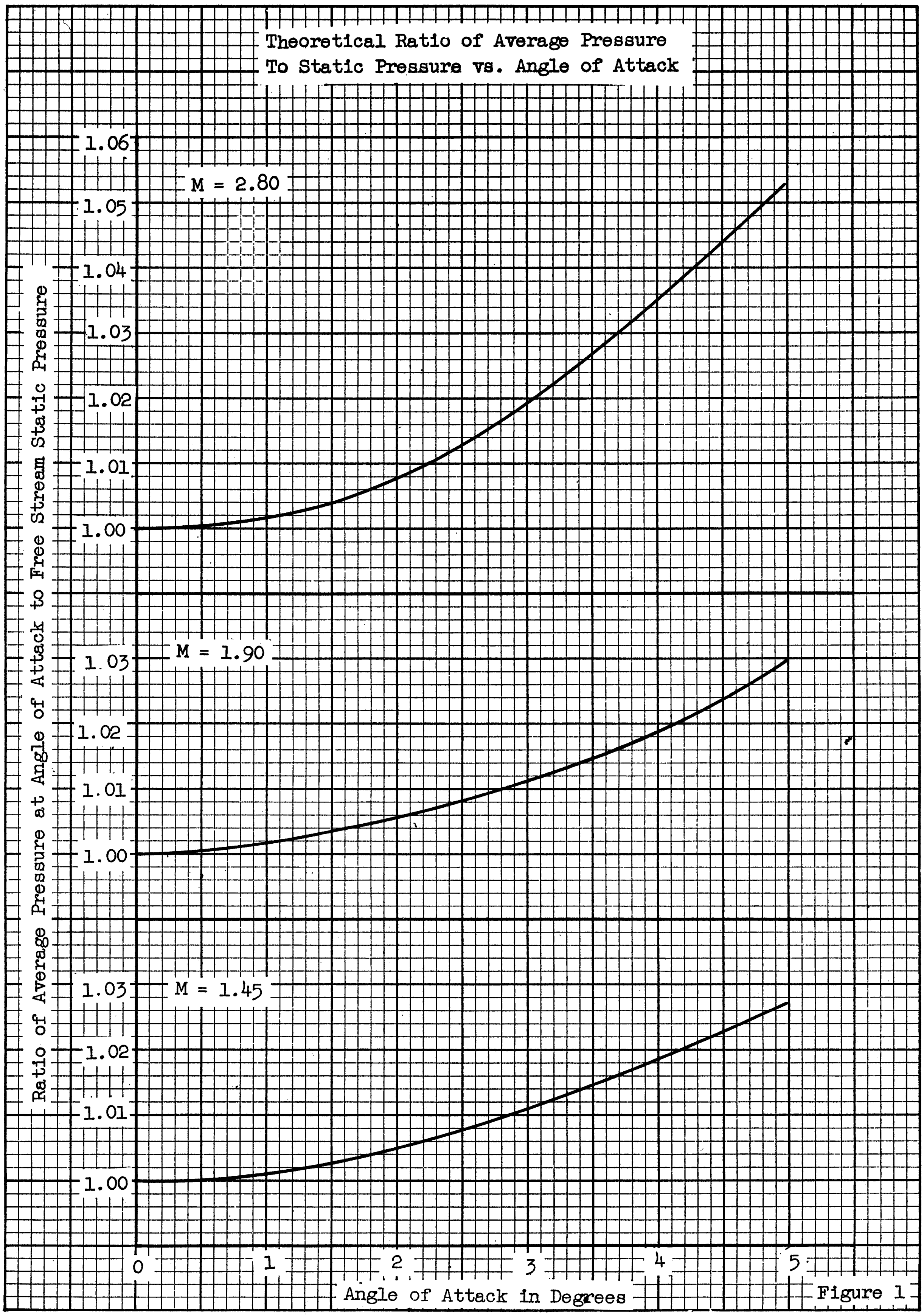


Theoretical Ratio of Average Pressure
To Static Pressure vs. Angle of Attack
Ratio of Average Pressure at Angle of Attack to Free Stream Static Pressure
M = 2.80
1.06
1.05
1.04
1.03
1.02
1.01
1.00
M = 1.90
1.03
1.02
1.01
1.00
M = 1.45
1.03
1.02
1.01
1.00
0
1
2
3
4
5
Angle of Attack in Degrees

Figure 1

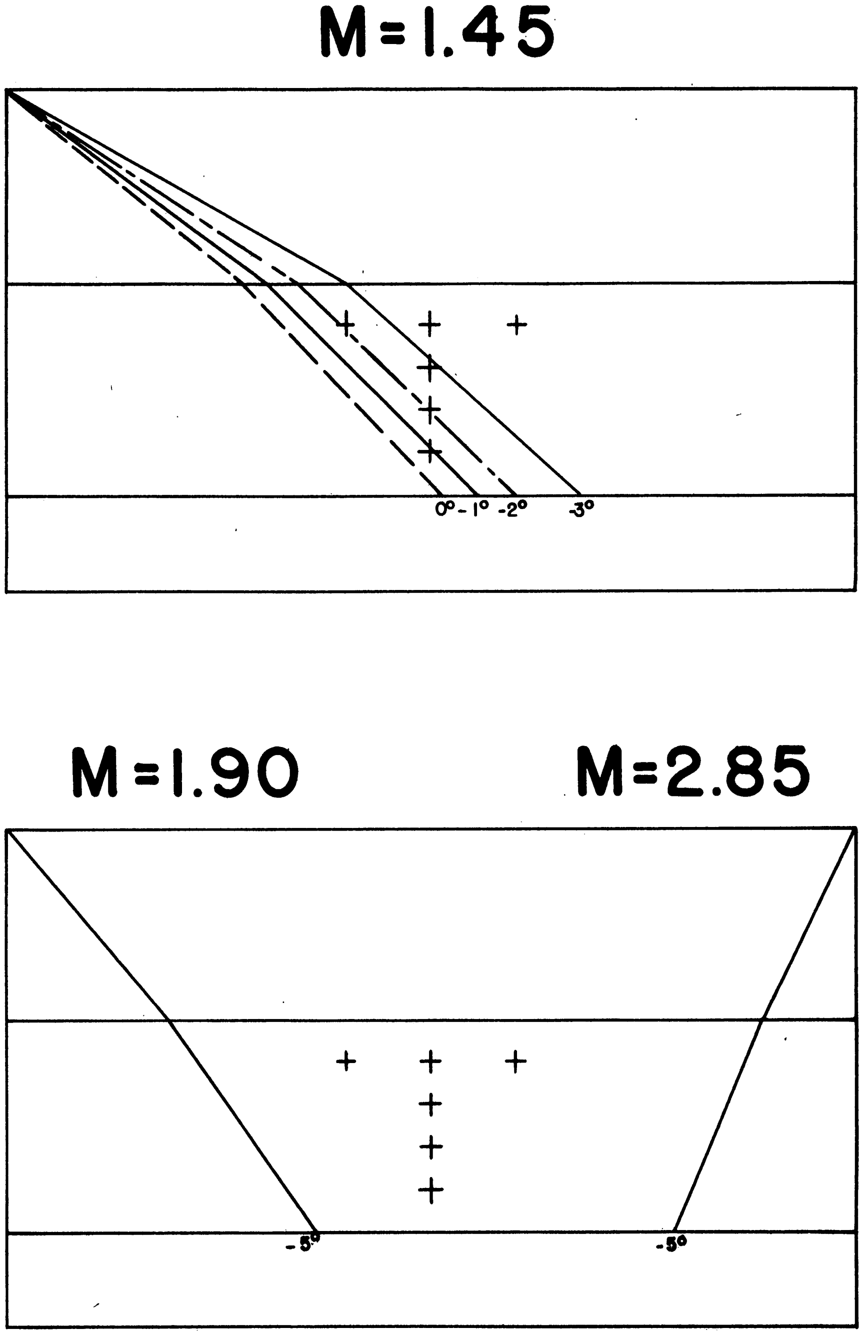
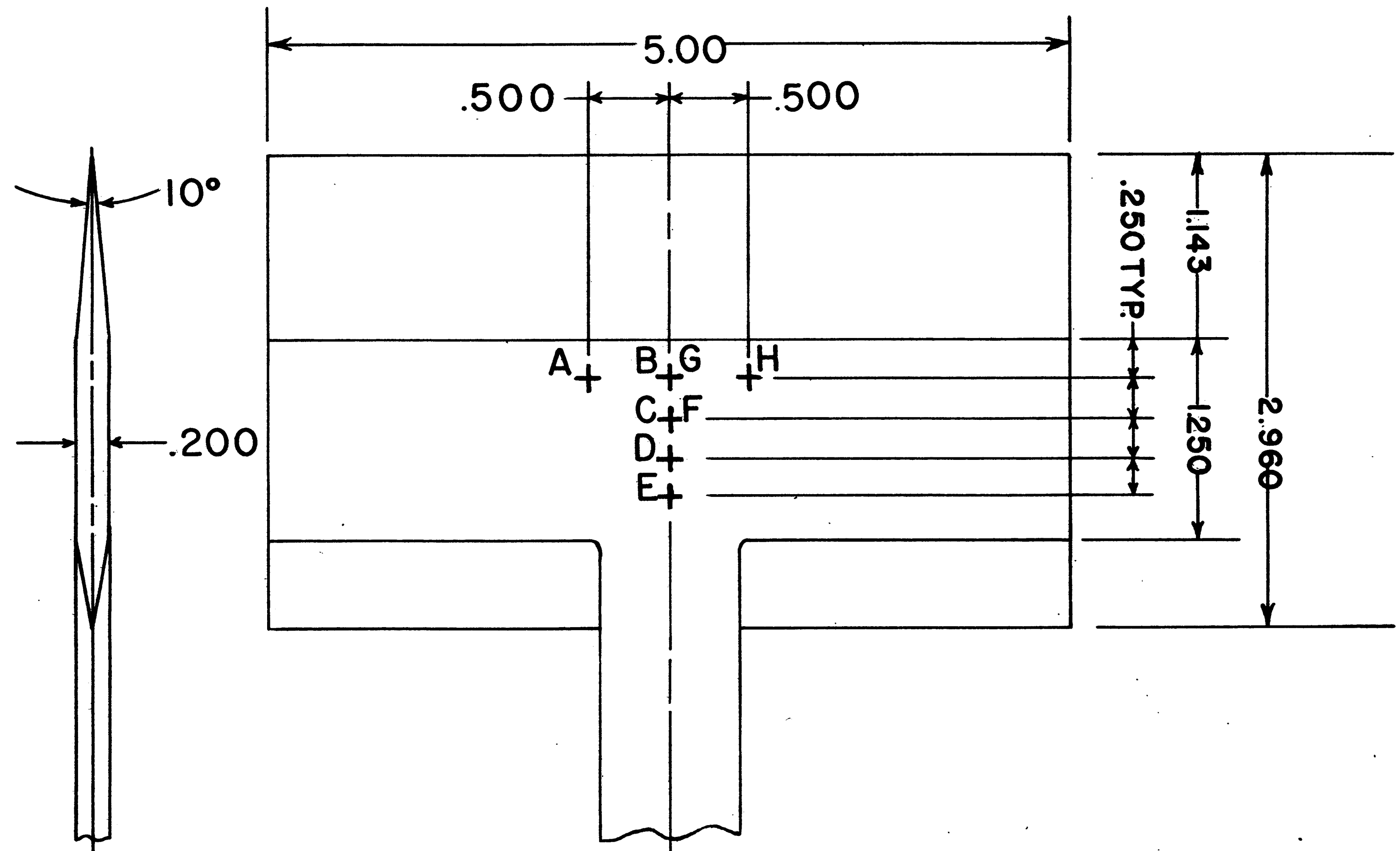


Figure 2



Orifices G & F are on Bottom Surface of Probe. Small Wedge is 1/2 Scale Replica of Large Wedge Except for Orifice Size. All Orifices on Both Wedges are .042" Diameter. Small Wedge Orifices Correspond to Large Wedge Orifices as Follows: J~A, P~B, O~C, M~D, N~E, L~F, K~G, Q~H.

FIGURE 3.

Small Wedge

Large Wedge

FIGURE 4

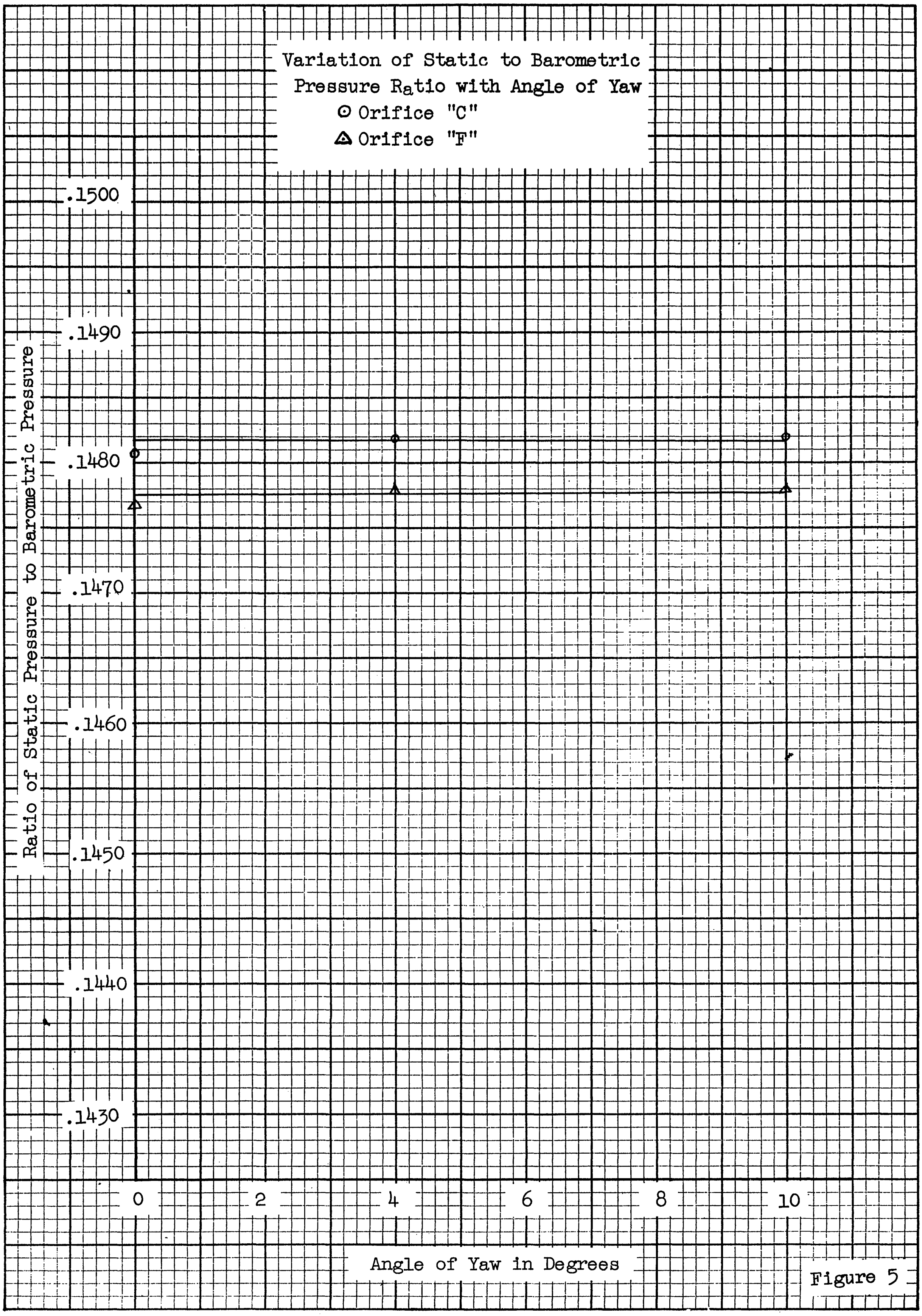
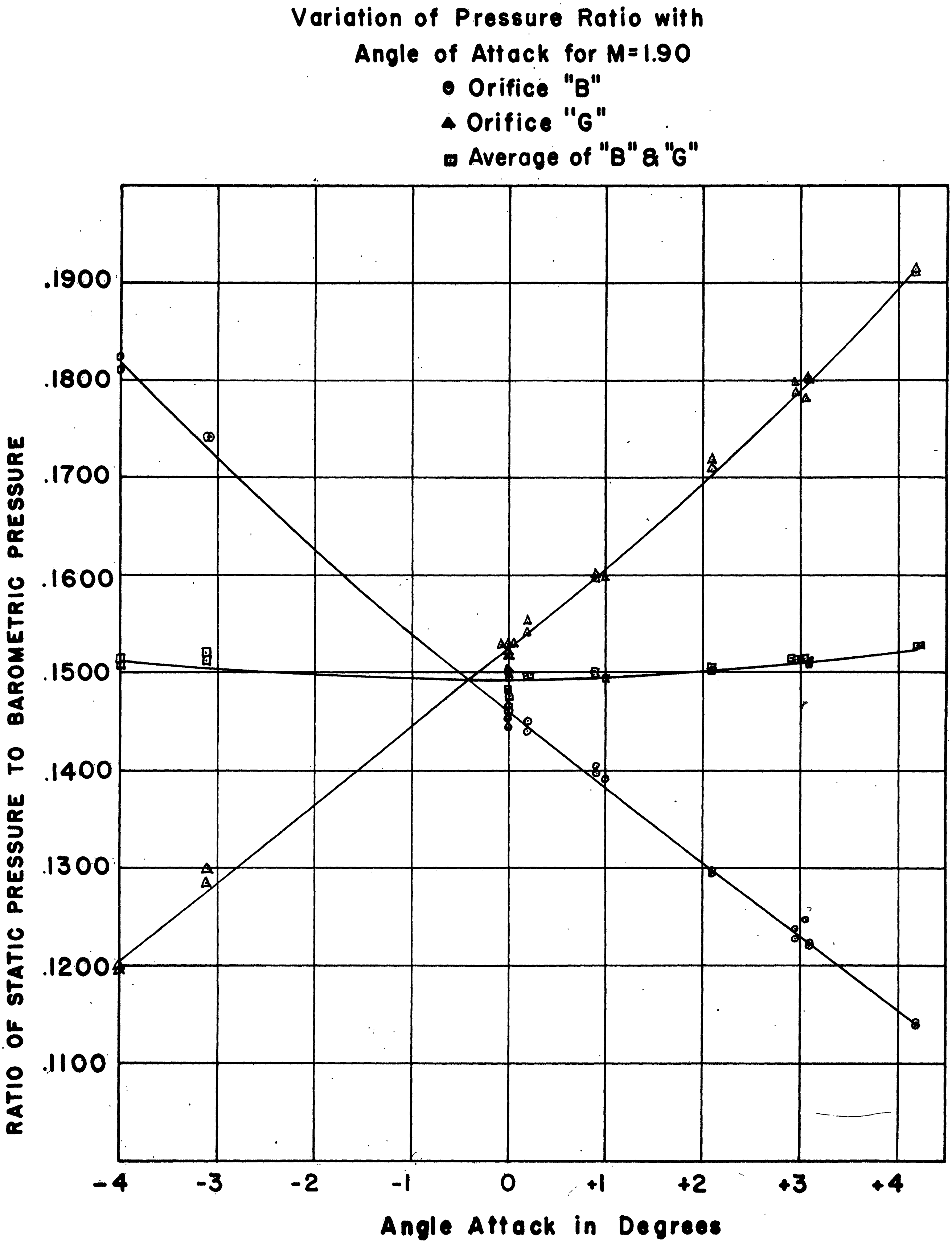

Variation of Static to Barometric
Pressure Ratio with Angle of Yaw
Orifice "C"
Orifice "F"
.1500
.1490
.1480
.1470
.1460
.1450
.1440
.1430
Ratio of Static Pressure to Barometric Pressure
0
2
4
6
8
10
Angle of Yaw in Degrees

Figure 5


Variation of Pressure Ratio with
Angle of Attack for M=1.90
Orifice "B"
Orifice "G"
Average of "B" & "G"
.1900
.1800
.1700
.1600
.1500
.1400
.1300
.1200
.1100
RATIO OF STATIC PRESSURE TO BAROMETRIC PRESSURE
-4
-3
-2
-1
0
+1
+2
+3
+4
Angle Attack in Degrees
FIGURE 6a.

Variation of Pressure Ratio with Angle of Attack for M=2.85

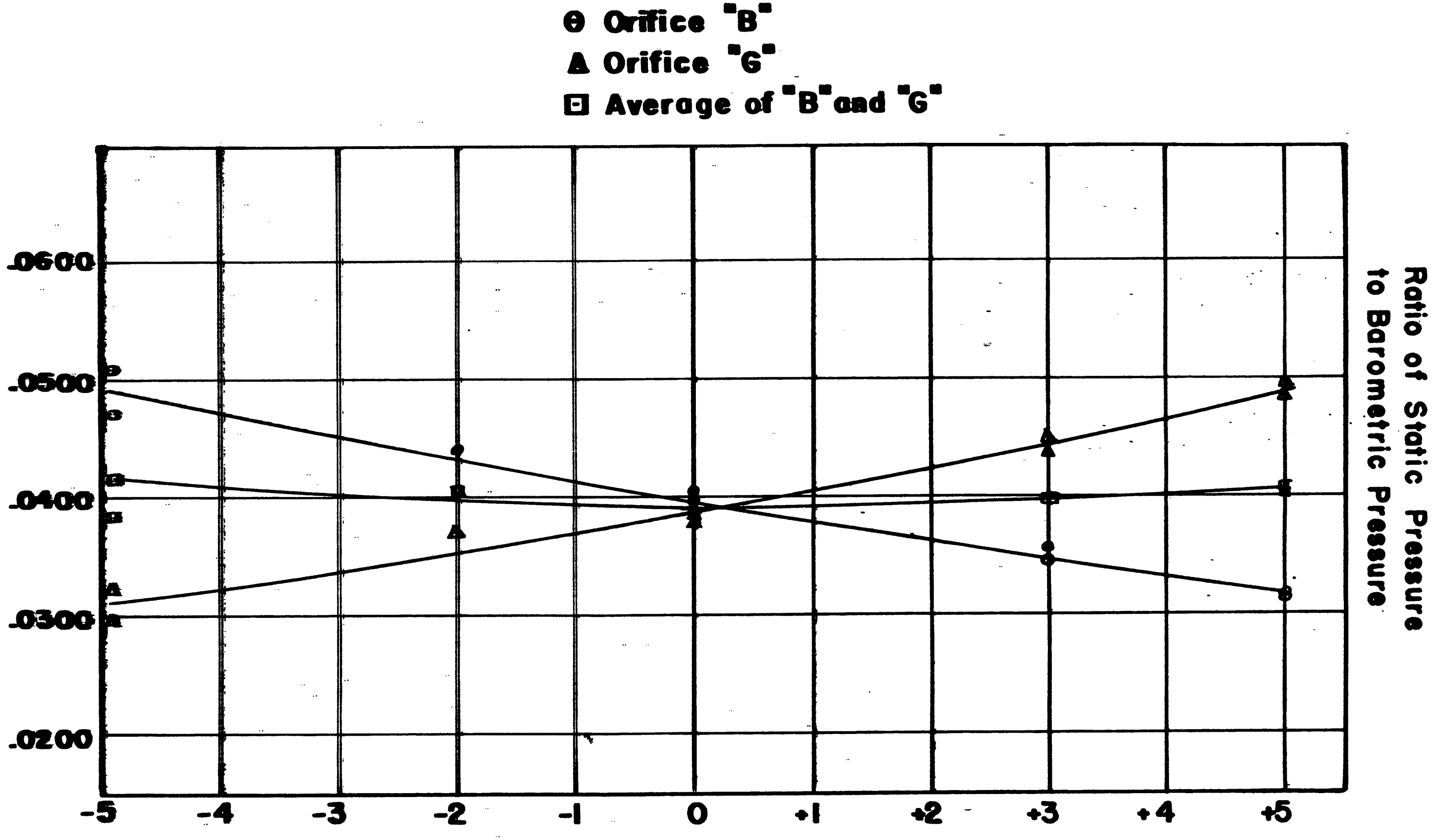


FIGURE 6b

Variation of Pressure Ratio with Angle of Attack for M=1.45

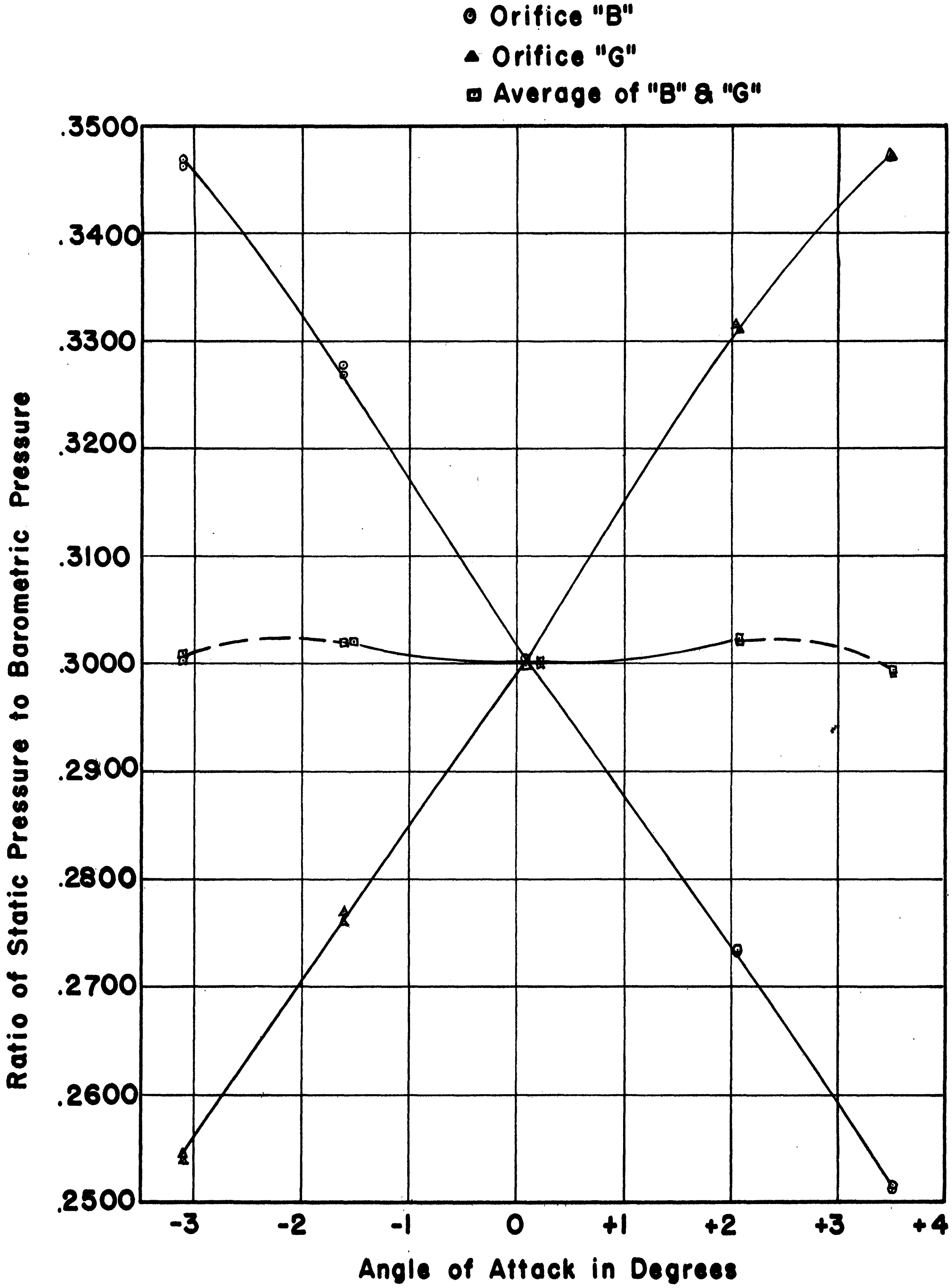


FIGURE 6c

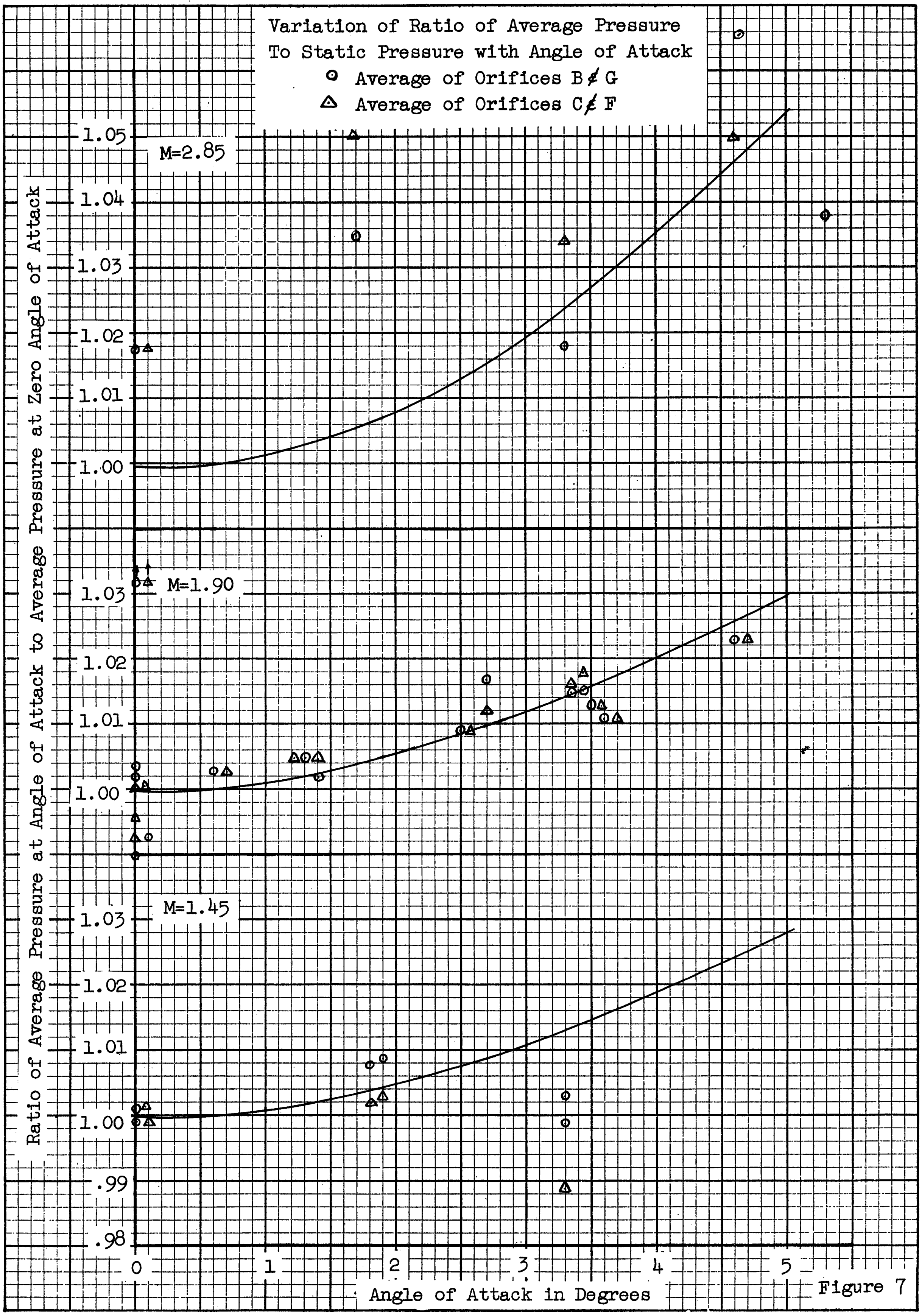

Variation of Ratio of Average Pressure
To Static Pressure with Angle of Attack
Average of Orifices B & G
Average of Orifices C & F
M=2.85
M=1.90
M=1.45
1.05
1.04
1.03
1.02
1.01
1.00
.99
.98
0
1
2
3
4
5
Ratio of Average Pressure at Angle of Attack to Average Pressure at Zero Angle of Attack
Angle of Attack in Degrees

Figure 7

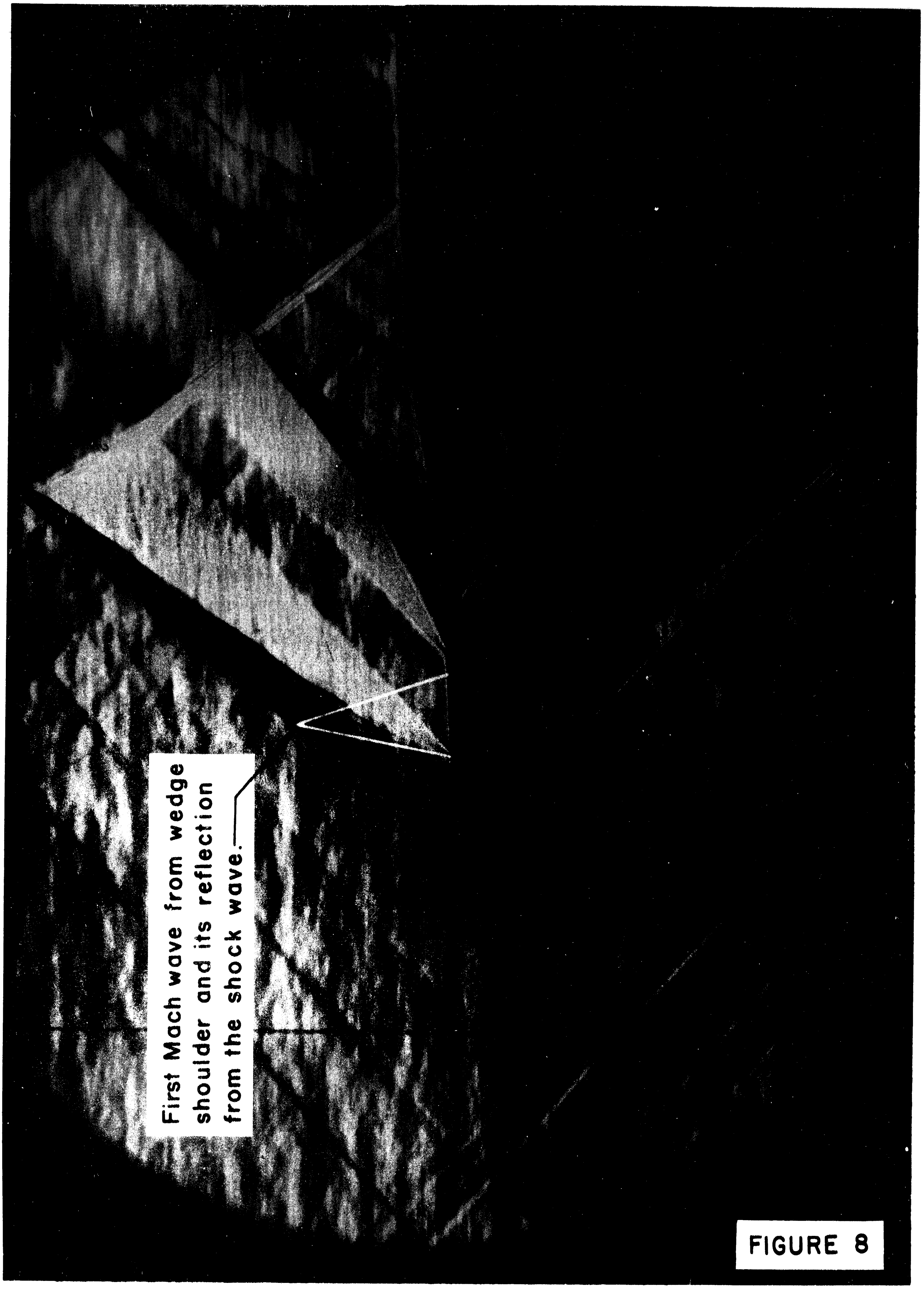

First Mach wave from wedge
shoulder and its reflection
from the shock wave.

FIGURE 8

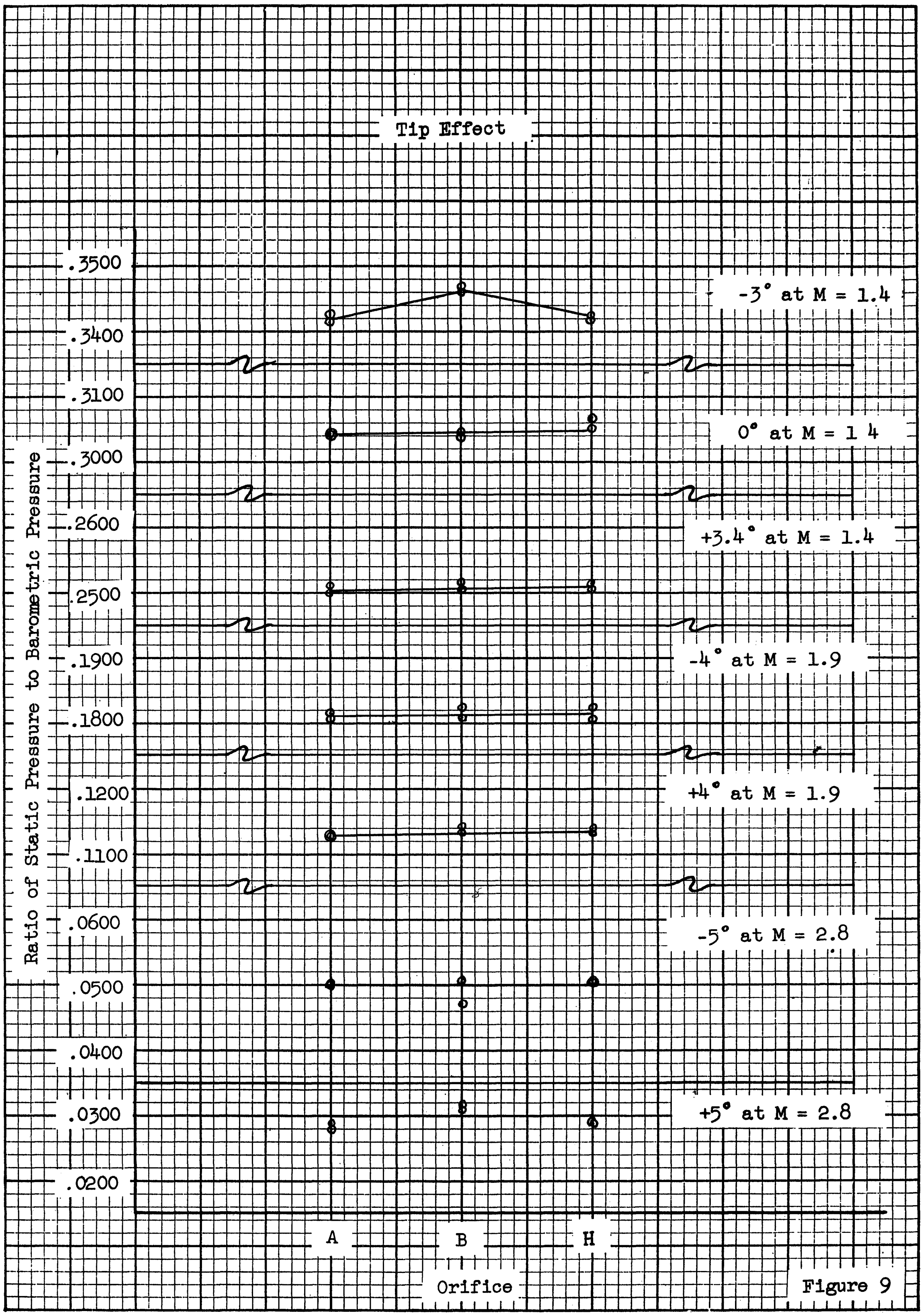
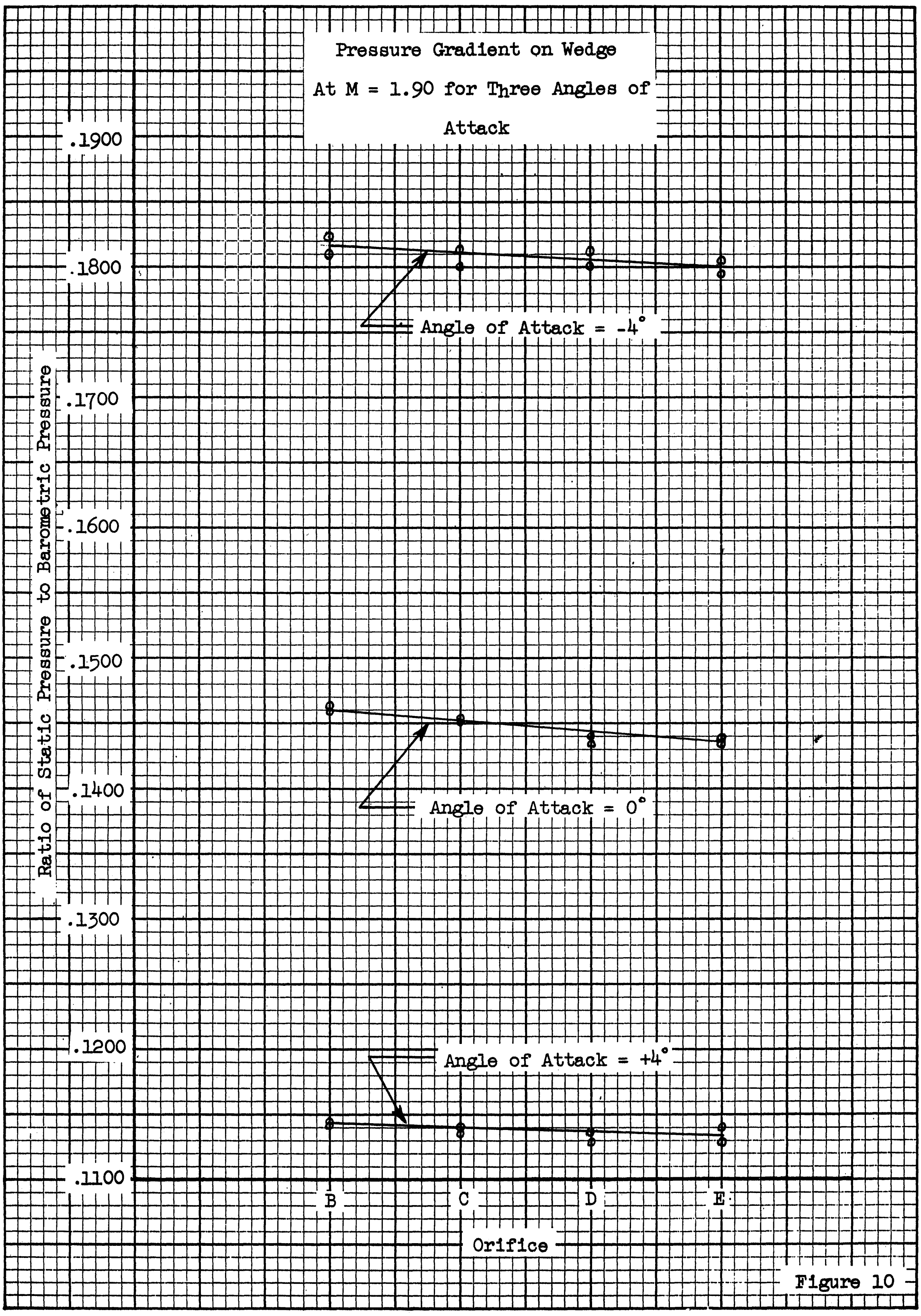
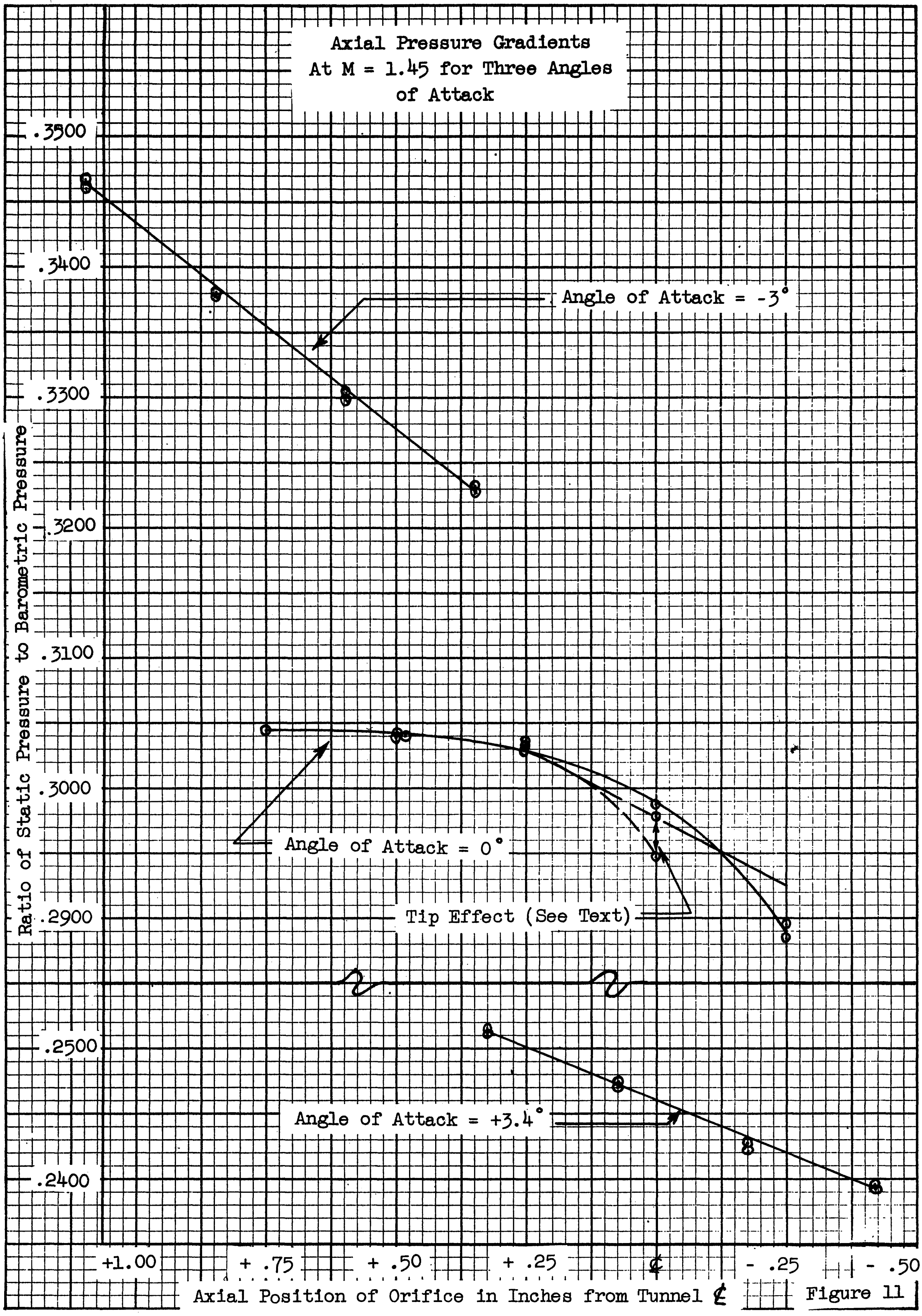

Tip Effect
Ratio of Static Pressure to Barometric Pressure
.3500
.3400
.3100
.3000
.2600
.2500
.1900
.1800
.1200
.1100
.0600
.0500
.0400
.0300
.0200
-3° at M = 1.4
0° at M = 1 4
+3.4° at M = 1.4
-4° at M = 1.9
+4° at M = 1.9
-5° at M = 2.8
+5° at M = 2.8
A
B
H
Orifice

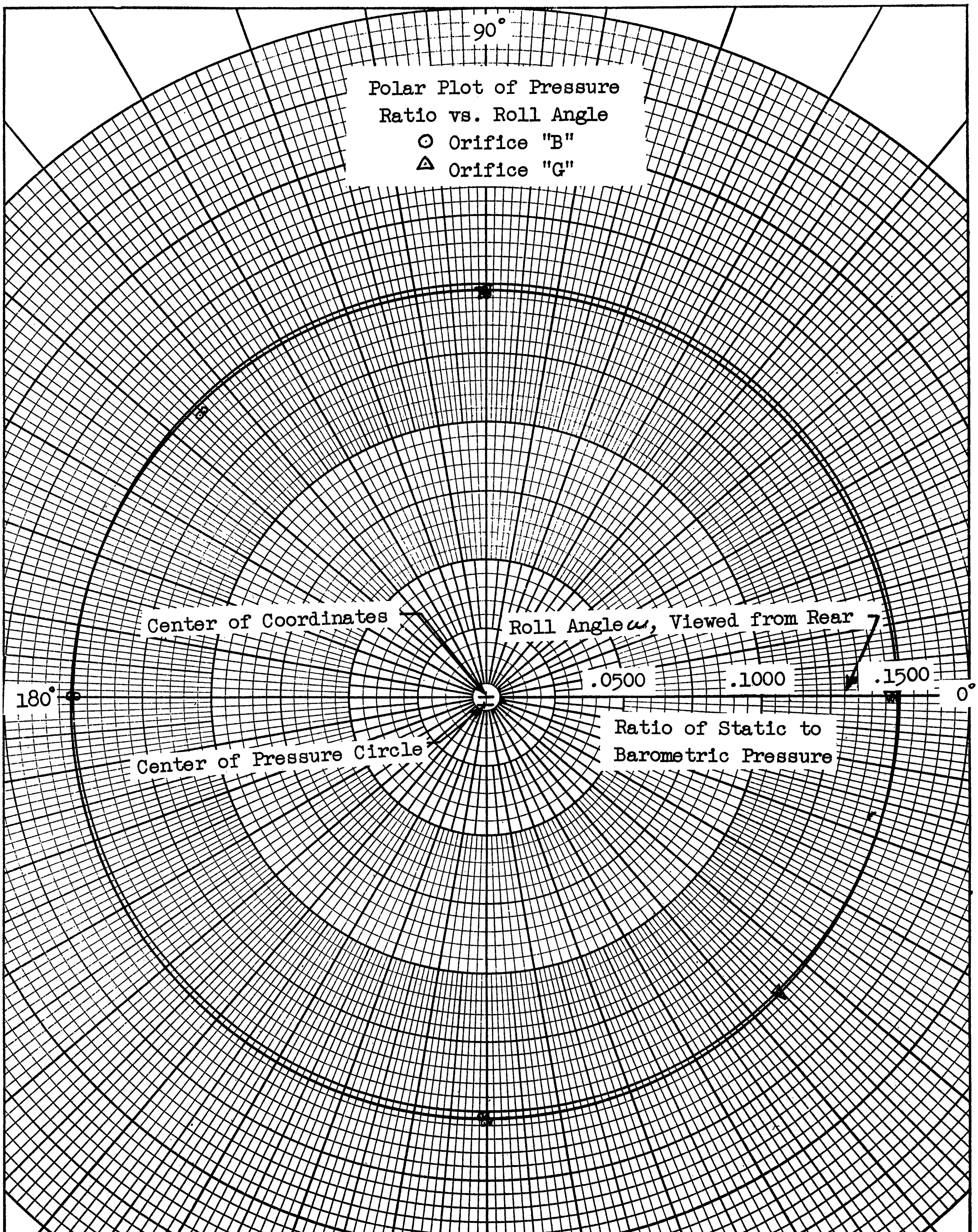
Figure 9



Pressure Gradient on Wedge
At M = 1.90 for Three Angles of Attack
Ratio of Static Pressure to Barometric Pressure
.1900
.1800
.1700
.1600
.1500
.1400
.1300
.1200
.1100
Angle of Attack = -4°
Angle of Attack = 0°
Angle of Attack = +4°
B
C
D
E
Orifice

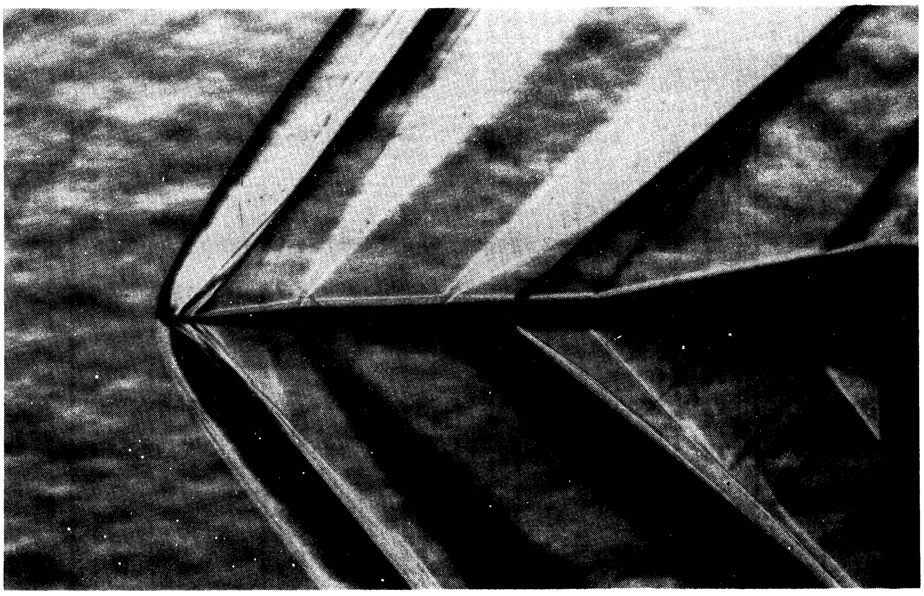
Figure 10


Axial Pressure Gradients
At M = 1.45 for Three Angles
of Attack
.3500
.3400
.3300
.3200
.3100
.3000
.2900
.2500
.2400
Ratio of Static Pressure to Barometric Pressure
Angle of Attack = -3°
Angle of Attack = 0°
Tip Effect (See Text)
Angle of Attack = +3.4°
+1.00
+ .75
+ .50
+ .25
℄
- .25
- .50
Axial Position of Orifice in Inches from Tunnel ℄
Figure 11

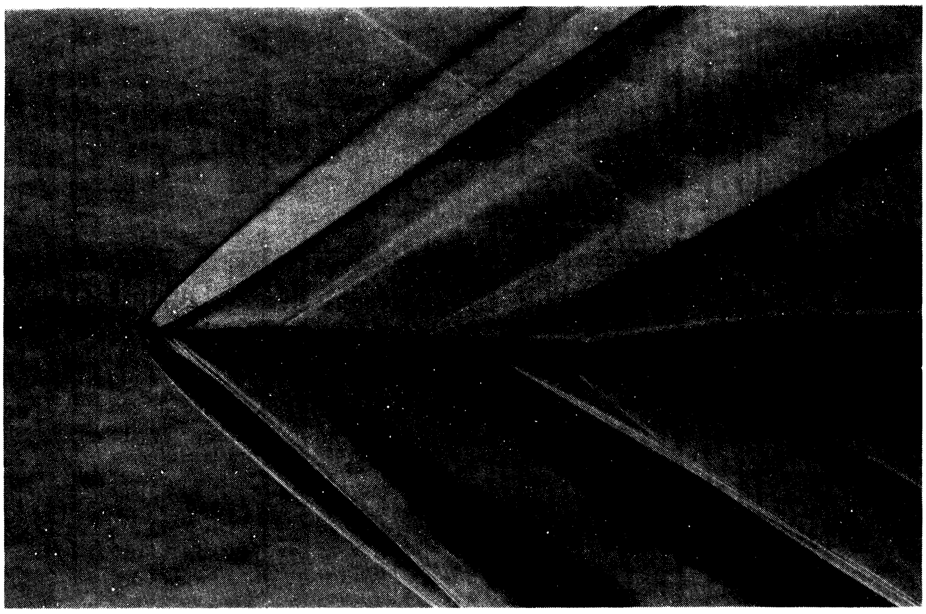


90°
Polar Plot of Pressure Ratio vs. Roll Angle
Orifice "B"
Orifice "G"
Center of Coordinates
Roll Angle ω, Viewed from Rear
.0500
.1000
.1500
180°
0°
Ratio of Static to Barometric Pressure
Center of Pressure Circle
270°

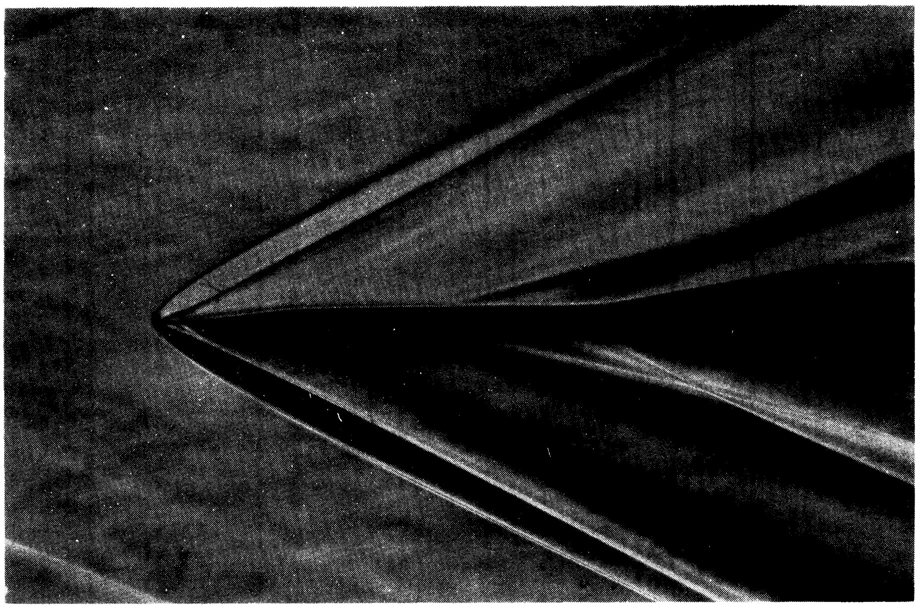
Figure 12



a. Mach Number 1.45, $\alpha = 0°$, Sharp Leading Edge, Smooth Surface.

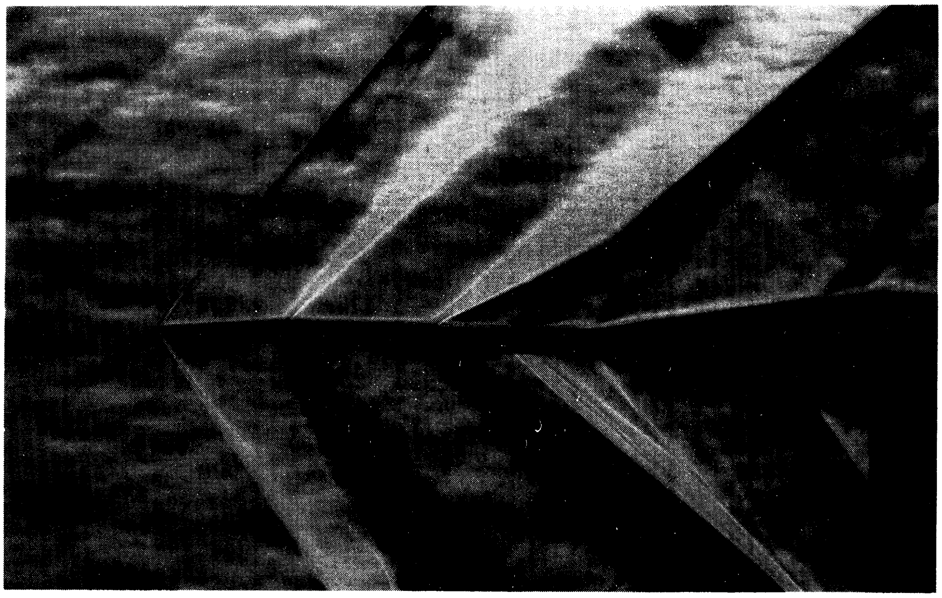


b. Mach Number 1.90, $\alpha = 0°$, Blunt Leading Edge, Smooth Surface.

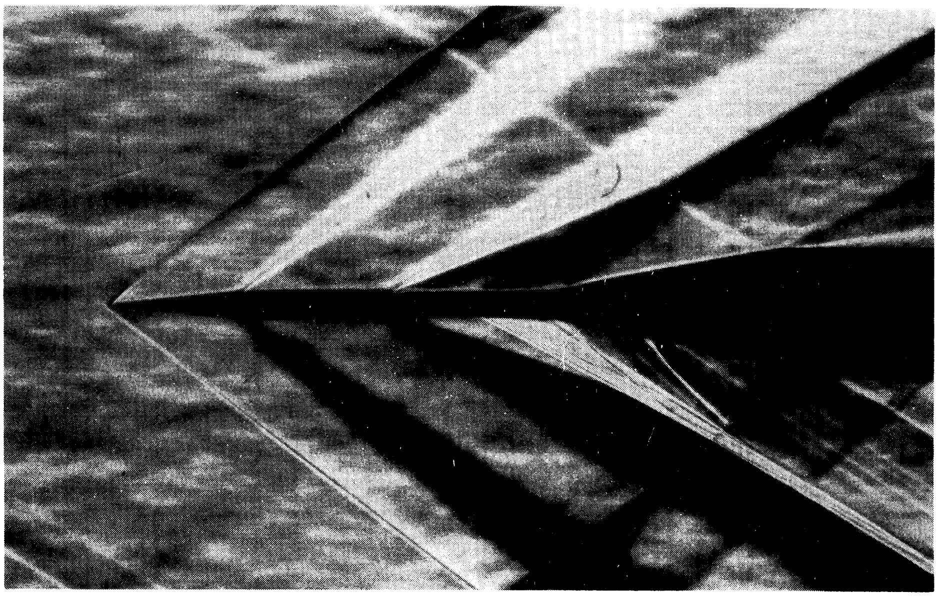


c. Mach Number 2.85, $\alpha = 0°$, Blunt Leading Edge, Smooth Surface.

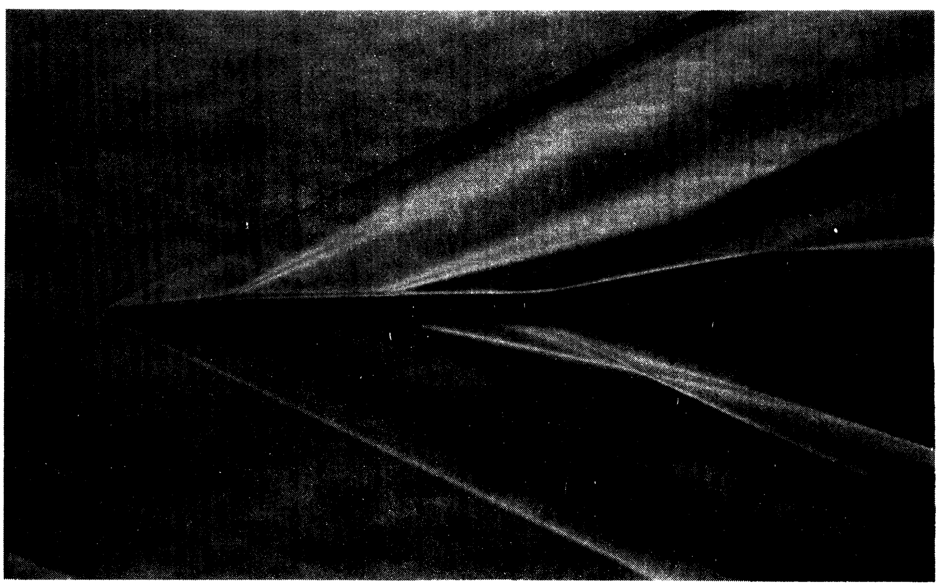
FIGURE 13



a. Mach Number 1.45, $\alpha = 0°$, Blunt Leading Edge, Smooth Surface.



b. Mach Number 1.90, $\alpha = 0°$, Sharp Leading Edge, Smooth Surface.



c. Mach Number 2.85, $\alpha = 0°$, Sharp Leading Edge, Smooth Surface.

FIGURE 14

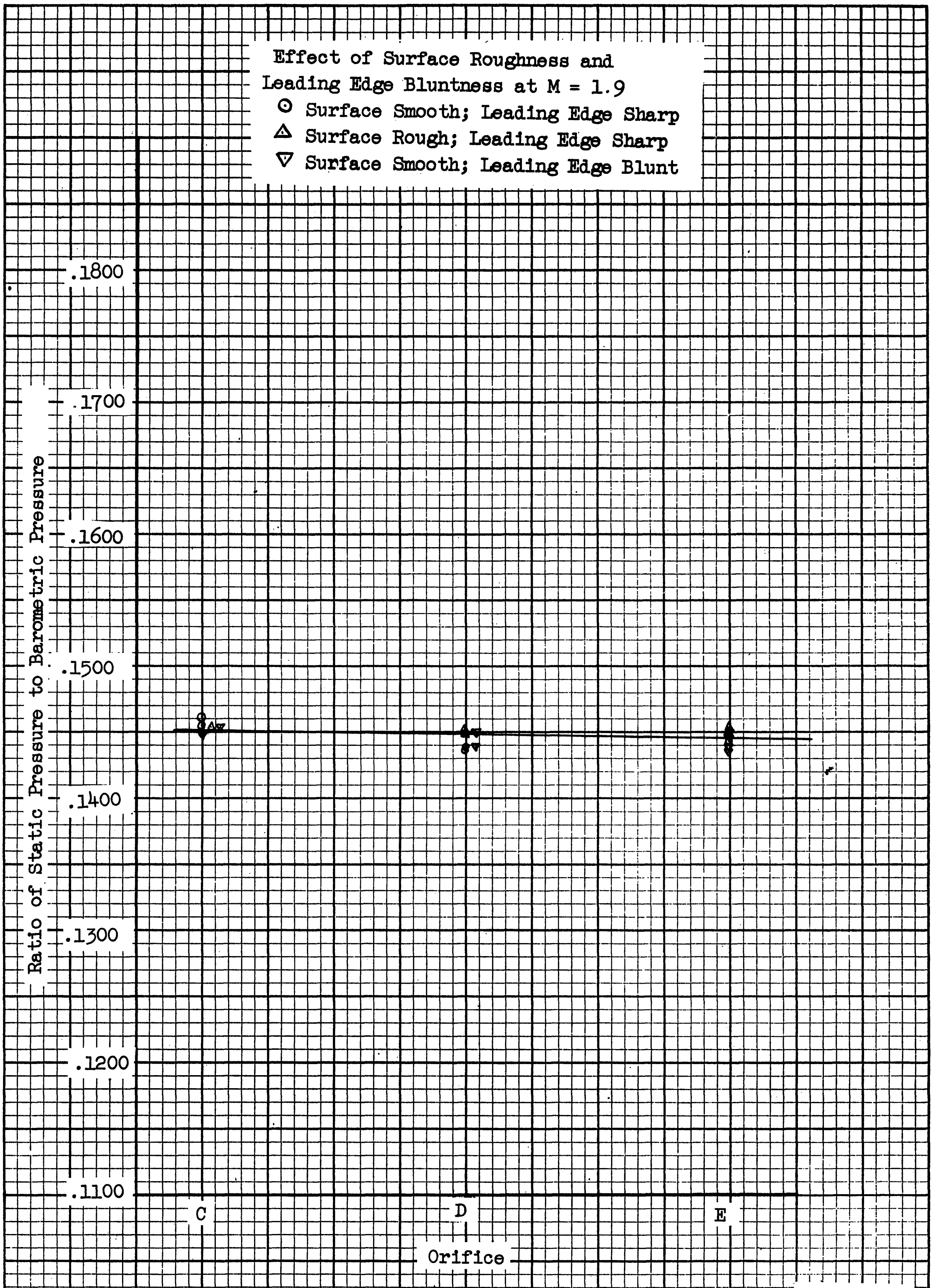

Effect of Surface Roughness and
Leading Edge Bluntness at M = 1.9
⊙ Surface Smooth; Leading Edge Sharp
△ Surface Rough; Leading Edge Sharp
▽ Surface Smooth; Leading Edge Blunt
Ratio of Static Pressure to Barometric Pressure
.1800
.1700
.1600
.1500
.1400
.1300
.1200
.1100
C
D
E
Orifice

Figure 15

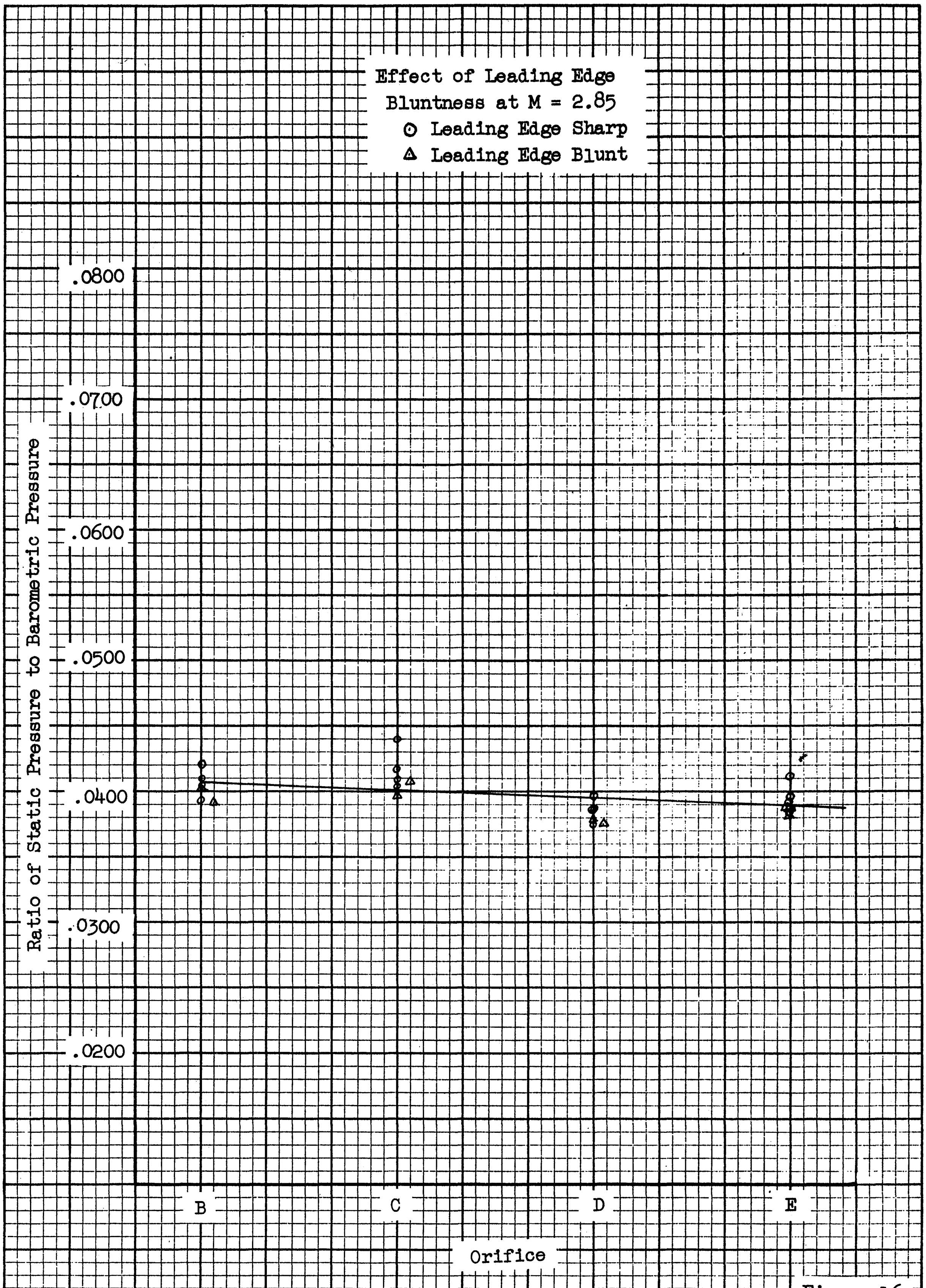

Effect of Leading Edge
Bluntness at M = 2.85
Leading Edge Sharp
Leading Edge Blunt
.0800
.0700
.0600
.0500
.0400
.0300
.0200
Ratio of Static Pressure to Barometric Pressure
B
C
D
E
Orifice

Figure 16

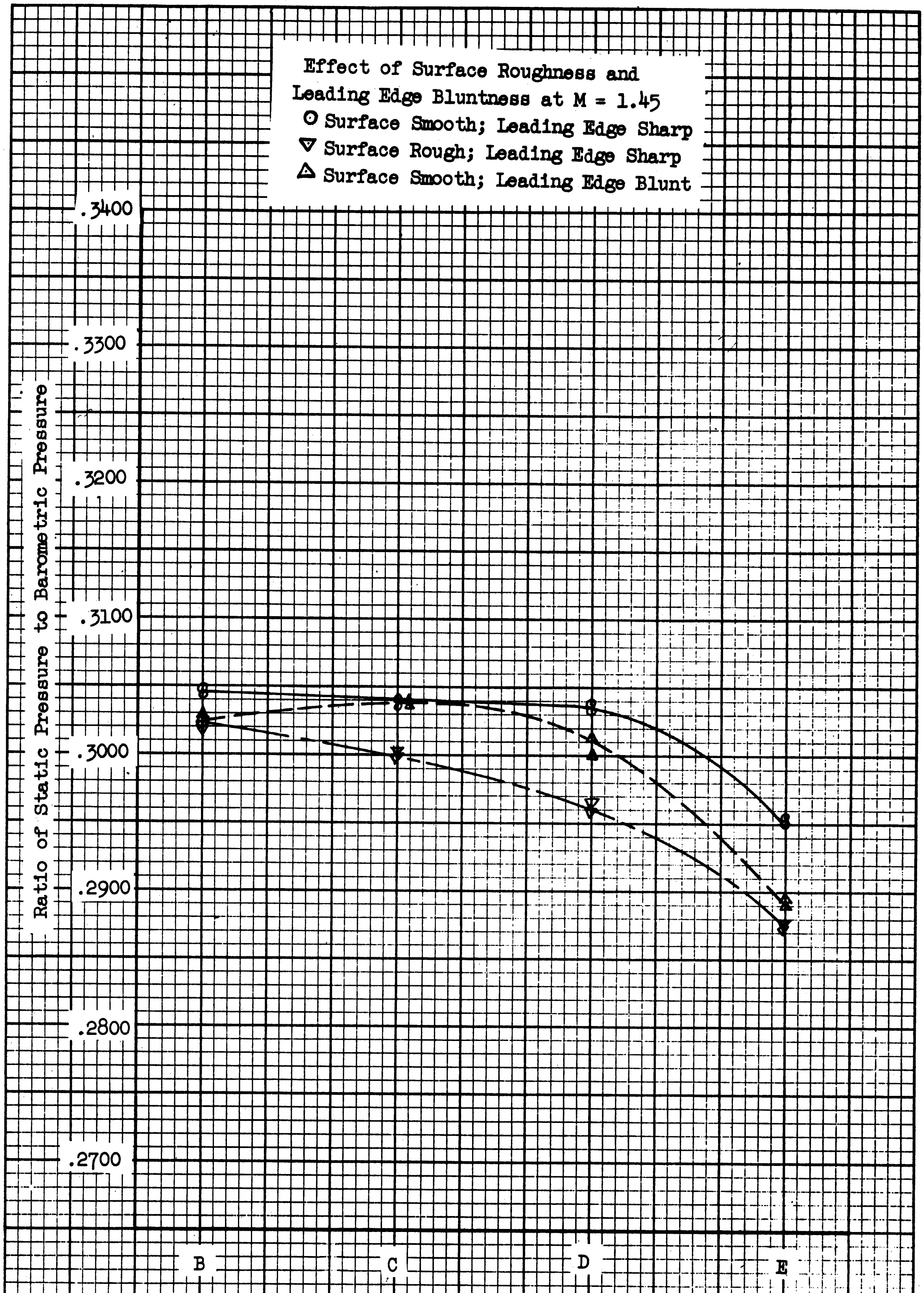
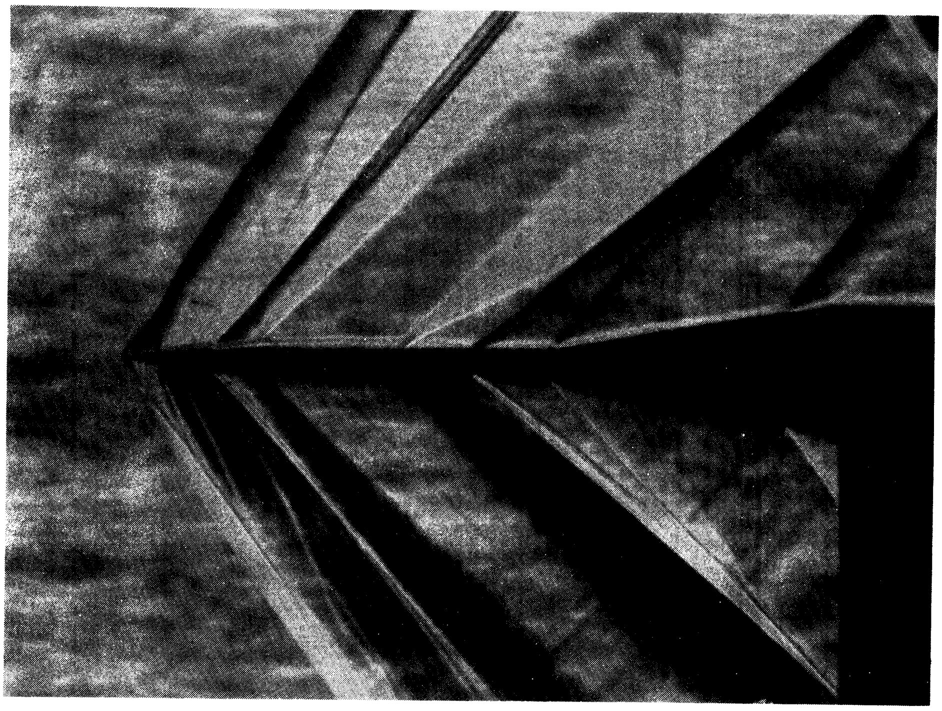
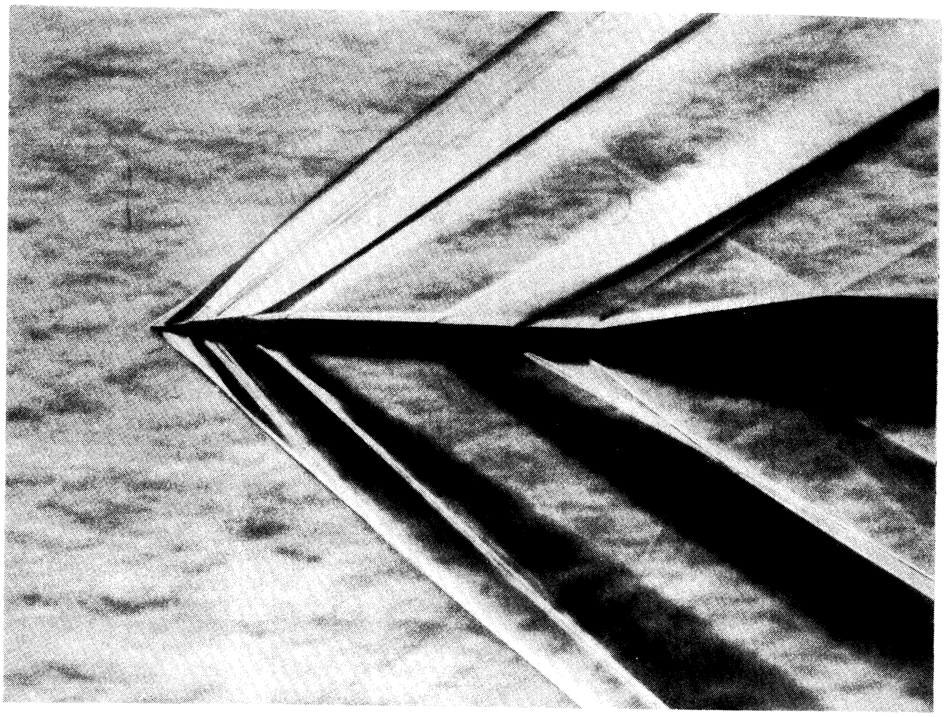

Effect of Surface Roughness and
Leading Edge Bluntness at M = 1.45
Surface Smooth; Leading Edge Sharp
Surface Rough; Leading Edge Sharp
Surface Smooth; Leading Edge Blunt
.3400
.3300
.3200
.3100
.3000
.2900
.2800
.2700
Ratio of Static Pressure to Barometric Pressure
B
C
D
E
Orifice

Figure 17



a. Mach Number 1.45, $\alpha = 0°$, Sharp Leading Edge, Rough Surface.



b. Mach Number 1.90, $\alpha = 0°$, Sharp Leading Edge, Rough Surface.

FIGURE 18