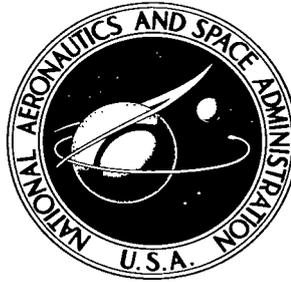


NASA TECHNICAL NOTE



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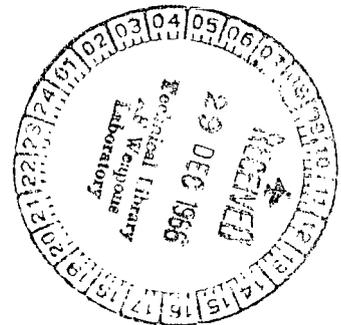
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EXPERIMENTAL PERFORMANCE OF A CONICAL PRESSURE PROBE AT MACH NUMBERS OF 3.0, 4.5, AND 6.0

*by John D. Norris and P. Kenneth Pierpont
Langley Research Center
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SUMMARY

A wind-tunnel investigation was conducted at Mach numbers of 3.0, 4.5, and 6.0 to study the performance of a previously calibrated conical pressure probe in determining local two-dimensional flow properties. The pressure probe was investigated in compression and expansion flow fields generated by a two-dimensional flat plate. A comparison was made between the local flow properties obtained by use of the pressure probe and those calculated by simple theory.

The results indicated that, in general, the values of Mach number and total pressure determined from the probe measurements agreed with the theoretical values within the calibration uncertainty. Also, flow angles determined from the probe-measured pressures agreed with those calculated from simple theory when account was taken of the flat-plate boundary layer, except for the local flow angle in an expansion field. This discrepancy in an expansion field was not resolved. Additional information in the form of schlieren photographs of the flow field was a significant aid in interpretation of results when the probe was near a disturbance.

INTRODUCTION

Present theoretical calculations generally provide inadequate information on the magnitude of the local flow properties in complex three-dimensional flow fields at hypersonic speeds. Information needed to effect useful performance calculations consists of knowledge of local flow properties such as Mach number, stagnation pressure, dynamic pressure, static pressure, and both downwash and sidewash flow angles. Because of the lack of demonstrated experimental techniques for determining such information from measured quantities at hypersonic speeds, an investigation was undertaken and reported in reference 1 to determine the ability of a single flow probe to measure pressures from which the required parameters could be deduced. In the reference report several different conical probes were calibrated in a uniform flow. Measurements of pitot pressure by an orifice at the cone tip together with four cone surface pressures were employed to derive the calibration curves. Local flow properties over a Mach number range from

3 to 6 and over a wide range of combined downwash and sidewash angles were derived. Reference 1 indicated that the local Mach number could be determined within 3 percent; the local downwash and sidewash angles, within 0.5° ; and the dynamic pressure, within 0.5 percent. Difficulty was demonstrated in determining local flow-field stagnation pressure to closer than 13 percent at a Mach number of 6.0. This difficulty is directly related to the fact that the variation with Mach number of the ratio of local cone static pressure to pitot pressure (both measured quantities) becomes small and continues to decrease with increasing Mach number, as shown in references 1 and 2. The indicated accuracies are not necessarily the limits achievable in the Mach 6 region, since more precise pressure measurement devices would be helpful. However, they are presently superior to accuracies resulting from any other verified experimental techniques. Caution must be exercised to employ only calibrated probes because of potential uncertainty caused by manufacturing tolerances, measurement methods, and handling damage.

The present investigation was made to study the performance of an existing calibrated conical pressure probe under real conditions in order to provide at least first-order information on whether or not the probe functions as well in a flow in which disturbances are present as in uniform flow. A flat plate was employed to create essentially two-dimensional flow fields in which probe measurements might be obtained in both compression and expansion regions where flow properties could be reasonably predicted by simple theory. Comparisons were then made between the known or estimated flow properties and those determined from the probe pressure measurements. Demonstration of a capability for determining local flow quantities would allow the probe to be applied to more complex flow fields typical of hypersonic wing-body configurations. The investigation was conducted at Mach numbers of 3.0, 4.5, and 6.0 with the flat plate inclined at approximately 0° , 10° , and -10° relative to the free stream. Reynolds number per foot (per 30.5 cm) varied from approximately 0.3×10^6 to 1.3×10^6 .

SYMBOLS

l	distance between axis of probe (tunnel center line) and center line of flat-plate support (fig. 1(a))
M_1	Mach number ahead of normal shock wave at cone apex (local stream Mach number)
M_∞	free-stream Mach number
$p_{t,1}$	total pressure ahead of normal shock wave at cone apex (local stream total pressure)

$p_{t,2}$	total pressure measured behind normal shock wave at cone apex (pitot pressure)
$p_{t,\infty}$	free-stream stagnation pressure
α	angle of incidence of flat plate relative to free stream
$\Delta\alpha$	increment in effective incidence of flat plate due to viscous effects
ϵ	angle of downwash
θ	pitch angle of cone probe axis relative to local flow direction, $\alpha + \Delta\alpha$
σ	angle of sidewash
τ	shock-wave angle (fig. 2)
ϕ	angle of roll (fig. 1(b))

MODEL AND APPARATUS

Figure 1 provides details of the dimensions of the flat plate and the cone probe employed. Figure 1(a) shows that the pressure probe was mounted on a sting at the tunnel center line. The probe remained fixed both longitudinally and laterally, but its angular position (roll angle about its own axis) could be changed so that different combinations of downwash and sidewash could be simulated. The flat plate was mounted on a sting support which could be moved vertically relative to the pressure probe. The angle of incidence of the plate could be changed to generate either compression or expansion fields ($\alpha = -10^\circ$, 0° , or 10°).

The flat plate had a chord of 8 inches (20.32 cm), a span of 14 inches (35.56 cm), and a thickness of 0.25 inch (0.64 cm). The leading edge was sharp with a radius less than 0.001 inch (0.0025 cm) and the upper surface consisted of a 5° wedge to the maximum thickness indicated. Essentially two-dimensional flow was estimated to exist over an 8-inch (20.32-cm) span in the vicinity of the measurement probe.

The cone-cylinder pressure probe (fig. 1(b)) had a diameter of 0.50 inch (1.27 cm) and a 20° cone half-angle. Four static-pressure orifices were located circumferentially 90° apart on the cone surface, and a pitot-pressure orifice was located at the cone apex. All orifice diameters were 0.052 inch (0.132 cm), and the lip thickness of the apex orifice was less than 0.002 inch (0.005 cm). The probe employed was the same as a probe calibrated in reference 1 and designated therein as probe 1.

TEST CONDITIONS, METHODS, AND ACCURACY

Test Conditions

The investigation was conducted in a 2-foot hypersonic facility at the Langley Research Center (ref. 3) at Mach numbers of 3.0, 4.5, and 6.0. Reynolds number per foot (per 30.5 cm) varied from approximately 0.3×10^6 to 1.3×10^6 and laminar flow probably existed on the flat plate at all test conditions. The free-stream stagnation pressures for the three plate incidence angles are summarized in the following table:

Condition	Stagnation pressure $p_{t,\infty}$, mm Hg, for -		
	$\alpha = 0^\circ$ (slight compression)	$\alpha = 10^\circ$ (compression)	$\alpha = -10^\circ$ (expansion)
$M_\infty = 3.0$	300	----	300 to 450
$M_\infty = 4.5$	900	900	900 to 1150
$M_\infty = 6.0$	2000	2000	-----

The flat plate was set, with no airflow in the tunnel, at a fixed geometric angle of incidence relative to the test-section center line. Simultaneous measurement of the five probe pressures was obtained from absolute-measuring pressure transducers. At each test condition a sequence of about 10 schlieren pictures was obtained to establish the location of disturbances and principal features of the plate boundary layer. The schlieren photographs were taken by a flash-synchronized movie camera operating at 40 frames per second and having a flash duration of 2 microseconds. At each test condition the facility operating pressures and temperatures were continuously monitored and recorded and sufficient time was permitted to insure that all quantities had stabilized.

Methods

For each test condition, the recorded facility stagnation pressure and reference static pressure were employed together with suitable calibration curves to obtain the stream conditions in the test region. Pressures measured by means of the cone probe were reduced to obtain the local flow-field properties by the iteration procedure outlined in reference 1 and by use of the actual calibration data for the particular probe employed. The local properties discerned consisted of Mach number, total pressure, and downwash and sidewash angles relative to the probe, which was alined with the test-section axis.

The experimentally determined local flow properties were then compared with similar quantities estimated from simple two-dimensional oblique-shock or expansion theory as provided by the relations of reference 4. In order to apply these relations, the facility conditions of free-stream Mach number and stagnation pressure, together with the flow

turning angle resulting from the presence of the flat plate, were needed. The effective turning angle ($\alpha + \Delta\alpha$), shown in figure 2, consisted of the flat-plate absolute incidence angle α incremented by an effective boundary-layer displacement angle $\Delta\alpha$.

The flat-plate absolute angle of incidence α was calculated to consist of the wind-off incidence corrected for sting bending caused by the aerodynamic loads on the plate. The loads were calculated by using the free-stream conditions and nominal plate incidence. The incremental angle $\Delta\alpha$ was estimated by measuring the apparent visible angle in the simultaneous schlieren photographs. Other methods, which take into account the local viscous effects of the low local Reynolds numbers, were considered for determining $\Delta\alpha$; however, the complex procedures required were considered to be outside the scope of this investigation. Figure 2 illustrates the probe in compression and expansion flow fields.

Accuracy

The absolute level of accuracy of the results is admittedly difficult to establish because of the combined effects of the many possible sources of error. A number of precautions were taken, however, to reduce both the magnitude and probability of significant errors and a brief description is made herein. The facility instrumentation consists primarily of high-sensitivity pressure measurement devices for determining both stagnation and reference static pressures. These pressures were calibrated both preceding and following the investigation. An earlier pitot pressure survey of the usable test section was made to provide a calibration applicable to the present investigation. With the care exercised to insure steady test conditions, the free-stream properties are considered accurate within the following limits:

M_∞	± 0.01
$P_{t,\infty}$	$\pm 0.3\%$

Based on previous facility experience, the average downwash and sidewash angles in the test region are believed to be less than 0.2° .

The initial angles of the flat plate and the probe could be reliably set or adjusted to within $\pm 0.05^\circ$ by using a sensitive bubble inclinometer. The probe was assumed to remain undeflected under aerodynamic load, and a maximum correction of approximately 0.4° was calculated for the flat plate under load. The correction for the flat plate was applied during the analysis, and the plate-angle error due to loading is believed to be less than 0.02° since the calculated two-dimensional flat-plate loading was used in conjunction with a sting-bending calibration. Therefore, plate alignment errors were less than the uncertainty in the free-stream flow angularity and hence were less than about 0.1° . The largest angular error is considered to have been caused by inaccuracies in determination of the effective flow angle caused by boundary-layer growth ($\Delta\alpha$). This angle was estimated

from the schlieren photographs. For the compression field ($\alpha \approx -10^\circ$), the boundary-layer growth was nearly linear, and measurement errors in $\Delta\alpha$ are probably less than 0.2° . For the expansion field ($\alpha \approx -10^\circ$), the boundary-layer growth was not linear because a slight overexpansion occurred at the leading edge followed by a slight recompression, and errors in $\Delta\alpha$ probably do not exceed 0.3° . For the plate near $\alpha = 0^\circ$, the slight bluntness of the leading edge coupled with local viscous effects probably resulted in the largest errors in estimating $\Delta\alpha$, and those errors are believed to amount to nearly 0.4° . These considerations suggest that the local flow angle ($\alpha + \Delta\alpha$) was determined to approximately the same accuracy as the probe is capable of discerning, or about 0.5° . Calculation of the other local flow properties is affected by the uncertainties discussed, and the limits estimated for $\alpha \approx 10^\circ$ (the incidence angle at which errors are largest) are as follows:

	Error at $M_\infty = 3.0$	Error at $M_\infty = 6.0$
M_1	± 0.10	± 0.12
$p_{t,1}$	0.8%	2.7%

Comparison of the potential errors in M_1 with the estimated probe capability (± 3 per cent) indicates that the Mach number error was approximately the same as the probe error at $M_\infty = 3.0$ but was appreciably less than the probe error at $M_\infty = 6.0$. Errors in estimating the local stagnation pressure were well within the anticipated probe inaccuracies (ref. 1) at both Mach numbers.

RESULTS AND DISCUSSION

The results have been divided into three categories for which the flow fields are characterized as slight compression ($\alpha \approx 0^\circ$), compression ($\alpha \approx 10^\circ$), and expansion ($\alpha \approx -10^\circ$). Local flow-field parameters, determined from the probe-measured pressures, are presented together with appropriate schlieren photographs in figures 3 to 8.

Slight Compression

Local Mach number M_1 and total pressure $p_{t,1}$, determined from the probe measurements and from theory, are presented in figure 3 for the flat plate set at $\alpha \approx 0^\circ$. Results for the probe located behind the leading-edge disturbance and for the probe located well ahead of the possible interference region are compared. Corresponding schlieren photographs are shown in figure 4. The abscissas in figure 3 correspond to either free-stream or local conditions. For the free-stream data, nearly 1 to 1 correspondence is shown at $M_\infty = 4.5$; however, at $M_\infty = 6.0$ both the Mach number and the total pressure are high but are still within the uncertainty bands shown. For slight compression ($\alpha \approx 0^\circ$), the properties derived from the probe and those calculated from the

flow field are in excellent agreement at all test Mach numbers. No flow angles have been plotted since they were too small to produce a meaningful figure; however, they varied from approximately 0.7° to 1.6° and compared favorably with effective compression angles determined from the schlieren photographs.

At $M_\infty = 4.5$, probe data were obtained for two additional vertical positions of the flat plate (fig. 4(b)). When the probe was located close to but behind the shock wave ($z = 3.35$), no differences were observed among the four static pressures. These pressures agreed closely with those for the probe located well behind the bow wave. When, however, the probe was located such that the bow wave impinged on the conical surface ($z = 3.75$), one orifice was noticeably affected and the pressure read as much as 50 percent higher than the other three cone pressures, which agreed within about 1 percent of each other. Neglecting this one high pressure resulted in derivation of values of Mach number and total pressure in good agreement with the values at free-stream conditions. Schlieren data were required to permit the interpretation of this phenomenon.

Inasmuch as some uncertainty exists in the measurement of the effective boundary-layer displacement angle $\Delta\alpha$, flow-field properties were also calculated by using measurements of the shock-wave angle τ produced by the plate. A comparison of the flow-field Mach number determined from these several methods indicates that the probe-determined Mach numbers were in close agreement with those obtained by the other two methods, as shown in the following table:

Condition	M_1 determined from -		
	Probe	$\alpha + \Delta\alpha$	τ
$M_\infty = 3.0$	2.95	2.96	2.89
$M_\infty = 4.5$	4.42	4.42	4.33
$M_\infty = 6.0$	5.77	5.79	5.75

Compression

Figure 5 shows that, when the plate is set at $\alpha \approx 10^\circ$ to generate a significant compression field, the flow properties derived from the probe measurements are in generally good agreement with those derived from the simple theory for both $M_\infty = 4.5$ and $M_\infty = 6.0$. No data are shown for $M_\infty = 3.0$ because the range of the instrumentation was inadequate. Errors are shown in both the Mach number determination and the total pressure deduced from the probe measurements; however, these errors are not reflected in the flow-angle determination. This result is consistent with the conclusion of reference 1 that, in the iteration procedure, errors in Mach number and total pressure should not affect the flow-angle determination.

Values of M_1 obtained by the three methods are compared in the following table (the singular high point shown on figure 5 has not been included):

Condition	M_1 determined from -		
	Probe	$\alpha + \Delta\alpha$	τ
$M_\infty = 4.5$	3.55	3.58	3.51
$M_\infty = 6.0$	4.58	4.51	4.55

From these results, it is concluded that the agreement between Mach numbers calculated from the probe pressure measurements and those obtained from the other two methods is approximately the same as in free-stream or slight-compression fields. The high point at $M_\infty = 6.0$ (fig. 5) was obtained when the probe was in very close proximity to the flat-plate bow wave (fig. 6(b)). Conceivably some form of interference resulted in the discrepancy although all four static pressures indicated by the probe were in substantial agreement. This result contrasts with results shown in the preceding section where, for the probe located close to but behind the disturbance ($z = 3.35$ in fig. 4(b)), the correct Mach number was indicated from the measured pressures. Again the usefulness of the schlieren data is illustrated in the interpretation of the results.

Expansion

The local Mach numbers and total pressures, determined from the probe measurements, are shown in figure 7 to be in fair agreement with those determined from simple theory with the aid of measurements from the schlieren photographs. The probe-determined flow angles are indicated to be greater than the estimated values by as much as 2.2° at $M_\infty = 3.0$ and 1.7° at $M_\infty = 4.5$. With the data available, the discrepancy cannot be resolved. Detailed examination of the photographs, and of similar ones not reproduced herein, suggests that an initial overexpansion occurred at the leading edge. Following the expansion and possibly a small region of flow detachment, a recompression is evident. The angle of the recompression wave was measured and the resultant total pressure loss was calculated to be less than 0.5 percent. As a result of those phenomena, close correlation of the flow properties obtained from the probe measurements with those calculated by simple theory is not necessarily expected.

The following table summarizes the determination of M_1 by the three methods available for the expansion region - probe measurements leading directly to Mach number, flow angles determined from flat-plate incidence angle with the boundary-layer increment added ($\alpha + \Delta\alpha$), and flow angles calculated from probe differential pressures (θ):

Condition	M ₁ determined from -		
	Probe	$\alpha + \Delta\alpha$	θ
M _∞ = 3.0	3.63	3.55	3.69
M _∞ = 4.5	5.45	5.35	5.41

The agreement for this parameter is within the expected accuracy that the probe can provide, and the errors were not more than 0.15 and 0.10 at M_∞ = 3.0 and M_∞ = 4.5, respectively.

CONCLUDING REMARKS

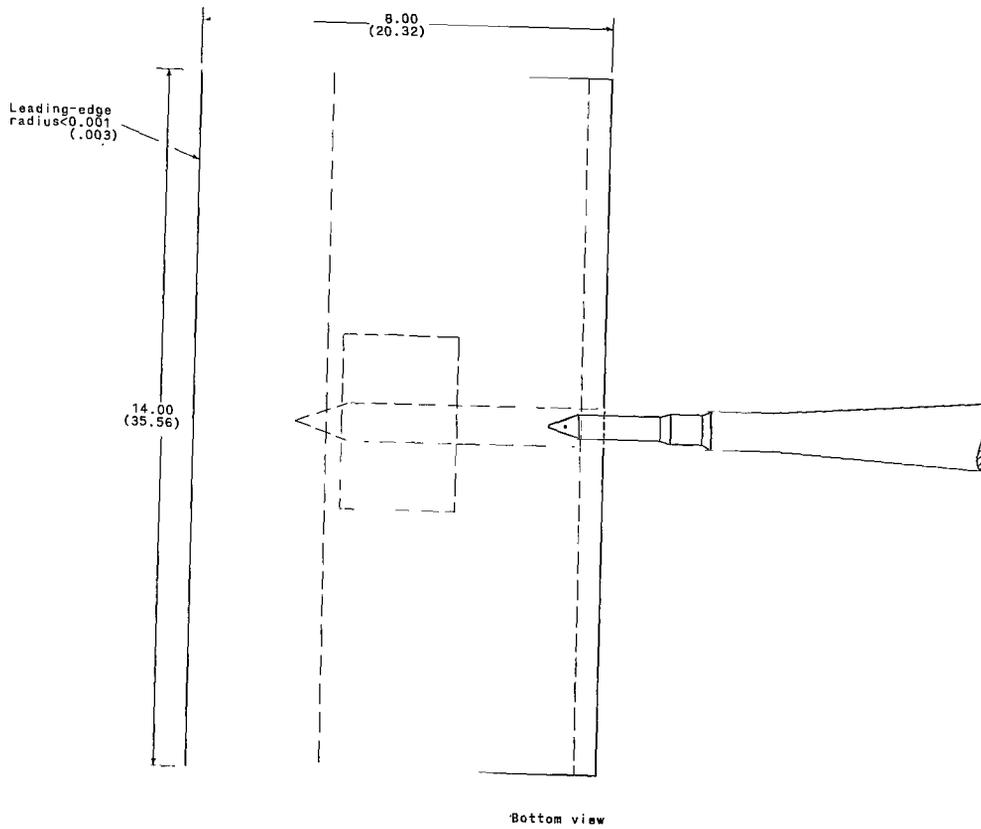
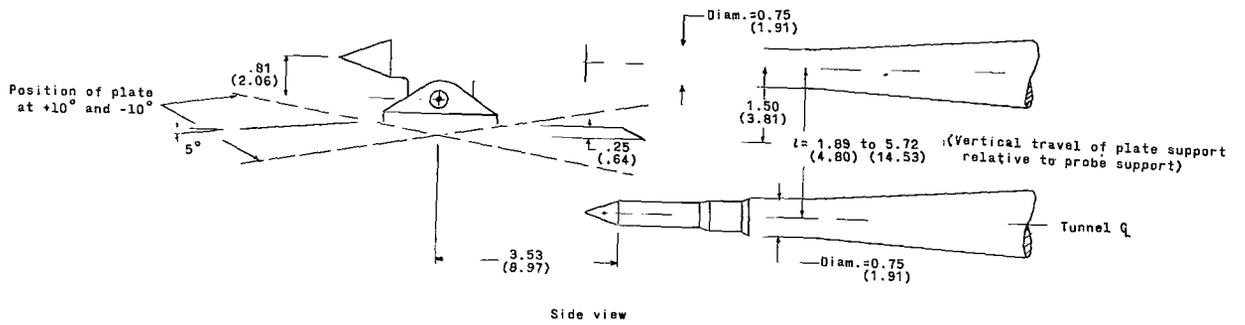
A wind-tunnel investigation was conducted to study the performance of a previously calibrated conical pressure probe in determining the local flow properties at hypersonic speeds. The pressure probe was investigated in compression and expansion flow fields generated by a two-dimensional flat plate. A comparison was made between flow properties obtained from the probe pressure measurements and those calculated by simple theory. The investigation was conducted at Mach numbers of 3.0, 4.5, and 6.0.

The results indicated that, in general, Mach number and total pressure determined from the probe measurements agreed with the theoretical values within the calibration uncertainty. Flow angles determined from probe measurements, except in an expansion field, agreed with those calculated from simple theory when account was taken of the flat-plate boundary layer. The discrepancy between experimental and theoretical flow angles in an expansion field was not resolved. Information obtained from schlieren photographs of the flow fields was a significant aid in interpreting results when the probe was near a disturbance.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., August 23, 1966,
126-15-03-03-23.

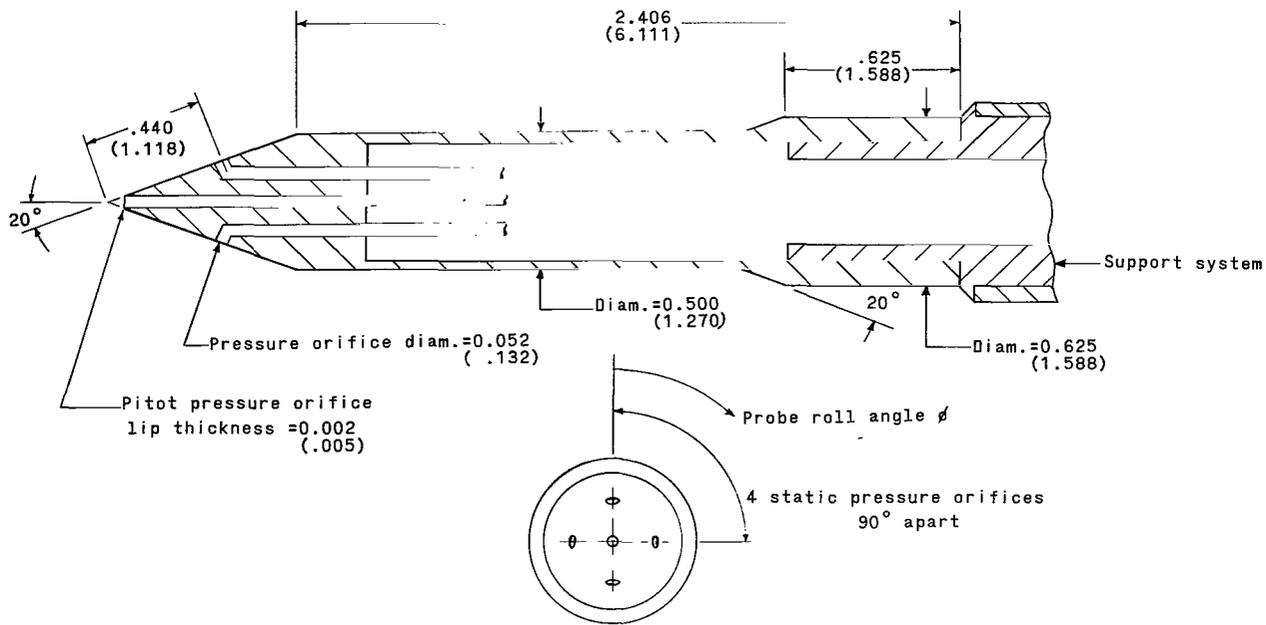
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1. Norris, John D.: Calibration of Conical Pressure Probes for Determination of Local Flow Conditions at Mach Numbers From 3 to 6. NASA TN D-3076, 1965.
2. Hill, J. A. F.; Baron, J. R.; Schindel, L. H.; and Markham, J. R.: Mach Number Measurements in High-Speed Wind Tunnels. AGARDograph 22, North Atlantic Treaty Organization (Paris), Oct. 1956.
3. Stokes, George M.: Description of a 2-Foot Hypersonic Facility at the Langley Research Center. NASA TN D-939, 1961.
4. Ames Research Staff: Equations, Tables, and Charts for Compressible Flow. NACA Rept. 1135, 1953. (Supersedes NACA TN 1428.)



(a) Flat plate and probe assembly.

Figure 1.- Model and support apparatus. Dimensions are given first in inches and parenthetically in centimeters.



(b) Pressure probe.

Figure 1.- Concluded.

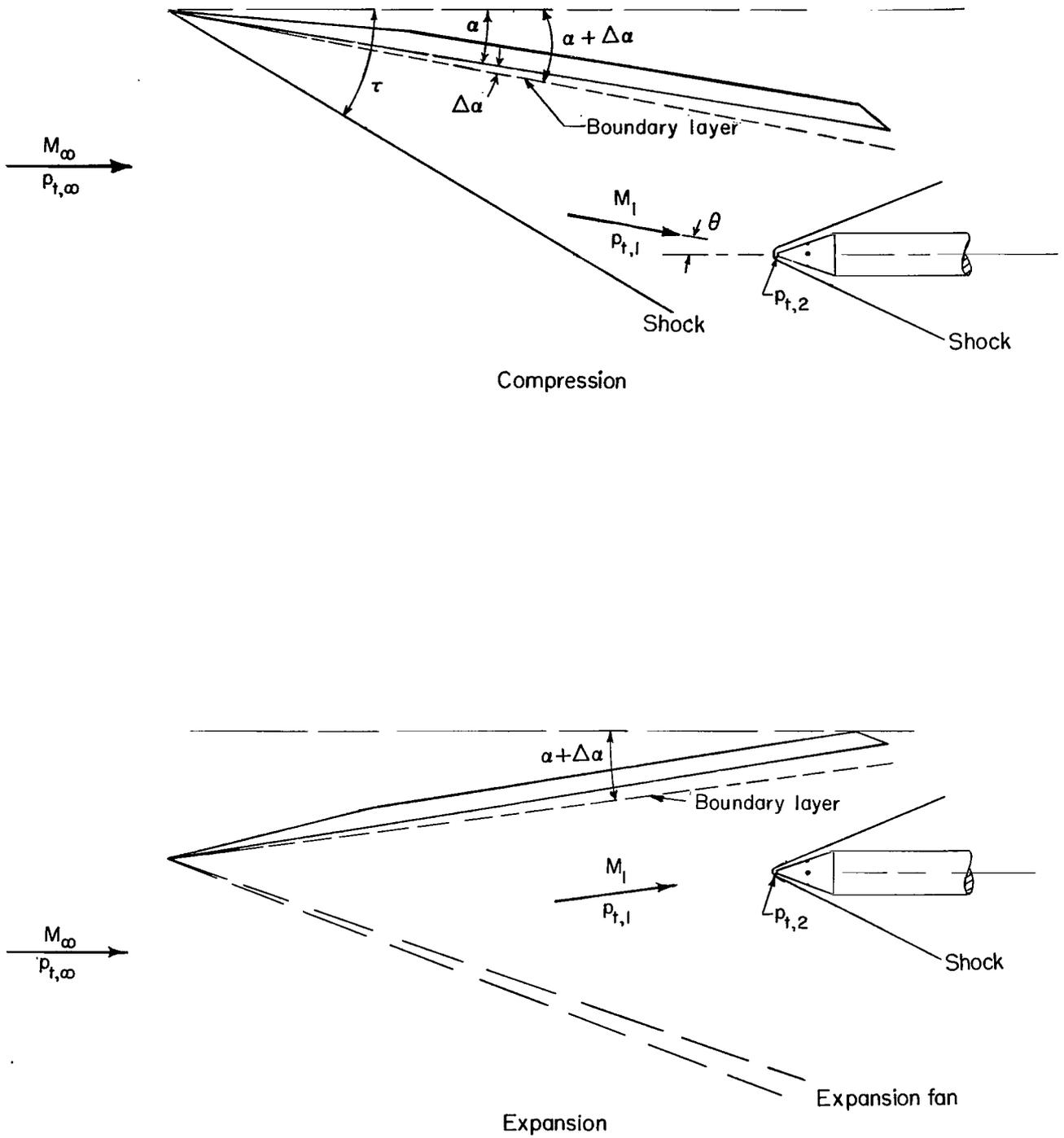


Figure 2.- Sketch showing physical flow characteristics in two-dimensional fields.

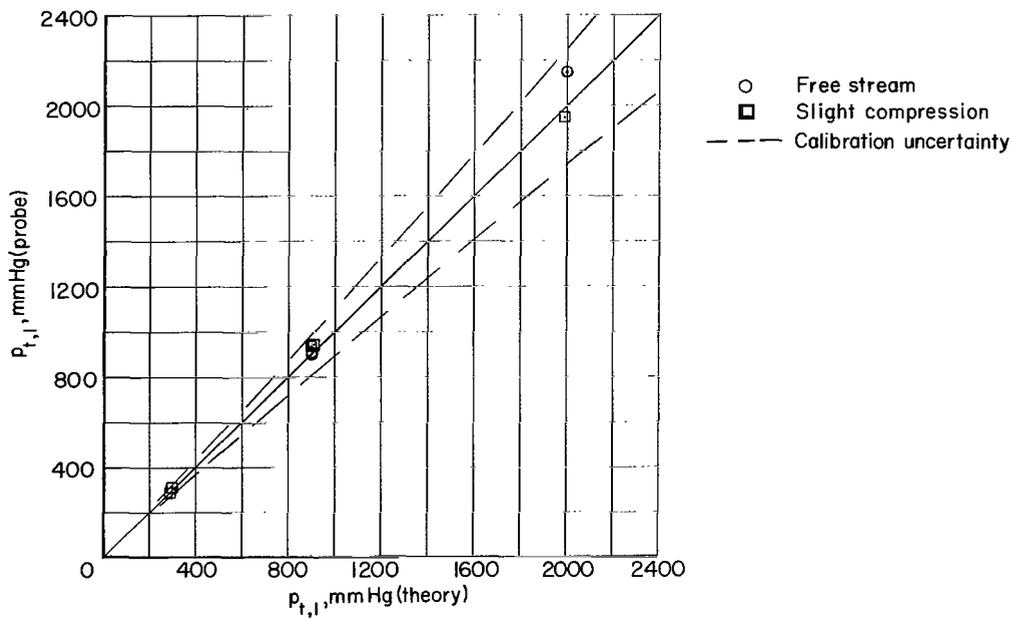
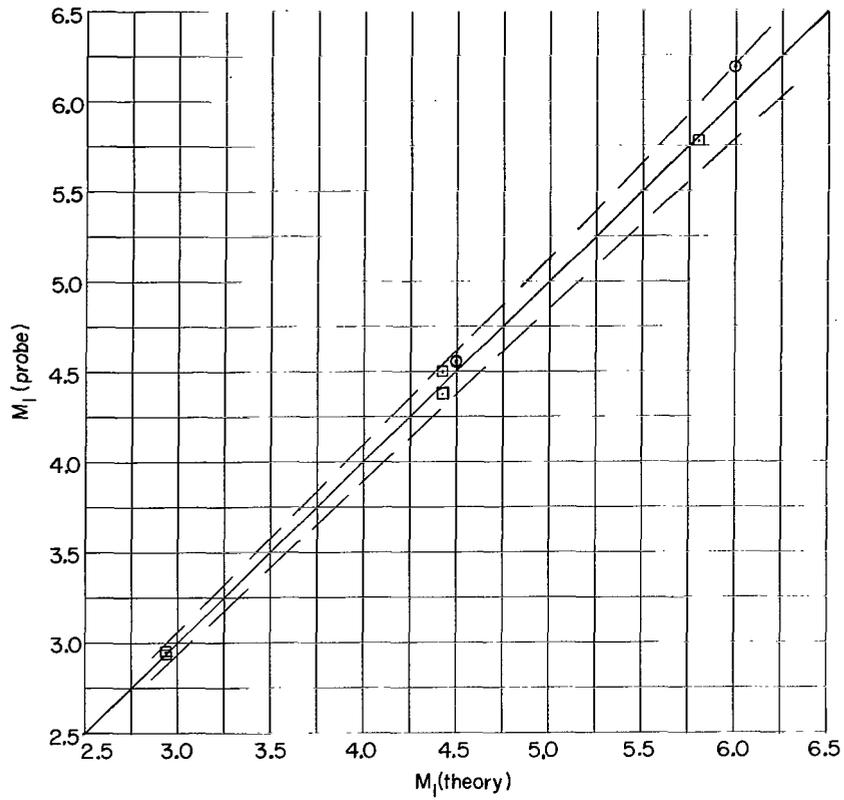
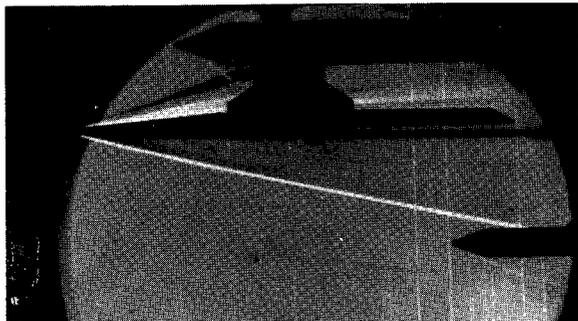


Figure 3.- Comparison between theoretical and probe-measured values of local Mach number and total pressure for slight compression and for free-stream conditions.

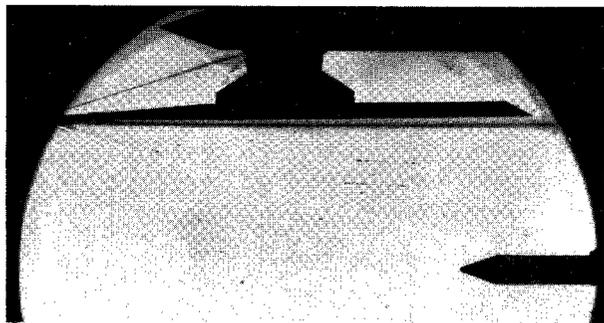


$z = 3.75(9.53)$

$M_{\infty} = 6.0$

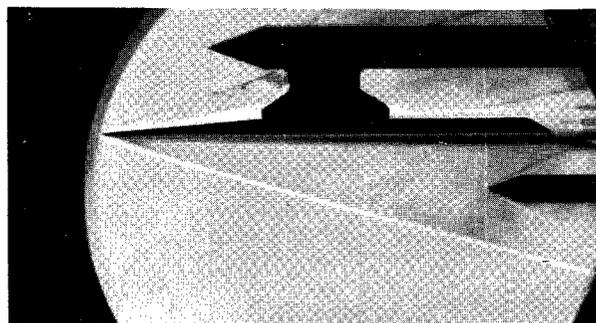
No picture available; probe located behind shock wave

$z = 2.51(6.38)$

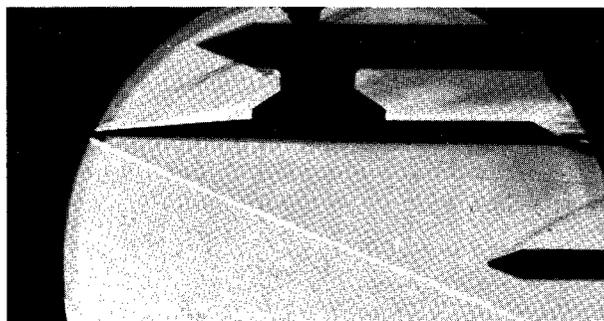


$z = 4.0(10.16)$

$M_{\infty} = 4.5$

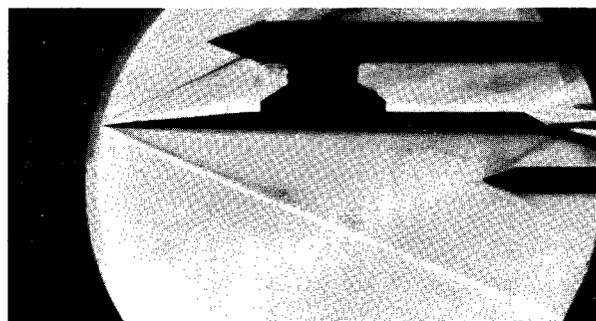


$z = 2.51(6.38)$



$z = 3.75(9.53)$

$M_{\infty} = 3.0$

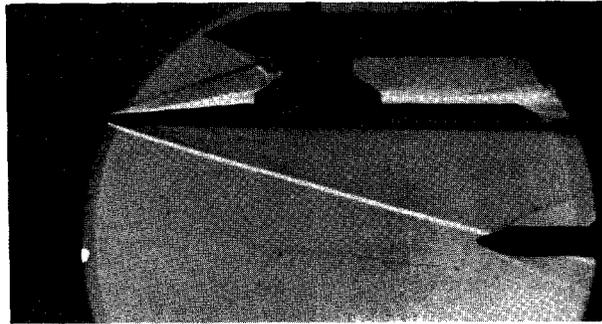


$z = 2.51(6.38)$

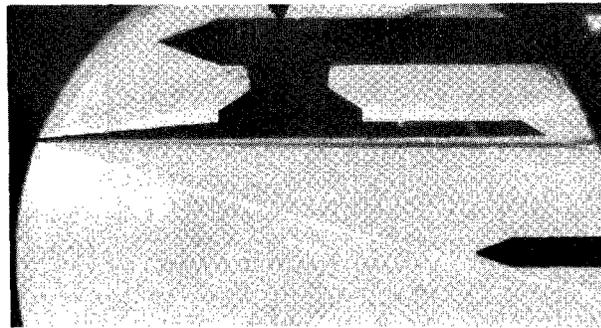
(a) Probe ahead or behind disturbance.

L-66-4558

Figure 4.- Schlieren photographs indicating position of pressure probe for slight compression and for free-stream flow. Dimensions are given first in inches and parenthetically in centimeters. $\phi = 0^\circ$.



$z = 3.75(9.53)$



$z = 3.35(8.51)$

(b) Probe near disturbance; $M_\infty = 4.5$.

L-66-4559

Figure 4.- Concluded.

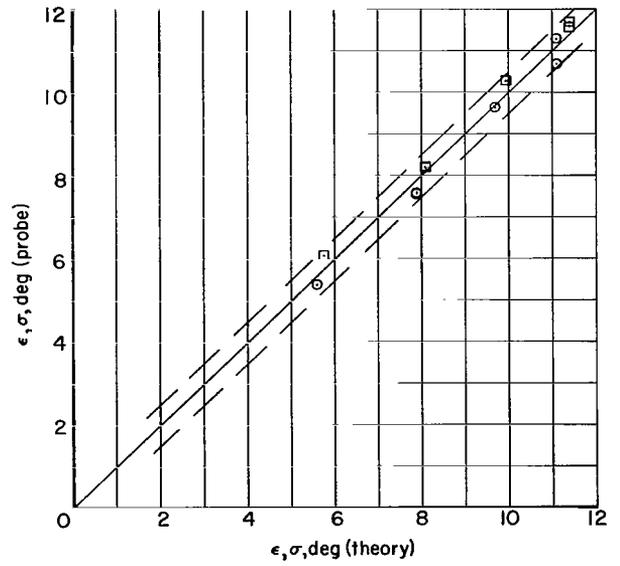
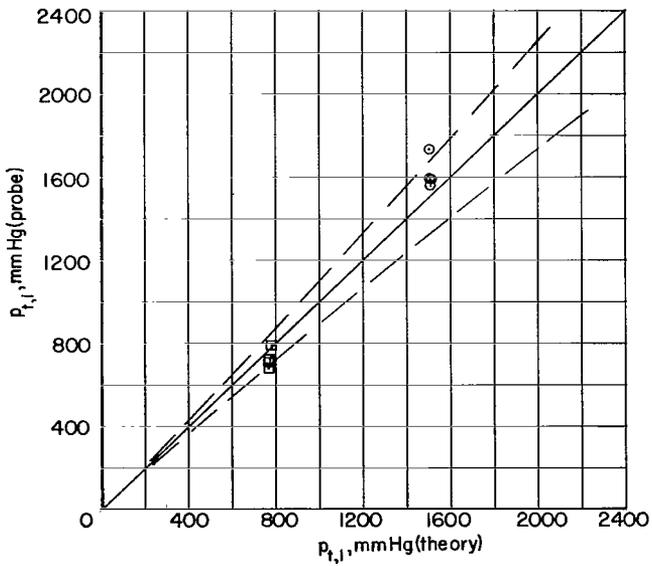
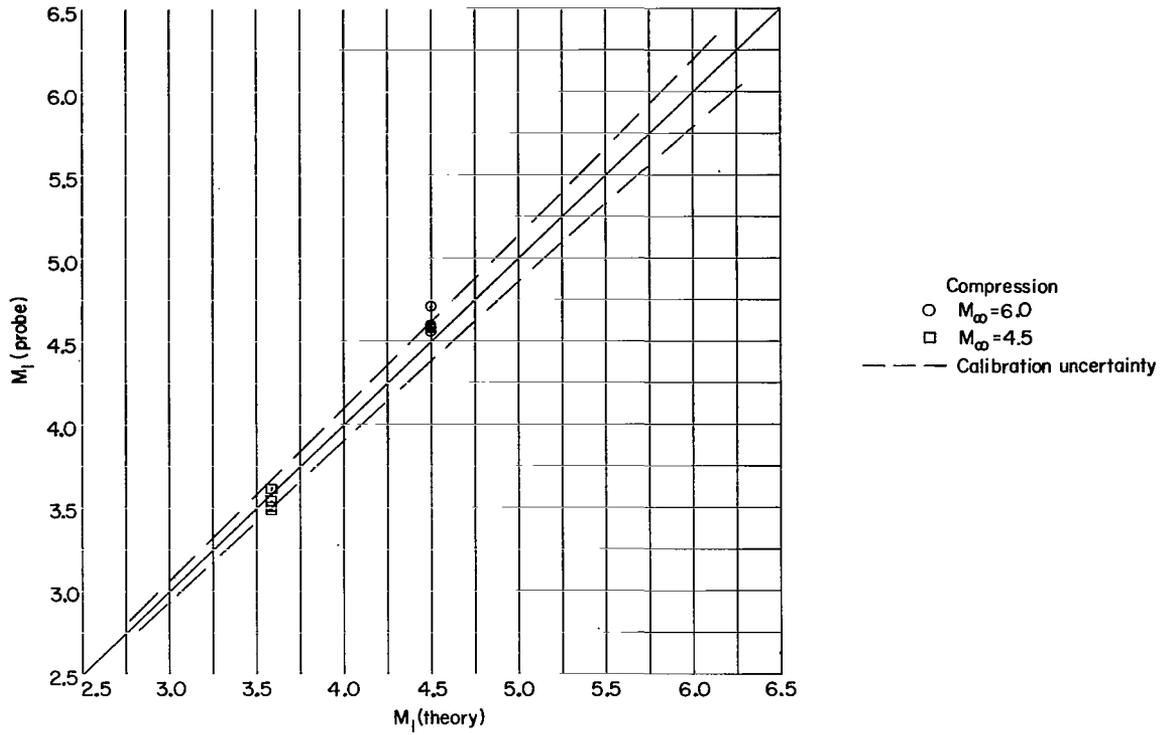
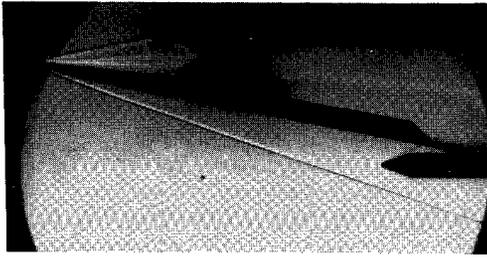
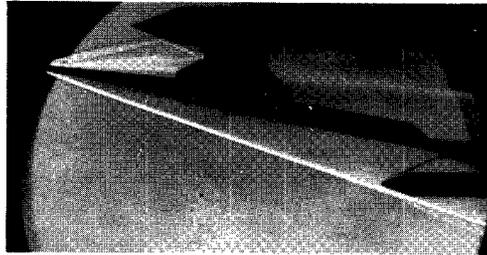


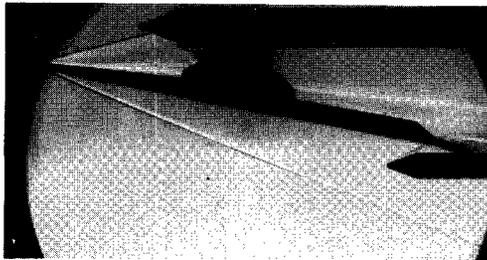
Figure 5.- Comparison between theoretical and probe-measured values of local Mach number, total pressure, and flow angles for compression.



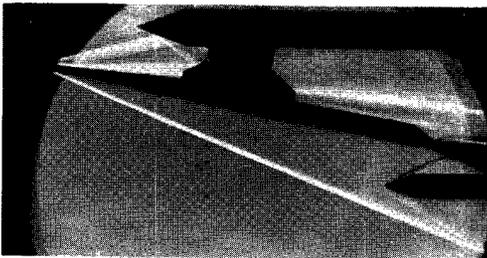
(a) $M_\infty = 6.0$; $l = 2.75$ (6.99); $\phi = 0^\circ, 30^\circ,$ and 45° .



(b) $M_\infty = 6.0$; $l = 3.10$ (7.87); $\phi = 0^\circ$.



(c) $M_\infty = 4.5$; $l = 2.75$ (6.99); $\phi = 0^\circ, 30^\circ,$ and 45° .



(d) $M_\infty = 4.5$; $l = 3.1$ (7.87); $\phi = 0^\circ$.

L-66-4560

Figure 6.- Schlieren photographs indicating position of pressure probe for compression. Dimensions are given first in inches and parenthetically in centimeters.

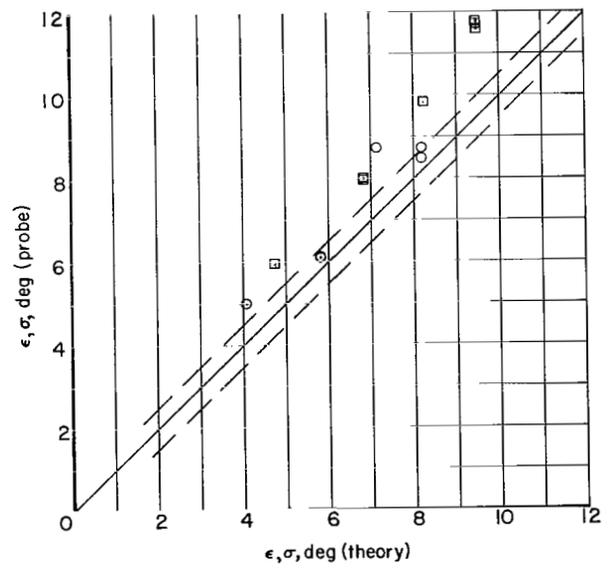
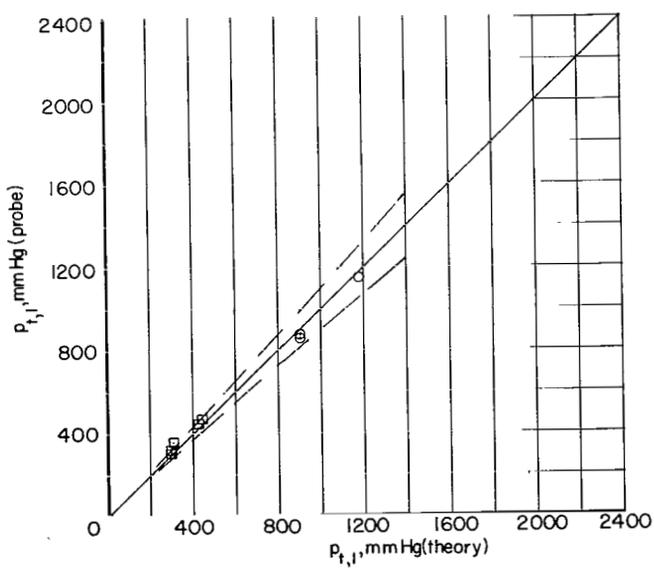
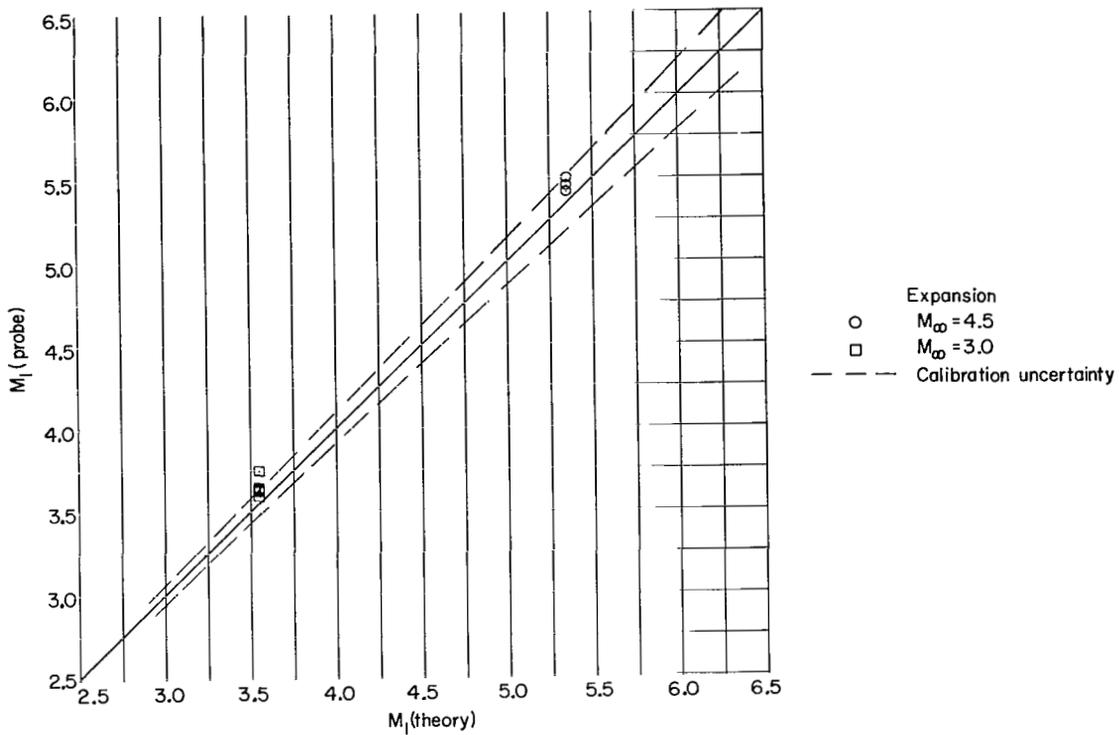
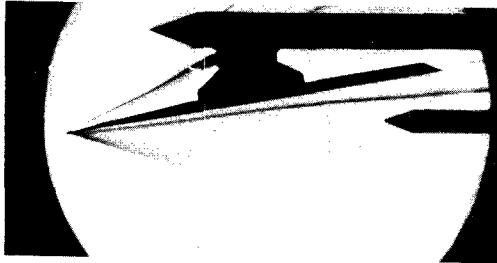
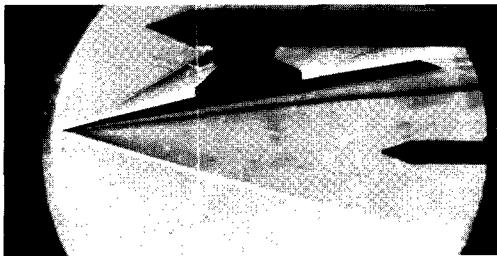


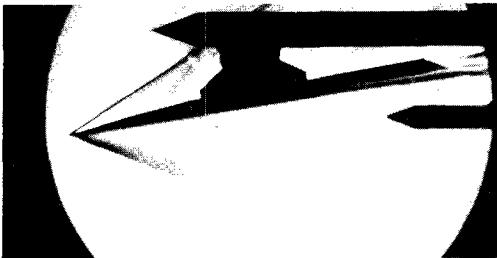
Figure 7.- Comparison between theoretical and probe-measured values of local Mach number, total pressure, and flow angles for expansion.



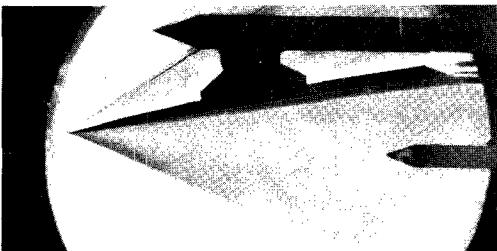
(a) $M_\infty = 4.5$; $l = 1.90$ (4.83); $\phi = 0^\circ, 30^\circ, \text{ and } 45^\circ$.



(b) $M_\infty = 4.5$; $l = 2.6$ (6.60); $\phi = 0^\circ$.



(c) $M_\infty = 3.0$; $l = 1.90$ (4.83); $\phi = 0^\circ, 30^\circ, \text{ and } 45^\circ$.



(d) $M_\infty = 3.0$; $l = 2.6$ (6.60); $\phi = 0^\circ$.

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Figure 8.- Schlieren photographs indicating position of pressure probe for expansion. Dimensions are given first in inches and parenthetically in centimeters.

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