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RESEARCH MEMORANDUM

COMPARISON OF TWO METHODS OF MODULATING THE THROAT AREA OF CONVERGENT PLUG NOZZLES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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COMPARISON OF TWO METHODS OF MODULATING THE THROAT AREA OF CONVERGENT PLUG NOZZLES

By H. George Krull and William T. Beale

SUMMARY

An investigation was conducted to determine the effect on performance of two methods (iris outer shell and translatable outer shell or translatable plug) of throat-area modulation of two convergent plug nozzles. These nozzles included a 30° conical plug nozzle and an isentropic plug nozzle. Data were obtained over a range of pressure ratios from about 1.5 to 30.

For a given outer-shell size, a nozzle with an iris outer shell provides higher thrust coefficients over a greater range of throat areas than a nozzle with a translatable outer shell. The peak thrust coefficients for the iris outer shell were insensitive to area modulation over the range covered (80 percent area change) while those of the translatable outer shell decreased at both the small and large throat areas. These decreases resulted from Prandtl-Meyer expansion losses at the small throat areas (throat located on curved portion of plug) and under expansion losses at the large throat areas. At the small throat areas, these losses can be alleviated, however, by increasing the size of both the outer shell and plug.

The effect of throat-area modulation on the internal performance characteristics was about the same for both the isentropic and the conical plug nozzles.

Based on an arbitrarily selected throat area, the flow coefficients for the configurations investigated varied from 0.80 to 0.94 when the flow was choked.

INTRODUCTION

The convergent plug nozzle has good thrust coefficients over a wide range of nozzle pressure ratios as shown in references 1 to 3. The peak thrust coefficients were as high as those of a convergent-divergent nozzle, and were relatively insensitive to nozzle pressure ratios below the design point.

The effect of plug design and outer shell design on plug nozzles of fixed design or given expansion ratio is presented in references 2 and 3, respectively. These data, however, did not show what the effect of throat-area variation, and hence changes in expansion ratio, would have on the performance of nozzles of given design.

This investigation was conducted to determine how throat-area modulation would affect the off-design performance of plug-type nozzles. The throat areas were varied by translating outer shells and by simulated iris outer shells.

The plug nozzles were investigated over a range of nozzle pressure ratios from 1.5 to 30. Two plug nozzles were investigated, an isentropic plug nozzle designed by the method of characteristics to provide axial flow at the discharge at a nozzle pressure ratio of 9.5 and a 30° conical plug nozzle. The ratio of the maximum throat area to the minimum throat area was as high as 2:1 for the configurations investigated.

APPARATUS AND INSTRUMENTATION

Nozzle Configurations

Both conical and isentropic plug nozzles were used in this investigation. Simulated iris and translatable outer shells were used to vary the throat area. Exploded views of the typical conical and isentropic plug nozzles are shown in figures 1(a) and (b), respectively. The aft section (downstream of the throat) of the isentropic plug was designed by the method of characteristics for a nozzle pressure ratio of 9.3. No boundary-layer correction was applied and the tail of the plug was cut off at a small diameter to reduce the length.

Outer shells with various exit angles were used to simulate the iris-type nozzles. The translatable outer-shell-type nozzles were simulated by insertion of spool pieces (fig. 1(a)) of various lengths, which changed the position of the outer-shell exit with respect to the plug. The dimensions of the parts of all configurations are given in table I.

Translatable outer-shell nozzles. - The nozzles used to study the effects of a translatable outer shell on the performance of the conical plug nozzle consisted of configurations 1 to 4 (table I(a)).

The effects of area modulation with a translating outer shell on the performance of the isentropic plug nozzle were investigated with configurations 8 to 10 (table I(b)).

The isentropic plug was modified to reduce the maximum diameter, as shown by the dashed line in table I(b). The performance of the modified plug with a translatable outer shell was shown by configurations 11 to 13.

Simulated iris-type nozzles. - The effect of area modulation with a simulated iris-type outer shell on the performance of the conical plug nozzle was studied with configurations 5 to 7.

The effect of simulated iris outer shell on the performance of the isentropic plug nozzle was shown by configurations 12, 14, and 15. The modified isentropic plug was used for these configurations.

Installation

The nozzles were installed in a test chamber that was connected to the laboratory combustion air and altitude-exhaust facilities as shown in figure 2. The nozzles were bolted to a mounting pipe that was freely suspended by four flexure rods connected to the bedplate. Pressure forces acting on the nozzle and mounting pipe, both external and internal, were transmitted from the bedplate through a flexure-plate-supported bell crank and linkage to a balanced-air-pressure diaphragm force-measuring cell. Pressure differences across the nozzle and mounting pipe were maintained by labyrinth seals around the mounting pipe that separated the nozzle inlet air from the exhaust. The space between the two labyrinth seals was vented to the test chamber. This decreased the pressure differential across the second labyrinth and prevented a pressure gradient on the outside of the diffuser section due to an air blast from the labyrinth seal.

Instrumentation

Pressures and temperatures were measured at the various stations that are indicated in figure 2. Total- and wall static-pressure measurements at station 1 were used to compare inlet momentum, and total- and static-pressure measurements (stream and wall static) at station 2 were used to compute air flow. Total pressure and temperature were measured at the nozzle inlet (station 3). Ambient-exhaust-pressure was provided at station 0, and a static-pressure survey was made on the outside walls of the bellmouth inlet.

PROCEDURE

Performance data for each configuration were obtained over a range of nozzle pressure ratios at a constant air flow. The nozzle inlet-air temperature was about 540° R and the nozzle pressure ratio was varied from about 1.5 to the maximum obtainable. Maximum pressure ratio varied from configuration to configuration because of the varying throat areas and the limiting air-handling capacity of the air supply and exhauster equipment. 3611

The thrust coefficient was calculated by dividing the actual jet thrust by the ideal thrust. The actual jet thrust was computed from the force measured by the balanced-air-pressure diaphragm and from pressure and temperature measurements made throughout the setup. The ideal jet thrust was calculated as the product of the measured mass flow and the isentropic jet velocity based on the nozzle pressure ratio and the inlet temperature. To simplify the use of the air-flow data, the throat area used in the calculation of the air-flow parameter was defined as the annulus area between the outer-shell exit and the plug in a plane perpendicular to the nozzle axis. The symbols and methods of calculation used in this report are presented in appendixes A and B, respectively.

DISCUSSION OF RESULTS

Performance of Translatable Outer-Shell-Type Plug Nozzle

Conical plug nozzles. - The thrust coefficient for a nozzle with a translatable outer shell and the conical plug are shown in figure 3(a) plotted against nozzle pressure ratio. Data are shown for relative throat areas from 0.72 to 1.4. Relative throat area is defined as the ratio of the effective throat area to the effective throat area of configuration 1. The effective throat area is the theoretical throat area for choked flow computed from air flow and nozzle-inlet total pressure and temperature. The effective throat area is tabulated in table I for each configuration.

The thrust coefficients were relatively insensitive to pressure ratio below the pressure ratio at which the peak thrust coefficients occurred. The peak thrust coefficients varied from 0.95 to 0.975. The thrust coefficient peaked at pressure ratios slightly above the pressure ratio corresponding to the expansion ratio of the nozzle (ratio of the outer-shell exit area to throat area A_s/A_t). Translating the shell toward the plug tip to increase the nozzle flow area decreased the expansion ratio; consequently, the peak thrust coefficients occurred at lower pressure ratios. Translating the outer shell toward the maximum diameter of the plug, which increased the expansion ratio, lowered the peak thrust coefficients because of a Prandtl-Meyer expansion induced by the curved portion of the plug (see refs. 2 and 3). This condition also increased the over-expansion losses.

Isentropic plug nozzle. - The effect of a translatable outer shell on the performance of the isentropic plug nozzle is shown in figure 3(b). The relative throat area (effective throat area/effective throat area of configuration 8) was varied from 0.80 to 1.22. The peak thrust coefficients for these configurations varied from 0.97 to 0.985, which was 1 or 2 percentage points higher than those for the conical plug nozzle. The thrust characteristics were the same as those for the conical plug nozzle except that the peak thrust coefficient did not drop off as much when the outer shell was translated toward the maximum diameter of the plug. This is a result of the more gradual curvature of the isentropic plug contour approaching the maximum diameter. As the curvature of the plug becomes more gradual, the maximum diameter increases.

The basic isentropic plug was modified to reduce the maximum diameter. The plug contour approaching the hump was redesigned with a greater rate of curvature as is shown by the dashed line in table I(b). The effect of the modified isentropic plug on the performance of a translatable outer-shell-type nozzle is shown in figure 3(c). The thrust coefficient is plotted against pressure ratio for a range of relative throat areas (effective throat area/effective throat area of configuration 12) from 0.71 to 1.25. The performance of the modified plug was the same as that of the basic isentropic nozzle for the design condition (relative throat area, $A_r = 1.00$). A greater decrease in thrust coefficient is shown, however, when the outer-shell exit is moved towards the maximum diameter of the plug because of the increased rate of curvature of the plug contour.

Performance of Iris-Outer-Shell-Type Plug Nozzles

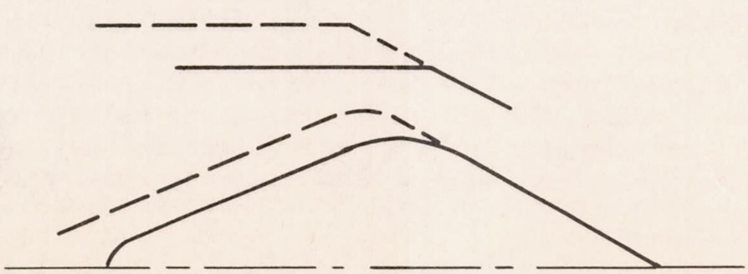
Conical plug nozzles. - The performance characteristics of a conical plug nozzle with an iris-type outer shell are shown in figure 4(a). Thrust coefficient is plotted against nozzle pressure ratio for a range of relative throat areas (effective throat area/effective throat area of configuration 1) from 0.78 to 1.41. The thrust coefficients were relatively insensitive to pressure ratio below the pressure ratio at which the peak thrust coefficient occurred. The thrust coefficients varied between 0.97 and 0.975. For this nozzle, as for the translatable-type outer-shell nozzle, the thrust coefficient peaked at pressure ratios slightly above the pressure ratio corresponding to the expansion ratio. In contrast to the performance of the translatable-type nozzle, there were no losses in peak thrust coefficient with the iris outer shell for variations in throat area. This improvement in performance results from the fact that the throat was always downstream of the curved section of the plug. The peak thrust coefficients occurred at lower pressure ratios as the throat area was increased because the expansion ratio decreased.

Isentropic plug nozzle. - The performance of the modified isentropic plug with a simulated iris-type outer shell is presented in figure 4(b). The thrust coefficient is plotted against nozzle pressure ratio for relative throat areas (effective throat area/effective throat area of configuration 12) from 0.87 to 1.28. The thrust characteristics for the modified isentropic plug were the same as those for the conical plug except that the peak thrust coefficients were 1/2 to 1 percentage point higher.

Sensitivity to Throat-Area Variation 3611

A comparison of the performance obtainable from the conical plug nozzle with two methods of throat-area variation is shown in figure 5. A similar plot for the isentropic plug nozzle was not included because the performance characteristics are the same except that the thrust coefficient would be slightly higher for the isentropic plug. The thrust coefficients at a nozzle pressure ratio of 3 and 10 are shown in figures 5(a) and (b), respectively. The thrust coefficients obtained with the iris outer shell were almost independent of throat-area variation at both nozzle pressure ratios of 3 and 10. At a nozzle pressure ratio of 3, the thrust coefficients obtained with the translatable outer shell were lower than those obtained with the iris shell at the low relative throat areas because of the greater overexpansion losses. At a nozzle pressure ratio of 10, the thrust coefficients obtained with the translatable outer shell were lower than those obtained with the iris outer shell at both the low and high values of relative throat area. The decrease in thrust coefficient at the high relative throat areas was caused by underexpansion. The reason the translatable outer shell had greater underexpansion losses than the iris outer shell is shown in figure 5(c). The expansion ratio of the iris-outer-shell nozzle varied less with throat-area modulation than the translatable outer shell.

From the foregoing it can be seen that in order to avoid serious losses in performance with a translatable outer shell, the throat must always be located downstream of the curved section of the plug. If serious thrust losses are to be avoided, a translatable outer-shell nozzle that is designed for the maximum throat area of a given flight plan would have to have a larger outer shell and plug than an iris-type nozzle. This is shown by the following sketch.



The solid line represents a nozzle that is designed for a given pressure ratio and maximum throat area. To provide a minimum outer-shell diameter, the flow area at the maximum diameter of the plug should just equal the throat area (see ref. 2) and the throat area should be just downstream of the curved section of the plug. Smaller throat areas with an iris nozzle can be obtained without serious performance penalties. In order to reduce the throat area with a translatable outer shell without performance losses the size of the plug and outer shell would have to be increased as shown by the dotted lines in the sketch. This increase would position the curved section of the plug further upstream and the throat would remain on the straight section of the plug as the exit was translated upstream. Therefore, for a given size outer shell the iris-type outer shell provides a greater range of throat areas without a serious penalty in performance.

Air-Flow Parameter

The corrected air-flow parameter for all configurations is plotted against nozzle pressure ratio in figure 6. The theoretical value of the air-flow parameter (0.344 lb/(sec)(sq in)) for choked flow is shown by a dashed line. The flow coefficients (ratio of experimental air-flow parameter to theoretical air-flow parameter) for these configurations varied from 0.80 to 0.985 when the flow was choked. To simplify the use of the air-flow data, the throat area used in the calculation of the air-flow parameter was defined as the annulus area between the outer-shell exit and the plug in a plane perpendicular to the nozzle axis (areas listed in table I). For most configurations this area was greater than the actual physical flow area, and consequently the flow coefficients were lower than those for a simple convergent-divergent nozzle.

SUMMARY OF RESULTS

The effect of two methods of throat-area modulation (iris outer shell and translatable outer shell or plug) on the internal performance characteristics of two convergent plug nozzles was determined over a range of nozzle pressure ratios from 1.5 to 30. The two nozzles consisted of a 30° conical plug nozzle and an isentropic plug nozzle.

For a given size outer shell, a nozzle with an iris-type outer shell provided higher thrust coefficients over a greater range of throat areas than a nozzle with a translatable outer shell. The peak thrust coefficients obtained with the iris outer shell were insensitive to throat-area variation over the range covered (80 percent area change), while those of the translatable outer shell decreased at both the small and large throat areas. These decreases resulted from Prandtl-Meyer expansion losses at the small throat areas (throat located on curved portion of plug) and underexpansion losses at the large throat areas. At the small throat areas, these losses can be alleviated, however, by increasing the size of both the outer shell and plug.

The effect of throat-area modulation on the internal performance characteristics was about the same for both the isentropic and the conical plug nozzles.

When the flow was choked, the flow coefficients for the configurations investigated varied from 0.80 to 0.94. Use of the air-flow data was simplified by defining the throat area as the annulus between the outer shell exit and the plug in a plane perpendicular to the nozzle axis. For most configurations, this area was larger than the actual flow area, and consequently the flow coefficients were lower than those for a simple convergent-divergent nozzle. 3611

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 14, 1954

APPENDIX A

SYMBOLS

The following symbols are used in this report:

A'	inside area, sq ft
A_L	pipe area under labyrinth seal, sq ft
A_p	plug projected area, sq ft
A_r	relative throat area
A_s	exit area of outer shell, sq ft
A_t	throat area (annulus between outer-shell exit area and plug in plane perpendicular to plug axis), sq ft
$A_{t,i}$	effective throat area for choked flow computed from mass flow, total pressure, and temperature
C_T	thrust coefficient
F	thrust, lb
F_d	balanced-air-pressure-diaphragm reading, lb
g	acceleration due to gravity, 32.174 ft/sec^2
L_p	distance from maximum diameter of plug to downstream tip of plug
L_s	distance from maximum diameter of plug to outer shell exit
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
p_{bm}	integrated static pressure acting on outside of bellmouth inlet to station 2, lb/sq ft
R	gas constant, 53.3 ft-lb/(lb)(^{o}R) for air
T	total temperature, ^{o}R
V	velocity, ft/sec
W_a	measured air flow, lb/sec
γ	ratio of specific heats

δ ratio of total pressure at nozzle inlet to absolute pressure at NACA standard sea-level conditions

θ ratio of total temperature at nozzle inlet to absolute temperature at NACA standard sea-level conditions

$\frac{W_a\sqrt{\theta}}{A_t\delta}$ corrected air-flow parameter, lb/(sec)(sq in)

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Subscripts:

e nozzle exit

i ideal

j jet

0 exhaust or ambient

1 inlet

2 diffuser inlet

3 nozzle inlet

APPENDIX B

METHODS OF CALCULATION

Air flow. - The nozzle air flow was calculated as

$$W_{a,2} = \frac{p_2 A_2}{RT_3} \sqrt{\frac{2g\gamma}{\gamma - 1}\left[\left(\frac{P_2}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\left(\frac{P_2}{p_2}\right)^{\frac{\gamma-1}{\gamma}}}$$

where γ was assumed to be 1.4.

Thrust. - The jet thrust was defined as

$$F_j = \frac{W_{a,2}}{g} \overline{V}_e + A_s(\overline{p}_e - p_0)$$

where $\overline{V}_e$ and $\overline{p}_e$ are effective values. The actual jet thrust was calculated from the equation

$$F_j = \frac{W_{a,2}}{g} V_1 + p_1 A_1 - p_{bm} A_1 + A_L(p_{bm} - p_0) - F_d$$

where F_d was obtained from balanced-air-pressure measurements.

The ideally available jet thrust, which was based on measured mass flow, was calculated as

$$F_i = W_{a,2} \sqrt{\frac{2R}{g} \frac{\gamma}{\gamma - 1} T_3 \left[1 - \left(\frac{p_0}{P_3}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

Thrust coefficient. - The thrust coefficient is defined as the ratio of the actual to ideal jet thrust

$$C_T = \frac{F_j}{F_i}$$

REFERENCES

1. Ciepluch, Carl C., Krull, H. George, and Steffen, Fred W.: Preliminary Investigation of Performance of Variable-Throat Extended-Plug-Type Nozzles over Wide Range of Nozzle Pressure Ratios. NACA RM E53J28, 1954.

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

3. Krull, H. George, and Beale, William T.: Effect of Outer-Shell Design on Performance Characteristics of Convergent-Plug Nozzles. NACA RM E54K22, 1954.

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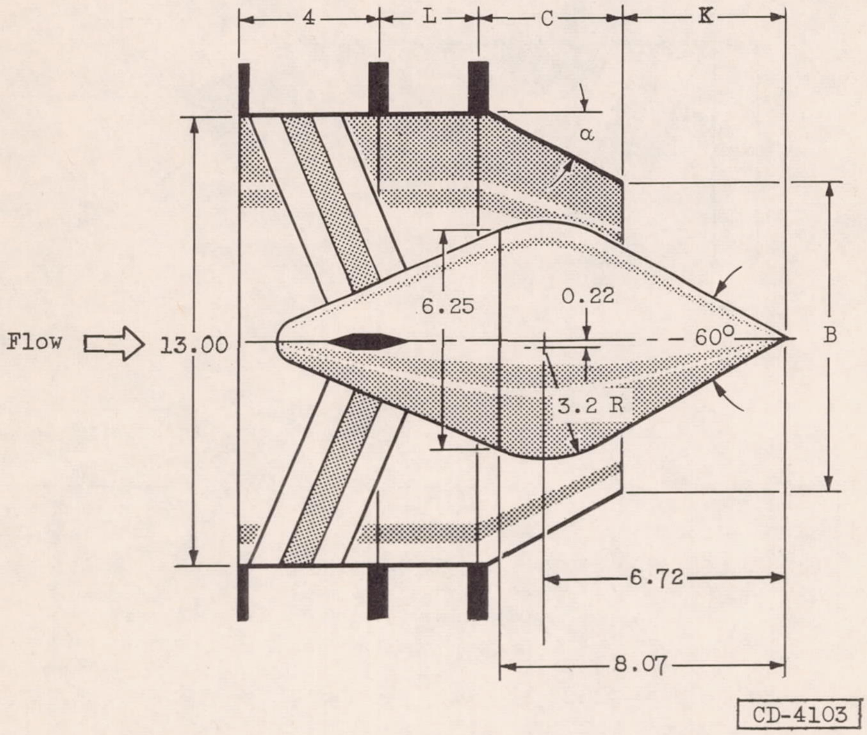
TABLE I. - DIMENSIONS OF NOZZLE CONFIGURATIONS

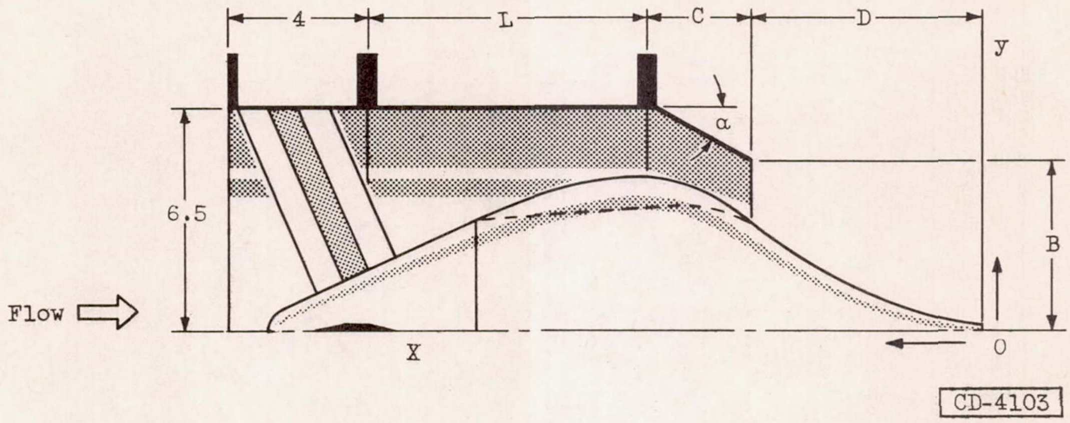
(a) Conical plug nozzle



Configuration	Expansion ratio, A_s/A_t	Isentropic pressure ratio corresponding to A_s/A_t, P_3/p_0	Effective throat area, $A_{t,i}$, sq in.	Throat area, A_t, sq in.	B, in.	C, in.	K, in.	L, in.	α
1	1.53	6.5	37.08	40.41	8.86	4.13	4.48	2.81	26° 40'
2	2.25	13.1	26.85	27.43	8.86	4.13	5.85	1.45	26° 40'
3	1.90	9.7	30.79	32.43	8.86	4.13	5.26	2.04	26° 40'
4	1.07	2.8	51.98	57.50	8.86	4.13	2.03	5.27	26° 40'
5	1.73	8.2	29.11	31.30	8.30	3.96	4.66	2.81	30° 40'
6	1.40	5.0	46.72	50.62	9.5	4.30	4.32	2.81	22° 8'
7	1.33	4.9	52.20	57.50	9.86	4.38	4.24	2.81	19° 40'

TABLE I. - Concluded. DIMENSIONS OF NOZZLE CONFIGURATIONS

(b) Isentropic plug



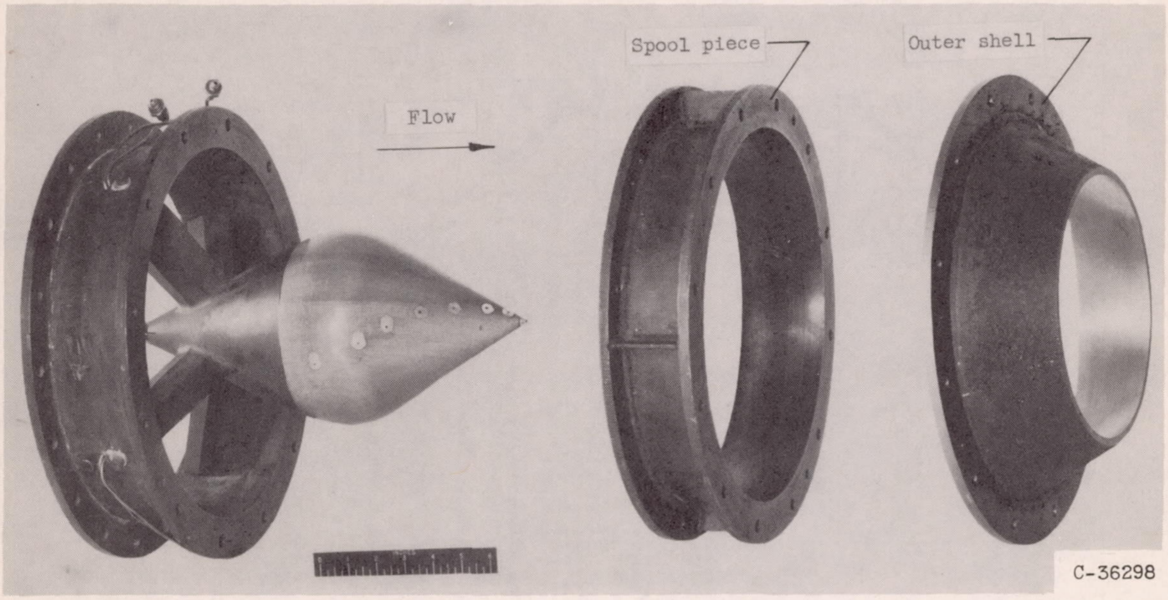
Basic plug (configurations 8-11)

x	y	x	y	x	y	x	y
0	0.18	3.50	1.09	7.00	3.14	10.50	4.50
.5	.25	4.00	1.30	7.40	3.52	11.00	4.42
1.00	.35	4.50	1.53	8.00	3.95	11.50	4.27
1.50	.47	5.00	1.79	8.50	4.20	12.00	4.05
2.00	.60	5.50	2.07	9.00	4.38	13.00	3.62
2.50	.74	6.00	2.39	9.50	4.42	14.00	3.17
3.00	.91	6.50	2.73	10.00	4.53	14.16	3.12

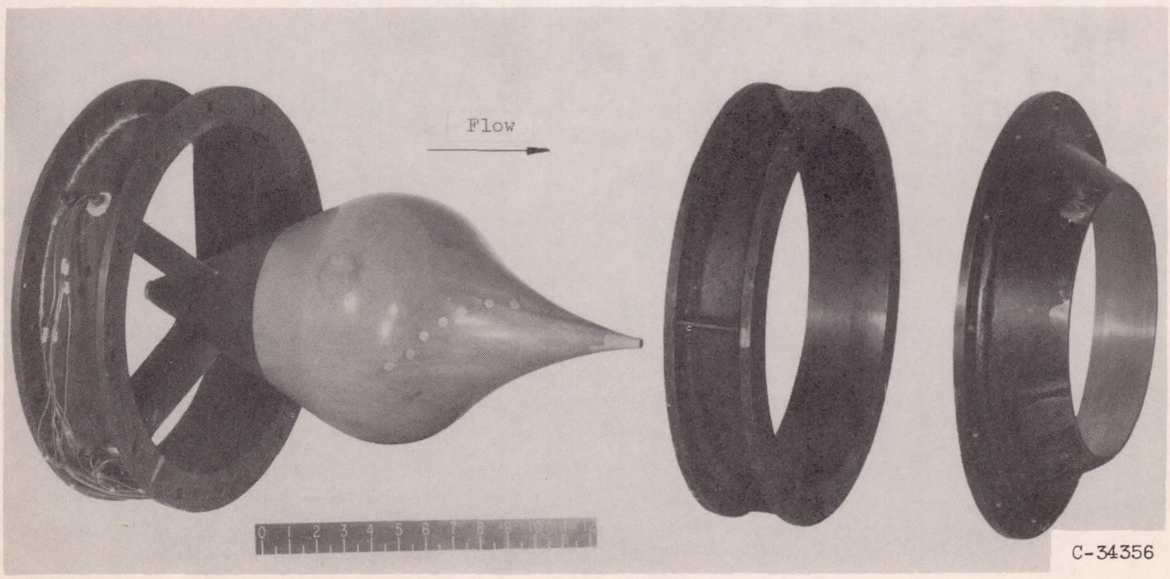
Modified plug (configurations 11-15) (shown by dashed line)

x	y	x	y
7	3.14	8.0	3.71
7.27	3.4	8.15	3.70
7.5	3.53	8.3	3.69
7.75	3.65	14.16	3.12

Configuration	Expansion ratio, A_s/A_t	Isentropic pressure ratio corresponding to A_s/A_t, P_3/p_0	Effective throat area, $A_{t,i}$, sq in.	Throat area, A_t, sq in.	B, in.	C, in.	D, in.	L, in.	α
8	1.55	6.2	38.00	45.3	4.73	2.98	6.57	7.87	30° 40'
9	1.87	9.4	30.51	37.46	4.73	2.98	7.10	7.36	30° 40'
10	1.18	3.7	46.37	59.49	4.73	2.98	5.84	8.60	30° 40'
11	2.37	14.2	27.83	29.57	4.73	2.98	7.62	6.77	30° 40'
12	1.5	6.2	39.13	46.87	4.73	2.98	6.48	7.91	30° 40'
13	1.24	4.2	48.76	56.70	4.73	2.98	5.50	8.90	30° 40'
14	1.63	7.3	33.96	40.16	4.56	2.88	6.60	7.89	34°
15	1.35	5.0	50.05	60.64	5.09	3.18	6.28	7.91	24°



(a) Conical plug nozzle.



(b) Isentropic plug nozzle.

Figure 1. - Exploded view of isentropic plug nozzle and conical plug nozzles.

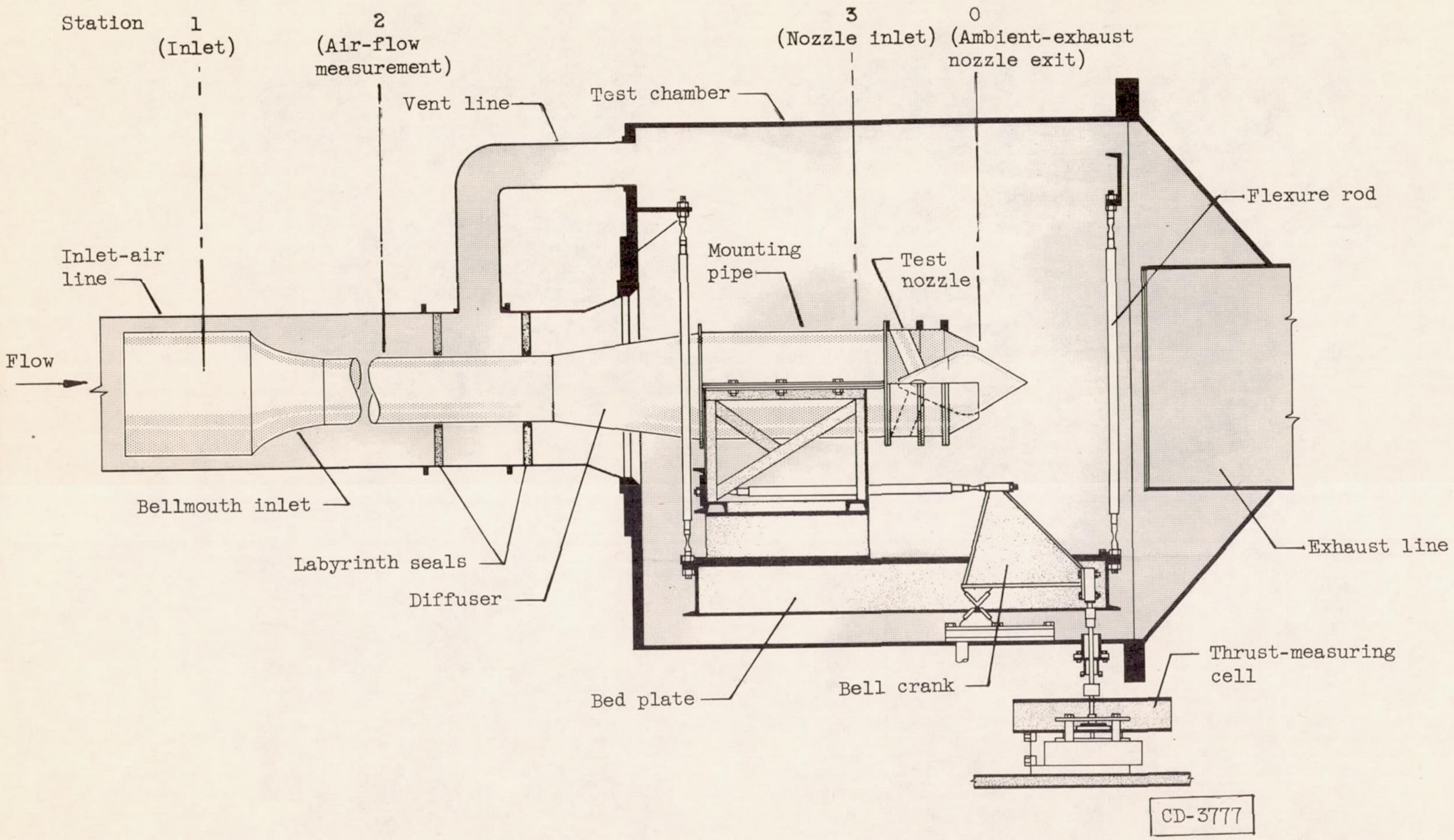
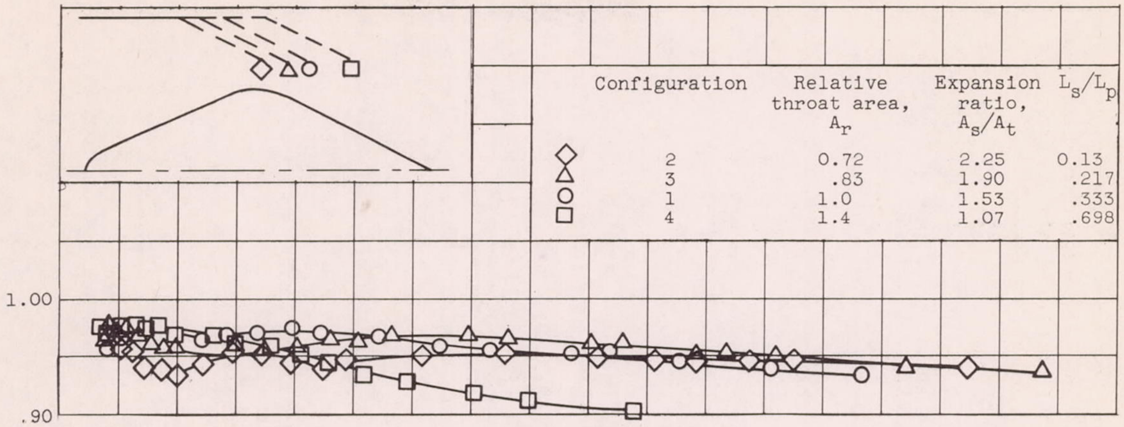
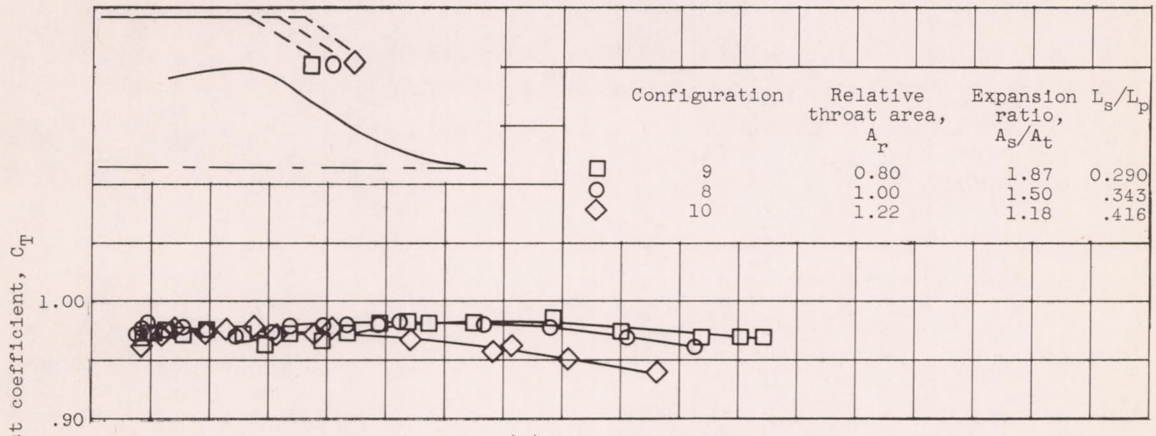


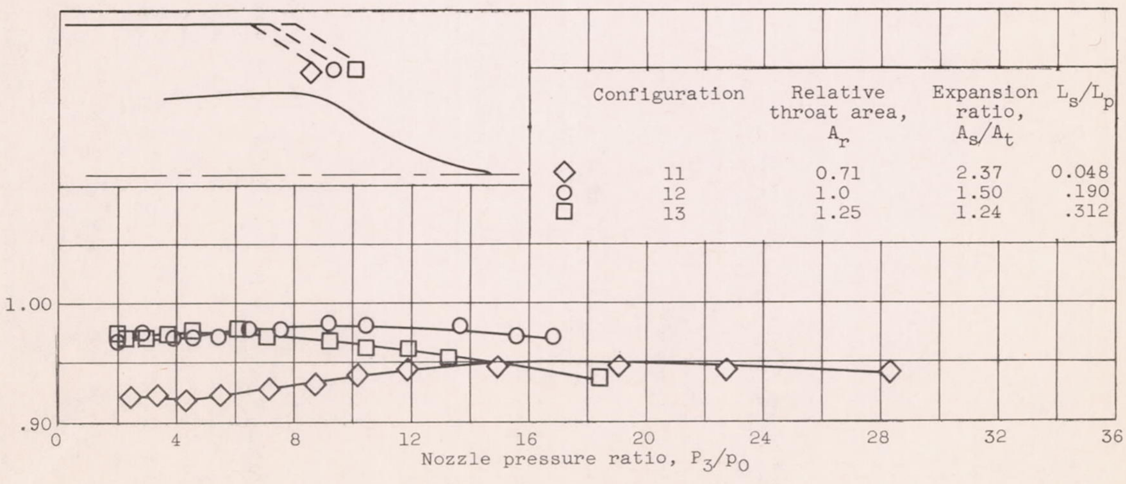
Figure 2. - Schematic drawing of nozzle in test chamber.



(a) Conical plug.

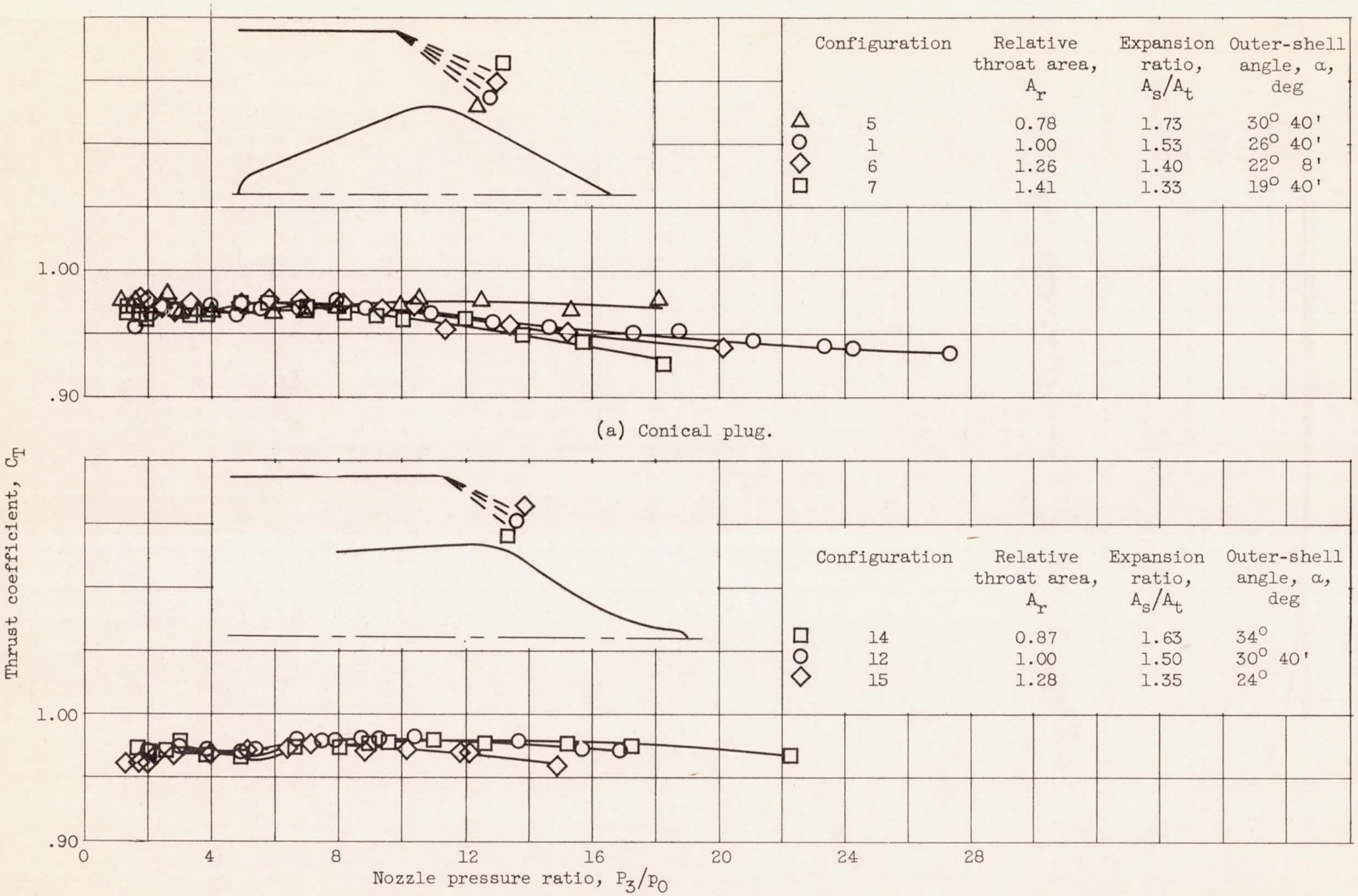


(b) Isentropic plug.



(c) Modified isentropic plug.

Figure 3. - Effect of throat-area modulation with translatable outer shell on performance of convergent plug nozzles.



(a) Conical plug.

(b) Modified isentropic plug.

Figure 4. - Effect of throat-area modulation with simulated iris outer shell on performance of convergent plug nozzles.

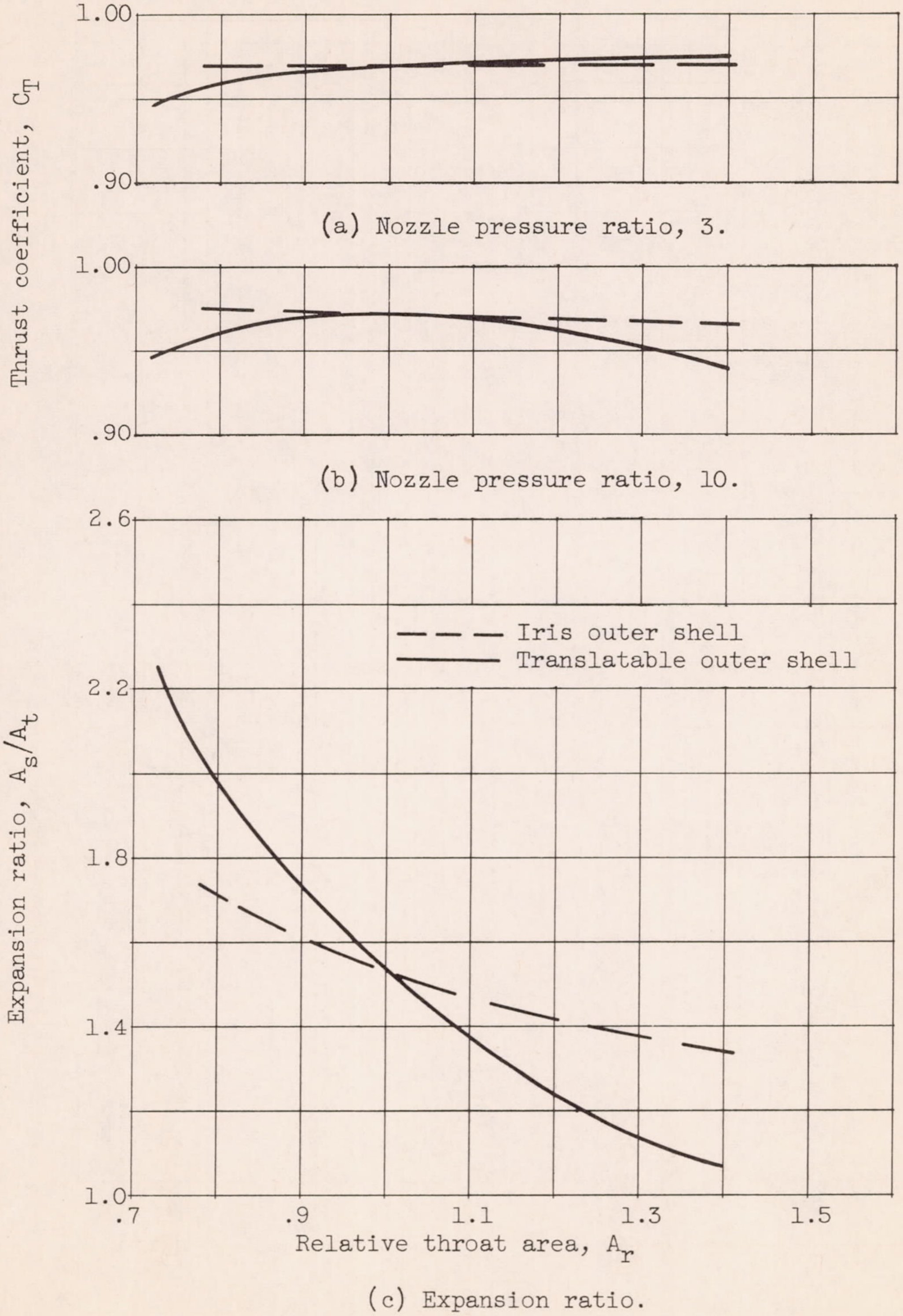
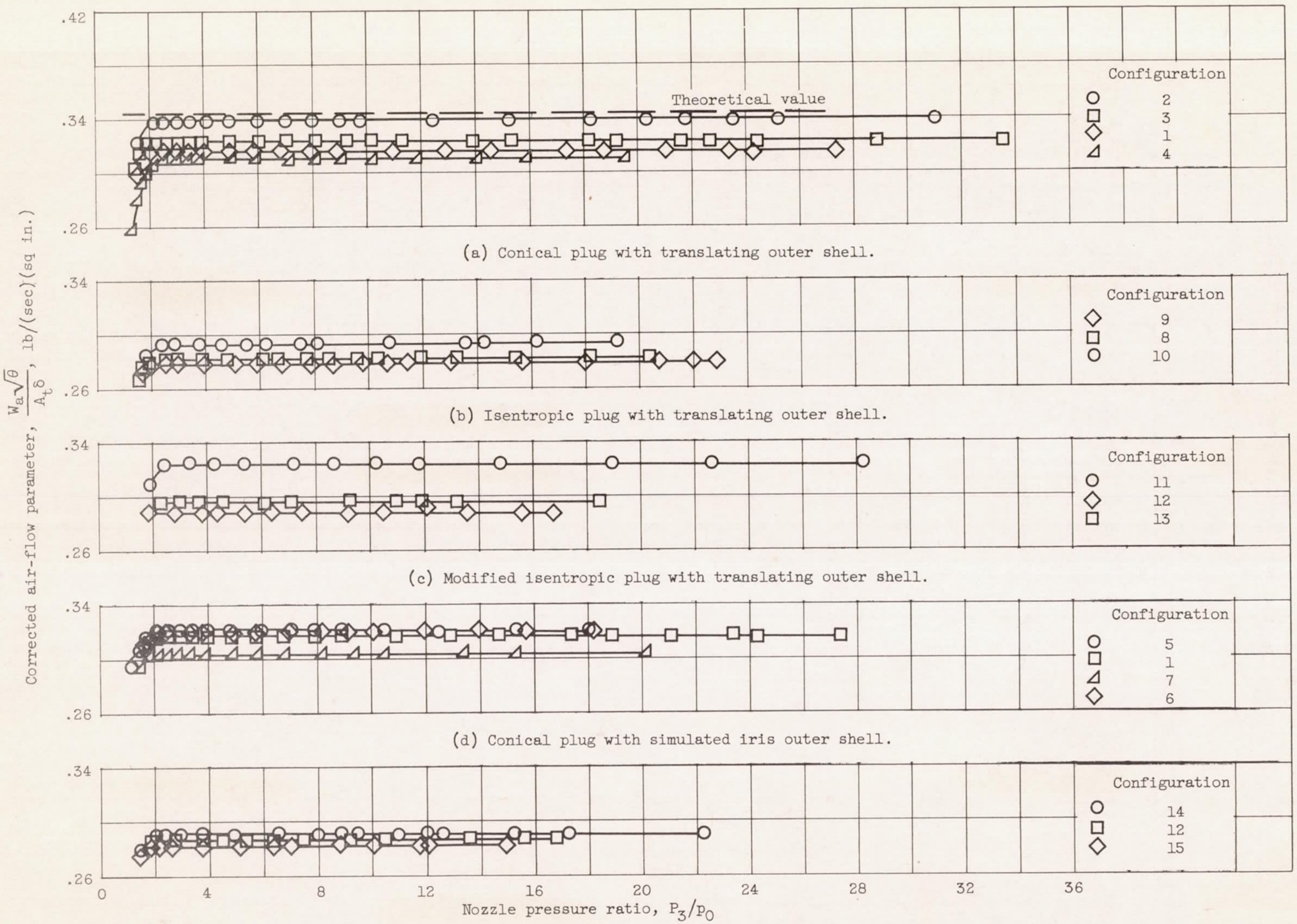


Figure 5. - Effect of throat-area modulation on thrust coefficients and expansion ratio of conical plug nozzle.



(e) Modified isentropic plug with simulated iris outer shell.

Figure 6. - Effect of throat-area modulation on air-flow parameter of convergent plug nozzles.