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TECHNICAL MEMORANDUM

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EFFECT OF EXTERNAL BOUNDARY LAYER ON PERFORMANCE OF AXISYMMETRIC INLET AT MACH NUMBERS OF 3.0 AND 2.5

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SUMMARY

The effect of an external boundary layer on the performance of an axisymmetric external-internal-compression inlet was evaluated at Mach numbers of 3.0 and 2.5 and Reynolds numbers from 2.2 to 0.5×10^6 per foot. The inlet was tested at locations up to two-thirds of the way into the 1.7- and 9.0-inch boundary layers generated by a flat plate and the tunnel floor, respectively. The inlet could be readily started at all conditions tested, including those where the boundary layer was separated upstream of the inlet by the various shock systems during the restart cycle. Although the inlet performance decreased with increasing immersion into the boundary layer at both Mach numbers, the inlet was more sensitive to boundary-layer ingestion at the design Mach number of 3.0.

INTRODUCTION

Modern high-speed aircraft require efficient component design and location for maximum over-all efficiency. Configurations employing air-breathing powerplants housed in nacelles may have the inlets located adjacent to the underside of the wing or fuselage. Location in these areas may be advantageous with respect to favorable interference effects leading to increased pressure recovery and decreased sensitivity to angle of attack. Locating an inlet near a wing or fuselage raises the question of external boundary-layer effects on the performance and starting characteristics of the inlet.

To cope with this problem, two approaches are possible. One utilizes a physical divider or splitter plate to separate the inlet from the boundary layer. Considerable work has been done in this area (e.g., refs. 1 to 3). The other approach is to locate the inlet as close as possible to the boundary layer without adversely affecting the inlet characteristics. Because of limited data in this second approach, an investigation was conducted on the inlet problems associated with the ingestion of various amounts of boundary-layer air and with flow disturbances due to shock impingement on a boundary layer ahead of a specific external-internal-compression inlet. Results are presented for a 19-inch-diameter Mach 3.0 design axisymmetric inlet tested in two boundary layers (δ = 1.7 and 9.0 in.) at Mach numbers of 3.0 and 2.5 and Reynolds numbers from 2.2 to 0.5×10^6 per foot.

SYMBOLS

A_{bl}	projected area of inlet immersed by boundary layer
A_{in}	inlet capture area, 257.2 sq in.
A_3	diffuser exit area, 119.94 sq in.
d	inlet diameter
h	distance from cowl lip to surface generating boundary layer
M	Mach number
m_3/m_0	inlet mass-flow ratio, $\rho_3 U_3 A_3/\rho_0 U_0 A_{in}$
n	exponent
P_3/P_0	total-pressure recovery
Re	Reynolds number
U	velocity
u	velocity in boundary layer
y	distance normal to surface generating boundary layer
δ	boundary-layer thickness (defined by $u/U_0 = 0.99$) at inlet station
ρ	density

Subscripts:

0	free stream
3	diffuser exit

APPARATUS AND PROCEDURE

Model

The inlet model was the combination external-internal-compression axisymmetric inlet system reported in reference 4. The model, as shown in figure 1, had an external 20° half-angle cone capable of $4\frac{1}{2}$ inches of remotely controlled translation. The internal compression was achieved by the cowl internal surface in two discrete steps. The cowl had a projected frontal area 9.3 percent of the maximum frontal area, with a constant external lip angle of $7\frac{1}{4}^{\circ}$ back to the maximum body diameter. The sting-mounted model had a remotely controlled exit plug to regulate the mass flow. A flush-slot throat bleed was employed to remove the spike boundary layer and to control the effects of the adverse pressure gradient produced by the internal shock system.

Plate Details

The model is shown installed in the test section adjacent to the flat plate in figure 2. In order to thicken the boundary layer and to ensure a turbulent profile, the 10- by $15\frac{1}{2}$-foot plate had a 1-foot-wide band of surface roughness, starting 1 inch aft of the sharp leading edge and having peaks approximately 1/8 inch in height. The boundary-layer height at the leading edge of the cowl (6 ft aft of the plate leading edge) was increased from 0.5 to 1.7 inches by adding the roughness band. In order to investigate inlet operation in a much thicker boundary layer, the inlet was also tested at various immersions in the 9.0-inch boundary layer along the tunnel floor.

Calculations and Instrumentation

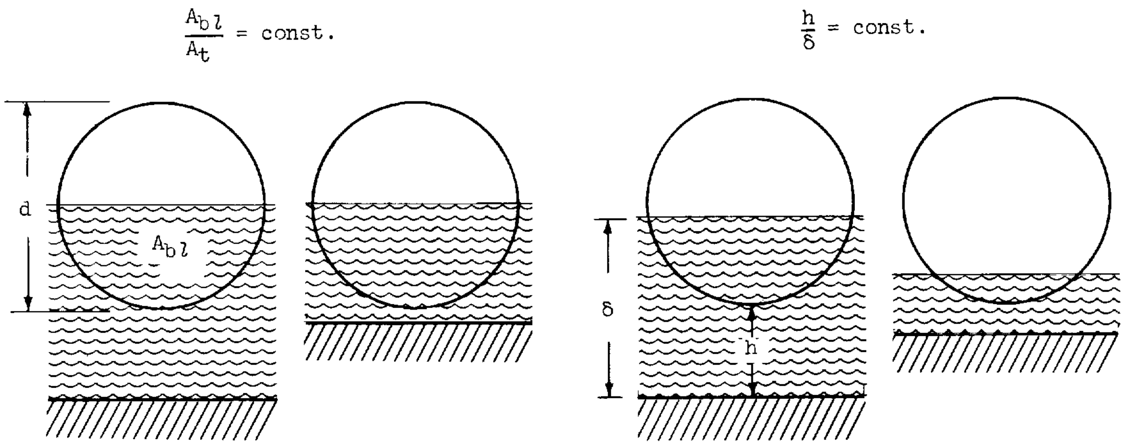
Mass flow was computed using a measured static pressure at the diffuser-exit station of the model (station 66) and the assumption of isentropic flow to a choked area at the plug exit. Total-pressure recovery was obtained from an area weighted average of 36 total-pressure tubes located at station 29. A distortion parameter defined as the maximum total pressure minus the minimum total pressure divided by the average total pressure was also obtained at station 29. Total-pressure rakes were also located at various stations along the flat plate to define the boundary-layer profile. This test was conducted in the Lewis 10- by 10-foot supersonic tunnel at Mach numbers of 3.0 and 2.5 and Reynolds numbers from 2.2 to 0.5×10^{6} per foot.

RESULTS AND DISCUSSION

Profiles of the flat-plate and tunnel-floor boundary layers at Mach 3.0 are shown in figure 3. Changes in Mach number from 3.0 to 2.5 and Reynolds number from 2.2 to 0.5×10^6 per foot had essentially no effect on the boundary-layer height at the inlet face (1.7 and 9.0 in. for the plate and floor, respectively). However, lowering the Reynolds number (holding Mach number constant) did have a tendency to change the profile by increasing the amount of low-energy air in the boundary layer. For example, fitting the boundary-layer profiles to the form $(y/\delta)^n = u/U_0$ at a Mach number of 3.0 increased n from a value of 1/10 to 1/7 and 1/11 to 1/8 when the free-stream Reynolds number was decreased from 2.2 to 0.5×10^6 per foot for the tunnel-floor and plate boundary layers, respectively.

The effect of Reynolds number on inlet performance is shown in figure 4. The inlet was located outside the boundary layer but within the plate leading-edge Mach wave; as such the inlet was considered to be operating essentially in the free stream. At both Mach numbers, a marked decrease in inlet pressure recovery was noted as the Reynolds number was decreased below 1.5×10^6 per foot. At Mach 3.0 the critical pressure recovery was 0.81 at a Reynolds number of 2.2×10^6 per foot and 0.75 at a Reynolds number of 0.5×10^6 per foot. The 0.81 pressure recovery is about 0.03 higher than the recovery obtained in the initial testing of the model (ref. 4). The spike in the present test was retracted farther (more internal compression) than in the original testing. This fact, along with possible slight plate misalinement from zero angle of attack, boundary-layer displacement effects, or minor fabrication differences in the model, could account for the difference in pressure recovery.

The effect of operating the inlet in boundary-layer regions is shown in figure 5 using h/δ as the parameter. This is an arbitrary choice, since it appears that no single parameter is satisfactory for generalizing the effects of immersing an axisymmetric inlet, by various amounts, into a boundary layer. For a given depth of immersion, the entering boundary-layer air can be either of comparatively high energy or very low energy, depending on its thickness relative to the cowl-lip diameter and type of profile. This obviously makes parameters based solely on geometric distances or areas useful for only one particular boundary layer and inlet. This can be seen in the following example:



(a) Two inlet - boundary-layer combinations having the same value of an area-ratio parameter (ratio of boundary-layer capture area to total inlet area) but with different boundary-layer weight flows being ingested because of different sized boundary layers.

(b) Two inlet - boundary-layer combinations having the same value of a distance ratio (distance from cowl lip to surface over boundary-layer height) but with different boundary-layer weight flows being ingested because of different sized boundary layers.

The starting technique used for this inlet (forward translation of the spike to permit swallowing of the terminal shock) was unaffected when operating in the boundary-layer region. The amount of internal contraction attainable with the inlet did, however, decrease as the amount of boundary-layer air ingestion was increased. This resulted in operating spike positions farther extended, with an accompanying lower pressure recovery than the optimum spike setting in the free stream. Locating the inlet at the outer edge of the boundary layer had no effect on the performance at Mach 3.0; at the lower Mach number a slight drop in recovery was noted (less than 0.02).

Typical total-pressure profiles at the diffuser exit (station 29) are shown in figure 6 for critical inlet operation in and out of the boundary-layer region. Schlieren photographs of the inlet boundary-layer interaction at various conditions are shown in figure 7. Figures 7(a) and (b) show the detailed shock structure with the inlet at a fixed h/δ at the two Mach numbers. Figure 7(c) shows the shock structure of the inlet at Mach 3.0 when it was unstarted. It was possible to restart the inlet from this condition.

CONCLUDING REMARKS

The inlet could be readily started at all conditions tested, including those where the boundary layer was separated upstream of the inlet by the various shock systems during the restart cycle. Although the inlet performance decreased with increasing immersion into the boundary layer at both Mach 3.0 and 2.5, the inlet was more sensitive to boundary-layer ingestion at the design Mach number.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, April 29, 1959

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1. Seddon, J., and Haverty, L.: Experiments at Mach Numbers from 0.5 to 1.8 on Side Intakes of Normal-Shock Type Without Boundary-Layer Control. Pt. I - The Nature of Pre-Entry Flow and Its Effect on Pressure Recovery. Tech. Note Aero 2329, British RAE, Oct. 1954.

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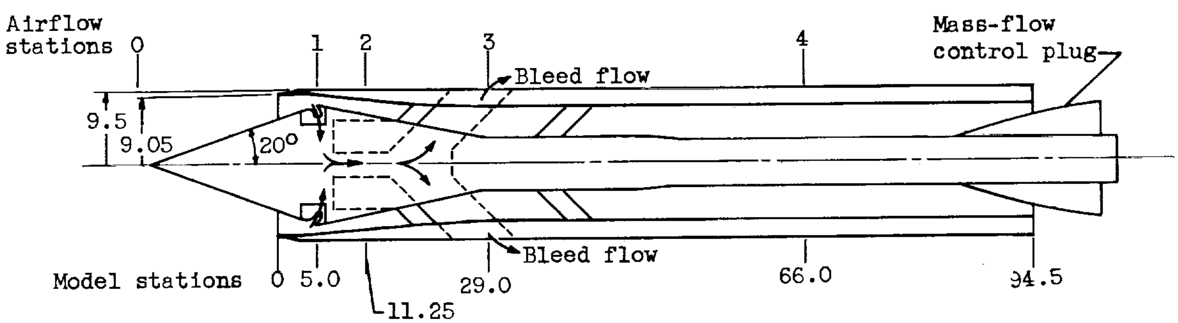
3. Piercy, Thomas G., and Johnson, Harry W.: A Comparison of Several Systems of Boundary-Layer Removal Ahead of a Typical Conical External-Compression Side Inlet at Mach Numbers of 1.88 and 2.93. NACA RM E53F16, 1953.

4. Obery, Leonard J., and Stitt, Leonard E.: Performance of External-Internal Compression Inlet with Abrupt Internal Turning at Mach Numbers 3.0 to 2.0. NACA RM E57H07a, 1957.



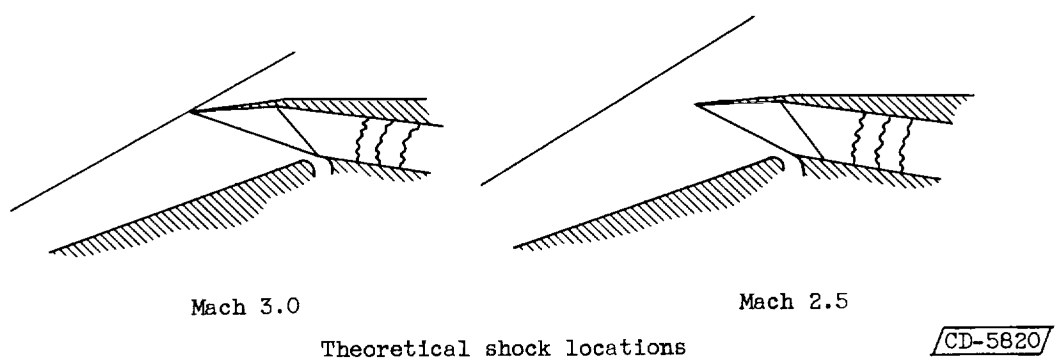


Figure 1. - Model details. (All dimensions in inches.)

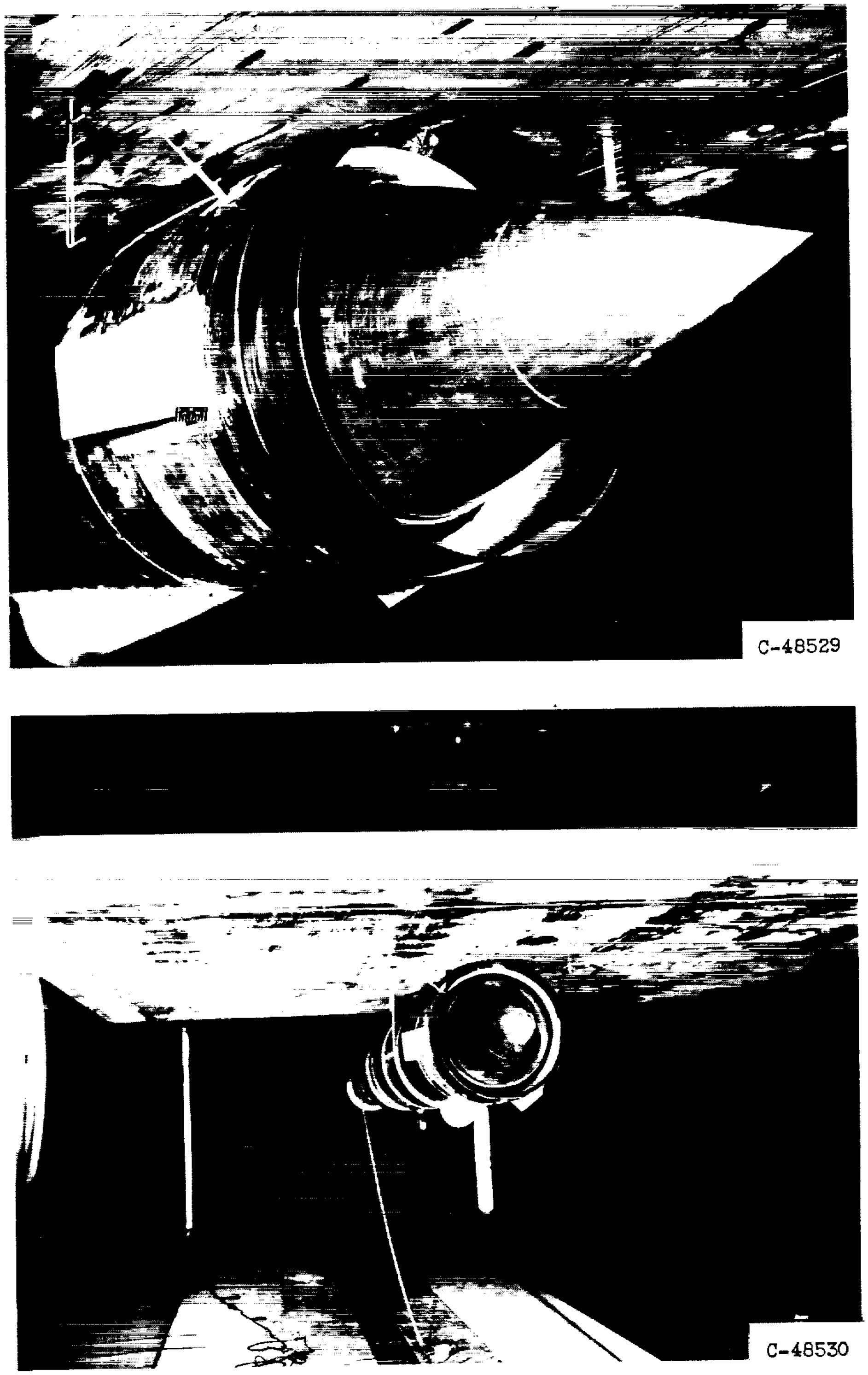
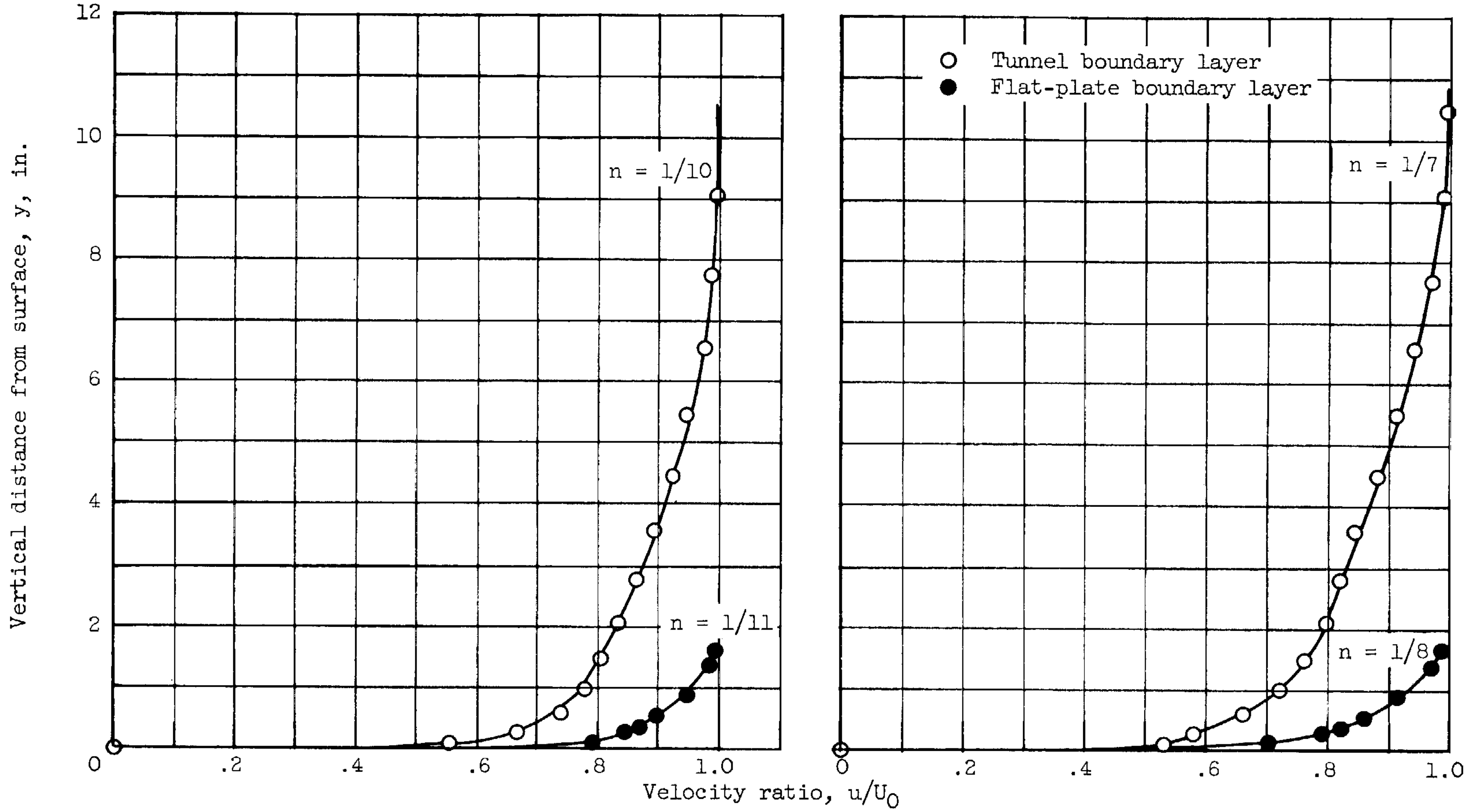


Figure 2. - Model installed in tunnel.



(a) Reynolds number, 2.2×10^6 per foot.

(b) Reynolds number, 0.5×10^6 per foot.

Figure 3. - Comparison of typical boundary-layer profiles. Free-stream Mach number, 3.0. Profile of form, $(y/\delta)^n = u/U_0$.

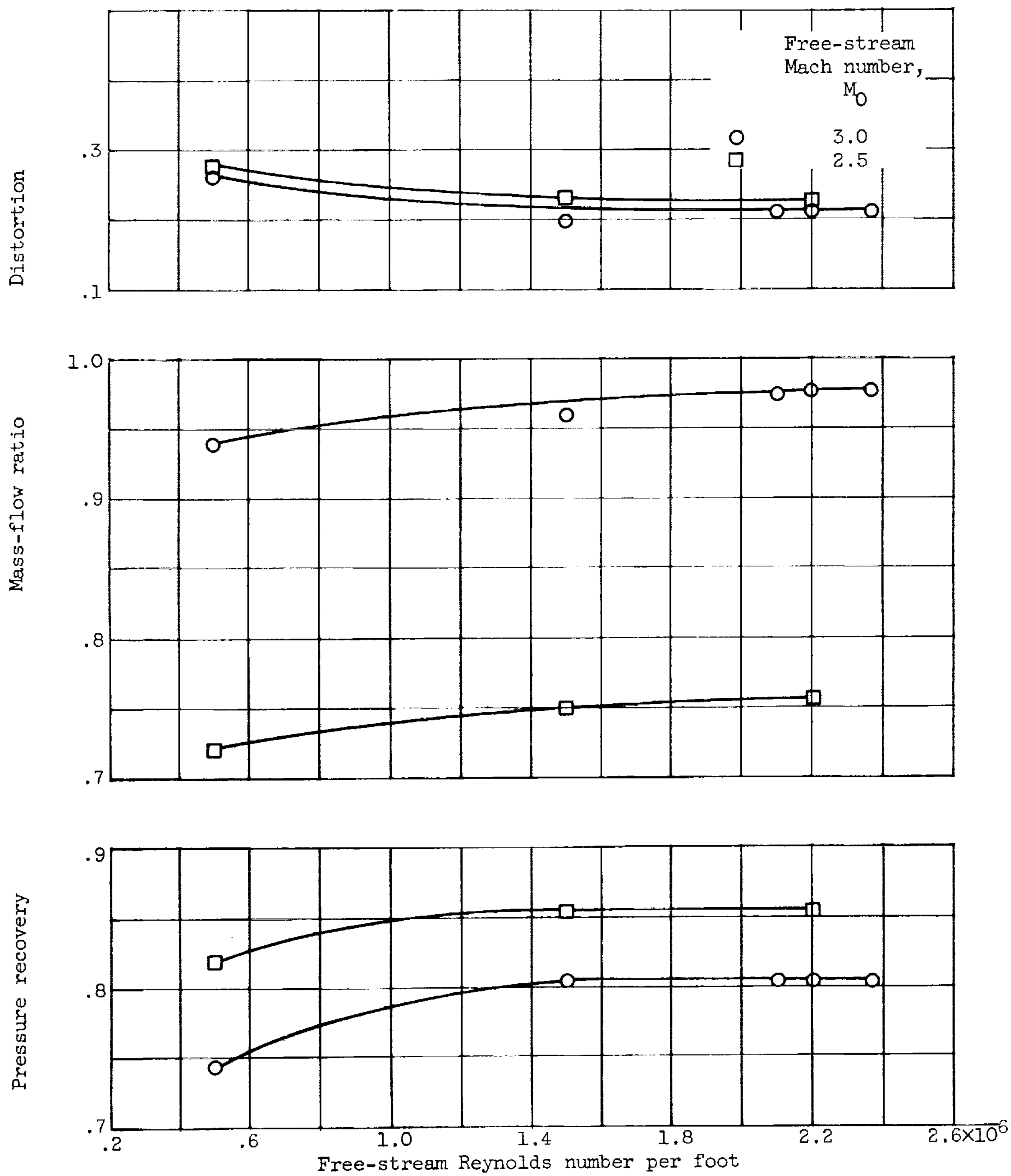
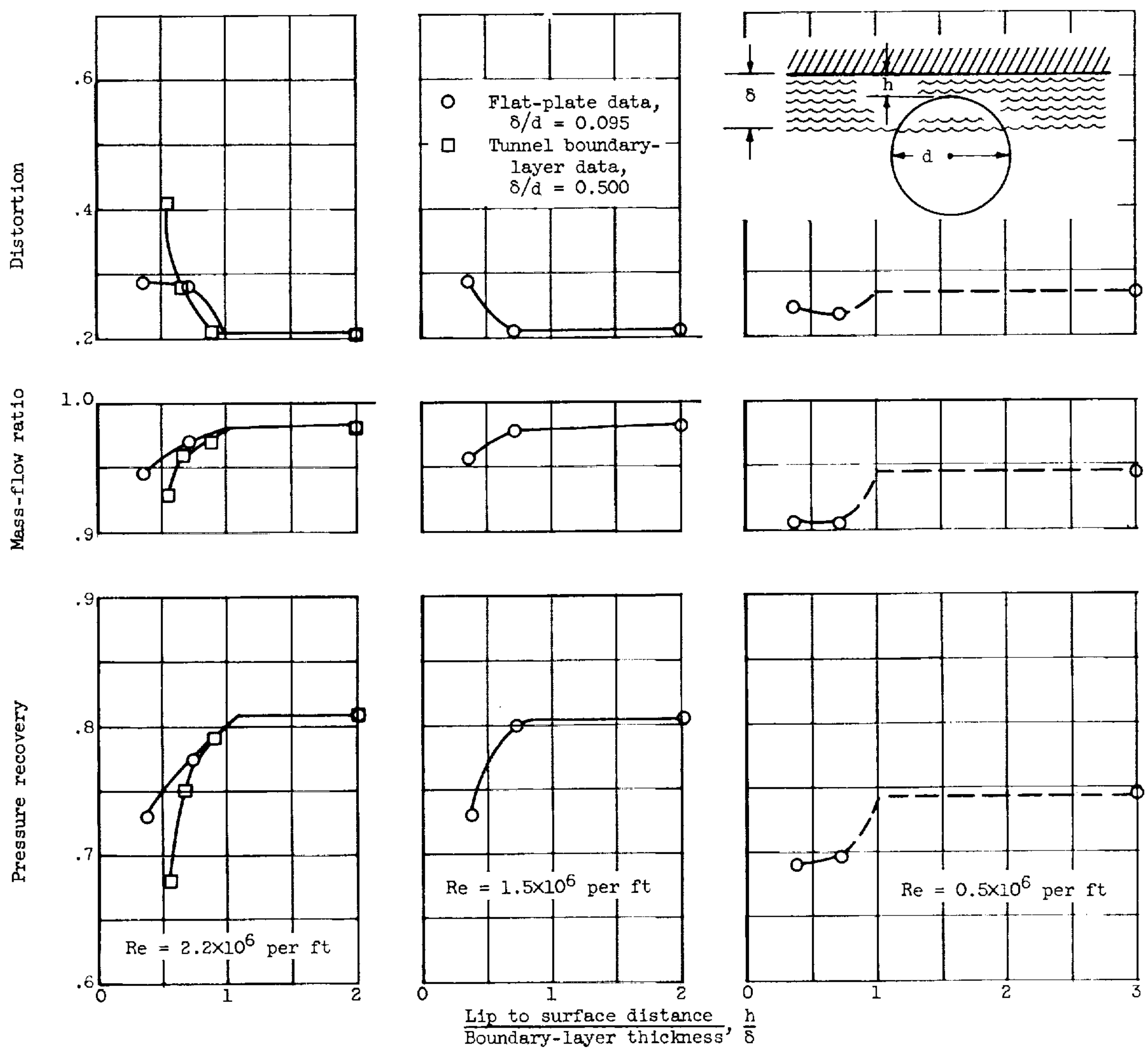
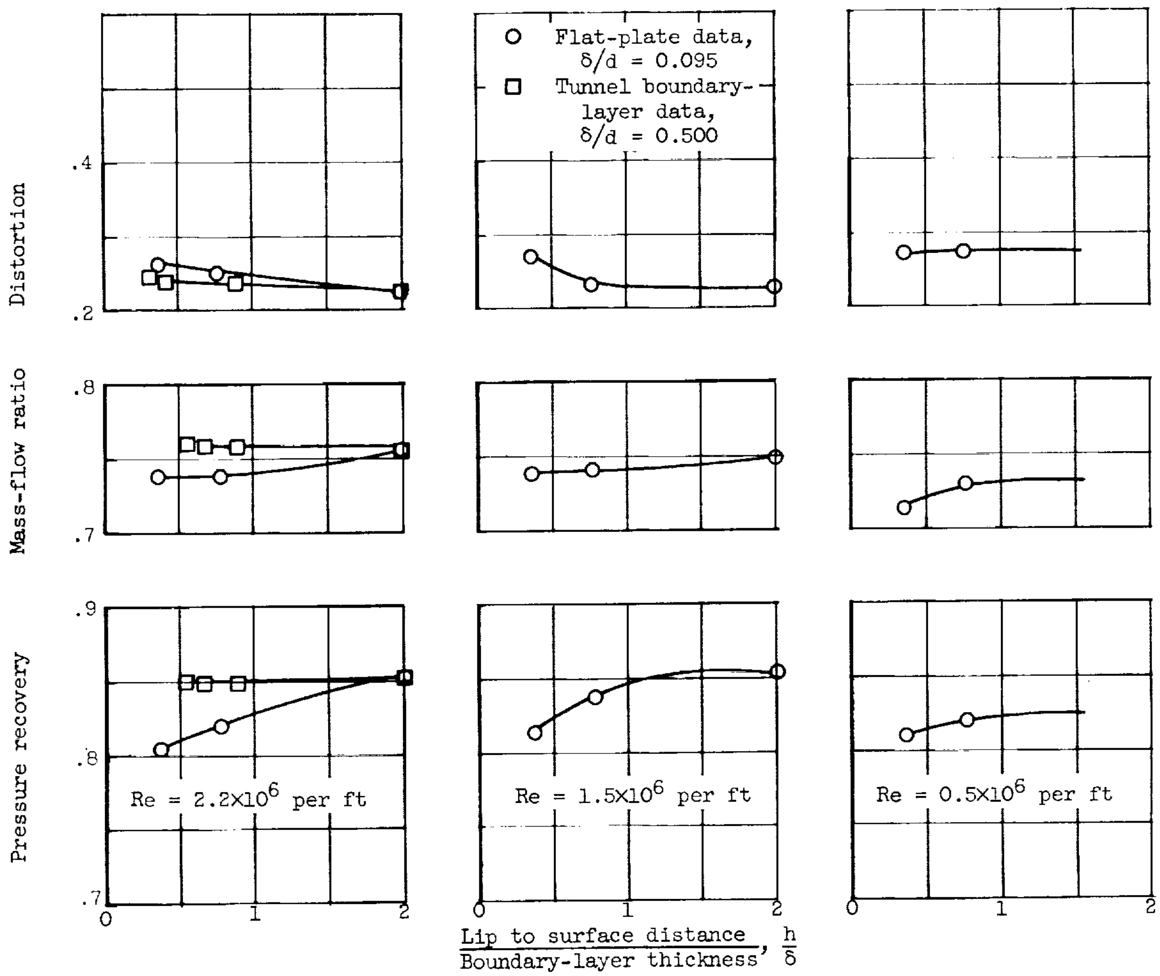


Figure 4. - Effect of Reynolds number on critical free-stream inlet performance.



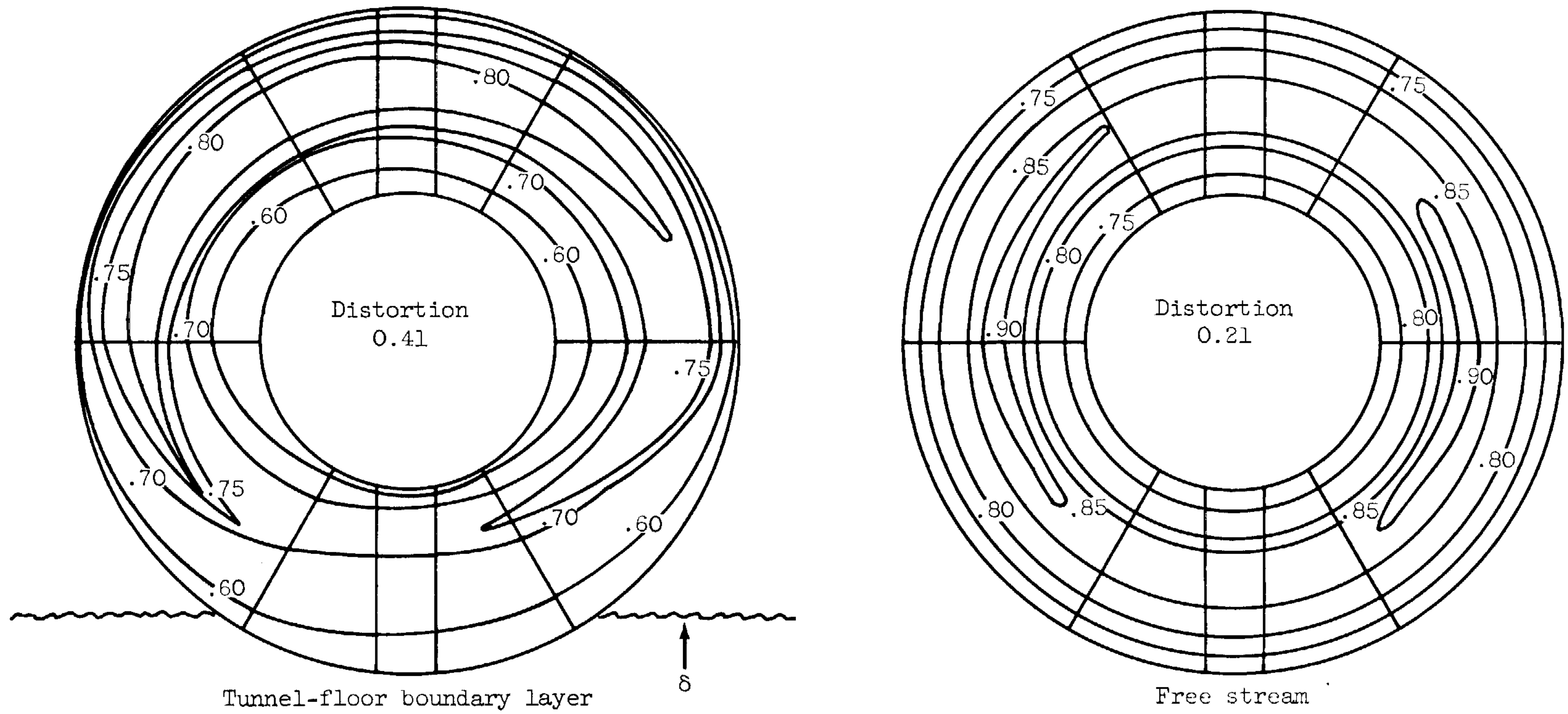
(a) Free-stream Mach number, 3.0.

Figure 5. - Critical inlet performance at various distances from an adjacent surface.



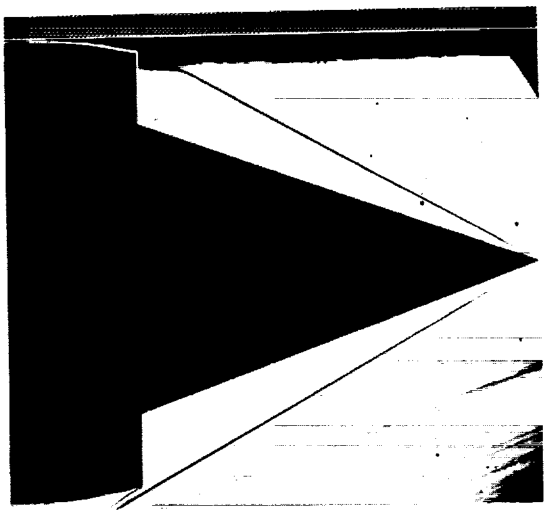
(b) Free-stream Mach number, 2.5.

Figure 5. - Concluded. Critical inlet performance at various distances from an adjacent surface.

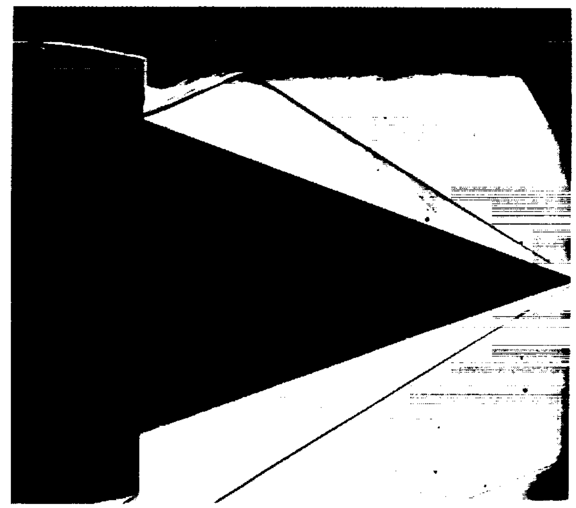


	Tunnel-floor boundary layer	Free stream
h/δ	0.55	>1.0
P_3/P_0	0.68	0.81
m_3/m_0	0.93	0.98

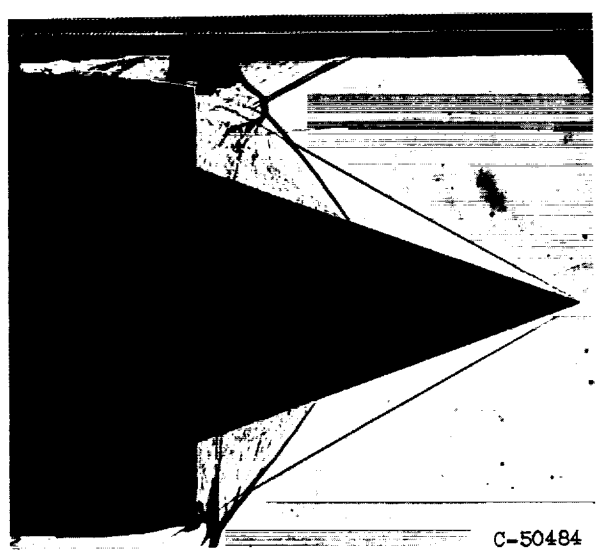
Figure 6. - Typical total-pressure contours at diffuser exit for inlet operation in and out of boundary layer. Free-stream Mach number, 3.0; Reynolds number, 2.2×10^6 per foot.



(a) M_0 = 3.0; h = 0.63 inch; δ = 1.7 inches.



(b) M_0 = 2.5; h = 0.63 inch; δ = 1.7 inches.



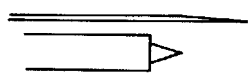
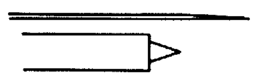
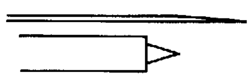
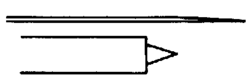
(c) M_0 = 3.0; inlet unstarted.

Figure 7. - Typical schlieren photographs of inlet boundary-layer interaction.

NOTES: (1) Reynolds number is based on the diameter of a circle with the same area as that of the capture area of the inlet.

(2) The symbol * denotes the occurrence of buzz.

INLET BIBLIOGRAPHY SHEET

Report and facility	Description			Test parameters				Test data				Performance		Remarks
	Configuration	Number of oblique shocks	Type of boundary-layer control	Free-stream Mach number	Reynolds number $\times 10^{-6}$	Angle of attack, deg	Angle of yaw, deg	Drag	Inlet-flow profile	Discharge-flow profile	Flow picture	Maximum total-pressure recovery	Mass-flow ratio	
NASA TM X-49 Lewis 10- by 10-foot Supersonic Wind Tunnel		3	Flush slot	3.0 and 2.5	1.4×10^6 to 0.3×10^6	0			✓	✓	✓	0.81 at $M_0 = 3.0$ 0.86 at $M_0 = 2.5$	0.72 to 0.98*	In general, locating the inlet lip into the boundary layer decreased the performance but did not affect the inlet starting capabilities.
NASA TM X-49 Lewis 10- by 10-foot Supersonic Wind Tunnel		3	Flush slot	3.0 and 2.5	1.4×10^6 to 0.3×10^6	0			✓	✓	✓	0.81 at $M_0 = 3.0$ 0.86 at $M_0 = 2.5$	0.72 to 0.98*	In general, locating the inlet lip into the boundary layer decreased the performance but did not affect the inlet starting capabilities.
NASA TM X-49 Lewis 10- by 10-foot Supersonic Wind Tunnel		3	Flush slot	3.0 and 2.5	1.4×10^6 to 0.3×10^6	0			✓	✓	✓	0.81 at $M_0 = 3.0$ 0.86 at $M_0 = 2.5$	0.72 to 0.98*	In general, locating the inlet lip into the boundary layer decreased the performance but did not affect the inlet starting capabilities.
NASA TM X-49 Lewis 10- by 10-foot Supersonic Wind Tunnel		3	Flush slot	3.0 and 2.5	1.4×10^6 to 0.3×10^6	0			✓	✓	✓	0.81 at $M_0 = 3.0$ 0.86 at $M_0 = 2.5$	0.72 to 0.98*	In general, locating the inlet lip into the boundary layer decreased the performance but did not affect the inlet starting capabilities.

Bibliography

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