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RESEARCH MEMORANDUM

EFFECTS OF EXTERNAL STREAM FLOW AND AFTERBODY VARIATIONS ON THE PERFORMANCE OF A PLUG NOZZLE AT HIGH SUBSONIC SPEEDS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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EFFECTS OF EXTERNAL STREAM FLOW AND AFTERBODY VARIATIONS ON THE PERFORMANCE OF A PLUG NOZZLE AT HIGH SUBSONIC SPEEDS

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SUMMARY

The effects of external stream flow and changes in afterbody geometry on the thrust of a small-scale plug-type nozzle were investigated at subsonic speeds up to a free-stream Mach number of 0.9. The nozzle, which was designed for all-external isentropic expansion at a jet pressure ratio of 15, was operated at jet pressure ratios up to 5.

Nozzle thrusts in the presence of external flow are compared with thrusts obtained in quiescent air at equal pressure ratios. With the nozzle installed in a cylindrical afterbody, the jet interaction with the external stream induced low base pressures on the annular nozzle lip. In addition to causing high drag, these reduced pressures caused the jet flow to overexpand on the plug surface with an equally large reduction in jet thrust. With the nozzle installed behind two different boattail configurations, the base pressures were increased and the jet overexpansion significantly reduced. The corresponding boattail drags were not evaluated, however.

The results of this investigation emphasize the fact that quiescent air tests of plug nozzles are not sufficient to establish their off-design performance. Rather the nozzle-afterbody combination must be considered as a unit, and the complex effects of jet interaction with the external stream must be accounted for.

INTRODUCTION

Current supersonic aircraft cruise at high subsonic speeds during most of their flight time. Accordingly, several investigations have been directed towards developing jet exit nozzles, which are efficient over the entire speed range. One nozzle type that has shown promise in quiescent air tests is the plug nozzle (refs. 1 to 3). Without variation in geometry, this nozzle exhibits high thrust coefficients over a wide range of jet pressure ratios.

The all-external-expansion plug nozzles are characterized by relatively high lip angles. Experience with other nozzle types at high subsonic speeds indicates that low base pressures might develop on those surfaces (refs. 4 and 5). This not only would cause a drag force, but also an overexpansion of the jet flow on the plug surface downstream of the nozzle throat. Accordingly, the NACA Lewis laboratory has undertaken several experimental investigations to determine the magnitude of stream effects on plug-nozzle performance for various afterbody shapes. This report presents the results of a preliminary small-scale study to define the nature and seriousness of the problem. 5001

The plug nozzle of the present investigation was designed to provide all-external isentropic expansion at a pressure ratio of 15 and was tested over a range of pressure ratios up to 5 in quiescent air and at subsonic Mach numbers up to 0.9. The effects of external flow on the plug thrust and base drag were determined with the nozzle installed in three afterbody configurations. The nozzle geometry was not varied from the design condition.

SYMBOLS

A area

C_p pressure coefficient, $(p - p_0)/q_0$

D drag

F propulsive force

F_w force due to tunnel interference

l longitudinal distance from tip to point of maximum plug diameter

M Mach number

m mass flow

P total pressure

p static pressure

q dynamic pressure

r plug radius

T thrust

V velocity

x longitudinal distance from tip of plug

θ angle between plug axis and plane of differential control surface area dA

ρ density

Subscripts:

b base

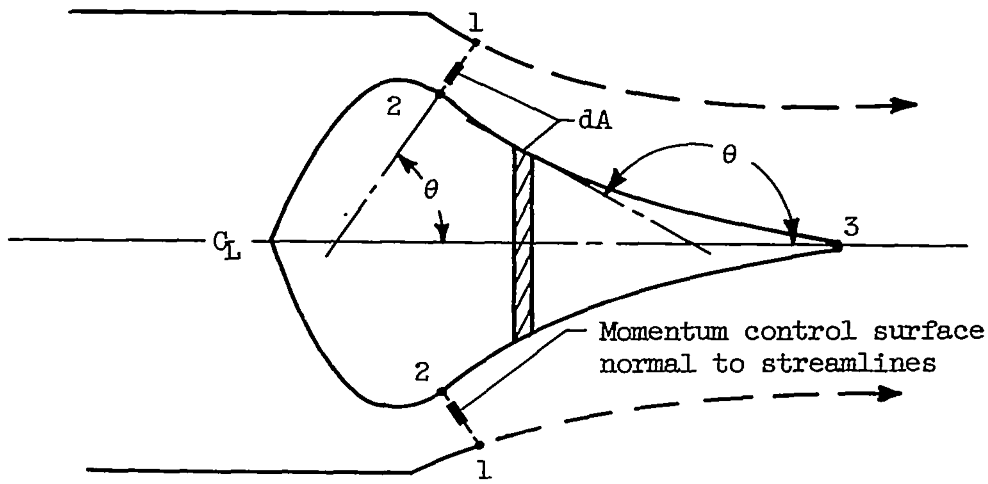
i ideal

j jet

n net

0 free stream

Thrust Definitions:



Jet thrust:

$$T_j = \int_1^2 (p - p_0)\sin\theta\, dA + \int_1^2 \rho V^2 \sin\theta\, dA +$$

$$\int_2^3 (p - p_0)\sin\theta\, dA$$

Net thrust:

$$T_n = T_j - V_0 \int_1^2 \rho V \, dA = T_j - m_j V_0$$

Ideal jet thrust:

$$T_{j,i} = m_j V_i$$

where V_i is the jet velocity with the jet expanded isentropically to p_0 5001

Ideal net thrust:

$$T_{n,i} = T_{j,i} - m_j V_0 = m_j (V_i - V_0)$$

APPARATUS AND PROCEDURE

The plug nozzle was designed by the method of characteristics for ideal isentropic expansion at a jet pressure ratio of 15. As shown in figure 1(a), the nozzle was installed in a basic nacelle configuration, which consisted of a cylindrical afterbody ahead of the nozzle lip. The lip angle of 37.1° corresponded to the turning angle required for axial discharge of the jet at a pressure ratio of 15. The boattail configurations (figs. 1(b) and (c)) were obtained by fitting contoured sleeves over the basic nacelle. Instrumentation consisted of nine static-pressure orifices on the plug and one orifice on the base side of the lip. Boattail pressures on the sleeves were not measured.

The models were installed in the subsonic tunnel by extending the model through the bellmouth as shown in figure 2. Atmospheric air was drawn through the tunnel by an exhauster system. The pressure data were recorded photographically from multitube manometer boards. The tests were conducted at nominal Mach numbers of 0.6, 0.8, and 0.9. In addition to the jet-off condition, the nozzle was operated at jet pressure ratios of 2, 3, 4, and 5.

The wind-tunnel-wall corrections F_w were derived from the change in total momentum of the tunnel air in diffusing over a solid surface from the cross-sectional-flow area upstream of the base to the area occupied by the free-stream flow at the plug tip. The corrections were applied only to the integrated forces and not to individual pressure measurements. The general method of these corrections is discussed in greater detail in reference 4.

DISCUSSION OF RESULTS

Qualitative Description

A plug nozzle generally should not be expected to perform with external flow as it would in quiescent air at the same pressure ratio. This is illustrated in figure 3 where the method of characteristics has been applied to a two-dimensional plug nozzle. The nozzle was designed to provide all-external isentropic expansion of the jet at a pressure ratio P_j/p_0 of 15. A straight sonic line across the minimum throat area was assumed, although centrifugal forces would actually result in a curved sonic line. Both the design pressure ratio and the ratio of base projected area to total projected area were chosen equal to those of the axisymmetric nozzle tested in this experiment. The same calculations could have been made for the case of axial symmetry but at considerably greater effort.

Plug pressure distributions were calculated for both the design pressure ratio of 15 and a pressure ratio of 5. In quiescent air at a P_j/p_0 of 5 the jet is seen to expand only to ambient pressure p_0, following which it is compressed by the continued turning of the plug surface. For the case with external flow the nozzle was assumed installed in a semi-infinite body having parallel surfaces forward of the nozzle lip. The approximate method of reference 6 was used to estimate the base pressure on the lip, which was found to be sufficiently below ambient static pressure so that with $P_j/p_0 = 5$, P_j/p_b actually exceeded the design value of the nozzle. The flow thus overexpanded beyond ambient static pressure on the plug surface until the trailing shock impinged on the surface.

Plug and Base Pressure Measurements

When jet pressure ratios are sufficiently high to choke the nozzle throat, differences between performances in a stream and in quiescent air manifest themselves as differences in plug surface pressures downstream of the throat and as differences in base pressure. These pressures are presented in figures 4 and 5 for the three nozzle installations studied.

The plug pressures obtained with the nozzle installed in the cylindrical body are shown in figure 4(a). Also shown for qualitative reference is the theoretical three-dimensional pressure distribution. Supersonic flow on the plug surface upstream of the geometric throat was indicated. This probably resulted from the effect of flow curvature, which should move the sonic point upstream on the plug. Downstream of the geometric throat the flow behaved in a manner qualitatively similar to that described by the two-dimensional calculation previously mentioned. In quiescent air the jet expanded to ambient static pressure, was recompressed to near sonic velocity, and then varied somewhat erratically. With external flow the jet expanded to the lower base pressure value before recompressing.

Plug pressure data with the nozzle installed behind the 8° conical boattail and the circular arc boattail are presented in figures 4(b) and (c), respectively. In these installations the pressures on the base with external flow were considerably higher than those for the cylindrical body, and the plug pressures indicated little overexpansion of 5001
the jet. This reduction of stream effect was partly due to favorable wall interference, as will be seen from subsequent integrated pressure data where the interference is accounted for.

The base pressure coefficients measured are presented in figure 5. The marked effect of the boattail in increasing the base pressure is evident, although wall interference effects account for some of the increase.

Jet Thrust and Drag Variations

The reduced plug pressures with external flow constitute a reduction in plug thrust. Jet thrust loss $\Delta T_j/T_{j,i}$ is defined herein as the difference between jet thrust in quiescent air and with external flow divided by the jet thrust of an ideal nozzle.

The effect of free-stream Mach number on jet thrust loss is shown in figure 6 for the case of the nozzle installed in the cylindrical body. Thrust losses increased with increasing Mach number and decreasing jet pressure ratio. Since the thrust loss should be zero at a jet pressure ratio of 15, the reversal in the curves at a jet pressure ratio of about 4 was unexpected. This reversal may be within the experimental accuracy of the tests. Since the variation of jet pressure ratio with flight Mach number is not arbitrary, the operating line for a hypothetical advanced engine is shown. The external flow reduced the plug thrust approximately 4 percent of the ideal jet thrust at a Mach number of 0.9.

The ideal plug nozzle designed for all-external expansion requires a relatively high lip angle to direct the flow inward. An evaluation of the propulsive force of the nozzle installation must consider the possible drag of this lip surface. Figure 7 presents the reduction in propulsive force of the plug nozzle in the cylindrical body and in the boattailed configurations at a free-stream Mach number of 0.9. For the case of the cylindrical body the base drag nearly equalled the loss of thrust on the plug surface. Behind the boattailed bodies (fig. 7) the loss in propulsive force was considerably reduced as was indicated previously by the pressure distribution data. The wall interference effects were appreciable for the larger boattailed bodies. However, despite the approximate nature of these corrections, the indicated effect of boattailing should be generally correct.

A final evaluation of the plug nozzle installed behind a boattail at subsonic speeds must include the boattail forces, which were not measured herein. This is necessary since nozzles producing the same jet thrust when installed in a given afterbody may induce different boattail drags, and it is the thrust-minus-drag of the nozzle-afterbody combination that is of ultimate importance.

Net Propulsive Force

A general summary of stream effects on the plug-nozzle performance in a cylindrical body is presented in figure 8 where net propulsive force is plotted as a function of free-stream Mach number. Net force, wherein inlet momentum is accounted for, represents most clearly the importance of the stream effects. Since only propulsive force losses due to stream effects were measured in this investigation, net force was established by subtracting the losses from the ideal net thrust. Actual net forces would be lower still by the amount that quiescent air thrust falls below ideal.

The experimental data obtained at subsonic speeds are presented in figure 8 in addition to the calculated thrust of the equivalent two-dimensional plug nozzle at supersonic speeds. Base pressures were estimated for the two-dimensional case by the approximate method presented in reference 6. In the calculation of the net-propulsive-force ratios, jet total temperatures of 3500° and 2200° R were assumed for the supersonic and subsonic cases, respectively, and a free-stream altitude of 35,000 feet was used. The assumed jet pressure curve (fig. 8), which represents a hypothetical advanced engine, was used in the calculation.

It is indicated that the maximum deviations from quiescent-air performance should be expected at sonic or low supersonic flight for the nozzle studied. The measured reduction in the net propulsive force of 12 percent at a free-stream Mach number of 0.9 for this particular nozzle installation would generally be considered intolerable for cruising flight. The need for additional research to improve in-flight off-design performance of plug nozzles is thus indicated.

SUMMARY OF RESULTS

The following results were obtained from a small-scale investigation of the effects of external flow and afterbody variations on the performance of a plug nozzle at high subsonic speeds:

1. With the nozzle installed in a cylindrical body with a sharp turn at the nozzle lip, low base pressures occurred on the lip. In addition to causing high drag, these low pressures induced the jet to overexpand on the plug surface with equally large thrust losses. Values 5001 of net thrust-minus-drag as much as 12 percent below quiescent air values were measured at a free-stream Mach number of 0.9.

2. With the nozzle installed behind two boattail configurations the nozzle base pressures were considerably increased and the nozzle thrust losses correspondingly reduced. These gains were obtained, however, at the expense of increased frontal area and boattail drag, the effects of which were not determined in the present investigation.

National Advisory Committee for Aeronautics
Lewis Flight Propulsion Laboratory
Cleveland, Ohio, June 18, 1956

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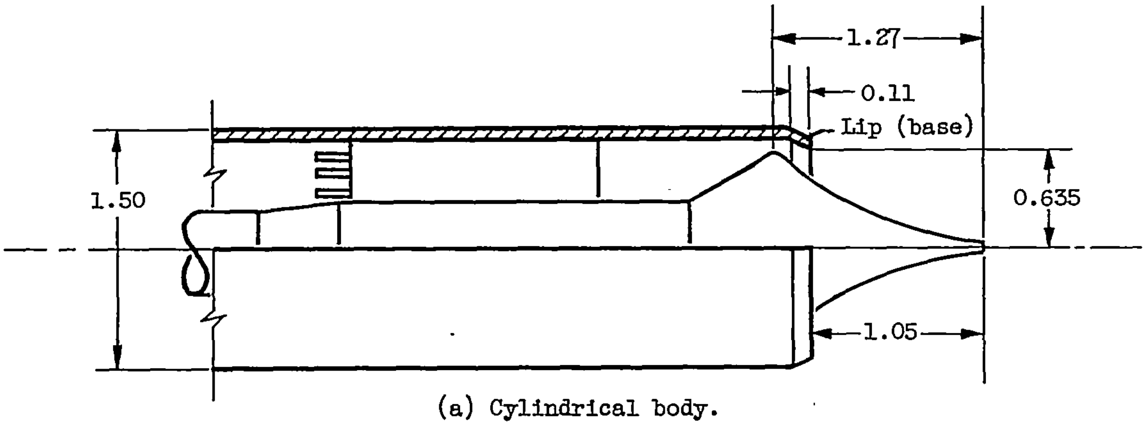

(a) Cylindrical body.

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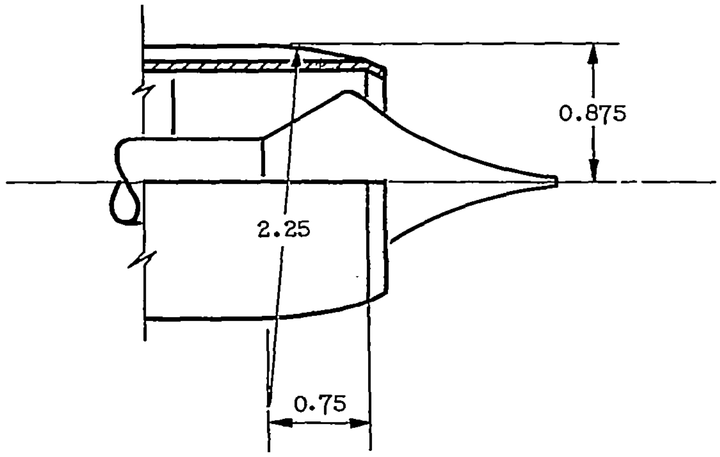
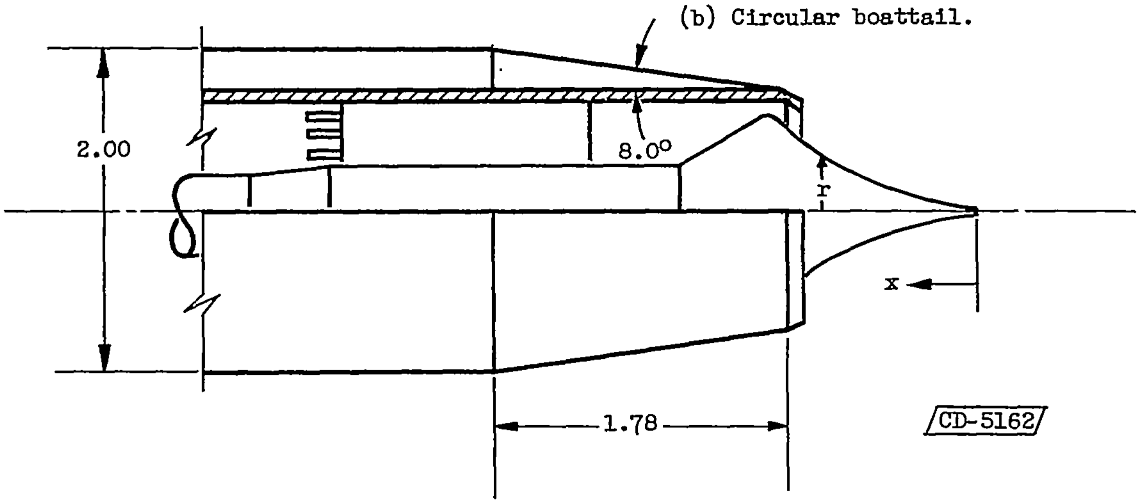
Plug coordinates			
x	r	x	r
0	0.023	1.20	0.556
.2	.059	1.25	.570
.4	.105	1.27	.573
.6	.172	1.30	.569
.75	.235	1.35	.551
.90	.319	1.55	.436
1.05	.425	1.80	.290
1.15	.517		



(b) Circular boattail.



(c) Conical boattail.

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

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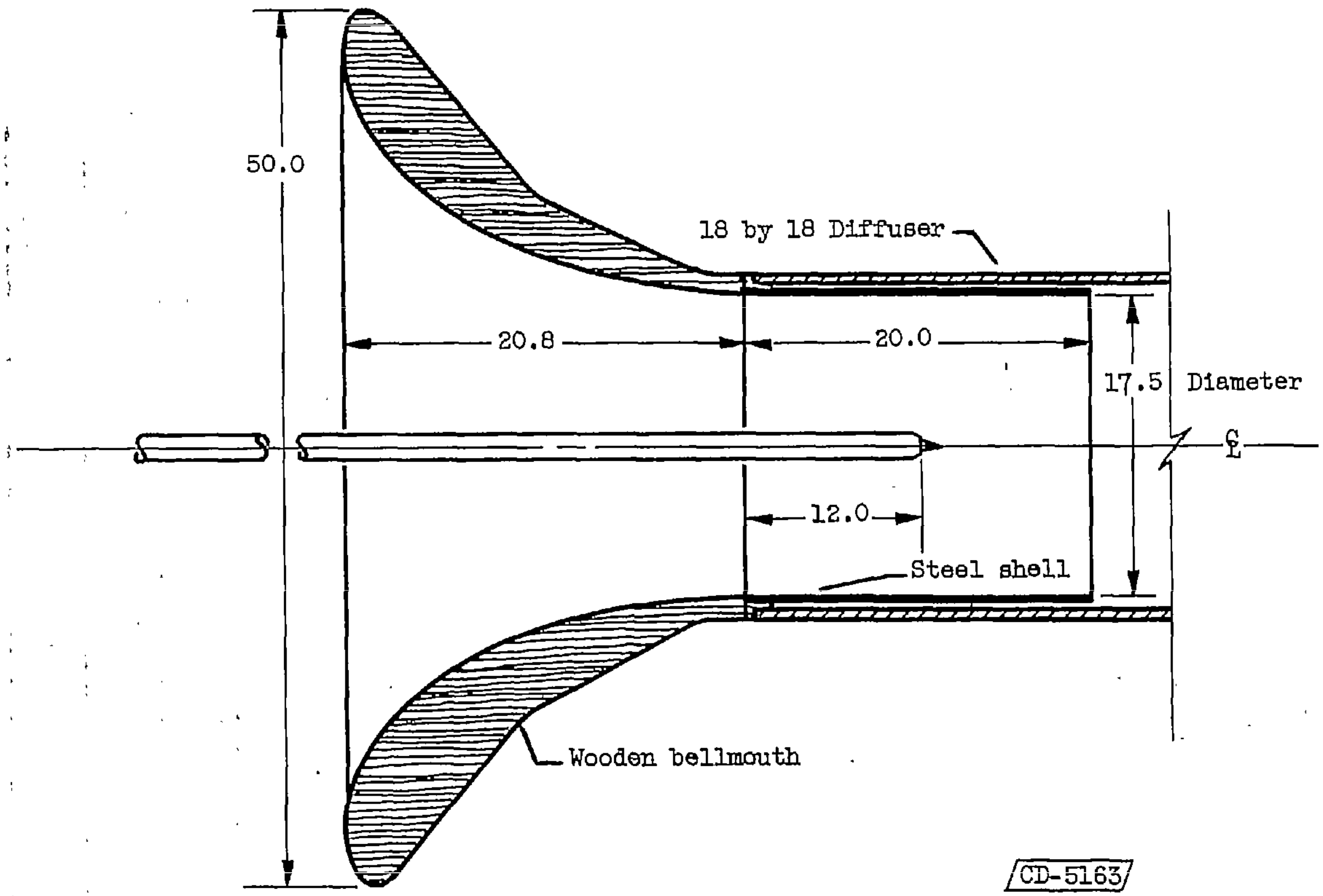


Figure 2. - Schematic diagram of tunnel and model.
(All dimensions in inches.)

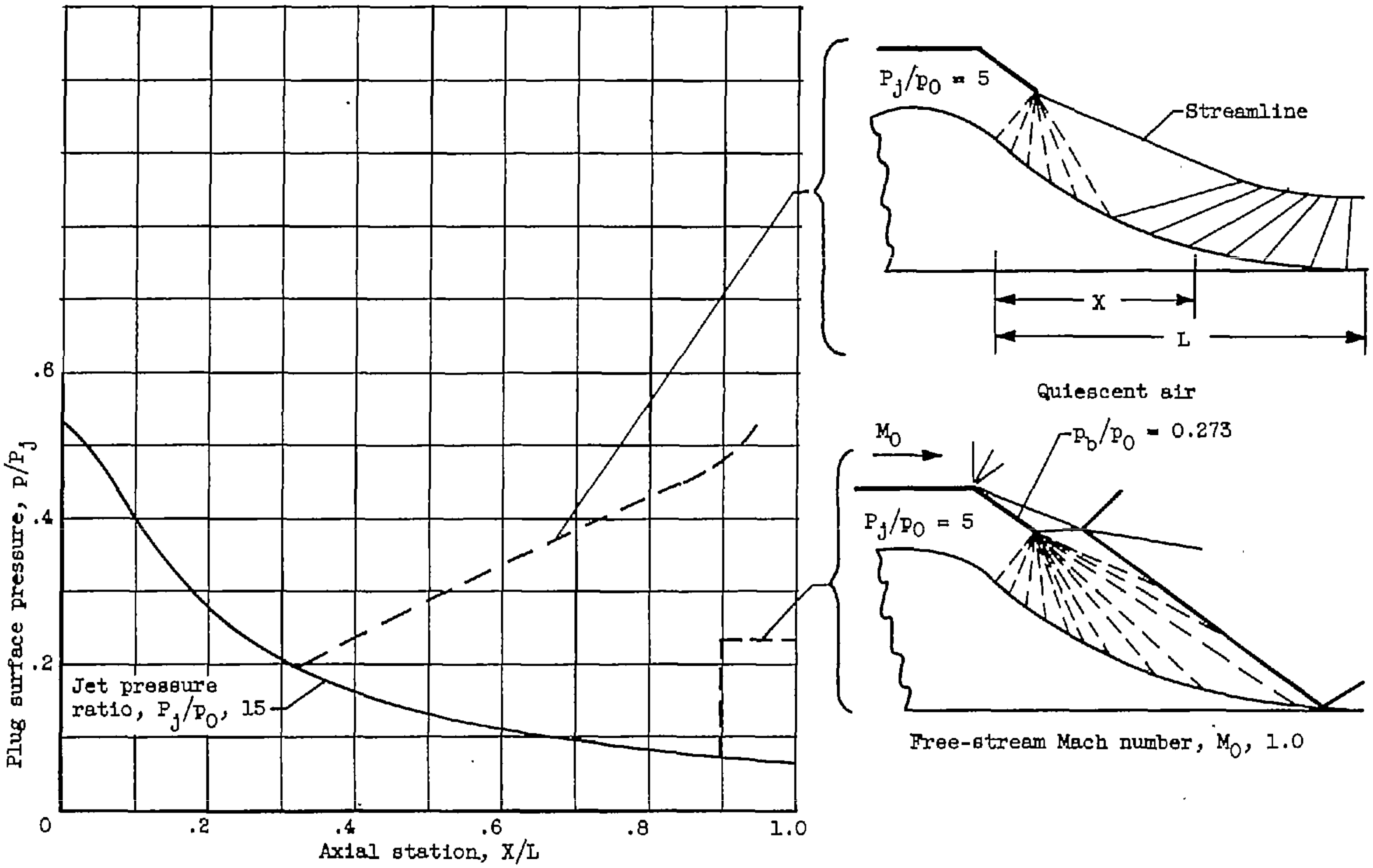
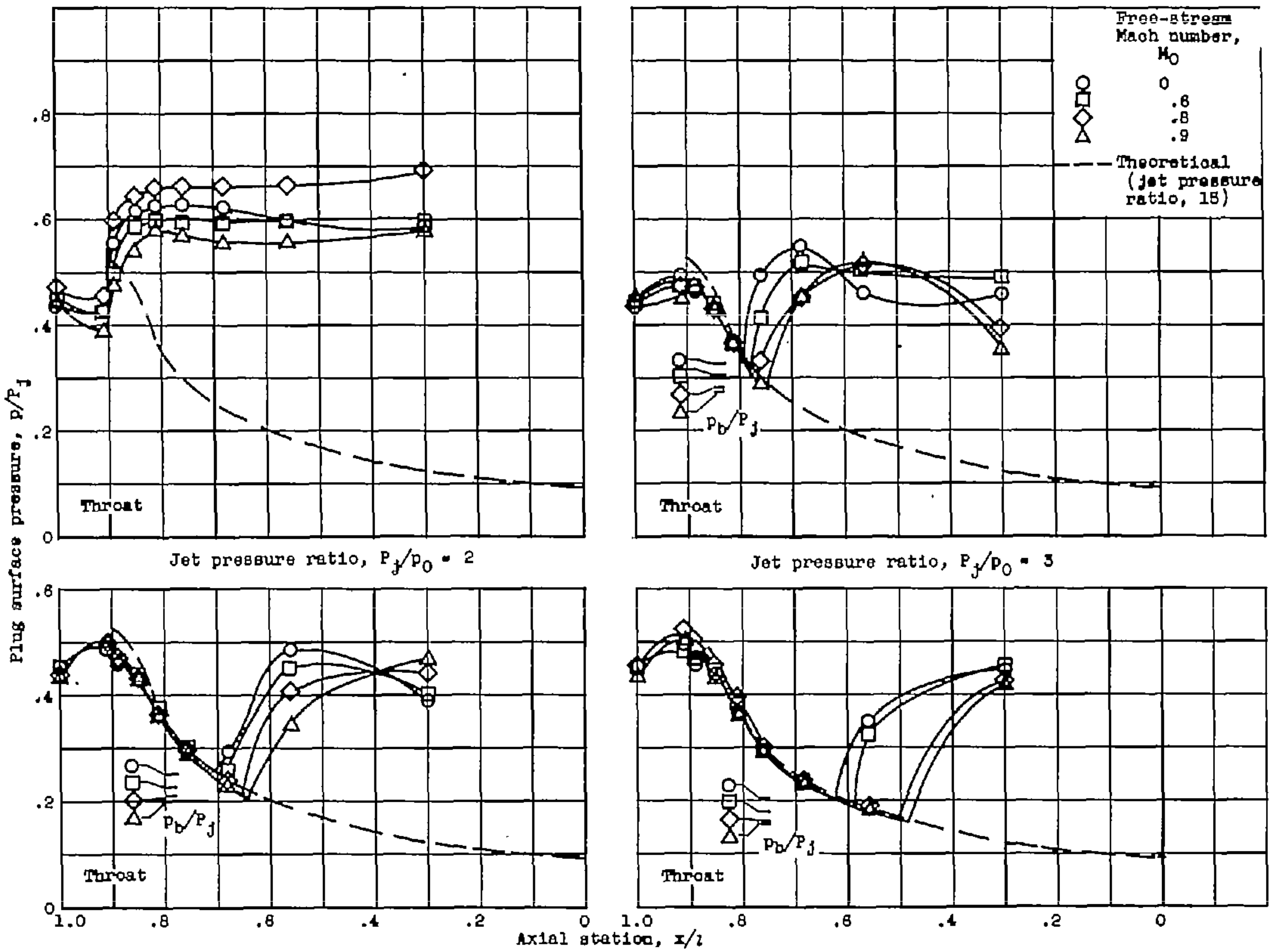
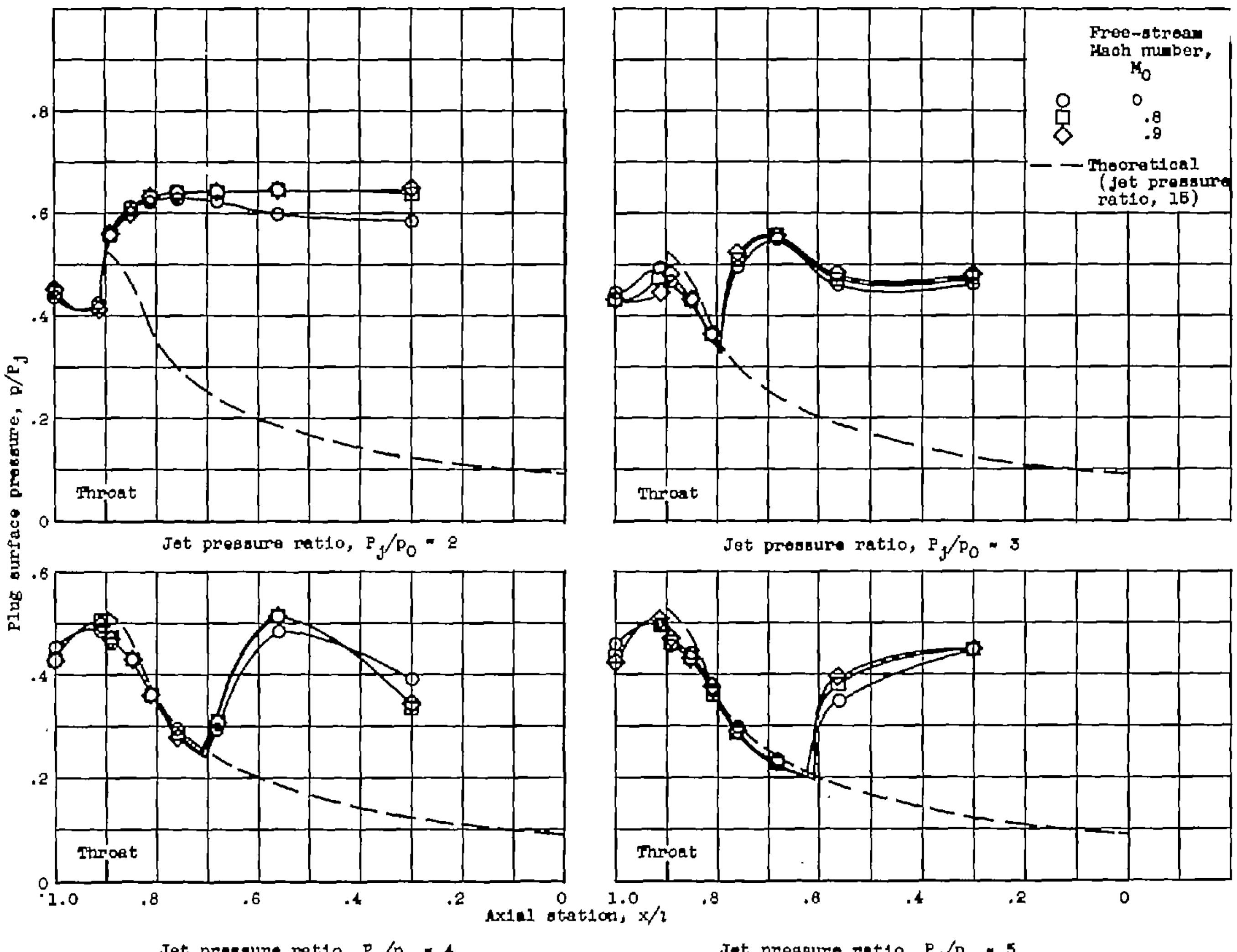


Figure 3. - Stream effect on plug-nozzle operation (theoretical two-dimensional case).



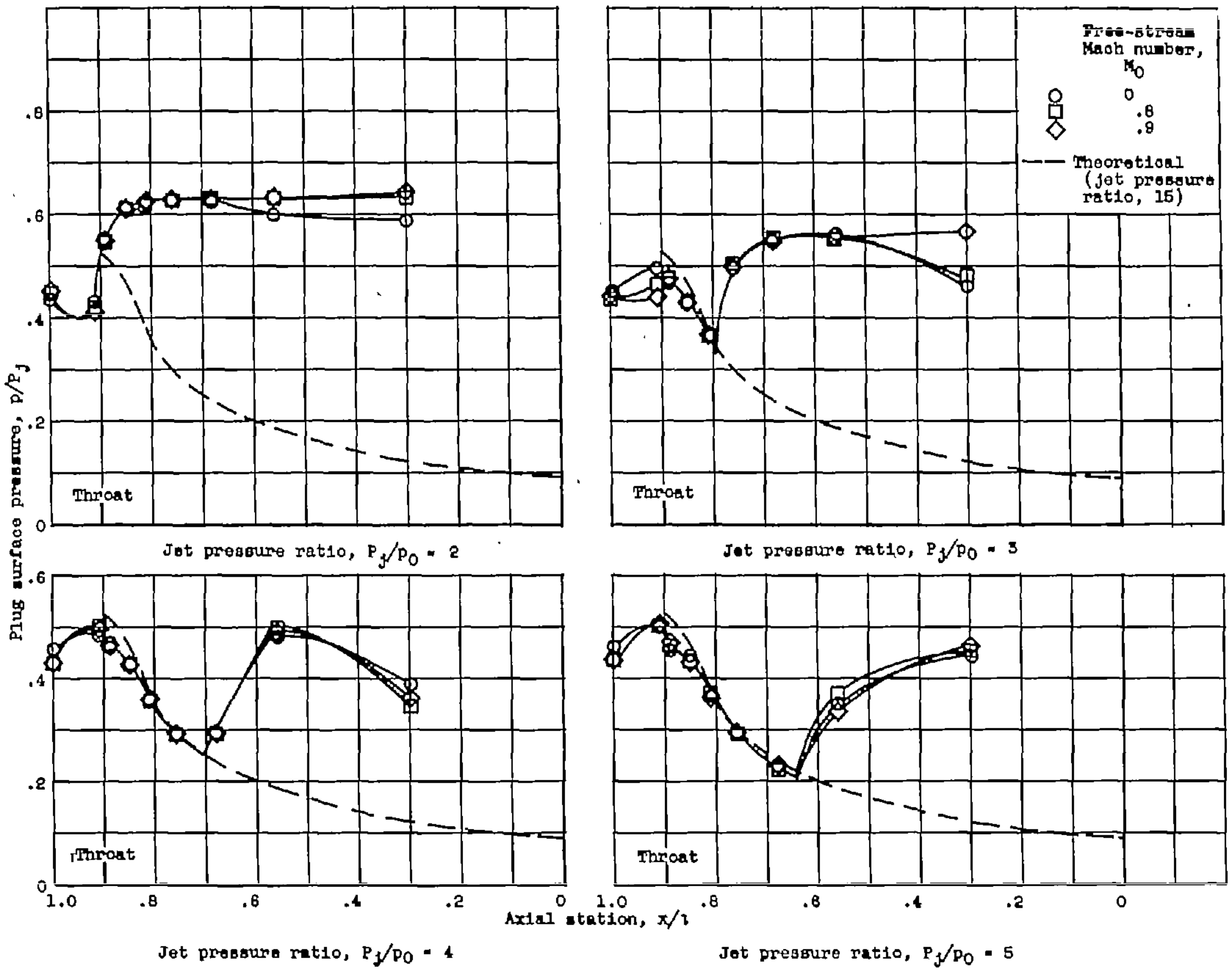
(a) Cylindrical body.

Figure 4. - Stream effect on plug pressure distributions.



(b) 8° Conical boattail.

Figure 4. - Continued. Stream effect on plug pressure distributions.



(c) Circular boattail.

Figure 4. - Concluded. Stream effect on plug pressure distributions.

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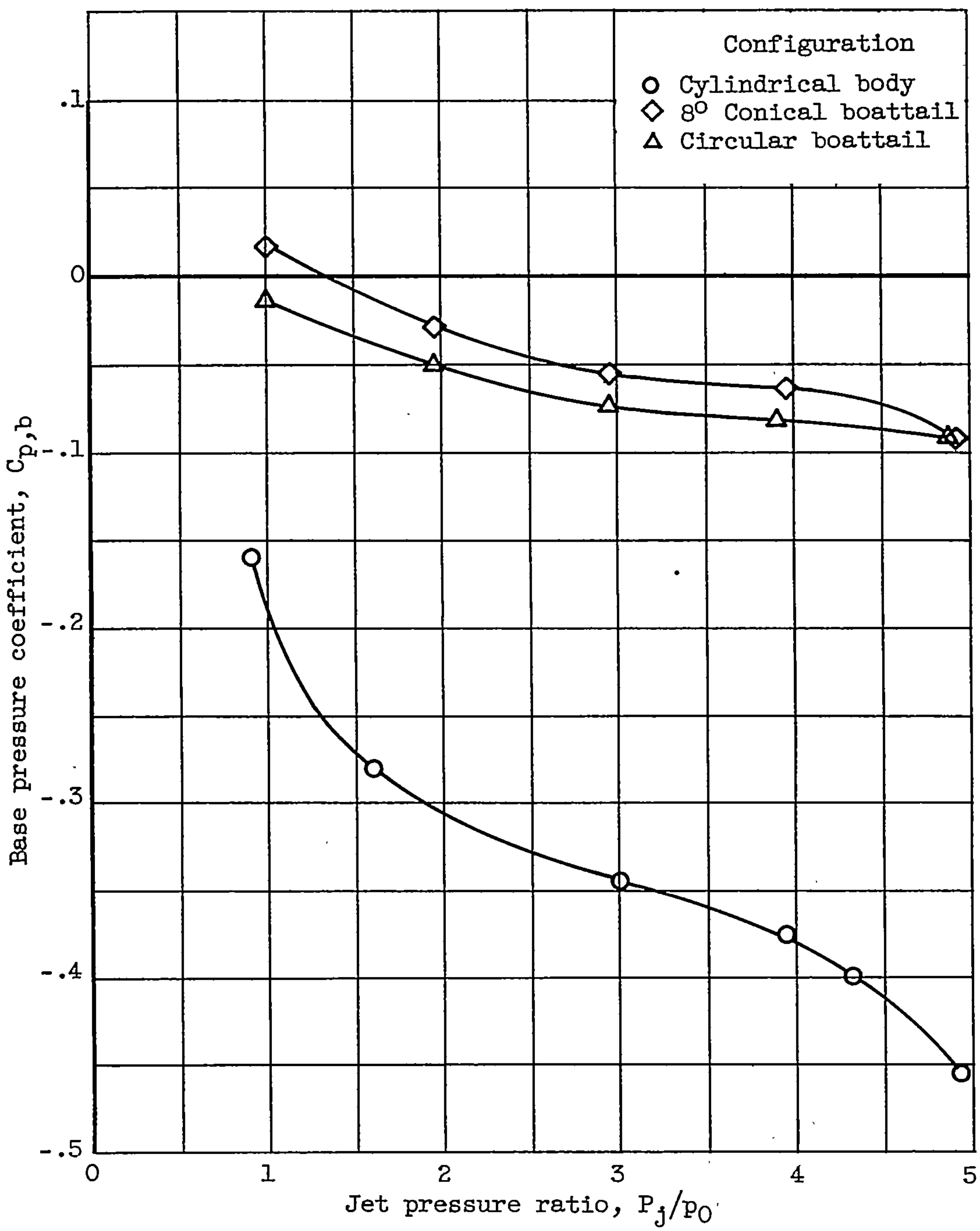

Figure 5. - Effects of boattailing on nozzle base pressures. Free-stream Mach number, 0.9.

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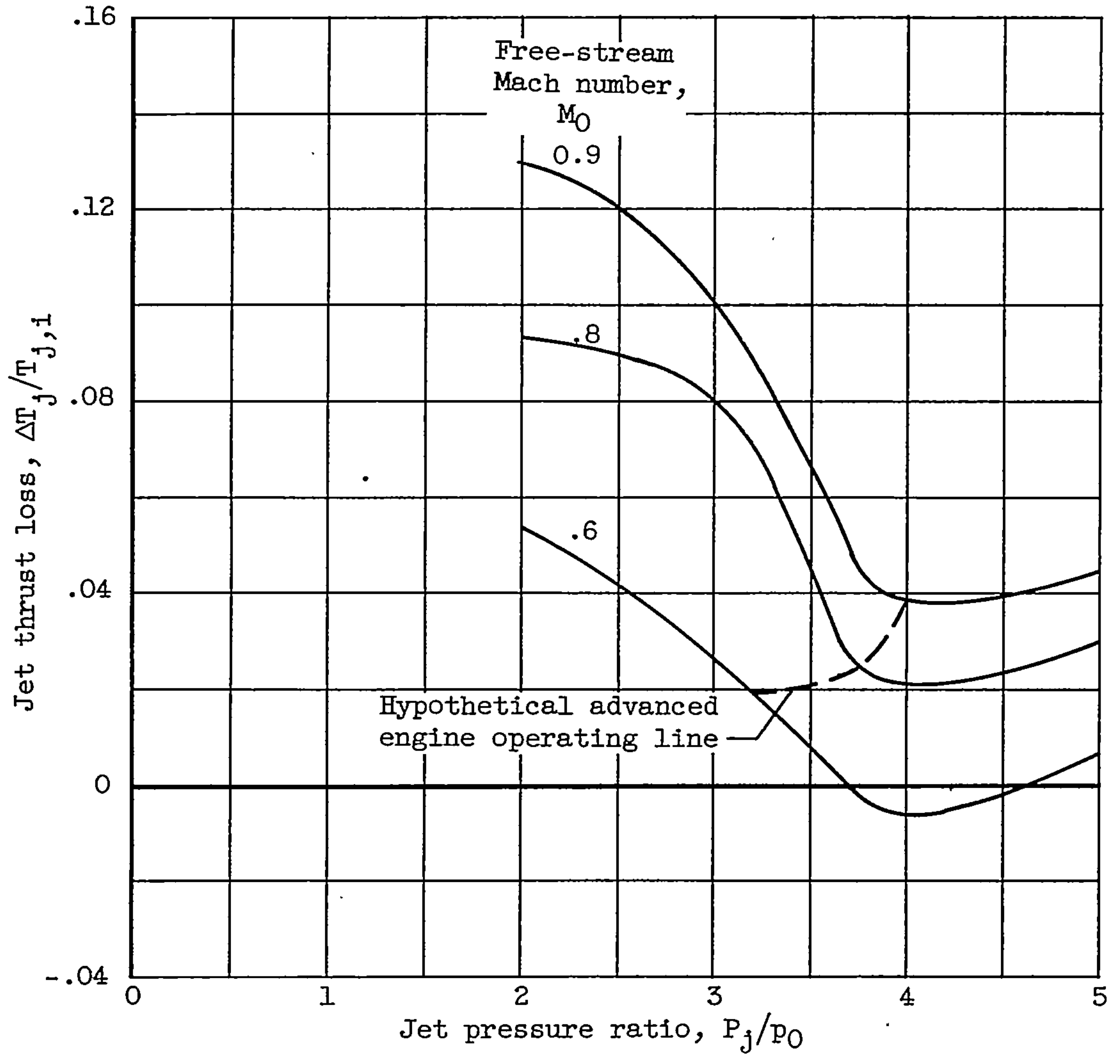

Figure 6. - Stream effect on jet thrust (cylindrical body).

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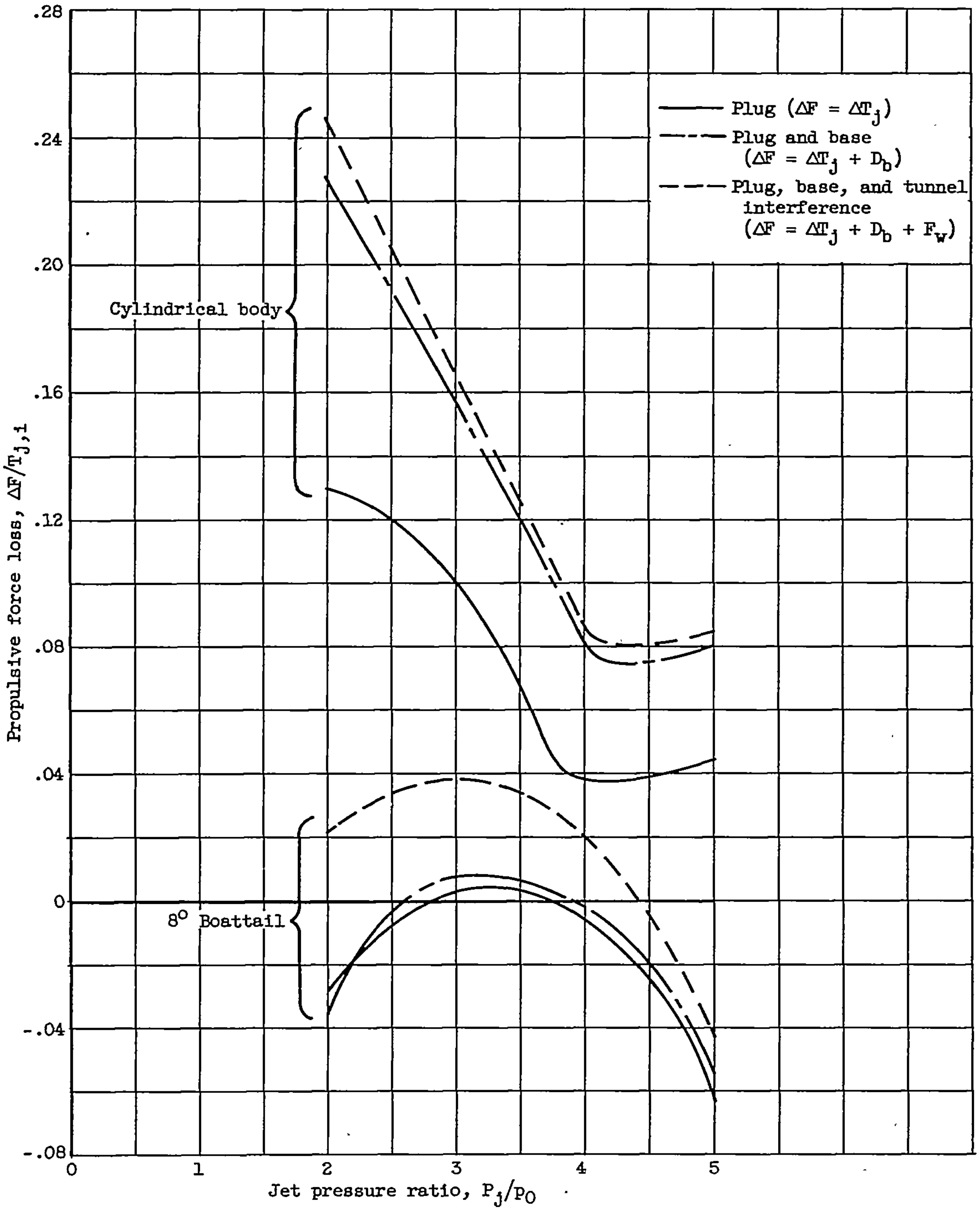
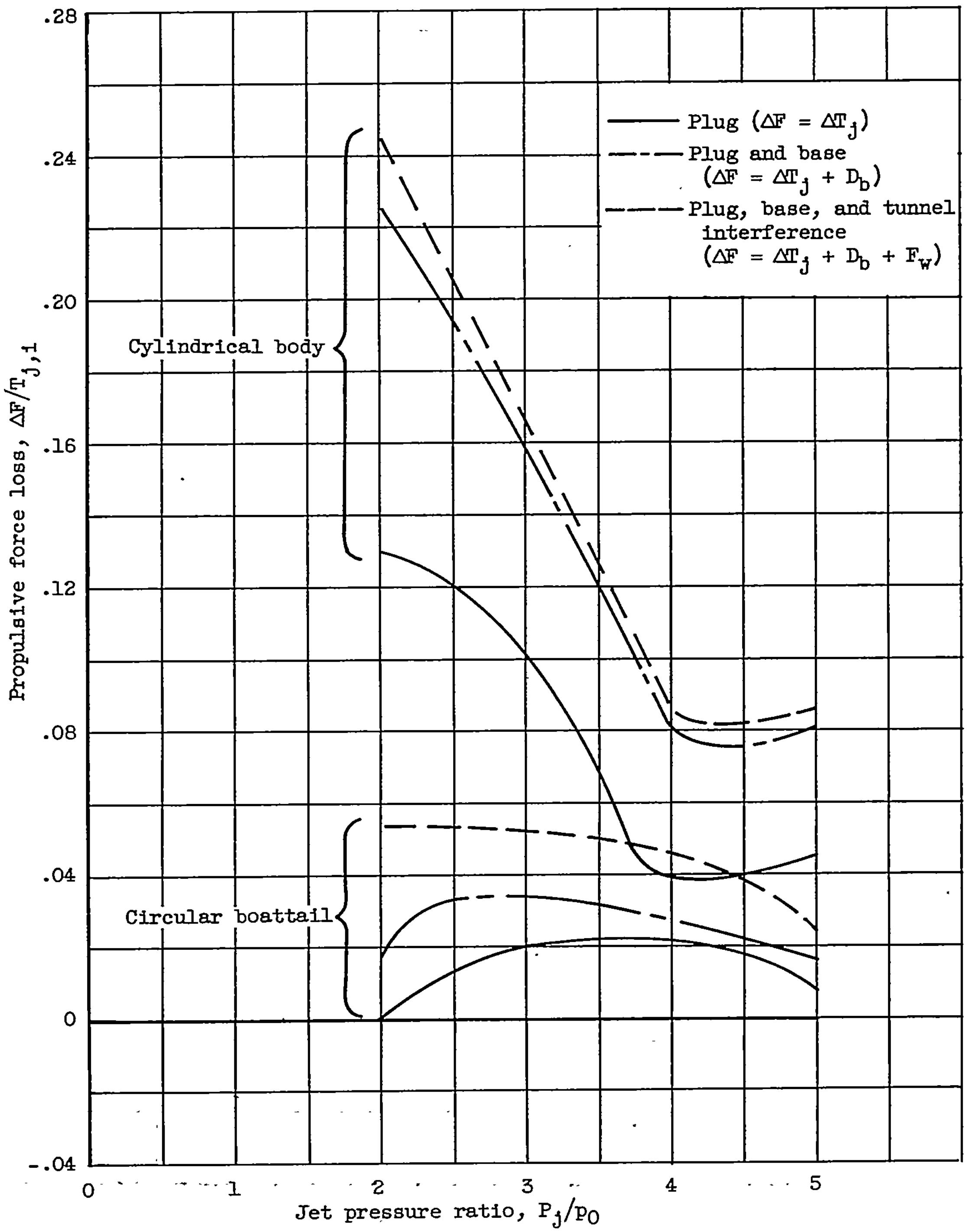


(a) Conical boattail.

Figure 7. - Effect of boattail on jet thrust and base drag. Free-stream Mach number, 0.9.



(b) Circular boattail.

Figure 7. - Concluded. Effect of boattail on jet thrust and base drag. Free-stream Mach number, 0.9.

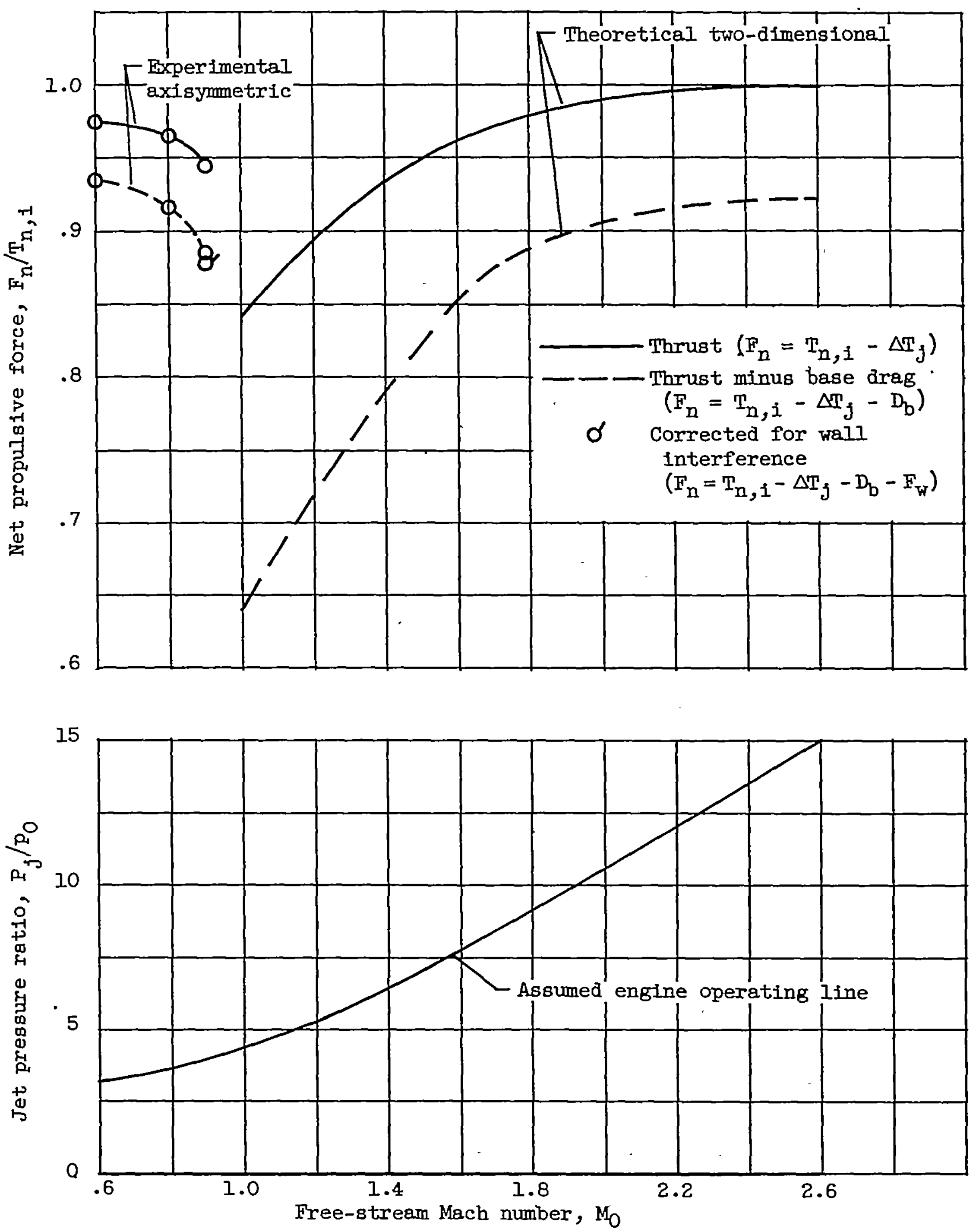


Figure 8. - Stream effect on net propulsive force (cylindrical body).