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EFFECT OF PLUG BASE CONTOUR ON PERFORMANCE OF A FULLY TRUNCATED PLUG NOZZLE WITH TRANSLATING SHROUD

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16. Abstract

An investigation of the effect of plug base contour on the thrust-minus-drag performance of a fully truncated plug nozzle with a simulated translating shroud has been conducted in the Langley 16-foot transonic tunnel at static conditions and at Mach numbers from 0.50 to 1.30. Two plug base contours were used, namely, flat and semitoroidal.

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EFFECT OF PLUG BASE CONTOUR ON PERFORMANCE OF A FULLY TRUNCATED PLUG NOZZLE WITH TRANSLATING SHROUD

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SUMMARY

An investigation of the effect of plug base contour on the thrust-minus-drag performance of a fully truncated plug nozzle with a simulated translating shroud has been conducted in the Langley 16-foot transonic tunnel at static conditions and at Mach numbers from 0.50 to 1.30. Two plug base contours, flat and semitoroidal, were used. The jet total-pressure ratio (i.e., the ratio of jet exhaust total pressure to free-stream static pressure) was varied from 1.0 (jet off) to 8.0, depending on Mach number. The exhaust gas used in the investigation consisted of the decomposition products of 90 percent concentration hydrogen peroxide and had a specific-heat ratio of 1.266.

The results show that the performance level of the fully truncated plug nozzles with the shroud retracted is lower than that of a comparable plug nozzle having a full-length plug. At subsonic speeds, a plug utilizing a flat base shape gave the highest thrust-minus-drag performance with the shroud fully retracted, but when the shroud was translated, the semitoroidal base shape became beneficial. At supersonic speeds, the plug using a flat base shape gave the highest thrust-minus-drag performance for all conditions of the investigation. The flat-base plug generally had the highest force for all test conditions except those at low jet total-pressure ratios.

INTRODUCTION

The operation of aircraft over a wide Mach number range requires nozzle systems which perform at high efficiency for varying flight conditions. One promising nozzle concept is the plug nozzle for which the outer boundary of the exhaust stream continually adjusts to external stream conditions. Many investigations of the performance of various plug nozzles have been made at static conditions and with an external stream. (See refs. 1 to 17 for examples.) Some studies have been aimed at reducing the weight and length of plug nozzles by truncating the plug at various lengths up to the geometric throat and by forming an "aerodynamic" central plug and are reported in references 5 to 8. In connection with these truncation studies, several base shapes have been investigated in order to establish and maintain the aerodynamic central plug (refs. 1, 4, and 5). As previous investigations have shown, plug nozzles with fixed geometry have exhibited high performance efficiency over a wide range of jet total-pressure ratio in quiescent air (refs. 9 and 10). Although competitive performance has been obtained with these nozzles at design operation conditions (ref. 3), poor performance has been exhibited at off-design conditions in the presence of an external stream (refs. 11 and 12). Hence, it is apparent that variable geometry is needed for thrust modulation. One method of applying variable geometry which has been suggested is the use of a translating plug or shroud (refs. 13 to 15). For plugs which are not fully truncated (i.e., not cut off at the geometric throat), the throat moves downstream on the plug and increases in area as the shroud translates downstream. For plugs which are fully truncated, the throat remains at a stationary point on the plug but increases in area as the shroud translates downstream; the result is some internal expansion of the exhaust flow (refs. 16 and 17).

The purpose of the present investigation was to determine the effect of plug base contour on the thrust-minus-drag performance of a fully truncated plug nozzle with a simulated translating shroud. Two plug base contours, flat and semitoroidal, were used for this purpose. The investigation was conducted in the Langley 16-foot transonic tunnel at static conditions and at Mach numbers from 0.50 to 1.30 and at an angle of attack of 0°. The jet total-pressure ratio (i.e., the ratio of jet exhaust total pressure to free-stream static pressure) was varied from 1.0 (jet off) to 8.0, depending on the Mach number. The nozzles with the shroud fully retracted were designed to operate at a jet total-pressure ratio of 16.5. The exhaust gas used in the investigation consisted of the decomposition products of 90 percent concentration hydrogen peroxide and had a specific-heat ratio of 1.266 and a stagnation temperature of 1013° K.

SYMBOLS

A — cross-sectional area, meters^2

$\overline{C}_{p,b}$ — average plug base pressure coefficient at common base radian position, $\dfrac{p_b - p_\infty}{q_\infty}$

$C_{F,plug}$ — plug base thrust coefficient, $\dfrac{\sum_{l=0}^{\text{Plug base}} p_b A_l}{q_\infty A_{max}}$

$C_{f,cyl}$ — skin-friction drag coefficient on cylindrical portion of afterbody, $\dfrac{\text{Cylinder skin-friction drag}}{q_\infty A_{max}}$

d	diameter, meters
D	drag, newtons
F	jet thrust, newtons
F_{bal}	axial force measured by balance, newtons
F_i	ideal thrust for complete isentropic expansion of jet flow, $\dot{m}\sqrt{2R\frac{\gamma}{\gamma - 1}T_{t,j}\left[1 - \left(\frac{p_\infty}{p_{t,j}}\right)^{\frac{\gamma-1}{\gamma}}\right]}$, newtons
M	free-stream Mach number
M_e	Mach number at shroud exit
$\dot{m}$	mass flow, kilograms/second
p	static pressure, newtons/meter^2
p_b	plug base pressure, newtons/meter^2
$\bar{p}_b$	average plug base pressure, newtons/meter^2
p_t	total pressure, newtons/meter^2
q	dynamic pressure, newtons/meter^2
R	gas constant, joules/kilogram-degree Kelvin
r	radius, meters
s	distance from plug end to shroud end, meters
T_t	stagnation temperature, degrees Kelvin
x	axial distance from station 142.75, positive downstream, meters

β	boattail angle, degrees
γ	ratio of specific heats

Subscripts:

e	shroud exit
i	internal
j	jet flow
l	local
max	maximum
plug	plug
t	throat
1,2,3	refers to plug geometry details
∞	free stream

APPARATUS AND METHODS

Wind Tunnel

The present investigation was conducted in the Langley 16-foot transonic tunnel, which is a single-return, atmospheric wind tunnel with a slotted octagonal test section. The tunnel has a continuously variable speed range from a Mach number of 0.20 to 1.30. Continuous air-exchange cooling permits jet simulation tests to be made.

Model and Support System

A sketch of the strut-supported turbojet-engine simulator model used in the investigation is presented in figure 1. The model consisted of a conical forebody, a cylindrical central body 15.24 cm in diameter, and an afterbody-plug combination having a cylindrical section (including spacing rings if applicable), a boattail, and a fully truncated plug. The afterbody-plug combination was detachable at the 104.39-cm station. A photograph of a plug nozzle mounted on the model is shown as figure 2.

A translating shroud was simulted by the addition of a metal ring spacer which was either 1.27 or 1.905 cm wide to the length of the basic 20° shroud as indicated in figure 3. Two fully truncated plugs, one of which had a flat base shape and the other a semitoroidal base shape, were used in this investigation. Six configurations representing three shroud positions for each plug were used. The basic configurations (those with shroud in retracted position) were designed for a jet total-pressure ratio of 16.5 $\left(M_e = 2.46\right)$ and for the specific-heat ratio γ of 1.266 for hydrogen peroxide and are fully discussed in reference 5.

Table I gives the basic geometric parameters of the six test configurations. A sketch giving dimensions, pressure-orifice locations, and general configuration details is presented as figure 4. A hydrogen peroxide turbojet-engine simulator similar to that described in reference 18 was used for the present investigation. The jet simulator produces a hot jet which closely matches the exhaust of a turbojet engine.

Instrumentation

The instrumentation included a one-component strain-gage thrust balance to measure gross thrust minus drag of the nozzle, four total-pressure probes (values averaged), and a total-temperature probe located in the tailpipe. Static-pressure orifices were located on the plugs, and a turbine electronic flowmeter was used to obtain the mass flow of the liquid hydrogen peroxide. Pressures were measured with pressure transducers. The electrical signals of all instruments were transmitted to and recorded by an automatic magnetic tape-recording system.

Data Reduction

Standard force and pressure coefficients were computed from the recorded data. Pressure forces on the plug were obtained by assigning an incremental area projected on a plane normal to the model axis to each pressure orifice and by numerically integrating the incremental forces. No correction was made for strut interference because the data from reference 19 indicate that the effect is small for the support system used.

The thrust balance measured the sum of the following axial forces: total momentum flux at nozzle throat, plug-pressure forces, external aerodynamic drag of the afterbody aft of station 104.39, and some internal tare pressure-area forces in the nacelle. Thrust minus drag for the nozzle was obtained from the following equation:

$$F - D = F_{bal} + \left(p_i - p_{\infty}\right)A_{max} + C_{f,cyl}q_{\infty}A_{max}$$

Test Conditions

All configurations were investigated at static conditions and at Mach numbers from 0.50 to 1.30. The angle of attack was held constant at 0°. Jet total-pressure ratio varied from 1.0 (jet off) to about 8.0. The average Reynolds number based on body length was 18.5×10^6.

RESULTS AND DISCUSSION

Plug Characteristics

Pressure distributions.- The radial distribution of base pressure coefficients for the two plug base contours (flat and semitoroidal) at several jet total-pressure ratios and Mach numbers is presented in figures 5 and 6. For $M = 0$, the static base pressure coefficients have atmospheric pressure as a reference and are therefore not numerically comparable with the coefficients for $M = 0.50$ to 1.30 which have dynamic pressure as a reference. For the shroud fully retracted (configurations 1F and 1S), the plug base pressure coefficients generally are approximately the same as the free-stream values at subsonic speeds except for $M = 0.50$; pressure coefficients become increasingly negative with increasing values of $p_{t,j}/p_\infty$ at supersonic speeds. With the exception of the higher jet total-pressure ratios at supersonic speeds, the recirculating flow pattern described in reference 1 is nearly nonexistent for these configurations. Translating the shroud exit downstream (configurations 2F, 2S, 3F, and 3S), which increased the nozzle throat area and allowed some internal expansion, produces plug base pressure coefficients greater than the local free-stream static pressure coefficients for all jet total-pressure ratios at subsonic speeds and for the higher jet total-pressure ratios at supersonic speeds. For all configurations with the shroud translated downstream, the plug base pressure coefficient generally increases with increasing jet total-pressure ratio. Distributions typical of vortex-ring type flow (ref. 1) are shown for the extended shroud configurations, especially for configurations 2F and 2S. As nozzle throat area is increased by translating the shroud, the local pressure over the plug base is also generally increased.

Base thrust.- The pressure distributions on the plugs presented in figures 5 and 6 were integrated over the plug base areas to obtain plug base thrust. The variation of plug base thrust coefficient with jet total-pressure ratio for various Mach numbers is presented in figure 7. At $M = 0$, results are presented in the form of static coefficients which are not numerically comparable with those obtained at other Mach numbers. The flat-base plug generally had the highest force for all test conditions except for low jet total-pressure ratios $\left(p_{t,j}/p_\infty < 2.5\right)$ and for configuration 3S at $M = 1.30$. The base thrust for the semitoroidal plug with the shroud in the fully retracted position (configuration 1S) remains near the jet-off level at subsonic speeds. The fact that the base thrust for the flat-base plug with a fully retracted shroud (configuration 1F) nearly always exceeds the jet-off level at subsonic speeds indicates that some of the momentum thrust lost as a result of exhaust flow convergence is recovered on the plug. At supersonic speeds, configurations 1F and 1S both show slight increases in plug thrust at low jet total-pressure ratios; a further increase in jet total-pressure ratio results in decreased plug thrust until some higher pressure ratio is reached. (See fig. 7(a).) When the shrouds are extended downstream (configurations 2F, 2S, 3F, and 3S), the plug base thrust exceeds the jet-off level for $M > 0$ (figs. 7(b) and 7(c)). At supersonic speeds, plug base thrust remains nearly constant at lower pressure ratios $\left(p_{t,j}/p_{\infty} < 3.0\right)$ probably as a result of the jet exhaust annulus being too small to exert changes on the flow field around the plug base.

Thrust-Minus-Drag Nozzle Performance

Variation with pressure ratio.- The variation of thrust-minus-drag ratio with jet total-pressure ratio for various Mach numbers is presented in figures 8 to 10. Thrust-minus-drag performance increases with increasing jet total-pressure ratio for all Mach numbers, but a maximum value was not obtained at any of the Mach numbers of the present investigation. When the shroud is fully retracted the performance of the flat-base plug nozzle (configuration 1F) is always higher than that of the semitoroidal-base plug nozzle (configuration 1S) except for $M = 0$. The semitoroidal base shape becomes beneficial at low Mach numbers when the shroud is extended. For example, when the shroud is translated 1.27 cm, the semitoroidal base (configuration 2S) gives the highest performance for $M \leqq 0.70$ (fig. 9). When the shroud is translated 1.905 cm (full translation), the semitoroidal base (configuration 3S) is more efficient for $M \leqq 0.90$ (fig. 10). At Mach numbers greater than 0.70 for configurations 2F and 2S, and greater than 0.90 for configurations 3F and 3S, the flat-base plug (configurations 2F and 3F) produces the highest thrust-minus-drag performance.

Performance at scheduled pressure ratio.- The variation of thrust-minus-drag ratio with Mach number for a typical turbojet total-pressure-ratio schedule is presented in figure 11. The level of gross thrust-minus-drag performance shows varied trends at low subsonic speeds but generally decreases with increasing Mach number up to $M = 1.00$ for all configurations. At supersonic speeds a general increase in performance is noted for all configurations except the semitoroidal-base plug nozzle with the fully translated shroud (configuration 3S) which exhibits no change with Mach number.

The variation of thrust-minus-drag ratio with nozzle-throat-area ratio is shown in figure 12 for several Mach numbers. The data are presented for jet total-pressure ratios typical of those of a turbojet engine operating schedule as shown in figure 11. As nozzle throat area is increased by shroud translation an increase in performance is noted for all Mach numbers except $M = 0$ where mixed results occur. Some of this increase in performance is probably due to internal expansion (ref. 16); however, most of the increase is probably a result of increasing exhaust mass flow and of decreasing drag relative to the ideal thrust. This increase in performance is opposite to the results given in reference 7 where a decrease in performance occurred for a nozzle which had a constant throat area and an internal area ratio that increased with shroud translation.

The thrust-minus-drag performance level for both configurations with no translation is low when compared with the static performance level of plug nozzles with full-length plugs (ref. 5) or similar annular nozzles with a concave central base (ref. 1). Data presenting the effects of plug truncation in reference 8 show that for a fully truncated plug the performance level is similar to that presented herein. (See fig. 12, M = 0.)

The data of the present investigation indicate that when the shroud is fully retracted, the flat-base plug nozzle (configuration 1F) gives the highest performance at subsonic speeds; when the shroud is translated, the semitoroidal base shape becomes beneficial. At supersonic speeds, the flat-base plug nozzle gives the highest thrust-minus-drag performance.

CONCLUDING REMARKS

An investigation of the effect of plug base contour on the thrust-minus-drag performance of a fully truncated plug nozzle with a simulated translating shroud has been conducted in the Langley 16-foot transonic tunnel at static conditions and at Mach numbers from 0.50 to 1.30. The effects of two plug base contours, flat and semitoroidal, on the nozzle performance were determined. The performance level of the fully truncated plug nozzles with the shroud retracted was low when compared with that of plug nozzles having a full-length plug. At subsonic speeds, a plug utilizing a flat base shape gave the highest thrust-minus-drag performance with the shroud fully retracted, but when the shroud was translated, the semitoroidal base shape became beneficial. At supersonic speeds, the plug with a flat base shape gave the highest performance for all conditions of this investigation. The flat-base plug generally had the highest force for all test conditions except those at low jet total-pressure ratios. Plug base pressures generally increased with increasing jet total-pressure ratio when the shroud was translated.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 1, 1969.

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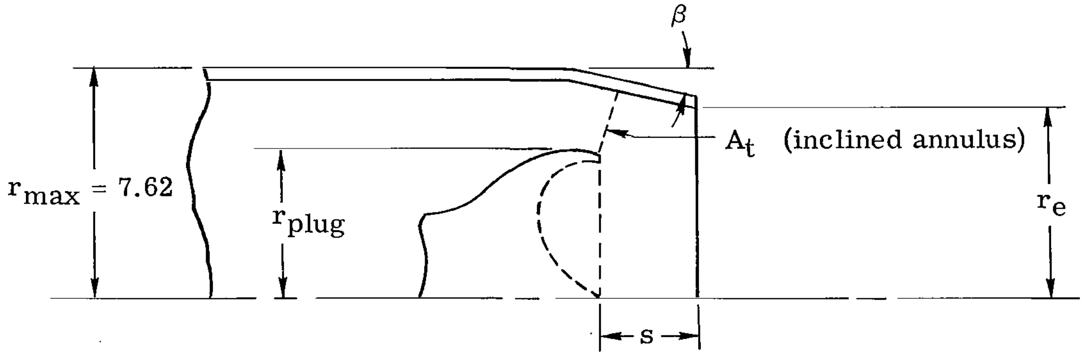
TABLE I.- IMPORTANT GEOMETRIC PARAMETERS OF TEST CONFIGURATIONS

[All dimensions are in centimeters]



Configuration	Base shape	s/d_{max}	d_{plug}/d_{max}	A_t/A_{max}	A_e/A_t	β, deg
1F	Flat	0.020	0.70	0.25	2.94	20
1S	Semitoroidal	.020	.70	.25	2.94	20
2F	Flat	.083	.70	.32	2.30	20
2S	Semitoroidal	.083	.70	.32	2.30	20
3F	Flat	.125	.70	.36	2.04	20
3S	Semitoroidal	.125	.70	.36	2.04	20

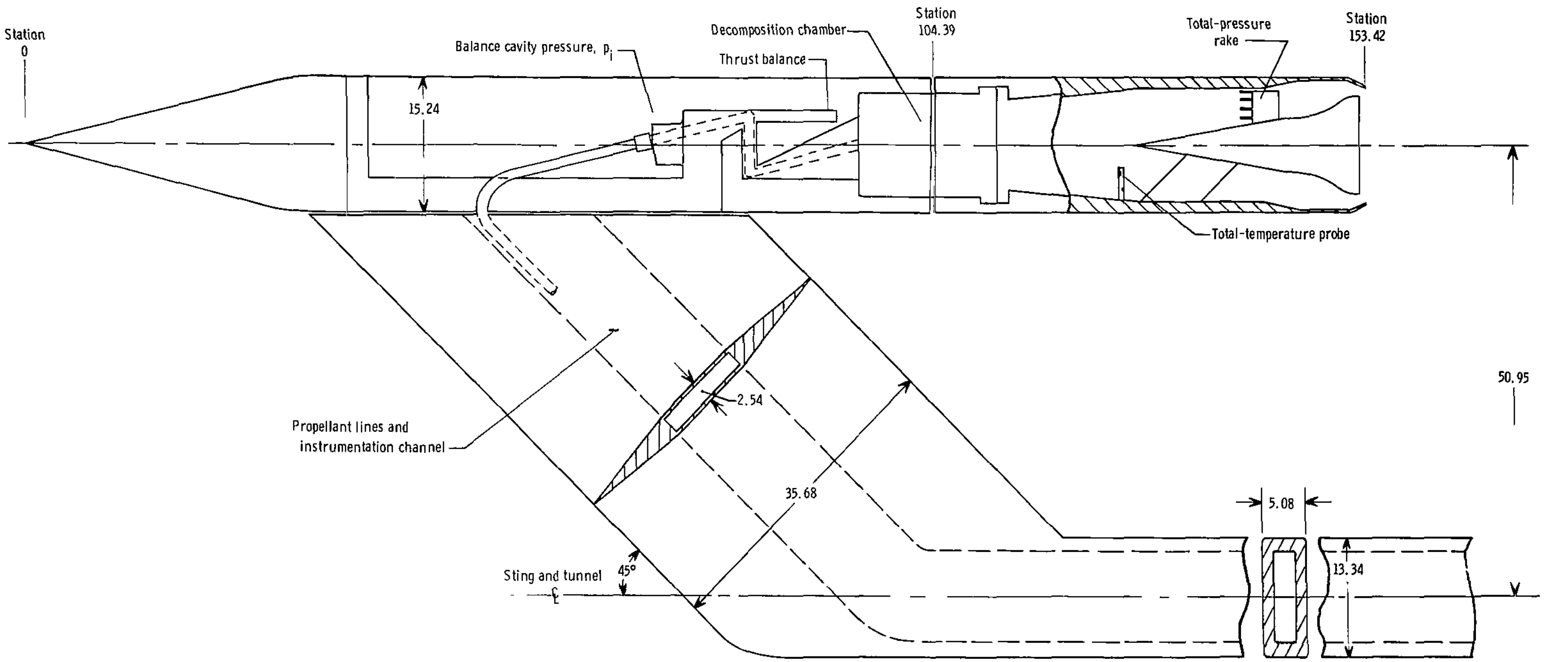


Figure 1.- Sketch of plug nozzle with shroud in retracted position installed on a nacelle model. All dimensions are in centimeters.

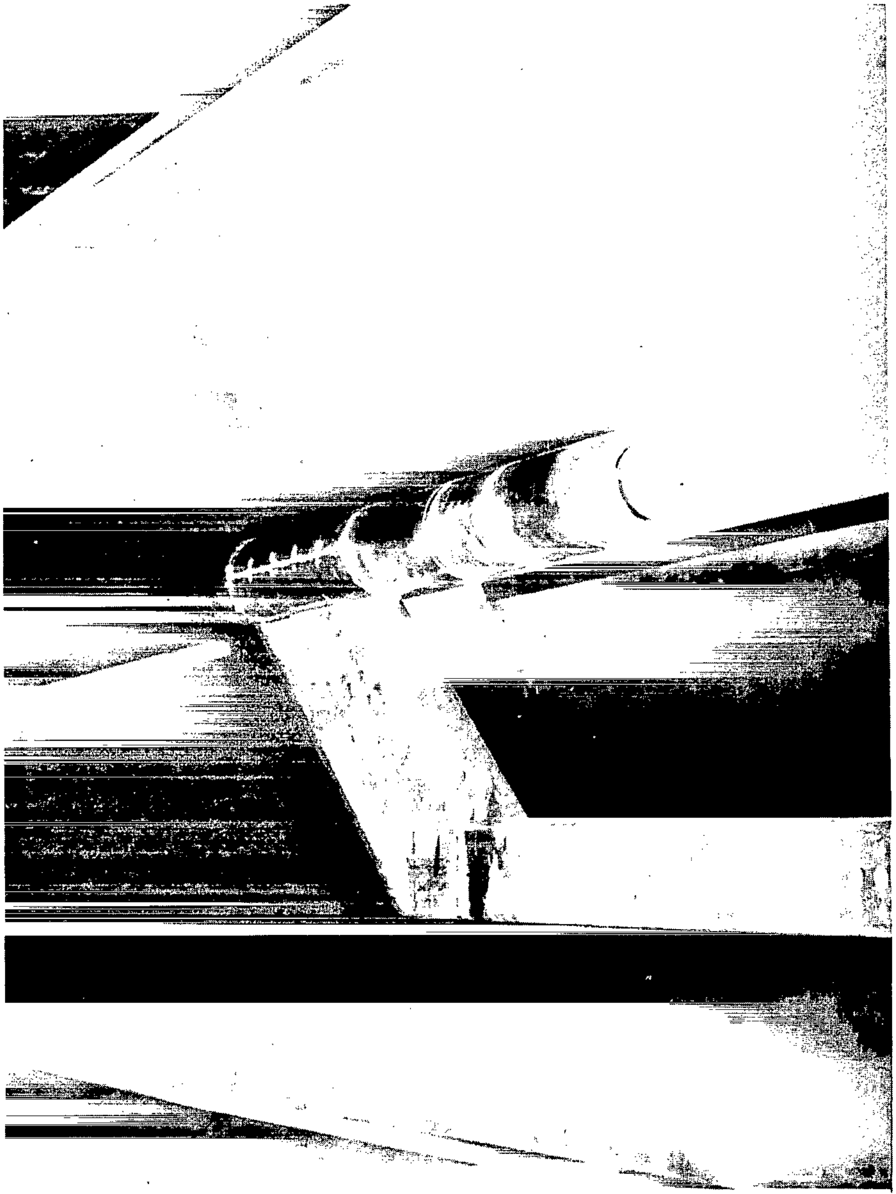


Figure 2.- Photograph of plug nozzle, configuration 1S, mounted on a nacelle model. L-66-4083

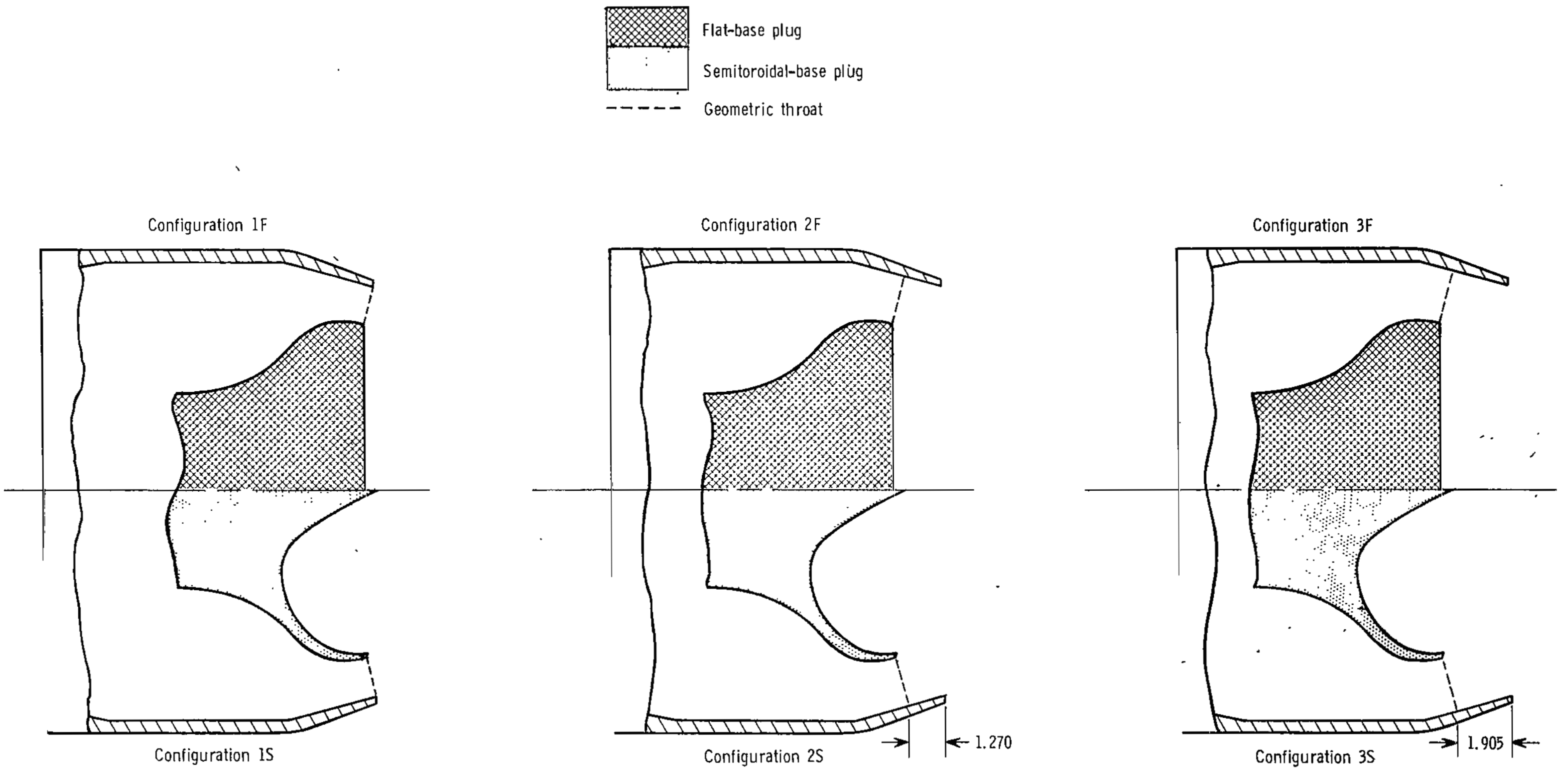
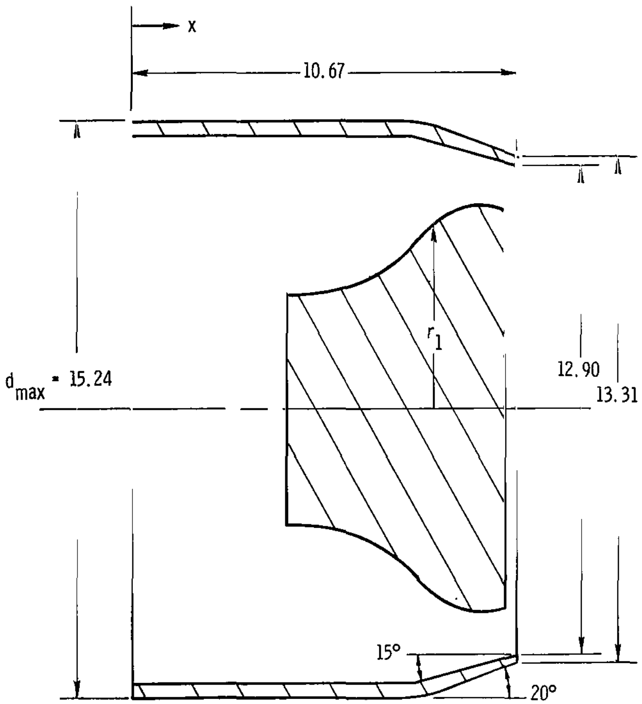
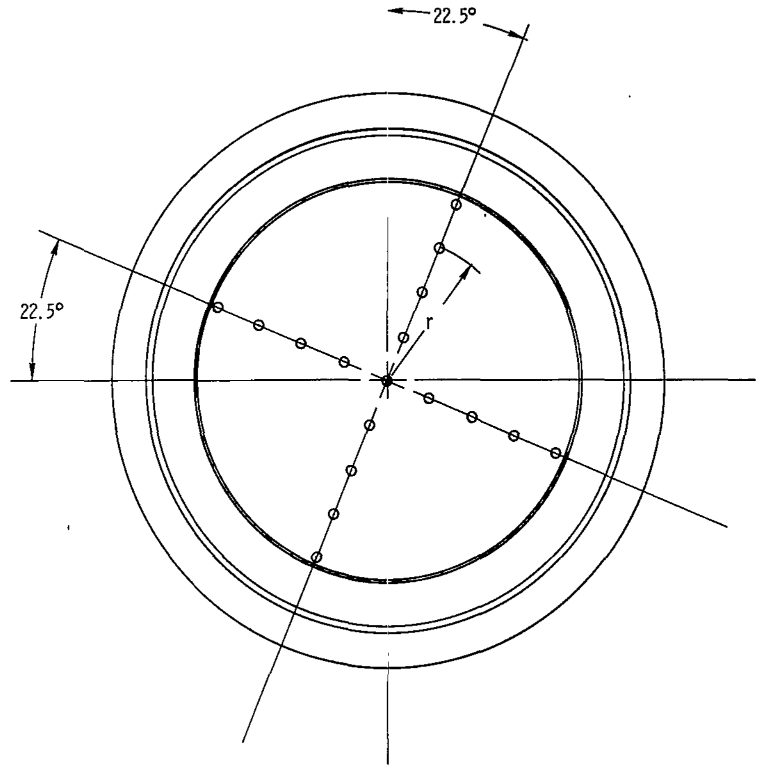


Figure 3.- Sketch illustrating translating shroud. All dimensions are in centimeters.



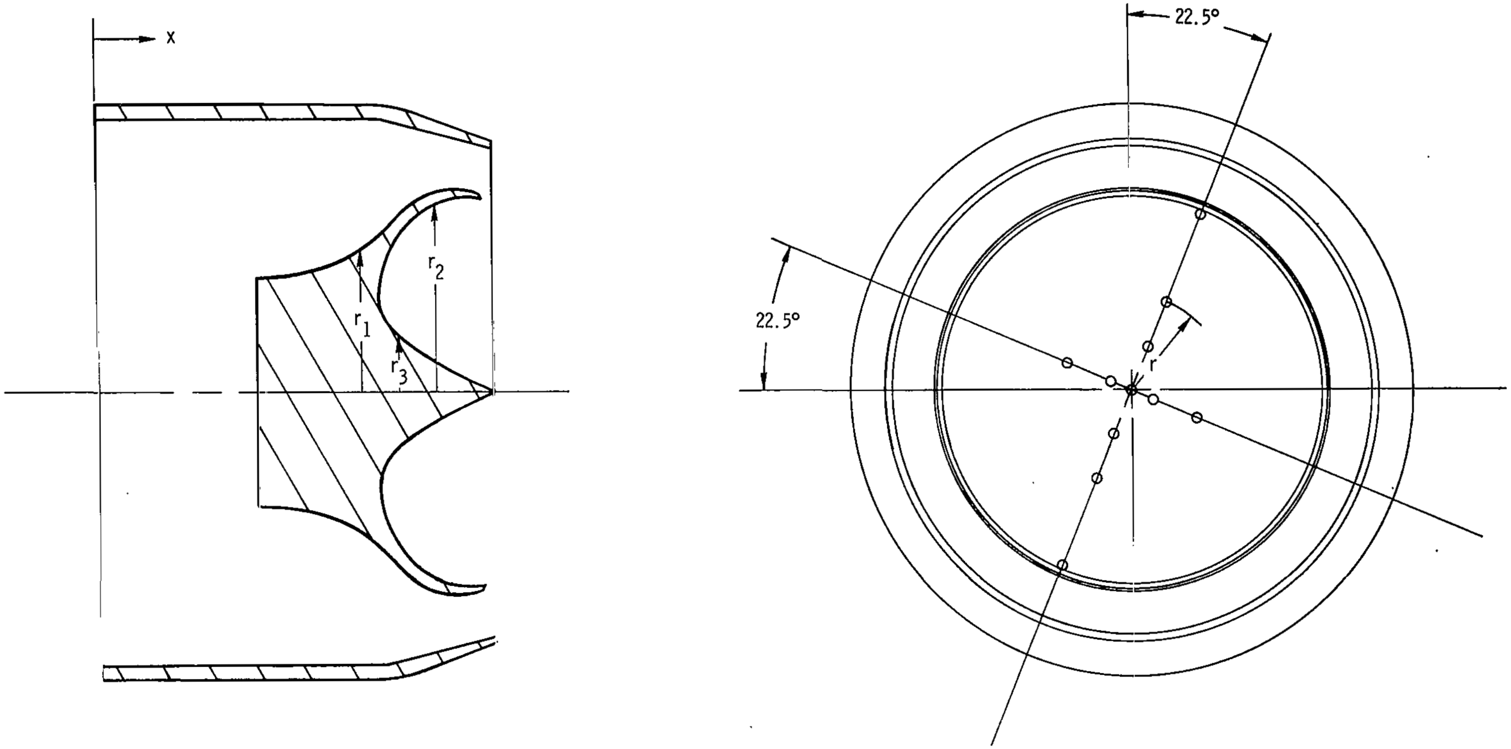
Plug coordinates			
x	r_1	x	r_1
4.32	3.05	8.89	5.21
5.34	3.12	9.15	5.28
6.10	3.30	9.40	5.33
6.86	3.63	9.65	5.36
7.37	3.91	9.91	5.33
7.88	4.39	10.16	5.31
8.38	4.88	10.37	5.26



Orifice locations	
r	Row
0	Center
1.27	22.5°, 112.5°, 202.5°, 292.5°
2.54	↓
3.81	
5.08	

(a) Flat-base plug configurations (configuration 1F shown).

Figure 4.- Sketch of plug and shroud with orifice locations indicated. All dimensions are in centimeters.

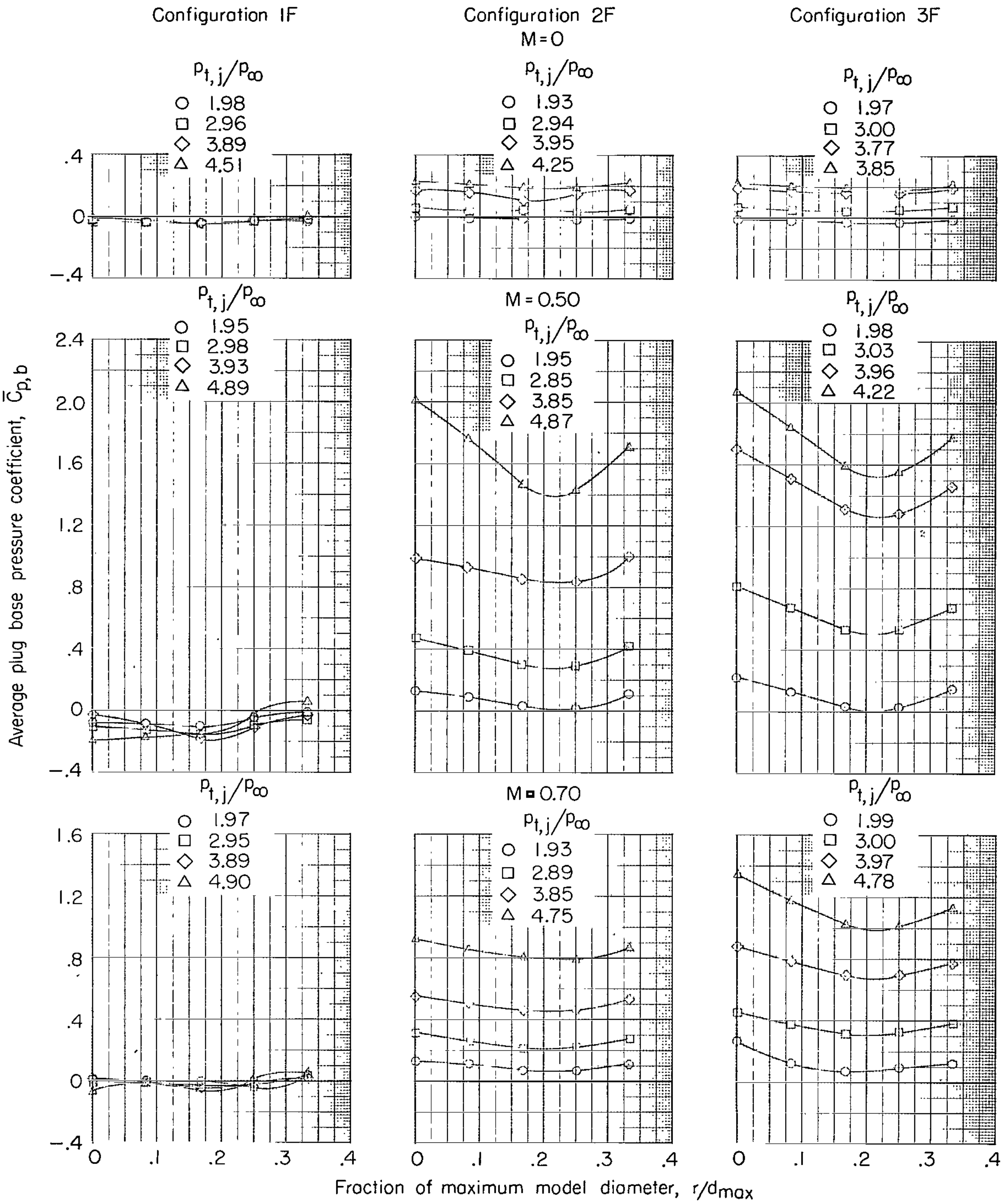


Plug coordinates							
x	r_1	r_2	r_3	x	r_1	r_2	r_3
4.32	3.05	—	—	8.38	4.88	4.39	1.27
5.34	3.12	—	—	8.64	5.03	4.62	1.09
5.59	3.15	—	—	8.89	5.21	4.80	.94
6.10	3.30	—	—	9.15	5.28	4.95	.81
6.61	3.51	—	—	9.40	5.33	5.08	.66
6.86	3.63	—	—	9.65	5.36	5.13	.51
7.11	3.78	—	—	9.91	5.33	5.16	.41
7.37	3.91	—	—	10.16	5.31	5.16	.28
7.62	4.14	2.67	2.67	10.37	5.26	—	—
7.88	4.39	3.66	1.75	10.42	—	5.13	.13
8.13	4.67	4.09	1.50	10.67	—	—	.03

Orifice locations	
r	Row
0	Center
.64	112.5° and 292.5°
1.27	22.5° and 202.5°
1.91	112.5° and 292.5°
2.54	22.5° and 202.5°
5.08	22.5° and 202.5°

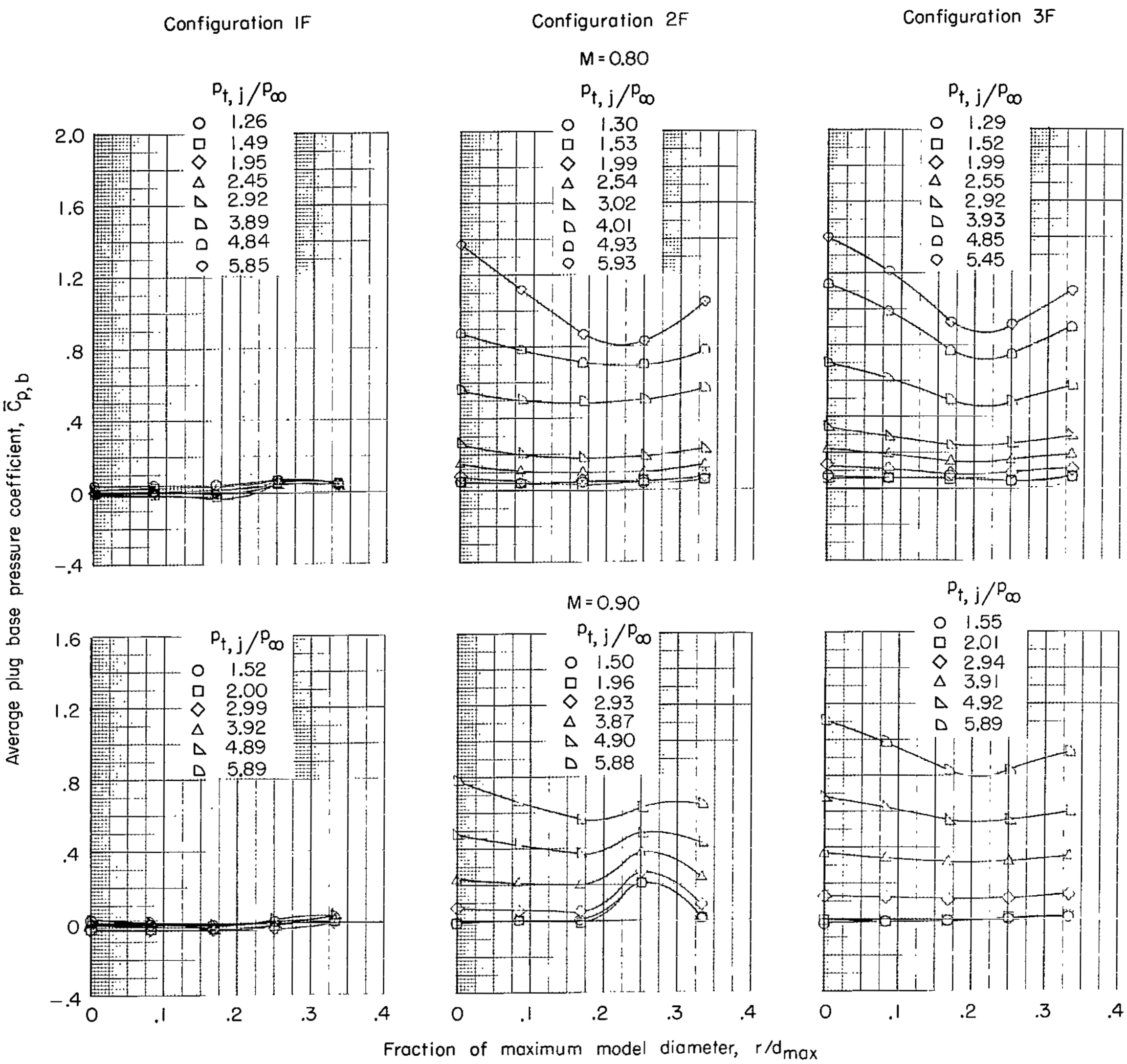
(b) Semitoroidal-base plug configurations (configuration 1S shown).

Figure 4.- Concluded.



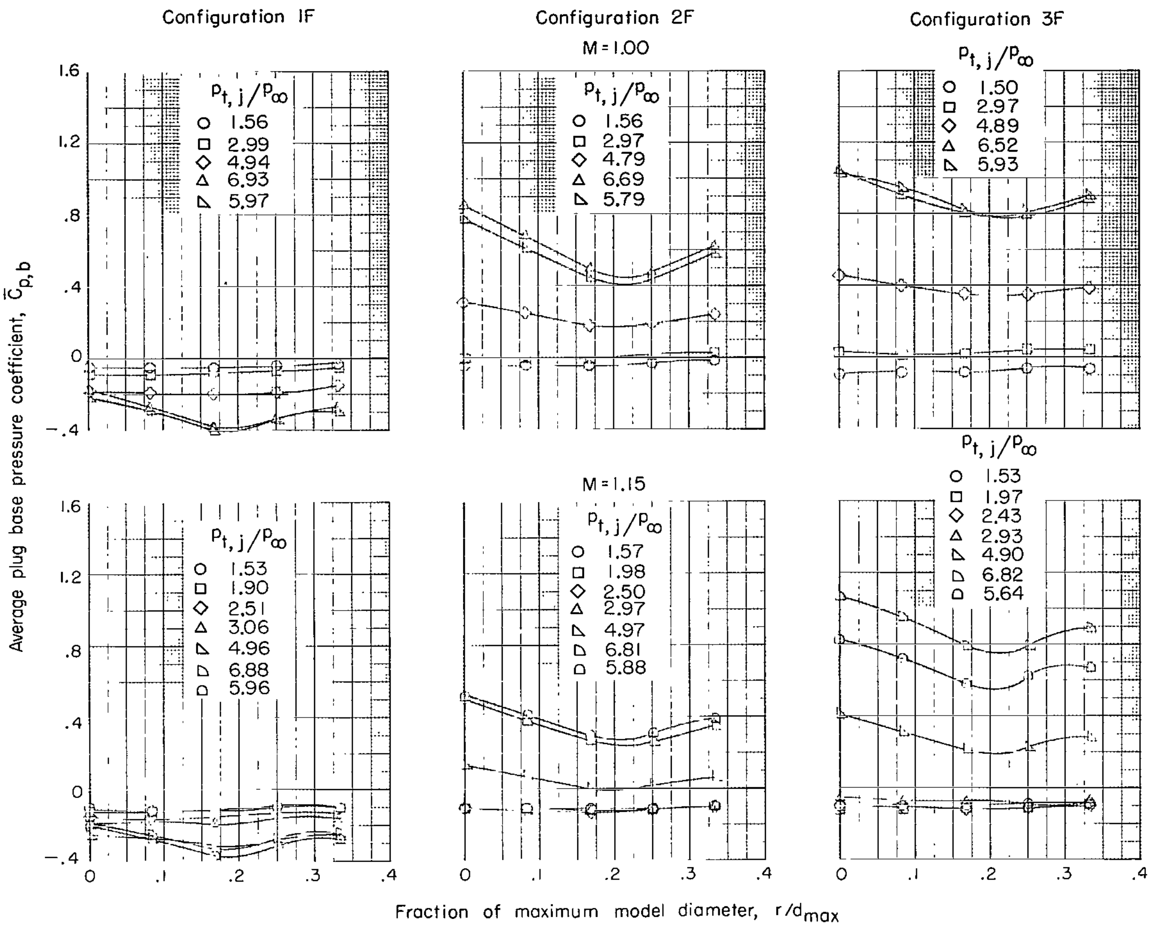
(a) M = 0, 0.50, and 0.70.

Figure 5.- Effect of jet total-pressure ratio on pressure distributions of flat-base plug at various Mach numbers.



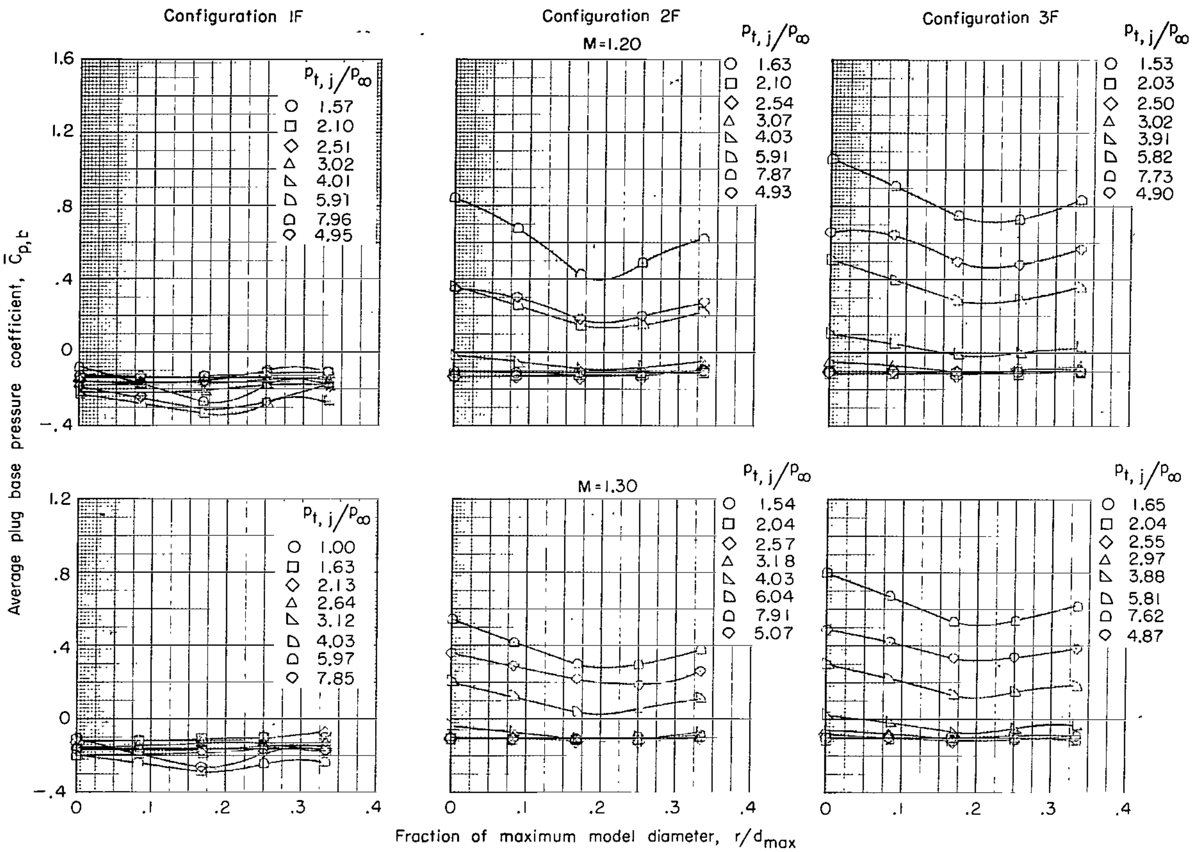
(b) M = 0.80 and 0.90.

Figure 5.- Continued.



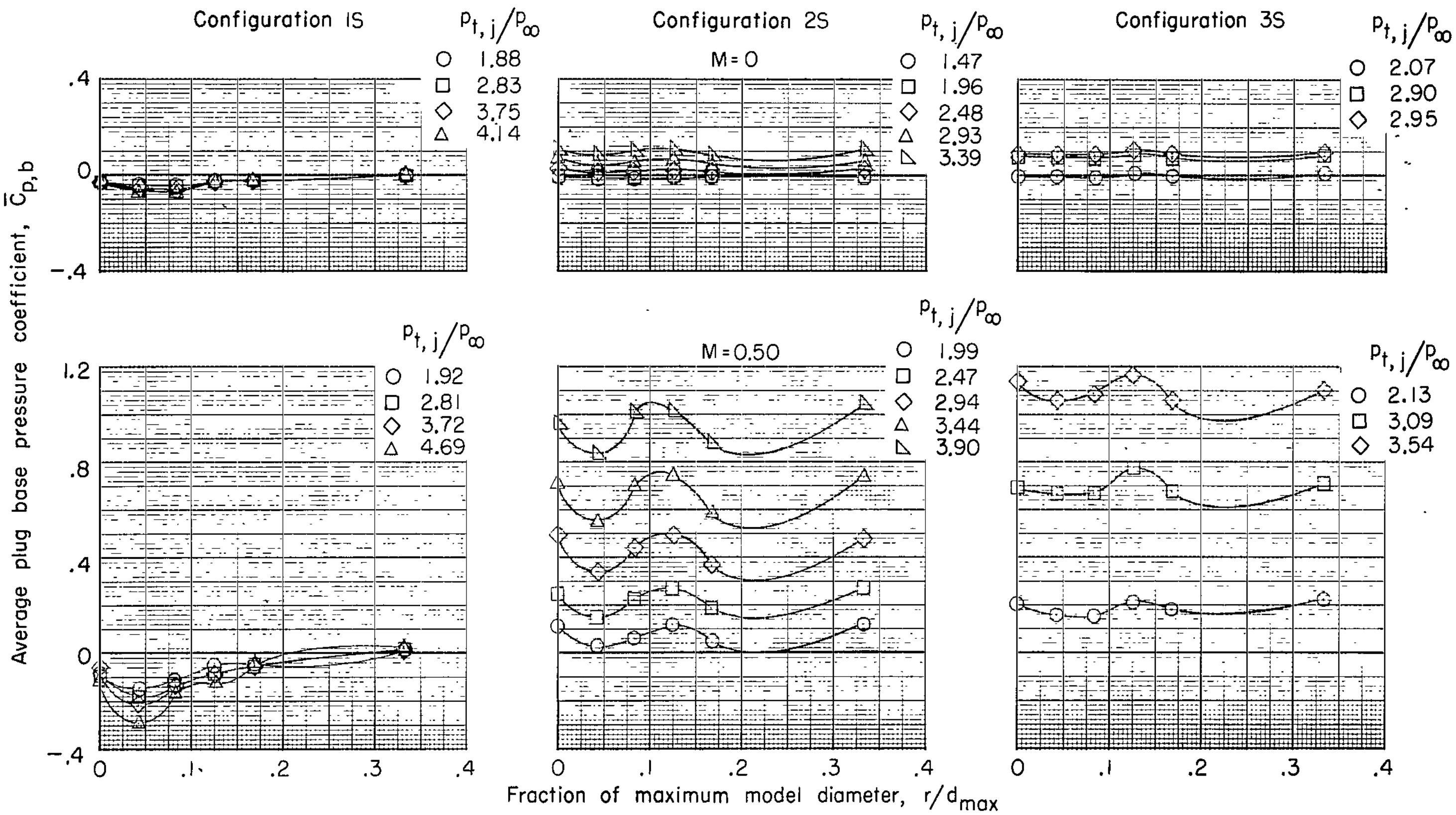
(c) M = 1.00 and 1.15.

Figure 5.- Continued.



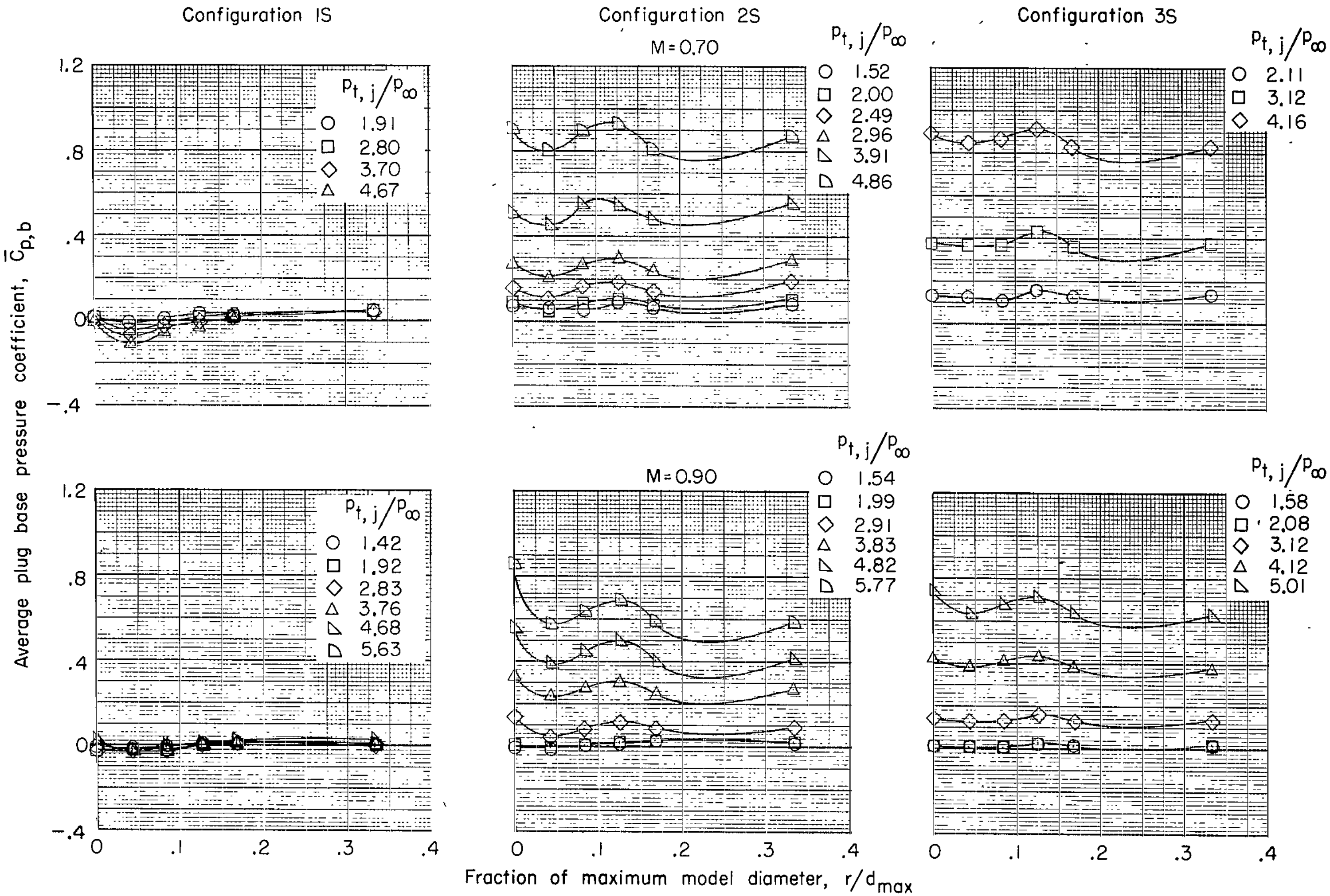
(d) M = 1.20 and 1.30.

Figure 5.- Concluded.



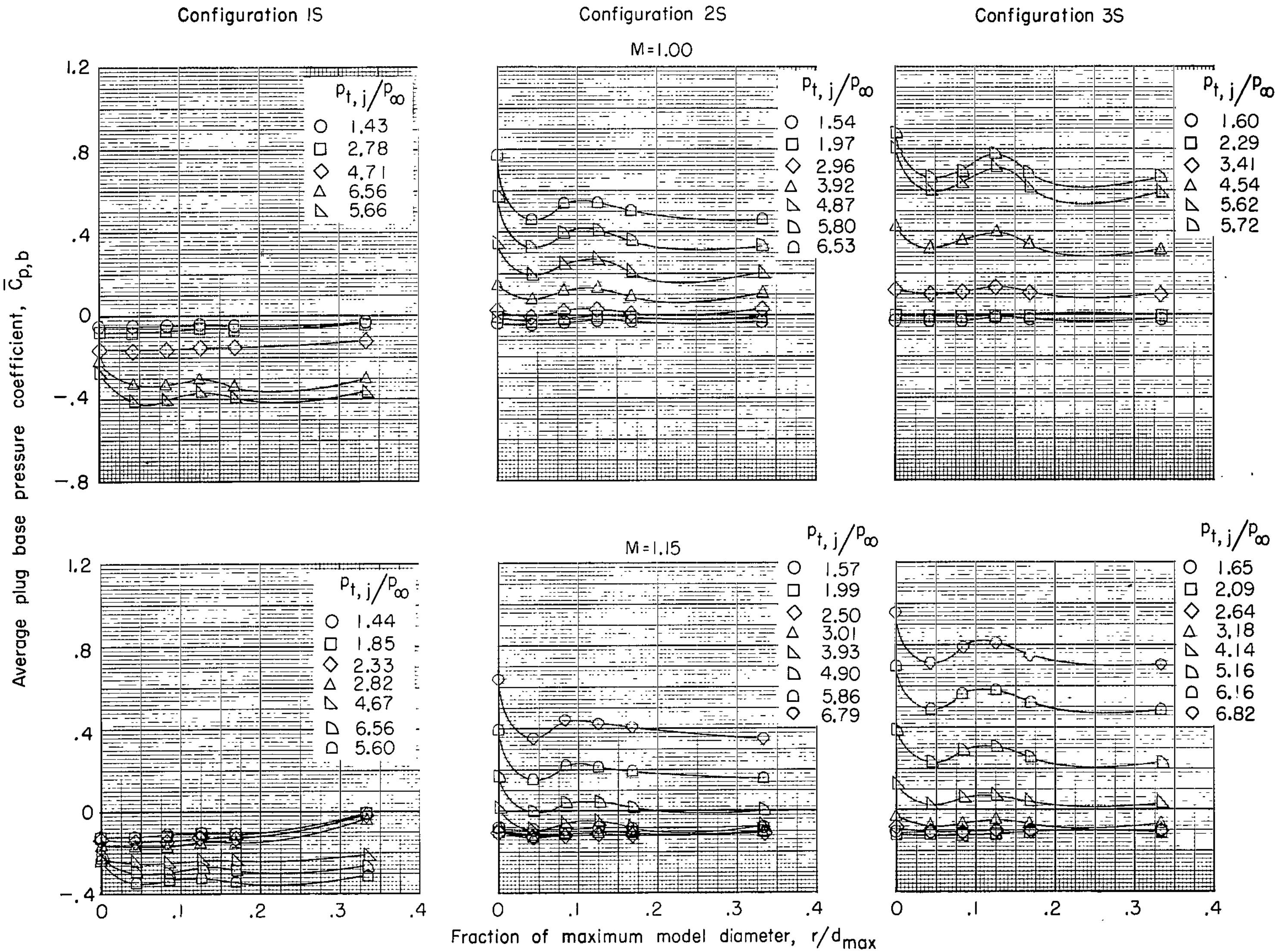
(a) M = 0 and 0.50.

Figure 6.- Effect of jet total-pressure ratio on pressure distributions of semitoroidal-base plug at various Mach numbers.



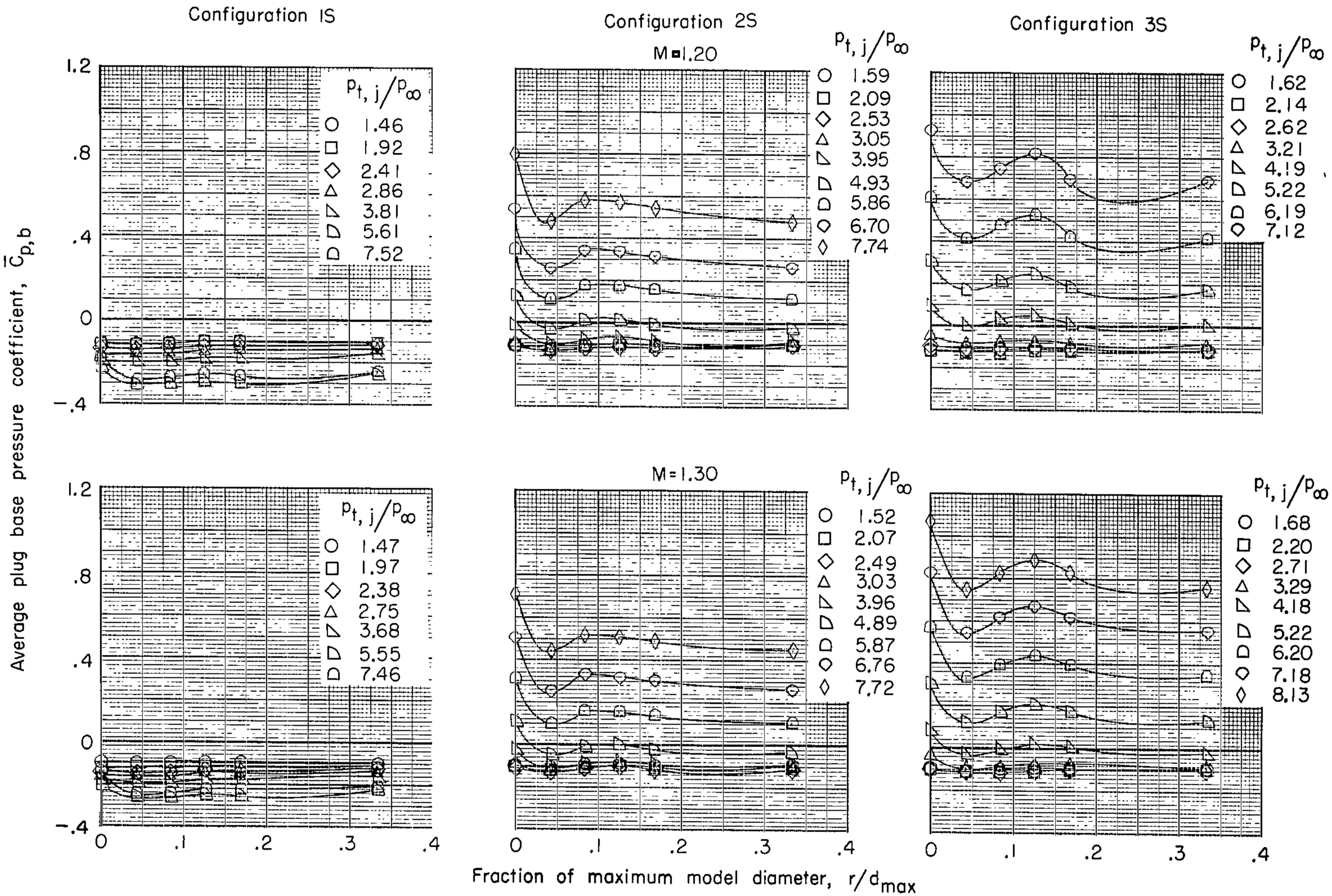
(b) M = 0.70 and 0.90.

Figure 6.- Continued.



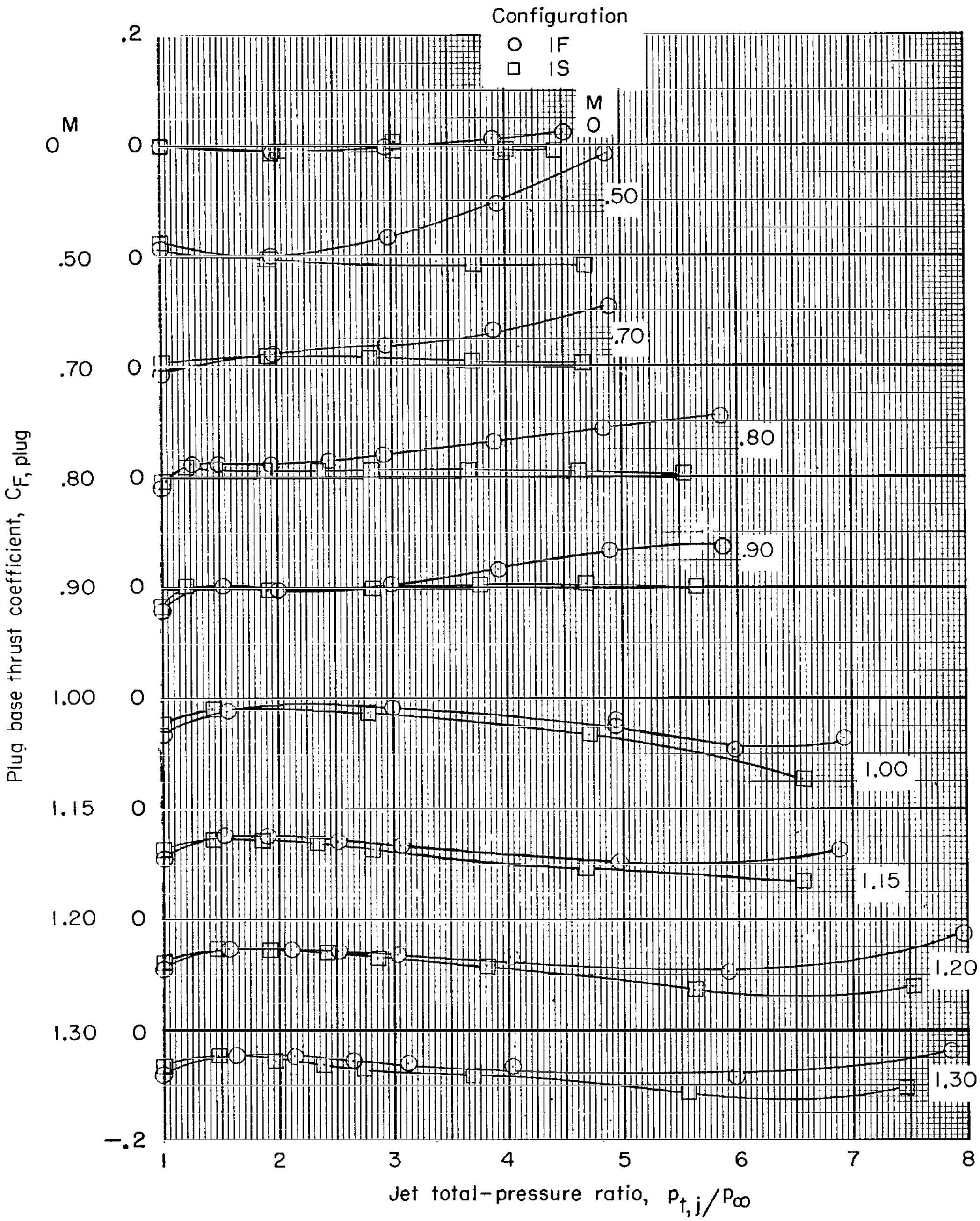
(c) M = 1.00 and 1.15.

Figure 6.- Continued.



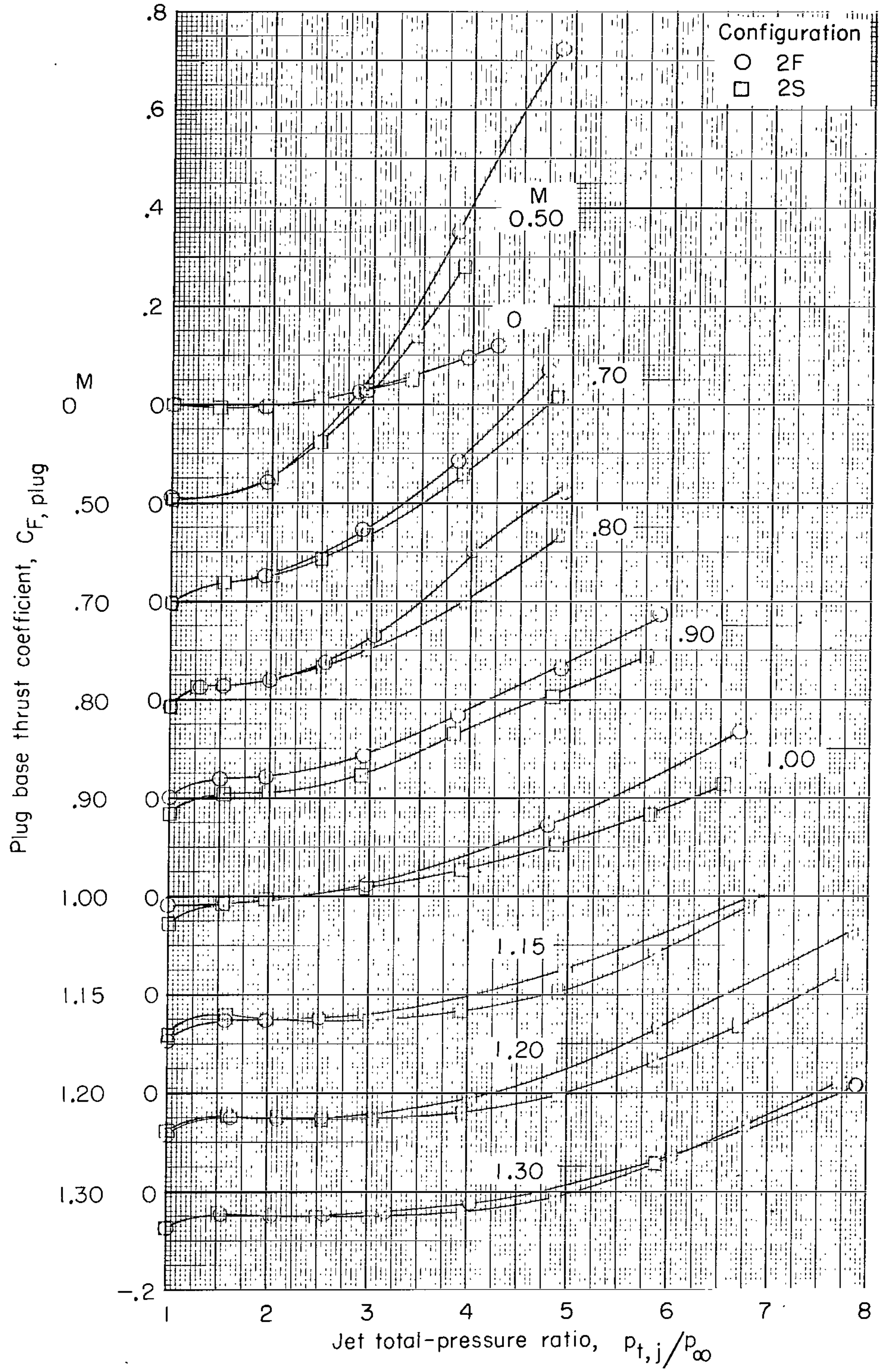
(d) M = 1.20 and 1.30.

Figure 6.- Concluded.



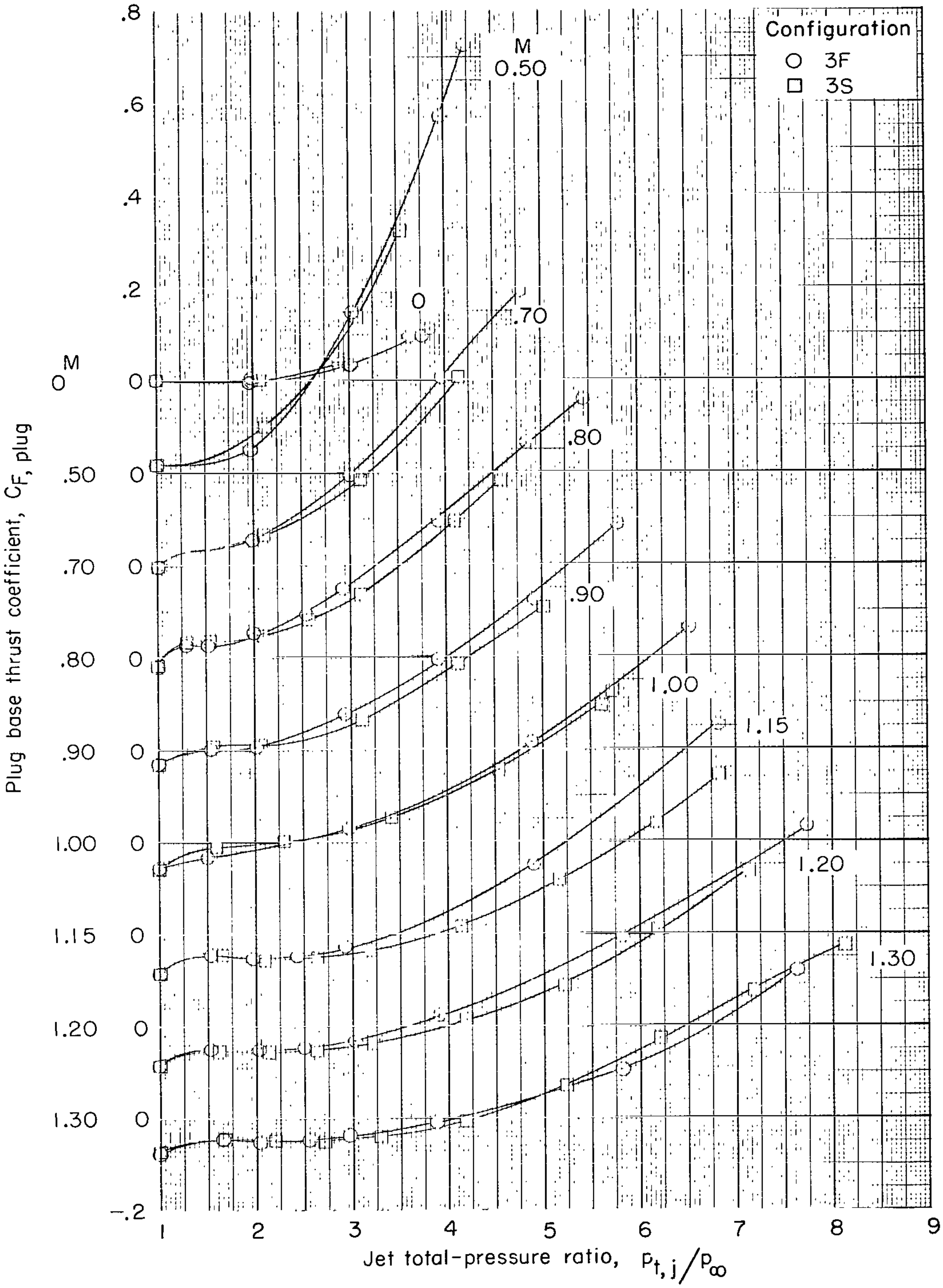
(a) Configurations 1F and 1S.

Figure 7.- Variation of plug base thrust coefficient with jet total-pressure ratio for various Mach numbers.



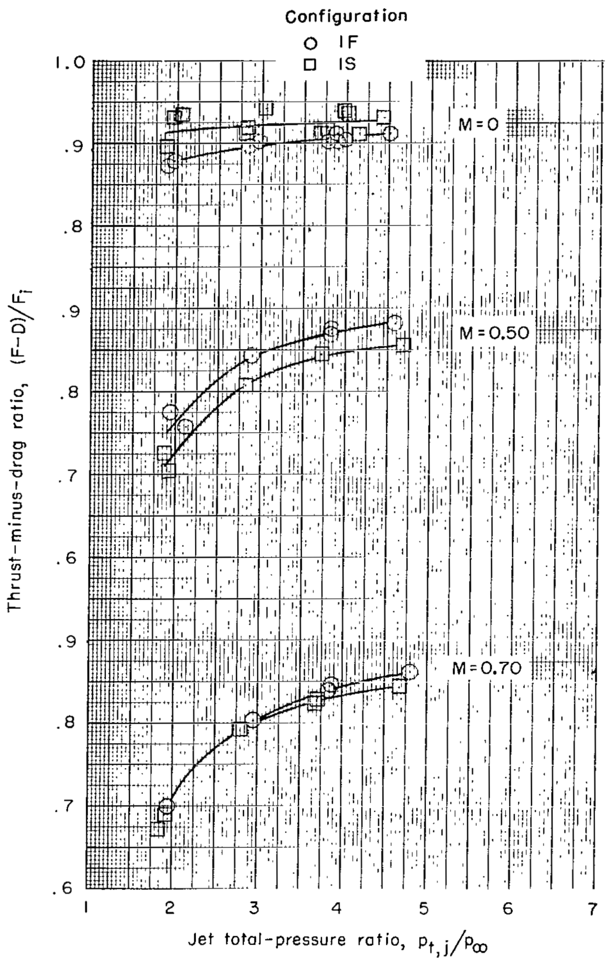
(b) Configurations 2F and 2S.

Figure 7.- Continued.



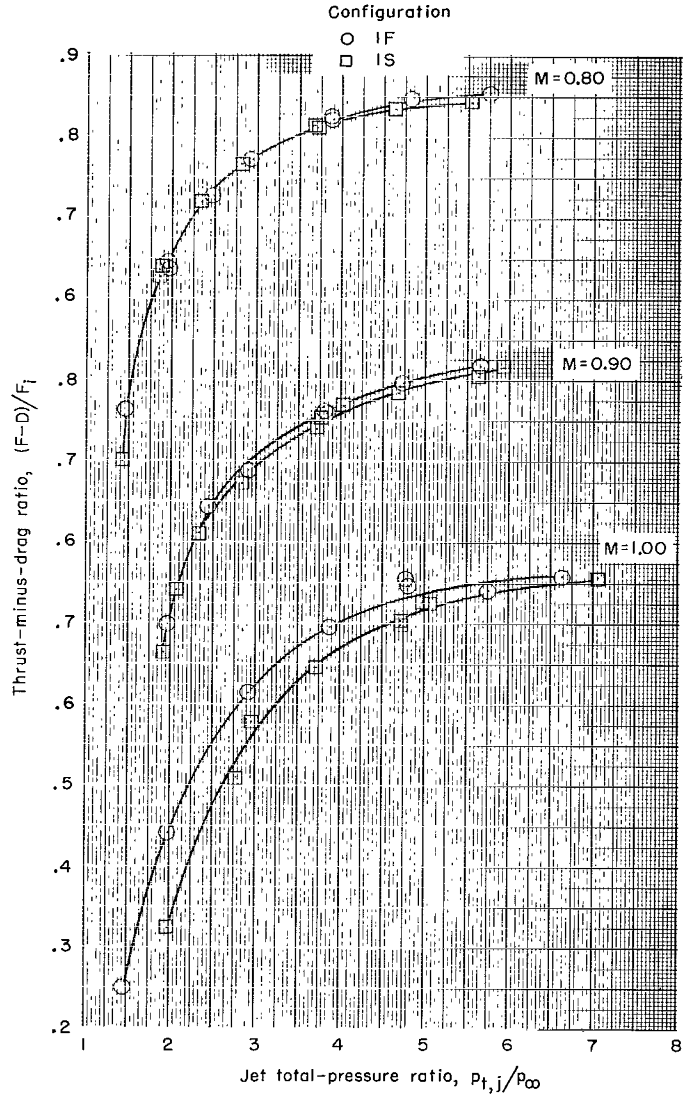
(c) Configurations 3F and 3S.

Figure 7.- Concluded.



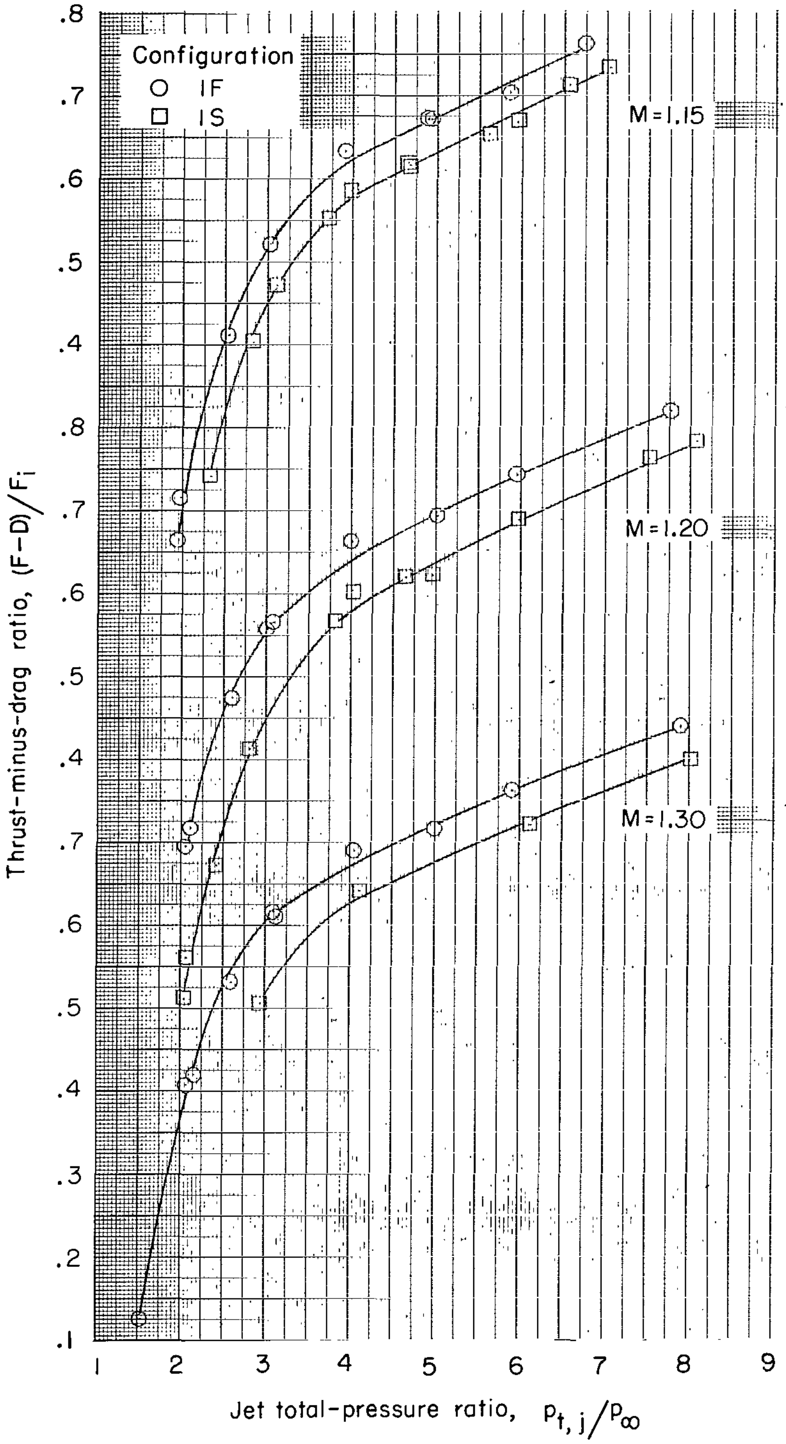
(a) M = 0, 0.50, and 0.70.

Figure 8.- Variation of thrust-minus-drag ratio with jet total-pressure ratio for shroud retracted.



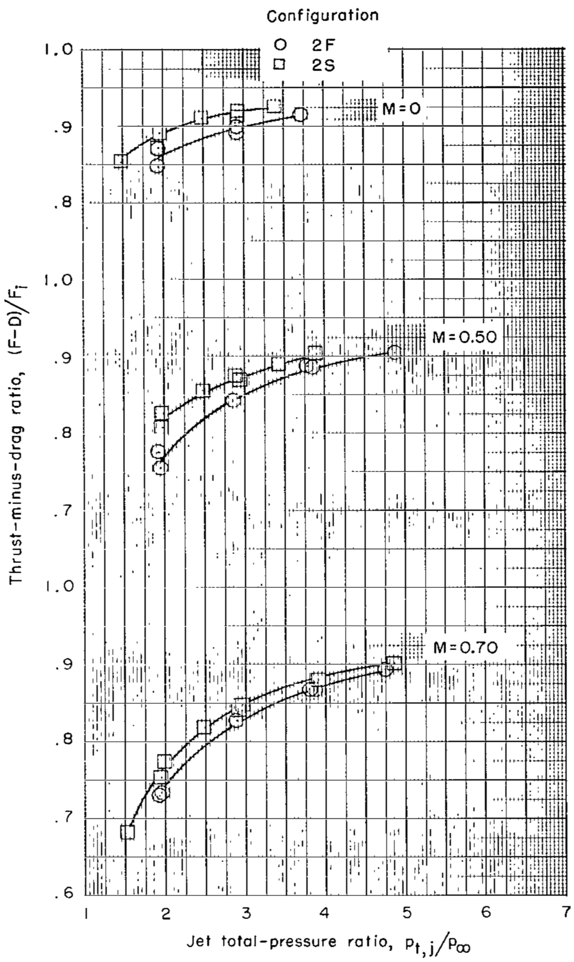
(b) M = 0.80, 0.90, and 1.00.

Figure 8.- Continued.



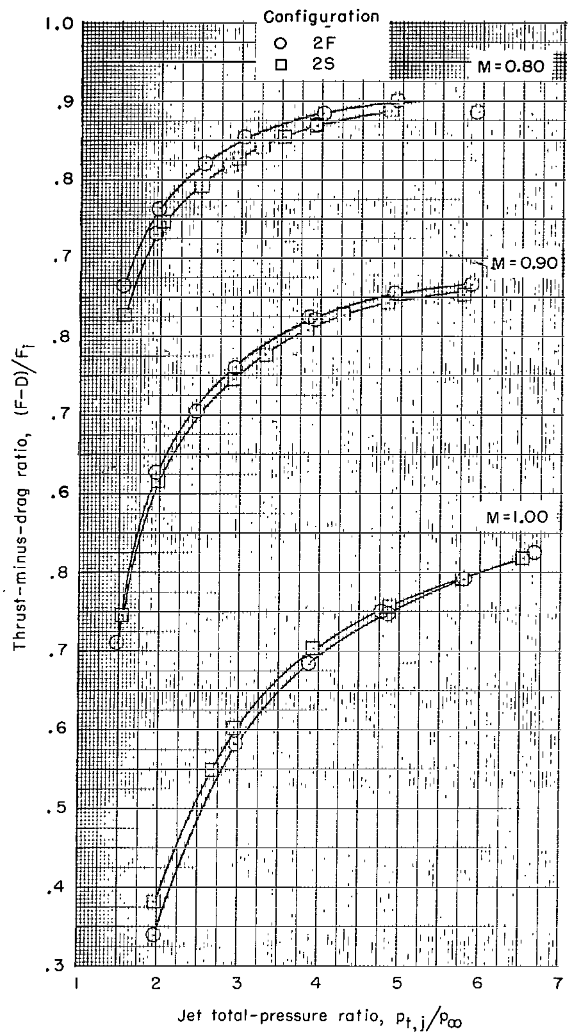
(c) M = 1.15, 1.20, and 1.30.

Figure 8.- Concluded.



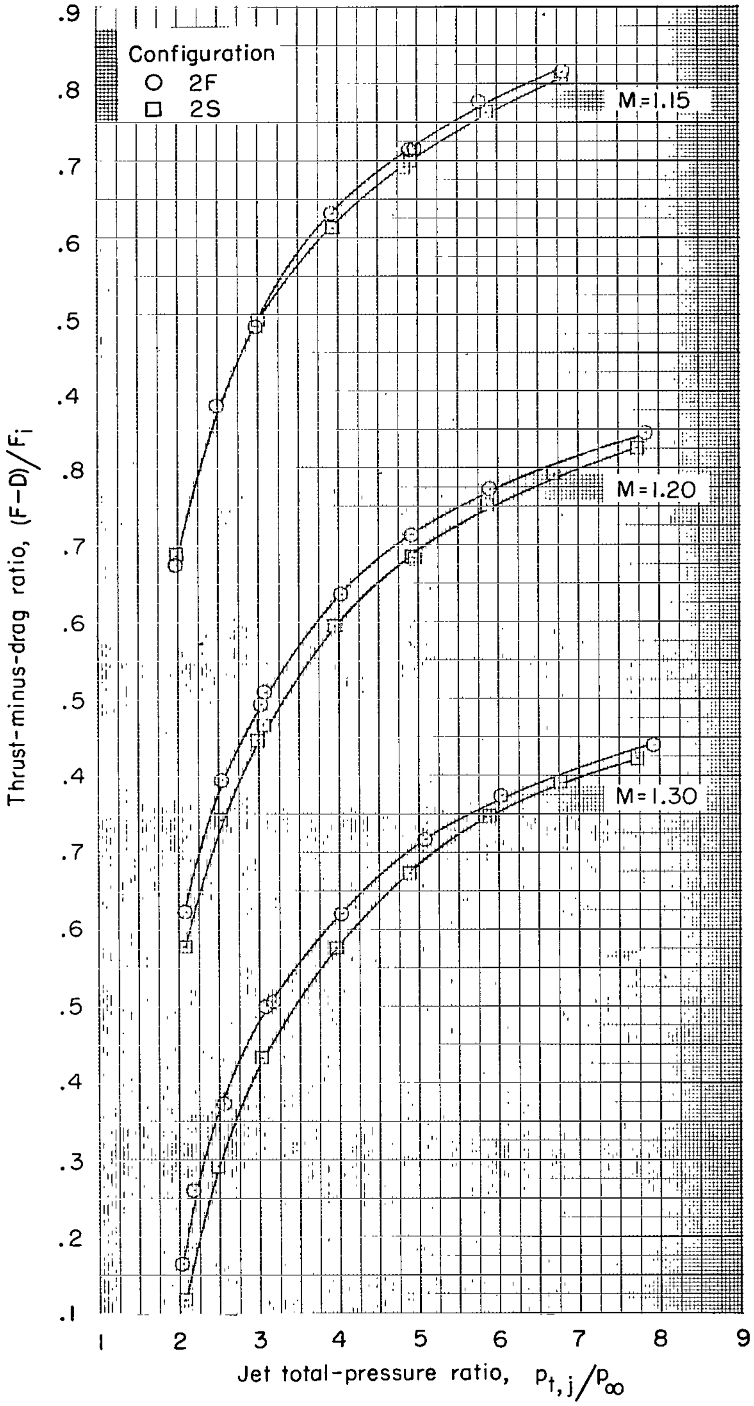
(a) M = 0, 0.50, and 0.70.

Figure 9.- Variation of thrust-minus-drag ratio with jet total-pressure ratio for shroud translated 1.27 centimeters.



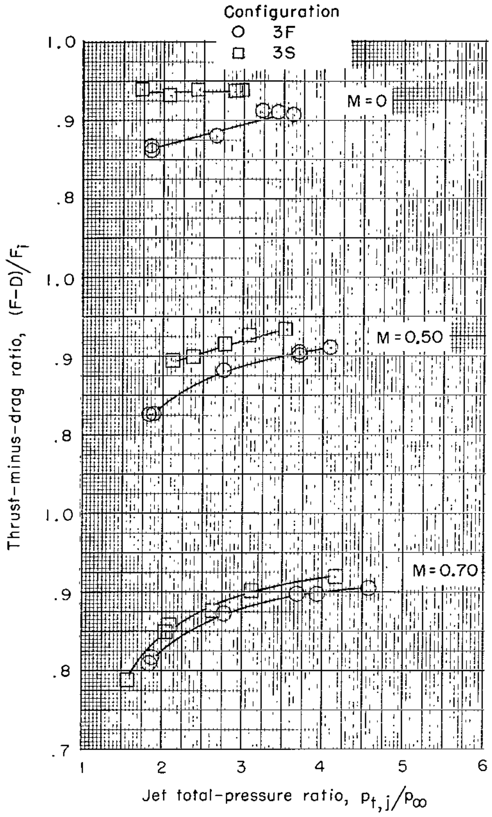
(b) M = 0.80, 0.90, and 1.00.

Figure 9.- Continued.



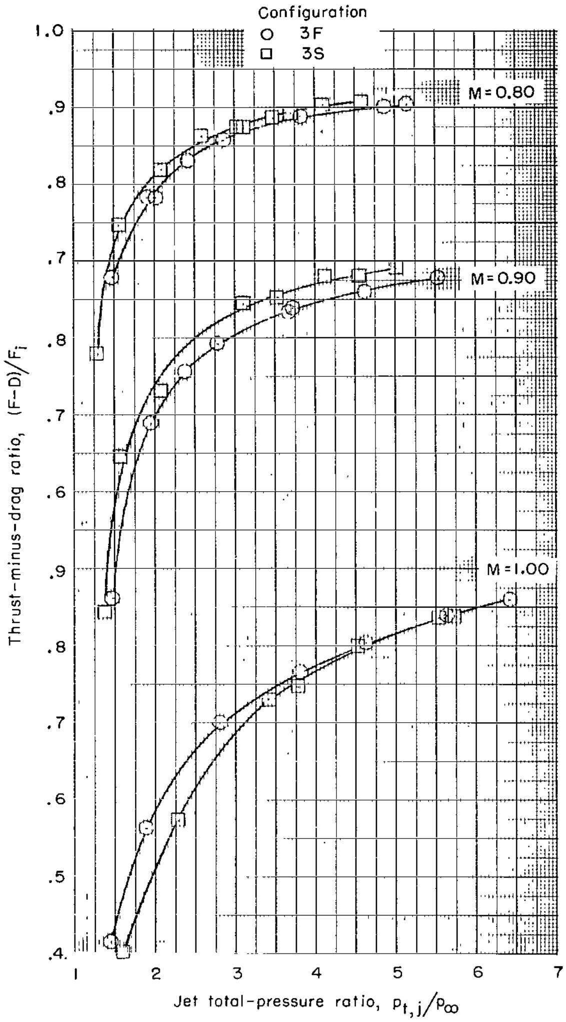
(c) M = 1.15, 1.20, and 1.30.

Figure 9.- Concluded.



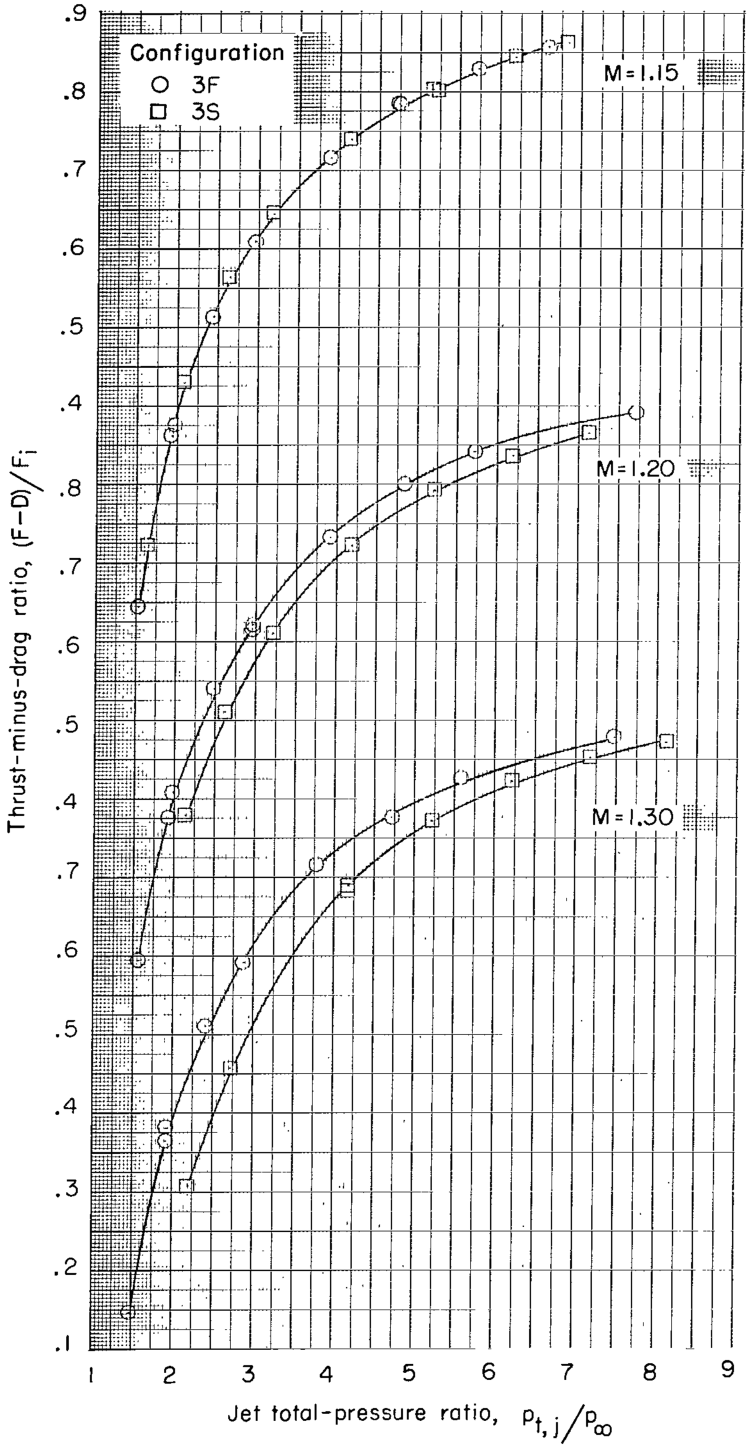
(a) M = 0, 0.50, and 0.70.

Figure 10.- Variation of thrust-minus-drag ratio with jet total-pressure ratio for shroud translated 1.905 centimeters.



(b) M = 0.80, 0.90, and 1.00.

Figure 10.- Continued.



(c) M = 1.15, 1.20, and 1.30.

Figure 10.- Concluded.

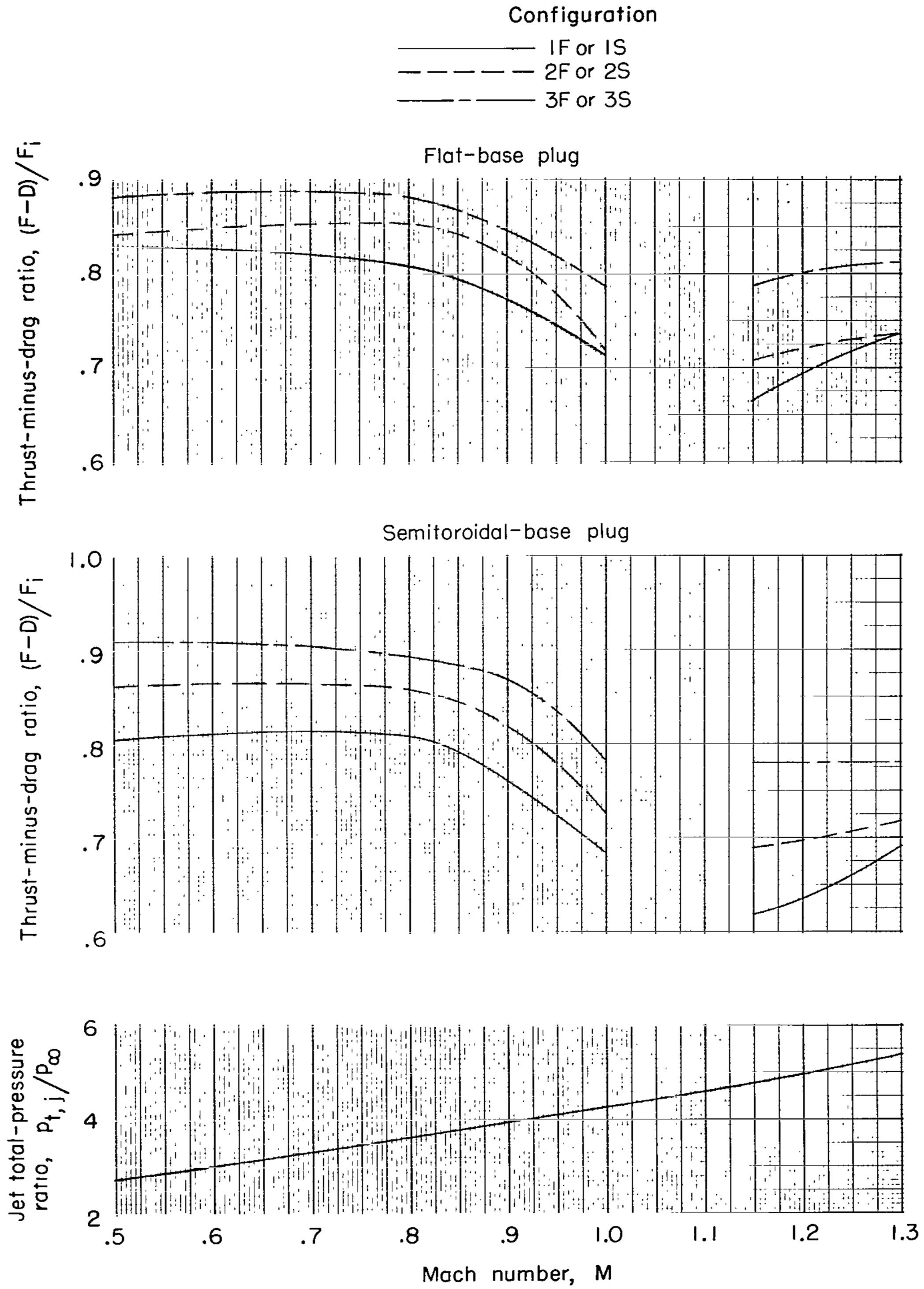


Figure 11.- Variation of thrust-minus-drag ratio with Mach number for typical turbojet total-pressure-ratio schedule.

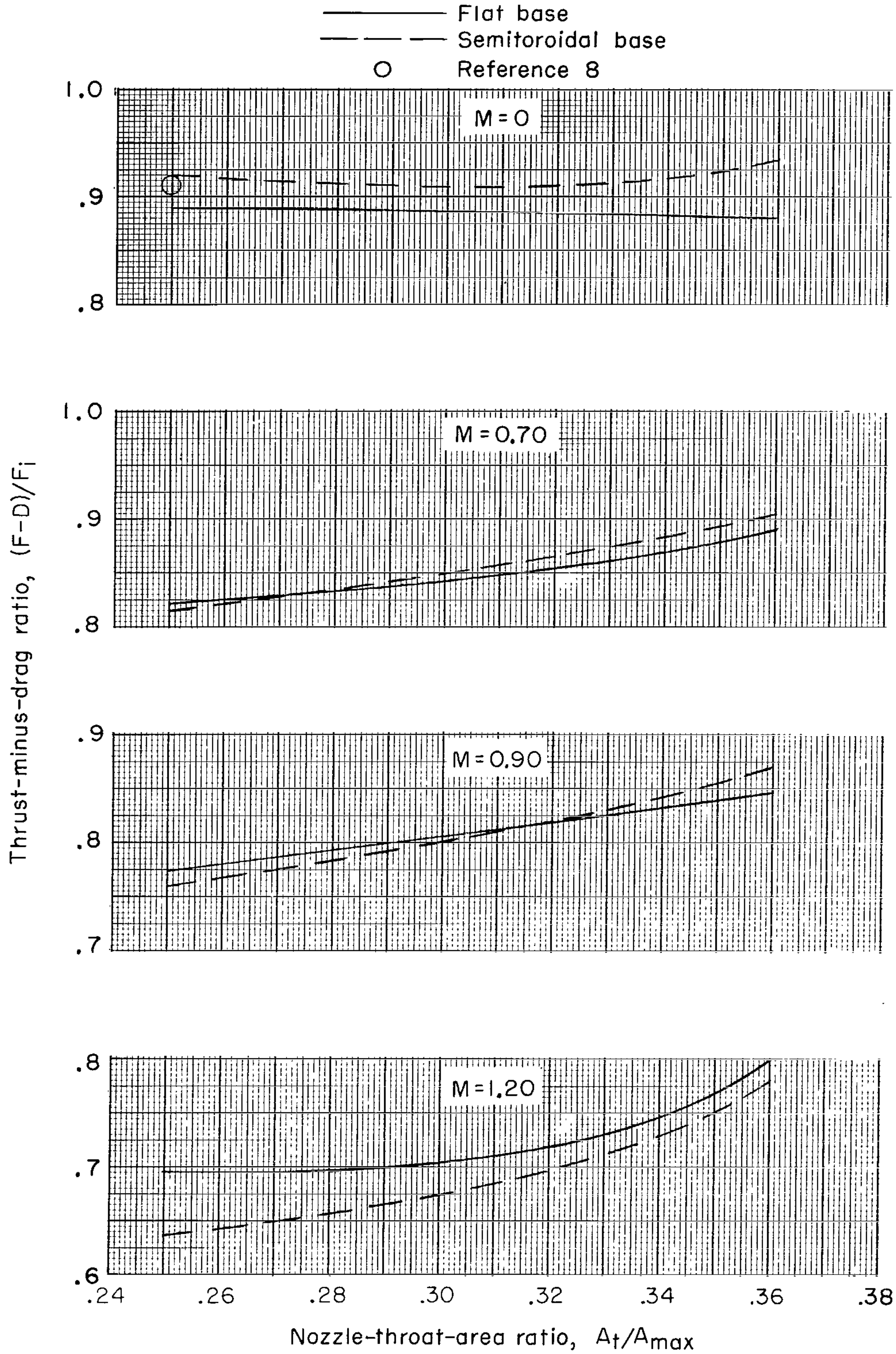


Figure 12.- Variation of thrust-minus-drag ratio with nozzle-throat-area ratio for several Mach numbers.

NASA-Langley, 1970 —— 28 L-6896

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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