RM E56K09a

RESEARCH MEMORANDUM

INVESTIGATION OF AN ASYMMETRIC "PENSHAPE" EXIT HAVING CIRCULAR PROJECTIONS AND DISCHARGING INTO QUIESCENT AIR

By James F. Connors and Rudolph C. Meyer

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

January 24, 1957
Declassified December 3, 1958

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

INVESTIGATION OF AN ASYMMETRIC "PENSHAPE" EXIT HAVING CIRCULAR PROJECTIONS AND DISCHARGING INTO QUIESCENT AIR

By James F. Connors and Rudolph C. Meyer

SUMMARY

An asymmetric "penshape" exit was designed by the method of characteristics for a nozzle pressure ratio of 15. This configuration was experimentally evaluated in quiescent-air tests over a range of pressure ratios from 4 to 16. In an attempt to achieve throat-area modulation, a scheme was also investigated wherein a teardrop-shape ramp moved out of the concave expansion surface to restrict the flow.

The penshape exit in the full-throat or flush-ramp position gave a maximum thrust coefficient of 0.965 and was generally insensitive to changes in nozzle pressure ratio. Thus, it was comparable in performance to previously reported plug-type nozzles. However, a normal force variation was encountered with a maximum of 8 percent of jet thrust at a pressure ratio of approximately 6. The variable teardrop-shape ramp did not prove satisfactory for throat-area modulation.

INTRODUCTION

For current turbojet aircraft, exhaust nozzles must maintain high thrust performance over a wide range of nozzle pressure ratios by taking advantage of the thrust gains available in expanding the jet to approximately ambient pressure. At design pressure ratio, the fixed-geometry convergent-divergent nozzle yields nearly the ideal maximum thrust; however, at lower pressure ratios, it suffers markedly in performance because of overexpansion losses, as described in reference 1. To avoid this penalty, a variable-geometry convergent-divergent configuration would be required. Mechanically it is quite difficult to achieve such variable geometry in an axisymmetric arrangement. In quiescent air, plug-type nozzles maintain high thrust levels over the full pressure-ratio range. With these nozzles, however, a cooling problem appears to exist in having the centerbodies submerged entirely in the hot gas stream. Also, with this type of nozzle serious losses can be incurred as a result of external-flow effects (ref. 1).

The present investigation proposes and demonstrates experimentally the quiescent-air performance of another type of exhaust nozzle, the penshape exit. This configuration, which appears to possess the same performance potential as the plug nozzle but without some of its disadvantages, is patterned after the asymmetric swept nose, or penshape, inlet of reference 2. The exit, as shown in the photographs of figure 1, has a skewed trailing edge with circular frontal projections. The concave expansion surface, determined by the method of characteristics for a design pressure ratio of 15, gives it somewhat of a sugar-scoop effect. Compared with the plug-type nozzle, the penshape exit appears to present smaller cooling problems, since its surfaces are all external to the jet and readily accessible for any cooling medium, and lesser performance penalties from external-flow effects, since the afterbody lip fairing occurs over only a small portion of the periphery rather than over the entire circumference.

In the present study, a penshape exit was evaluated in quiescent-air tests, covering a range of pressure ratios from approximately 4 to 16 (design value, 15). Performance is given in terms of the axial thrust coefficient, the ratio of the actual to the ideal jet thrust. The magnitude of normal forces was also ascertained. In addition, a scheme of throat-area modulation by means of a variable ramp moving out of the concave expansion surface was investigated.

SYMBOLS

The following symbols are used in this report:

C_F axial thrust coefficient, F/F_{id}

F actual jet thrust

F_{id} ideal jet thrust assuming isentropic expansion to ambient pressure, p_0

F_n normal force

P jet total pressure

p_0 ambient pressure

p_l local static pressure

M_l local Mach number

λ flow inclination at the throat

APPARATUS AND PROCEDURE

A schematic drawing of the test facility and model installation is presented in figure 1(a). The investigation was conducted in the Lewis 2- by 2-foot supersonic wind tunnel. The upstream valve was maintained in the closed position (no flow through the tunnel nozzle). In this way the tunnel exhausters pumped the test chamber down to low pressures by means of the downstream ejector system indicated in figure 1(a). Dry atmospheric air for the exit model was throttled to vary the overall nozzle pressure ratio. To measure axial and normal forces, a balance supported the exit model from the end of the sting. A sliding-ring seal minimized leakage but still left the model isolated from ground for force measurements. Flow-straightening screens were located just upstream of the inlet rakes.

Details of the penshape exit are given in the drawing of figure 1(b) and in the photographs of figure 1(c). The design nozzle pressure ratio P/p_0 was arbitrarily selected as 15.0. With the assumption of a circular jet, the nozzle contours were determined by tracing streamlines back through a known two-dimensional Prandtl-Meyer flow field. The resulting configuration with circular frontal projections has a concave expansion surface which develops from a point at the trailing edge back to an ellipse at the throat (section C-C). The trailing edge is swept back at the Mach angle corresponding to the design pressure ratio. The design technique employed herein is, of course, equally applicable to nozzles of other arbitrary shapes dictated by airplane fuselage considerations. A plaster-of-Paris fill indicated by the dotted section in figure 1(b) was used to refair the subsonic approach contour in order to study its effect upon the sonic-point location.

In an attempt to provide throat area modulation as would be required, for example, between afterburner "on" and "off" operation, a teardrop-shaped ramp was designed to move out of the concave expansion surface. The minimum area was maintained at section C-C and corresponded to the maximum width of the variable ramp. In the fully extended position (3/4 in. up from the flush position), the ramp reduced the throat area to 0.64 of its maximum value.

The following pressure instrumentation was used in this investigation (see fig. 1(a) for relative locations):

(1) Inlet momentum survey; 24 Pitot tubes on four radial rakes and four wall static-pressure orifices

(2) Base pressures inside seal chamber; four static-pressure orifices

(3) Balance chamber pressure; one static-pressure orifice inside the sting

(4) Static-pressure distributions; 32 static orifices located longitudinally along the centerline of the throat and expansion surfaces

(5) Total-pressure survey in throat; eleven Pitot tubes on a rake located along the theoretical, straight sonic line

For visual flow observation, separate runs were made wherein Cardox (carbon dioxide) was injected approximately 10 feet upstream of the throttle valve to give some opaqueness to the exiting jet. This technique permitted photographing the flow in order to obtain some qualitative definition of jet boundaries.

To check out the entire test rig, experiments were made with a 20°-included-angle convergent nozzle having approximately the same throat area as the penshape exit. Mass-flow and thrust coefficients checked closely with previously published data obtained in other larger test facilities.

RESULTS AND DISCUSSION

In general, the flush-ramp, or design, configuration of the penshape exit had an over-all thrust performance in quiescent air which was comparable to that previously reported for plug-type nozzles. In the following sections, data will be presented detailing the various aspects of performance, including pressure distributions, thrust levels, normal force variation, and visual flow observations.

Pressure and Mach Number Distributions

Static-pressure distributions for the flush-ramp, or design, configuration of the penshape exit are presented in figure 2 for nozzle pressure ratios P/p_0 equal to or greater than the design value. As evidenced by the pressures, the actual sonic line was considerably distorted from the assumed theoretical, straight sonic line. Because of the rather sharp rate of turning along the expansion surface centerline near the throat, the experimental sonic-point location ($p_l/P = 0.528$) occurred approximately 2 inches upstream of the theoretical sonic point. From this theoretical location, the flow accelerated supersonically along the ramp to a local Mach number of 1.75 at the theoretical sonic station (-1.0 in.) shown by the corresponding decrease of the static- to total-pressure ratio to 0.188. Beyond this station, the flow was recompressed through a shock system with the local static pressures increasing to nearly the theoretical value and then approximating the theoretical expansion curve out to the tip. Although no data are presented, the local static pressures along the expansion surface at less than design nozzle pressure ratio never fell below the value of ambient pressure. This is contrary to the case for the overexpanded convergent-divergent nozzle.

An attempt was made to improve the throat flow and make it conform more to the theoretical sonic condition assumed in the design by refairing the subsonic approach section. This modification was accomplished by a plaster-of-Paris fill shown by the dotted portion of figure 1(b). Although no data are shown, the pressure distributions in the vicinity of the throat were not affected. Actually this fairing did not alter the turning radius of the flow immediately near the throat, which, no doubt, explains the lack of a significant change in the pressure distribution. This modification was left in for subsequent force and visual flow studies.

Mach number distribution across the geometric throat line is presented in figure 3 and is based on Pitot-rake measurements. Mach numbers were calculated using the relations for total-pressure ratio across a normal shock. The accuracy of this method decreases as the local Mach number approaches unity. Thus, the experimental curve was rather arbitrarily faired to a local Mach number of 1.00 at the lip. Towards the expansion surface, the Mach number increased monotonically to 1.75, the value determined from the static-pressure distribution of figure 2. This large Mach number variation is in contrast to the assumed straight sonic line used in the design of this configuration.

Axial Thrust Performance

The performance of the penshape exit was evaluated in terms of a thrust coefficient, defined as the ratio of actual to ideal jet thrust. The actual jet thrust was obtained by subtracting the measured axial force from the inlet total momentum, and the ideal jet thrust was calculated by assuming isentropic expansion to ambient pressure. For the flush- and two extended-ramp positions, the variation of thrust coefficient with nozzle pressure ratio is shown in figure 4. Thrust coefficient for the flush-ramp configuration was generally insensitive to nozzle pressure ratio, remaining fairly constant at 0.965 as the nozzle pressure ratio P/p_0 decreased from above the design value down to about 7, and then falling off to 0.94 at a nozzle pressure ratio P/p_0 of approximately 4. Apparently from this relatively high thrust coefficient at the design pressure ratio the loss in thrust on the expansion surface evidenced by the low pressures in the vicinity of the throat (fig. 2) was for the most part recovered in the form of increased throat flow momentum. This observation was verified by calculations based on the measured pressures and by comparisons between the actual and ideal flow conditions.

The particular method of throat-area modulation investigated herein employed a contoured ramp to move out of the expansion surface and restrict the flow at the throat. The results with this technique were generally unsatisfactory. With the ramp fully extended to restrict the throat area to 64 percent of the full-open value, the thrust coefficient remained less than that for a simple convergent nozzle for all pressure ratios of less than about 14. At the intermediate or half-way position (82 percent of the full-open area), the thrust coefficient was a maximum of 0.94 and fell off rapidly with decreasing pressure ratio. This poor performance was no doubt caused by the blunt surfaces of the ramp, which extended into the region of high supersonic velocities along the surface near the throat, as well as by the cosine λ effect. These high throat velocities persisted as the nozzle pressure was reduced.

Better area modulation might have been accomplished by making the lip surface adjustable. This observation is somewhat supported by results from previously published plug-nozzle studies, (ref. 3) which seemed to indicate a greater freedom to change the lip geometry without greatly penalizing performance.

A comparison was made to show the relative performance of the penshape exit and several other types of exhaust nozzle. Only the design flush-ramp configuration of the penshpe exit was considered. Results are shown in figure 5. The penshape exit is comparable in performance to the plug-type nozzles, generally insensitive to changes in nozzle pressure ratio, and has thrust coefficients intermediate between those of the isentropic and conical plugs of reference 3. Thrust coefficients for the convergent and convergent-divergent nozzles of references 3 and 4, respectively, are also included for relative comparisons.

Normal Force Variation

In figure 6, the ratio of normal force to axial jet thrust is presented as a function of nozzle pressure ratio. At a pressure ratio of about 6, a maximum normal force equal to 8 percent of jet thrust was realized. This normal force is positive above design pressure ratio, zero at about design, negative down to a design pressure ratio of approximately 8, and then positive again. For an airplane application this normal force variation would, of course, have to be taken into consideration. If it were not utilized in the trim characteristics of the aircraft, this normal force could be neutralized through the use of twin back-to-back or opposed installations.

Visual Flow Study

By injecting Cardox (carbon dioxide) into the airstream before it passed through the penshape exit, the jet became sufficiently opaque and the jet boundaries could be readily defined. Photographs of the resulting patterns are shown in figure 7 for nozzle pressure ratios below, at, and above the design value. At below design pressure ratio, the flow followed the expansion surface contour all the way to the tip. This observation of the flow adhering to the surface was typical for the entire range of pressure ratios and indicates the lack of boundary-layer separation. On design, a circular jet flows out full in the axial direction. Above design, the flow continued to expand outside the confines of the nozzle and exhibited a downward velocity component to the flow (i.e., away from the expansion ramp).

CONCLUDING REMARKS

The penshape exit based on the results of this quiescent-air study appears to offer some promise as a practical exhaust nozzle for supersonic aircraft. This configuration should also be adaptable to several variable-geometry techniques. For example, a single clamshell flap working off the lip surface might be better for achieving throat-area modulation than the type of movable ramp investigated herein, or a variable flap at the tip might be used for jet deflection in order to create a normal force for aircraft control or merely to trim out an existing normal force. Several schemes, such as these or variations thereof, appear feasible.

Further investigation is required for full evaluation of the penshape exit. External-flow studies are needed to determine boattail drags and external stream effects upon thrust coefficient. In addition, an improved method of modulating the throat area must be demonstrated.

SUMMARY OF RESULTS

A quiescent-air study of an asymmetric penshape exit, having circular projections and designed for a pressure ratio of 15, gave the following results:

1. The penshape exit gave a maximum thrust coefficient of 0.965 and was generally insensitive to changes in nozzle pressure ratio. This configuration for the full-throat or flush-ramp position was comparable in performance to plug-type nozzles.

2. A normal force variation was encountered with a maximum equal to 8 percent of jet thrust at a pressure ratio of approximately 6. In an

aircraft application, this force would probably have to be trimmed out or counteracted by twin back-to-back or opposed installations.

3. A variable teardrop-shape ramp moving out of the contoured expansion surface did not prove satisfactory as a means of throat-area modulation.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 9, 1956

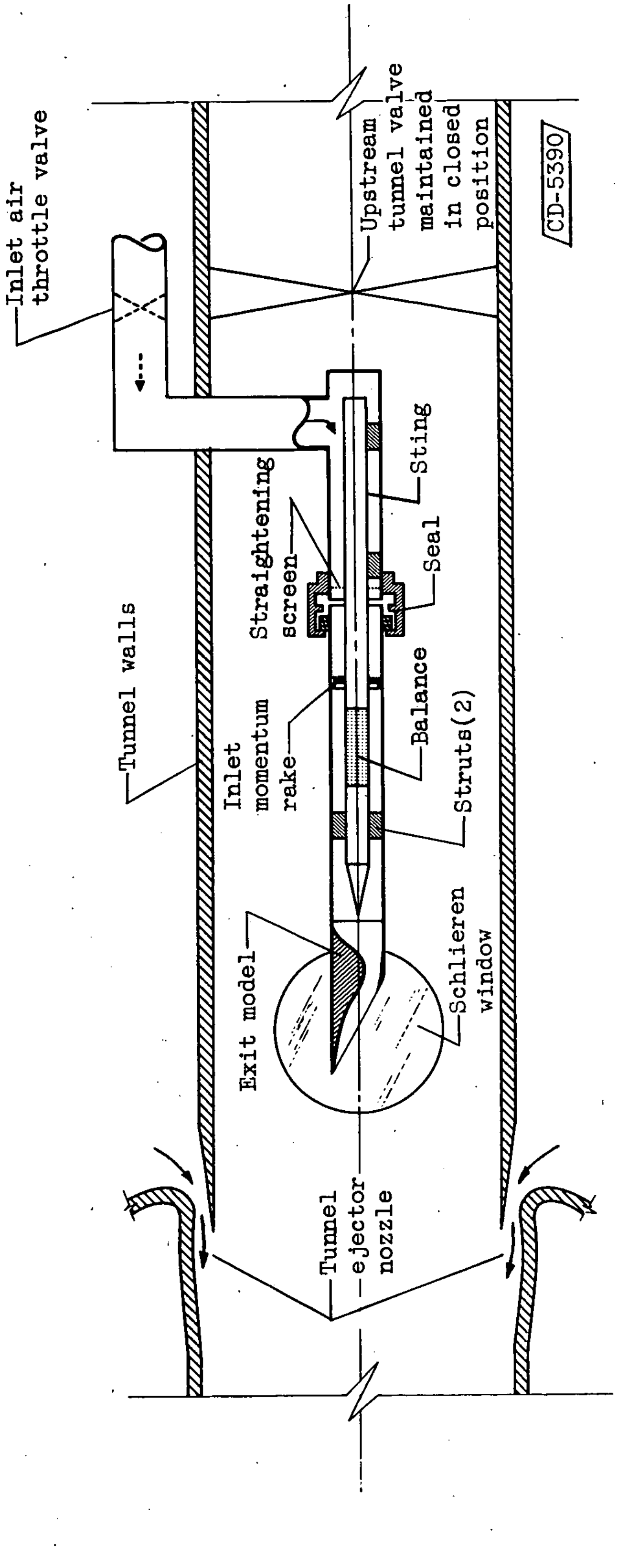
REFERENCES

1. Cortright, Edgar M., Jr.: Some Aerodynamic Considerations of Nozzle-Afterbody Combinations. Preprint No. 614, Inst. Aero. Sci., 1956.

2. Connors, James F., and Woollett, Richard R.: Preliminary Investigation of an Asymmetric Swept Nose Inlet of Circular Projection at Mach Number 3.85. NACA RM E54G26, 1954.

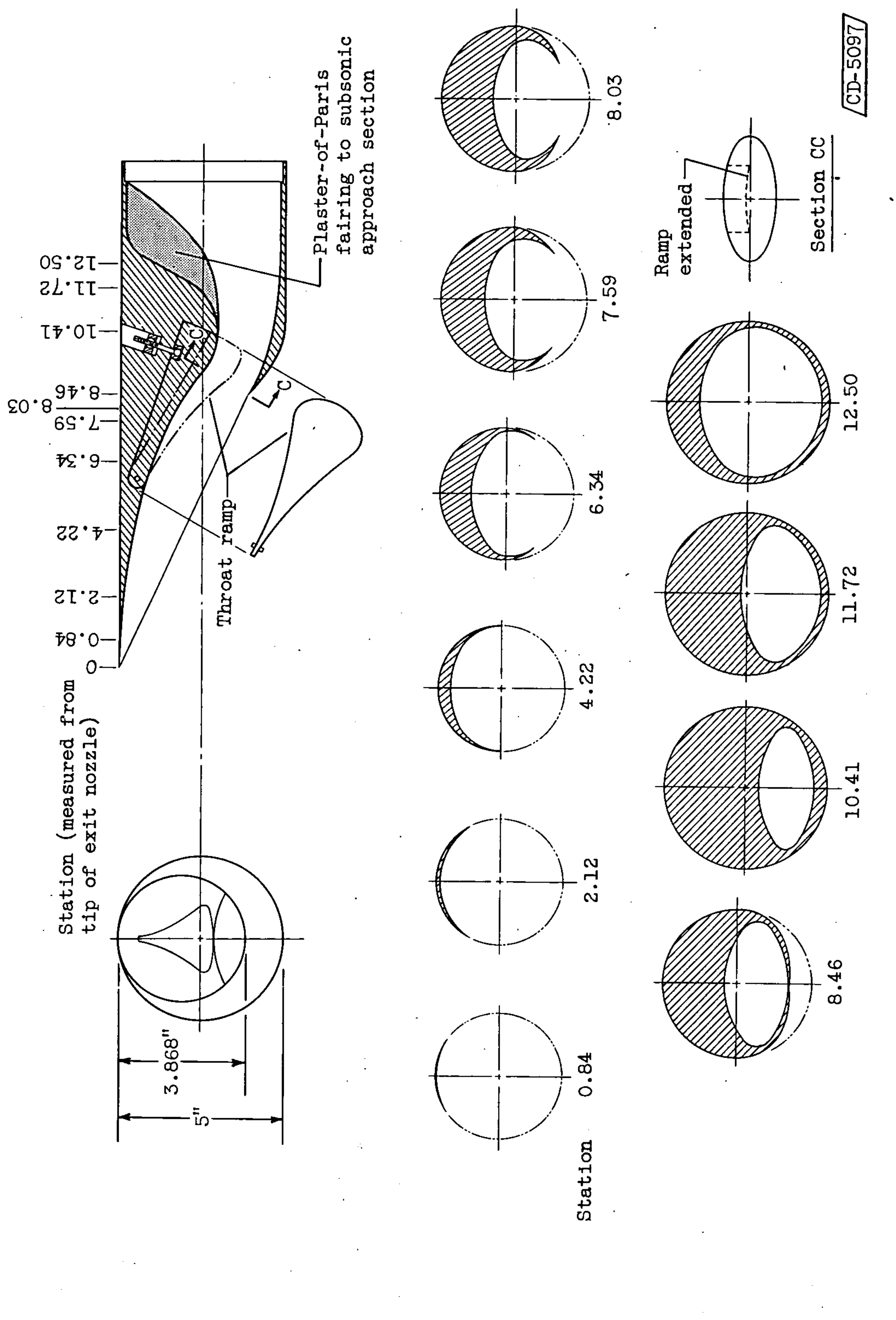
3. Krull, H. George, and Beale, William T.: Effect of Plug Design on Performance Characteristics of Convergent-Plug Exhaust Nozzles. NACA RM E54H05, 1954.

4. Greathouse, William K., and Beale, William T.: Performance Characteristics of Several Divergent-Shroud Aircraft Ejectors. NACA RM E55G21a, 1955.



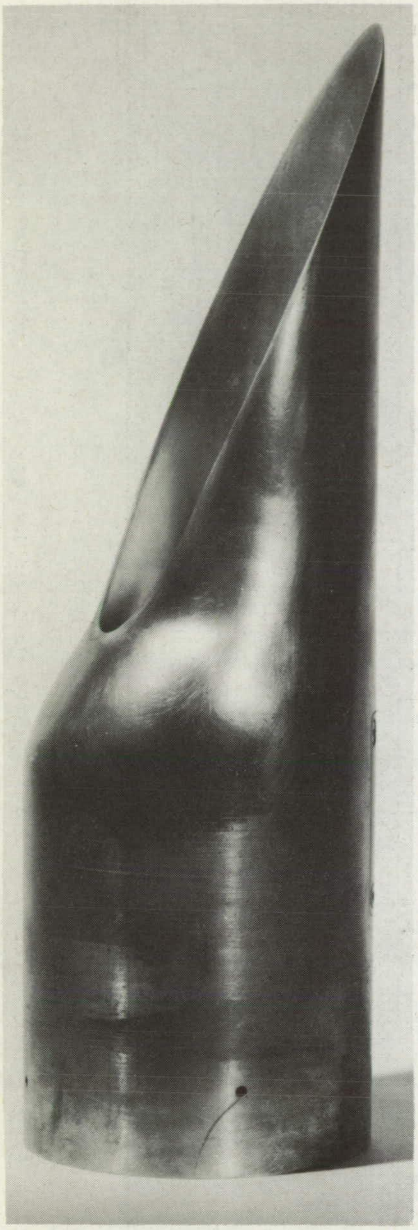
(a) Schematic drawing of tunnel installation.

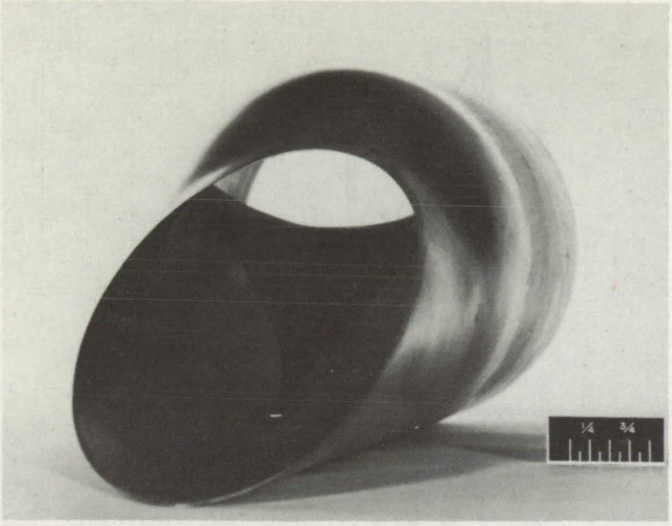
Figure 1. - Experimental apparatus.



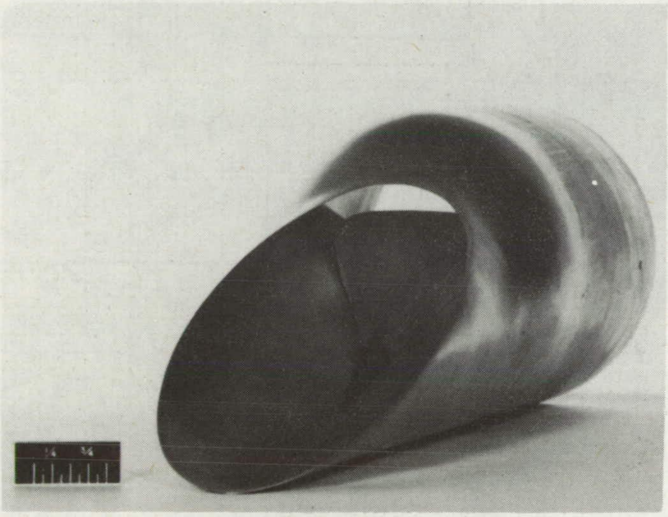
(b) Details of penshape exit.

Figure 1. - Continued. Experimental apparatus.





Flush ramp



Extended ramp C-43307

(c) Penshape exit.

Figure 1. - Concluded. Experimental apparatus.

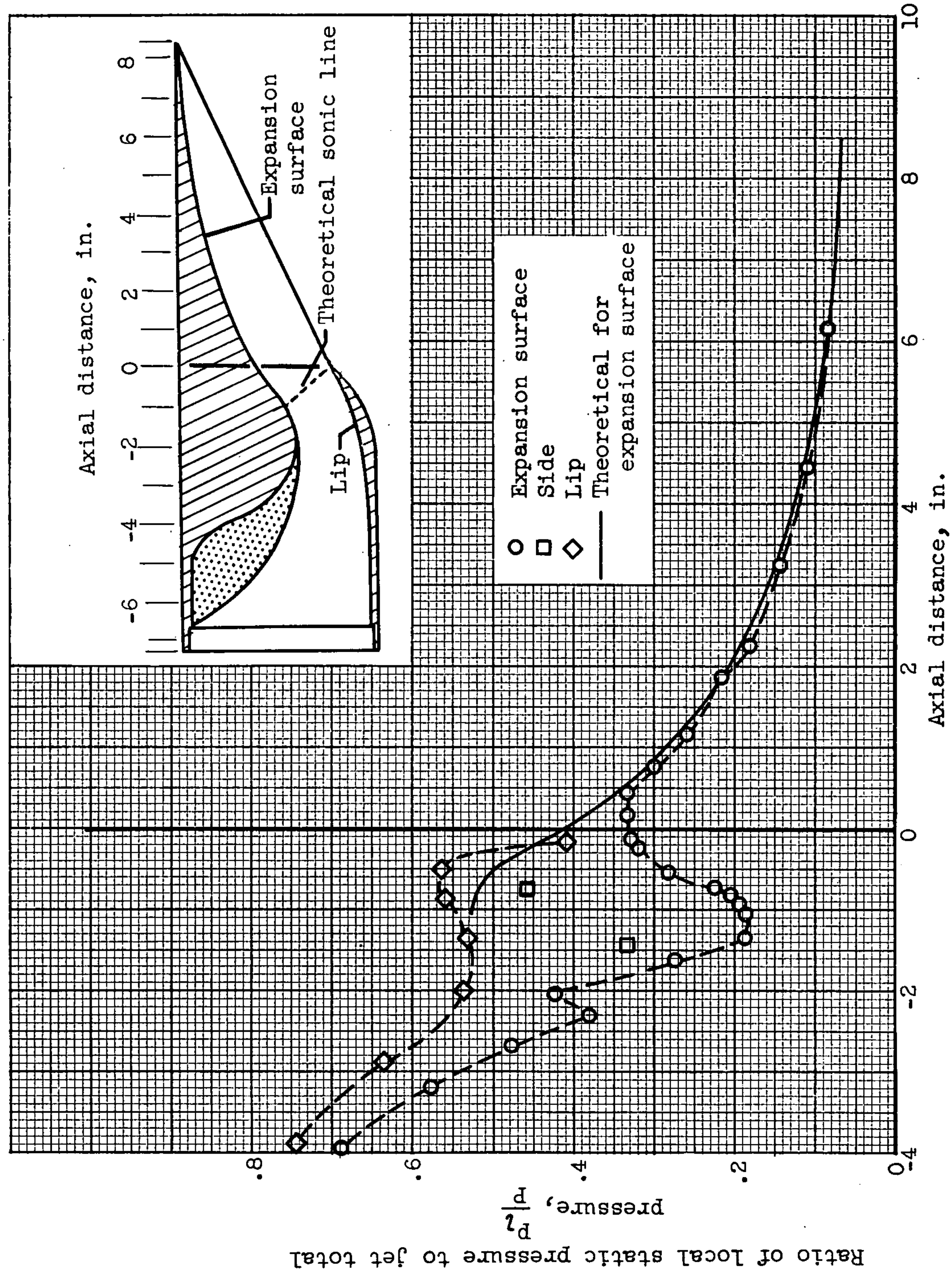


Figure 2. - Static-pressure distribution for penshape exit (flush-ramp position); jet pressure ratio greater than design value.

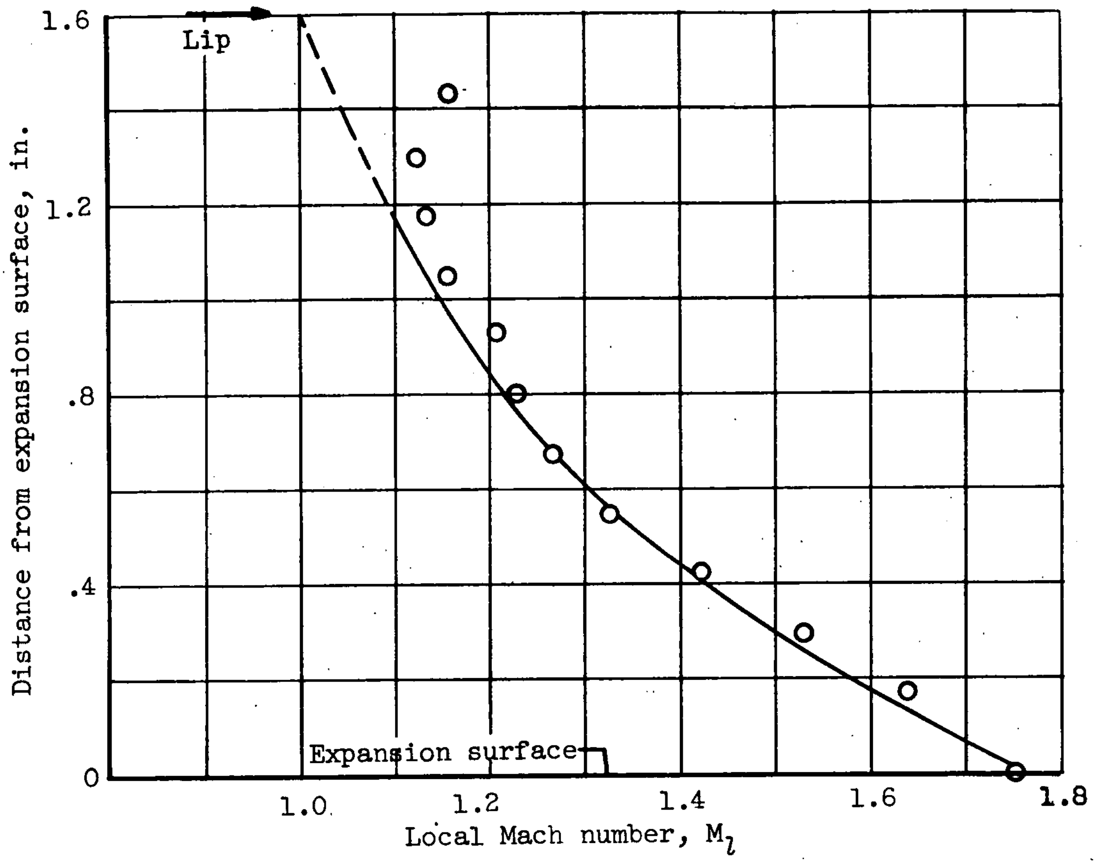


Figure 3. - Mach number distribution across geometric throat line.

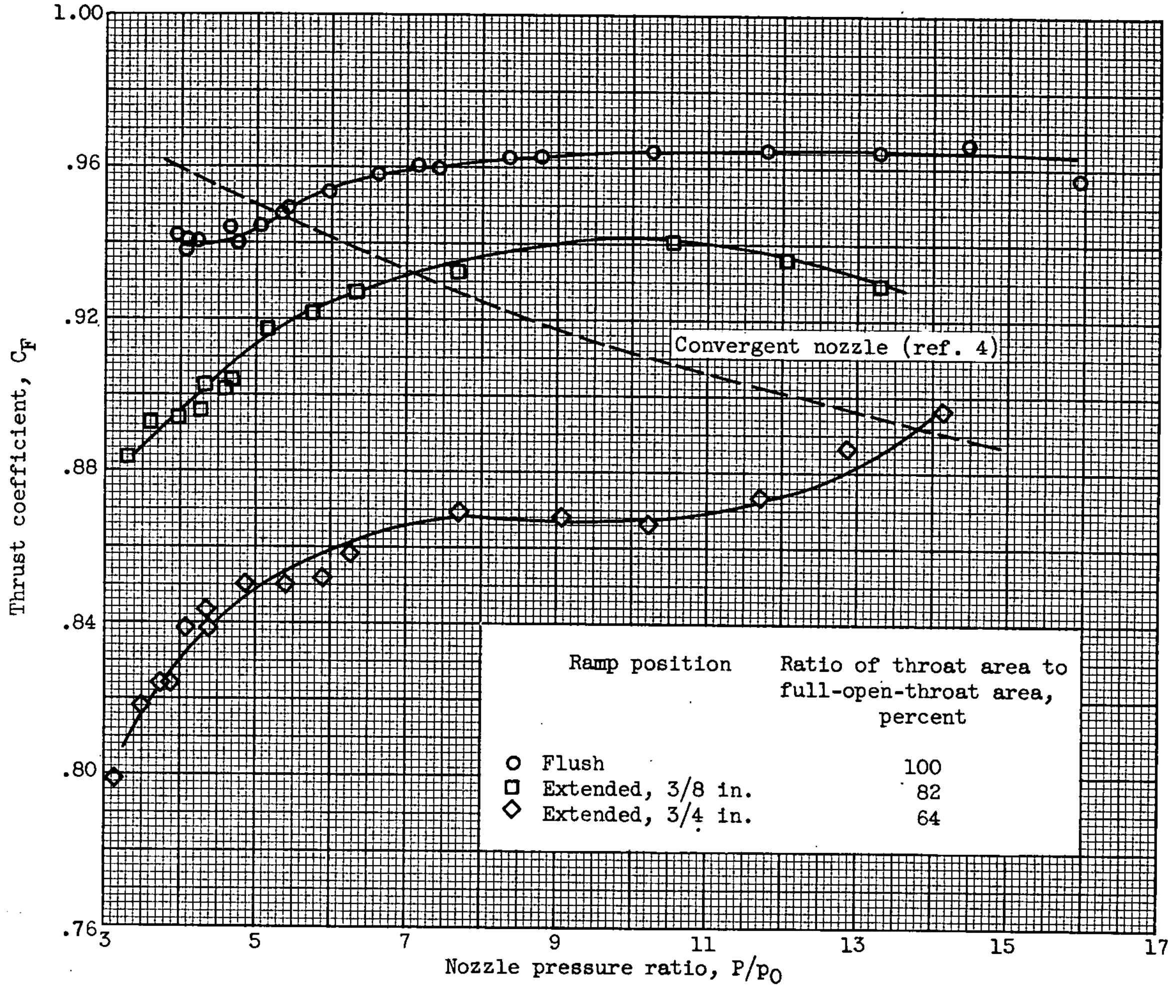


Figure 4. - Thrust performance of penshape exit.

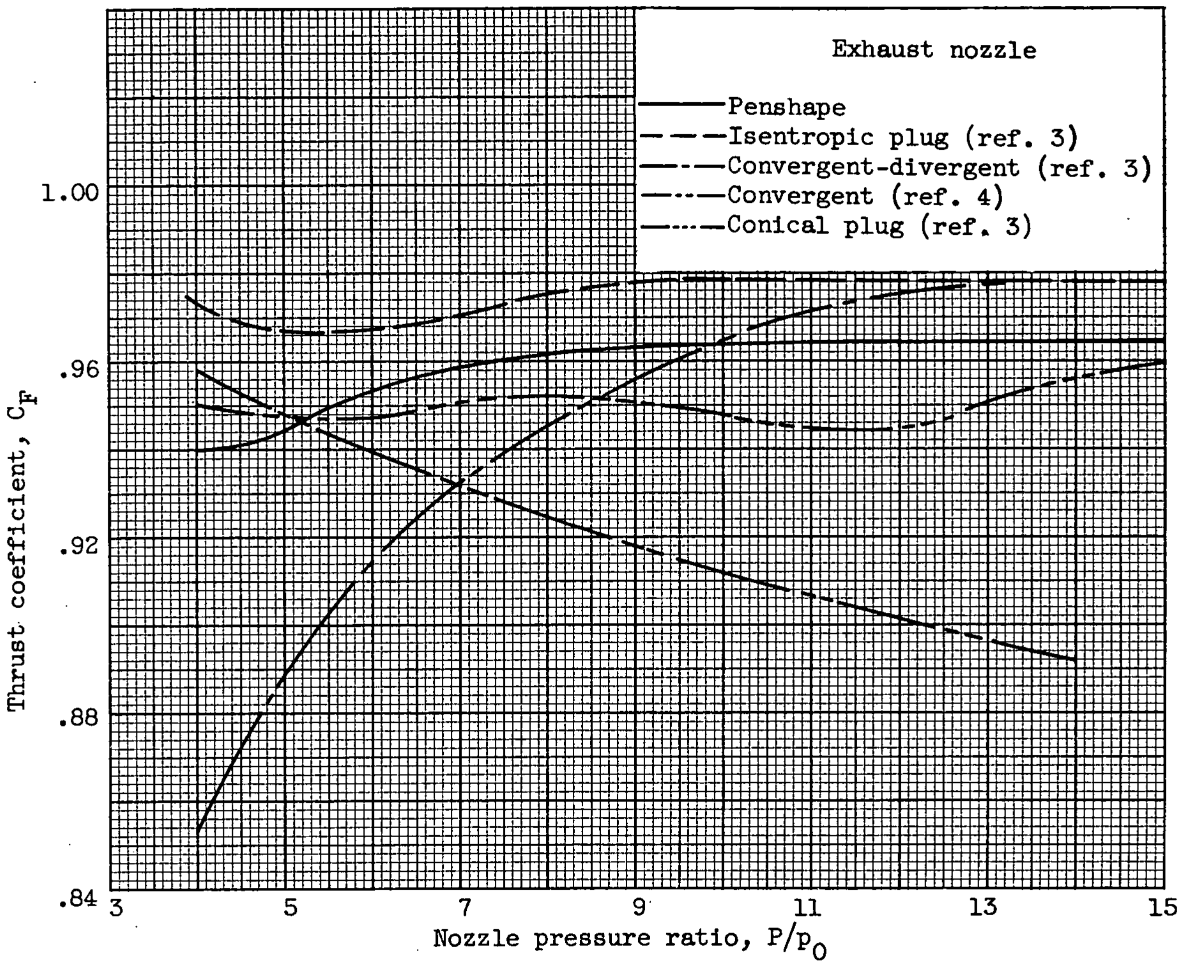


Figure 5. - Performance comparison of the penshape exit with other types of exhaust nozzle.

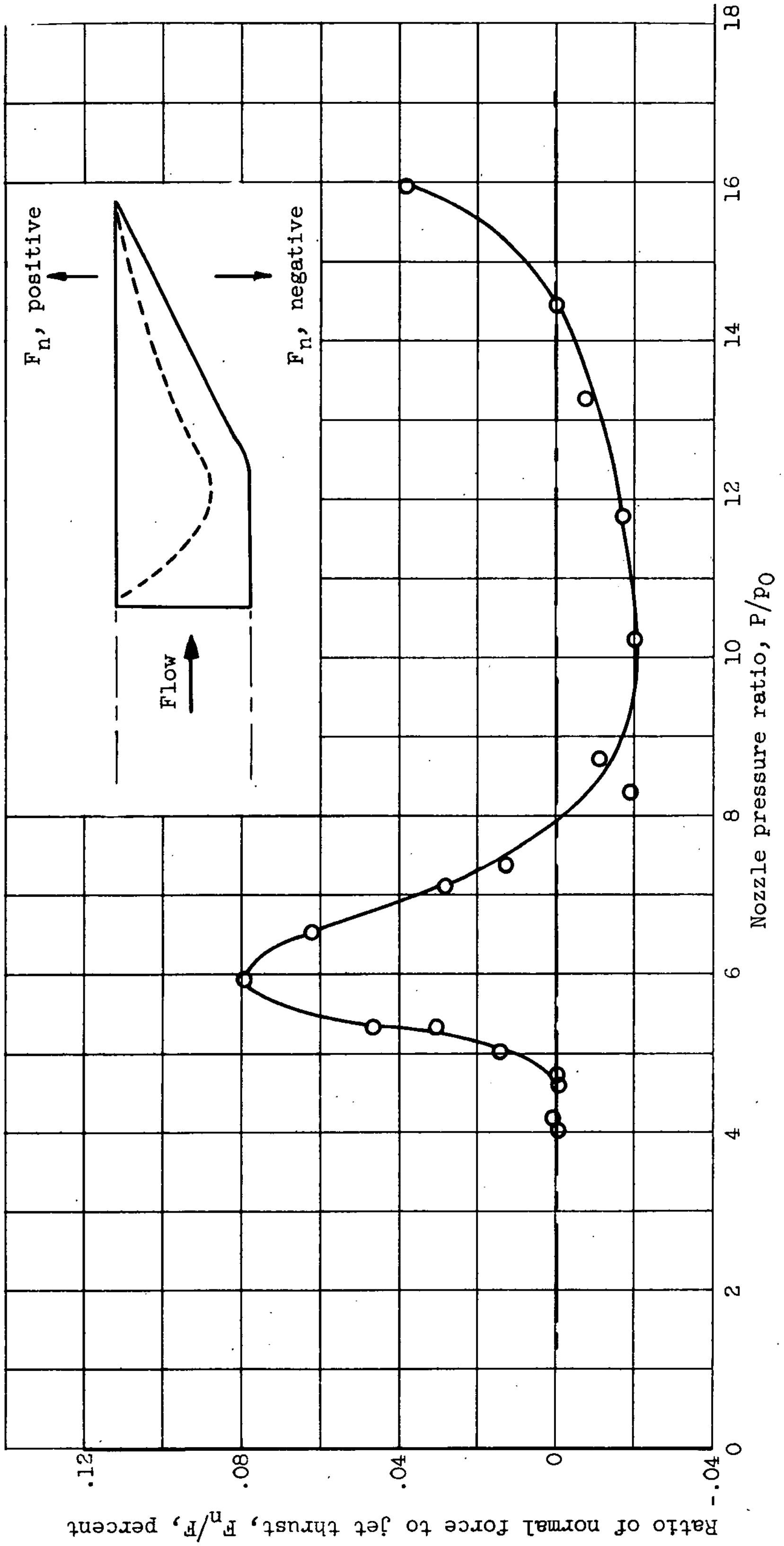
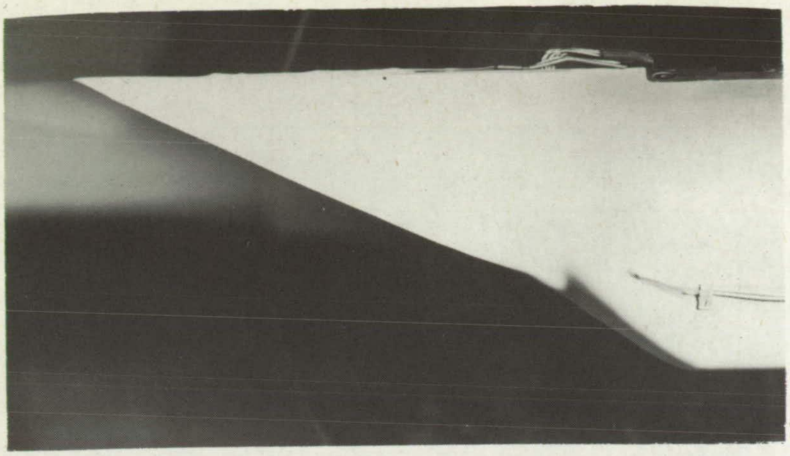
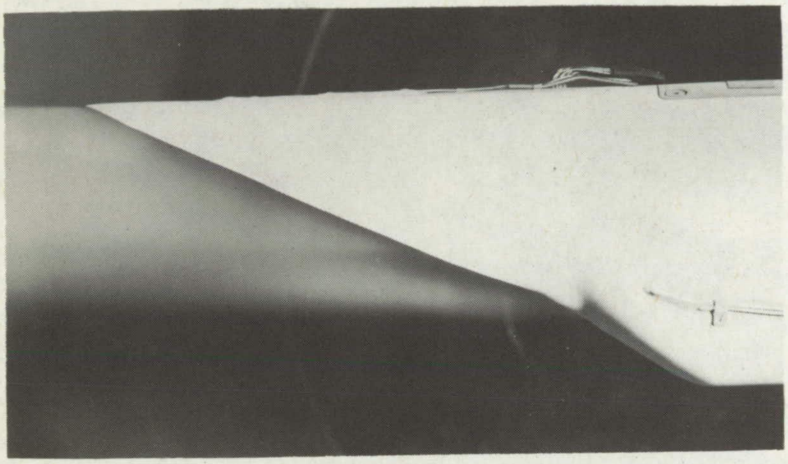


Figure 6. - Variation of normal force with nozzle pressure ratio for penshape exit (flush-ramp position).



(a) Below design pressure ratio.



(b) Approximately design pressure ratio.

C-43308

(c) Above design pressure ratio.

Figure 7. - Visual flow study of jet from penshape exit discharging into quiescent air; design pressure ratio, 15.

NACA - Langley Field, Va.