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RESEARCH MEMORANDUM

EFFECT OF PLUG DESIGN ON PERFORMANCE CHARACTERISTICS OF CONVERGENT-PLUG EXHAUST NOZZLES

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NATIONAL ADVISORY COMMITTEE
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EFFECT OF PLUG DESIGN ON PERFORMANCE CHARACTERISTICS OF CONVERGENT-PLUG EXHAUST NOZZLES

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SUMMARY

An evaluation of the internal performance characteristics of several plug-type nozzles was obtained over a range of pressure ratios from about 1.5 to 30, as part of a comprehensive experimental investigation of large-scale exhaust nozzles.

Plug nozzles, which were designed for nozzle pressure ratios of 9.5 and 14 by the method of characteristics (called herein isentropic nozzles), had peak thrust coefficients of about 0.98. Thrust coefficient was relatively insensitive to nozzle pressure ratio (varied from 0.96 to 0.98) for values below the design point. Conical plug nozzles had peak thrust coefficients that were within 1 percent of the value for the isentropic plug nozzles. For optimum performance, a plug angle of 60° was required for a design pressure ratio of 7 and an angle of 80° was required for a design pressure ratio of 18.5. Varying the design of the throat and the throat-approach section altered the peak thrust coefficient 3 percentage points. 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

It was shown in reference 1 that the extended plug nozzle has good thrust characteristics over a range of pressure ratios from 1.5 to at least 16. The peak thrust coefficients were about as high as those of a convergent-divergent nozzle, and were relatively insensitive to pressure ratio below the design point. These data did not necessarily represent the optimum for a plug nozzle, however, because no attempt was made to refine the design.

The purpose of this investigation was to determine whether a gain in thrust coefficient could be obtained by refinements in plug design.

The plug variables that were investigated include plug expansion section contour (isentropic and conical), conical plug angle, and a rounded throat-approach section.

The plug nozzles were investigated over a range of nozzle pressure ratios from 1.5 to 30. The isentropic plug nozzles (designed by the method of characteristics to provide axial flow at discharge) were designed for nozzle pressure ratios of 9.5 and 14, and the conical plug nozzles, for nozzle pressure ratios ranging from 4.8 to 19.2. The conical plug angle was varied from 40° to 80°

APPARATUS AND INSTRUMENTATION

Nozzle Configurations

Isentropic plug nozzles. - An exploded view of a typical isentropic plug nozzle is shown in figure 1(a). The aft sections (downstream of throat) of these nozzles were designed by the method of characteristics (ref. 2) for nozzle pressure ratios of 9.5 and 14. No boundary layer correction was applied, and the tail of the plugs was cut off at a small diameter to reduce the length. The coordinates for each nozzle are listed in figure 2. The design pressure ratio and throat areas are listed in table I. In order to simplify the use of the air-flow data, the throat area used in the calculations was defined as the annulus area between the outer shell exit and the plug in a plane perpendicular to the nozzle axis.

Conical plug nozzles. - The 10 conical plug nozzle configurations investigated are listed in table I along with their respective component parts. An exploded assembly of a typical configuration is shown in figure 1(b). The component parts of each configuration consisted of a spool piece, an outer shell, and a plug. The dimensions of the various parts used to make up the configuration are shown in figure 3. Plug angles of 40°, 50°, 60°, and 80° were investigated. The 40° plug was designed for pressure ratios of 4.8, 7.7, 10.3, and 19.2 (pressure ratio corresponding to outer shell exit to throat area ratio). The 50°, 60°, and 80° plugs were designed for pressure ratios of approximately 7 and 18.5. The throat area is defined in the same manner as for the isentropic plug nozzles.

Instrumentation

Pressures and temperatures were measured at various stations which are indicated in figure 4. Total- and wall static-pressure measurements at station 1 and total- and static-pressure measurements (stream and wall static) at station 2 were used to compute inlet momentum and air flow, respectively. Total pressure and temperature were measured at the nozzle inlet (station 3). Ambient-exhaust-pressure instrumentation was provided at station 0, and a static-pressure survey was made on the outside walls of the bellmouth inlet. Wall static pressures were measured along the surfaces of each of the plugs (from maximum diameter to downstream tip).

Installation

The nozzles were installed in a test chamber which was connected to the laboratory combustion air and altitude exhaust facilities as shown in figures 4 and 5. The nozzles were bolted to a mounting pipe which was freely suspended by four flexure rods that were connected to the bed plate. Pressure forces acting on the nozzle and mounting pipe, both external and internal, were transmitted from the bed plate through a flexure-plate-supported bell crank and linkage to a balanced-air-pressure diaphragm force-measuring cell. Pressure difference across the nozzle and mounting pipe was maintained by labyrinth seals around the mounting pipe which separated the nozzle inlet air from the exhaust. A vent line between the two labyrinth seals and the test chamber 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.

PROCEDURE

Performance data for each configuration were obtained over a range of nozzle pressure ratios at a constant air flow. 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 limited air-handling capacity of the air supply and exhauster equipment.

The thrust coefficient was calculated by dividing the actual jet thrust by the ideal thrust. The actual jet thrust was obtained from the force measured by the balanced-air-pressure-diaphragm and from pressure and temperature measurements made throughout the test 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. The methods of calculation used in this report and the symbols are shown in appendixes A and B, respectively.

RESULTS AND DISCUSSION

Effect of External Expansion Section on Performance Characteristics

Isentropic plug nozzles. - The isentropic plug nozzles were designed by the method of characteristics to provide axial flow at the nozzle discharge. The thrust coefficients over a range of nozzle pressure ratios for two isentropic plug nozzles (design pressure ratios of 9.5 and 14) and a convergent-divergent nozzle (design pressure ratio of 16, ref. 3) are shown in figure 6. The isentropic plug nozzles had a peak thrust coefficient of about 0.98. Thrust coefficient was relatively insensitive to nozzle pressure ratio for values below the design point, varying from only 0.96 to 0.98. This characteristic was similar to that obtained previously (ref. 1). The peak thrust coefficients were, however, about 2 percentage points higher with isentropic than with the conical extended plug nozzles of reference 1. The peak thrust coefficients occurred near the design pressure ratios and were as high as the value for the convergent-divergent nozzle.

Conical plug nozzles. - The isentropic plug nozzle would be expected to have higher thrust coefficients than the conical plug nozzle, provided all other factors were equal, because the flow from the isentropic nozzle is discharged axially, whereas the flow from the conical nozzles is not. The isentropic plug nozzle performance therefore serves as a reference for comparison with other types of nozzle designs. The isentropic plug, however, would be difficult to construct because of the complex curvature of the expansion section. To see how closely the performance of a simple conical plug which could be easily constructed would compare with that of the isentropic plug, various conical plug nozzles were also investigated.

As a first approach, a 40° plug was chosen because it was about the same length as the isentropic plug. The thrust coefficients of a 40° conical plug nozzle designed for pressure ratios of 4.8, 7.7, 10.3, and 19.2 are shown in figure 7 plotted against nozzle pressure ratio. The design pressure ratio is the pressure ratio corresponding to the ratio of outer shell exit area to throat area. The peak thrust coefficients, which occurred near the design pressure ratios, were several points lower than the peak thrust coefficients of the isentropic plug nozzles. Generally, there was little variation in thrust coefficient with pressure ratio (about 2 percentage points) for values below the design pressure ratio. The 40° plug nozzle had a peak thrust coefficient of 0.97 for a design pressure ratio of 4.8, but at a design pressure ratio of 19.2 the peak thrust coefficient had decreased to 0.94.

The flow angles in the vicinity of the isentropic plug nozzle throat were greater than 40°, which suggested that higher conical plug angles might give better performance. The thrust coefficients for nozzles with plug angles greater than 40° are shown in figure 8 as a function of nozzle pressure ratio. Data are shown for 40°, 50°, 60°, and 80° conical plug nozzles designed for nozzle pressure ratios of approximately 7 and 18.5. The 50°, 60°, and 80° plug nozzles had higher performance over the range of pressure ratios than the 40° plug nozzle. Thrust coefficients above 0.96 were obtained up to a pressure ratio of about 30 with the nozzles having a high design pressure ratio. Generally, plug angle had little or no effect on thrust coefficient at pressure ratios below the design point.

The effect of plug angle on peak thrust coefficient is shown in figures 9(a) and 9(b). These curves were obtained by cross plotting the data of figure 8. The peak thrust coefficient for the isentropic plug nozzles is shown by a dashed line. These results show that a conical plug nozzle has a peak thrust coefficient which is only 1 percentage point lower than that of an isentropic plug nozzle. The peak thrust coefficient was more sensitive to plug angle for a design pressure ratio of 18.5 than for a design pressure ratio of 7. A 60° plug angle gave the highest performance for a design pressure ratio of 7, while a plug angle of 80° gave the best performance at a design pressure ratio of 18.5.

Effect of Throat and Throat-Approach Section on Performance

Two conical plug nozzles designed for a pressure ratio of 10 were chosen to show the effect of throat and throat-approach section on nozzle performance. One nozzle, which is designated the sharp plug herein, is denoted as configuration F in reference 1. The outer shell exit (throat) is located at a sharp corner on the plug (see sketch, fig. 10). With this arrangement a Prandtl-Meyer expansion was induced around the plug corner. The other nozzle, which is referred to as the rounded plug, is the 40° plug nozzle reported herein. The throat-approach section of this plug was rounded so that the sharp corner at the throat was eliminated. The curved portion of the plug became tangent at the conical expansion section just upstream of the throat (see sketch, fig. 10). The effect of these two designs on the pressure distribution along the plug is shown in figure 10.

The Prandtl-Meyer expansion of the flow around the corner on the sharp plug nozzle lowers the pressure on the plug surface considerably below that of the rounded plug. Therefore, it would be expected that the sharp plug nozzle would have the lower thrust coefficient because of the lower pressure force on the plug. The thrust coefficients for these two nozzles are shown as a function of nozzle pressure ratio in figure 11. As expected, the rounded plug nozzle had a peak thrust coefficient which was as much as 3 percentage points higher than that of the sharp plug nozzle. In addition, the thrust coefficients at pressure ratios below the design point were also higher for the rounded plug.

Air-Flow Parameter

The air-flow parameter for all configurations is plotted against nozzle pressure ratio in figure 12. The theoretical value of the air-flow parameter (0.344 lb/sec/sq in.) for choked flow is shown by a dashed line. The ratio of the experimental air-flow parameter to the theoretical value gives flow coefficients for these configurations ranging from 0.80 to 0.94 when the flow is 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. This area was greater than the actual flow area, and consequently the flow coefficients were lower than for simple convergent-divergent nozzles.

SUMMARY OF RESULTS

The internal performance characteristics of several plug type nozzles were obtained over a range of pressure ratios from 1.5 to 30. The isentropic plug nozzles designed by the method of characteristics to produce axial flow at the nozzle discharge for nozzle pressure ratios of 9.5 and 14 had peak thrust coefficients of about 0.98. The peak thrust coefficients occured near the design pressure ratios and were as high as those of convergent-divergent nozzles. The thrust coefficient was relatively insensitive to pressure ratio below the design point, varying only from 0.96 to 0.98.

The conical plug nozzles, which are simpler to manufacture, had peak thrust coefficients that were within 1 percentage point of the peak value for the isentropic plug nozzle. As the design pressure ratio was increased, the plug angle for best performance was increased. The conical plug nozzles designed for a pressure ratio of 7 had best performance with a 60° plug, whereas the nozzles designed for a pressure ratio of 18.5 had best performance with a plug angle of 80°.

As expected it was found that higher thrust coefficients could be obtained if the plug nozzles were designed so that the plug was rounded in the region of the throat rather than having a sharp corner at the throat section. The rounded plug gave a 3 percentage point increase in peak thrust coefficient over the value for a plug nozzle with a sharp corner at the throat.

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 used in the calculations of the air-flow parameter as the annulus between the outer shell exit and the plug in a plane perpendicular to the nozzle axis. This area was greater than the actual flow area, and consequently the flow coefficients were lower than for simple convergent-divergent nozzles.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 13, 1954

APPENDIX A

METHODS OF CALCULATION

Air flow. - The nozzle air flow was calculated as

$$W_{a,2} = \frac{p_2 A'_2}{\sqrt{RT_3}} \sqrt{\frac{2g\gamma}{\gamma - 1}\left[\left(\frac{P_2}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\left(\frac{P_2}{p_2}\right)^{\frac{\gamma-1}{\gamma}}}$$

where γ was assumed to be 1.4.

Thrust. - The jet thrust was defined as

$$F_j = \frac{W_{a,2}}{g} V_e + A_{f,t}(p_t - p_0) + \int_0^{A_{p,t}} p\, dA_p - p_t A_{p,t}$$

or, as defined in the conventional manner,

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

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

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

APPENDIX B

SYMBOLS

A outside area, sq ft

A' inside area, sq ft

A_f flow area (annulus between outer shell exit area and plug in plane perpendicular to plug axis), sq ft

A_l pipe area under labyrinth seal, sq ft

A_p plug projected area, sq ft

A_s exit area of outer shell, sq ft

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

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)($^{\circ}$R) for air

T total temperature, $^{\circ}$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

Subscripts:

e	nozzle exit
i	ideal
j	jet
p	plug
t	throat
w	plug surface or wall
0	exhaust or ambient
1	inlet
2	diffuser inlet
3	nozzle inlet

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.

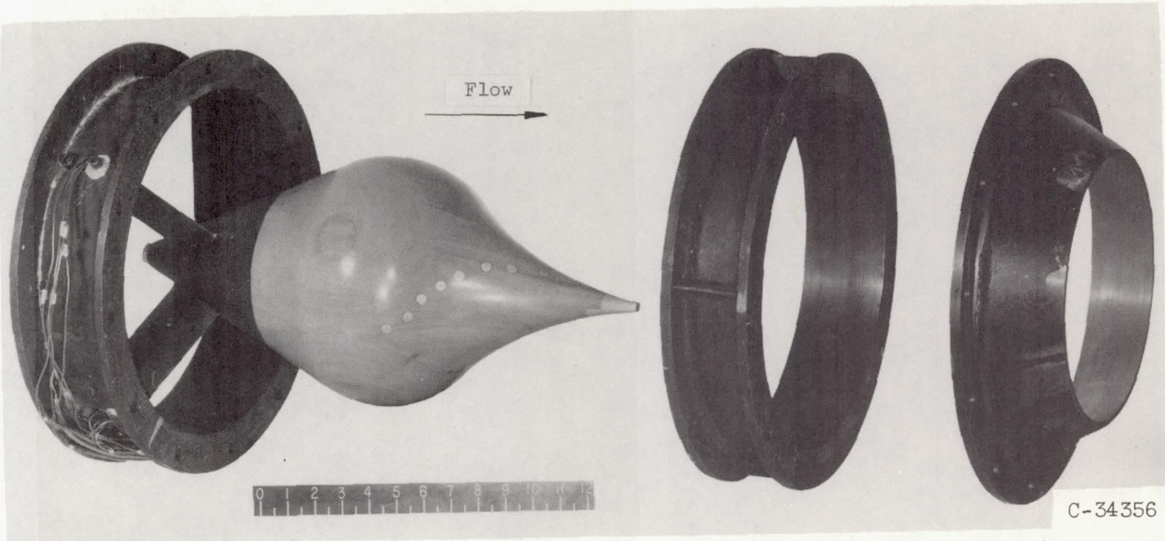
2. Ferri, Antonio: Application of the Method of Characteristics to Supersonic Rotational Flow. NACA Rep. 841, 1946. (Supersedes NACA TN 1135.)

3. Krull, H. George, and Steffen, Fred W.: Performance Characteristics of One Convergent and Three Convergent-Divergent Nozzles. NACA RM E52H12, 1952.

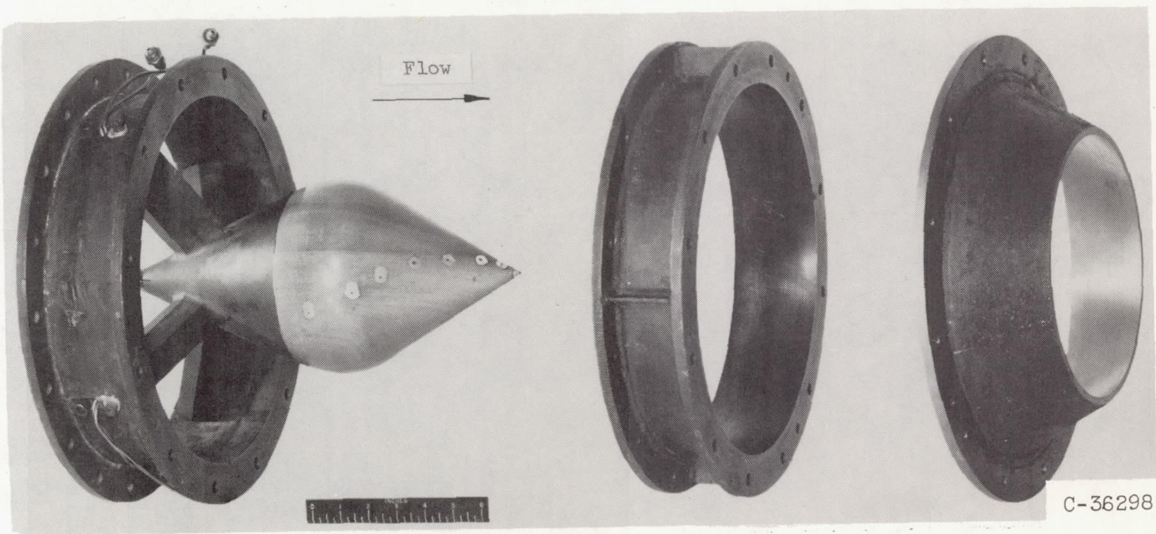
TABLE I. - NOZZLE CONFIGURATIONS

Plug angle	[a]Plug	[a]Shell	[a]Spool piece	Shell Exit Area / Throat Area $A_s/A_{f,t}$	Design pressure ratio	Throat area, A_{ft}, sq in.
Isentropic					9.5	46.87
Isentropic					14.0	49.5
40° conical	1	4	4	1.33	4.8	67.04
40° conical	1	3	2	1.68	7.8	36.78
40° conical	1	2	1	1.96	10.3	26.73
40° conical	2	1	8	2.83	19.2	33.74
50° conical	3	3	2	1.62	7.2	38.06
50° conical	4	1	7	2.72	18	35.07
60° conical	5	3	3	1.52	6.4	40.62
60° conical	6	1	7	2.89	19.9	32.99
80° conical	7	3	5	1.50	6.2	41.22
80° conical	8	1	6	2.58	16.3	37.31

[a]Numbers refer to parts shown in fig. 5.

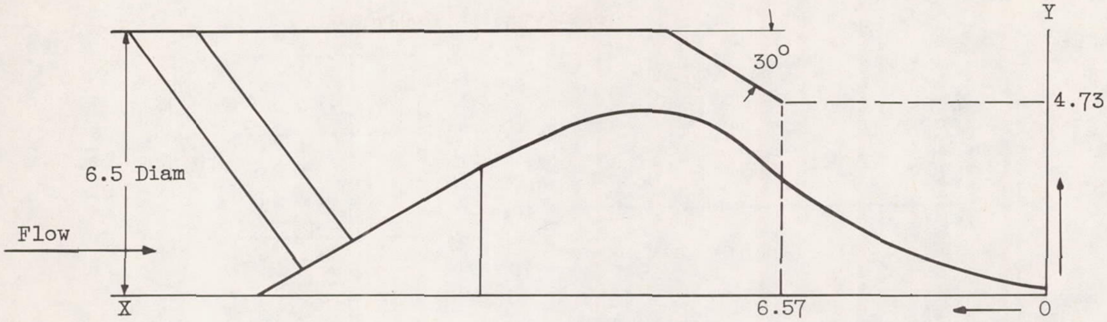


(a) Isentropic plug nozzle.



(b) Conical plug nozzle.

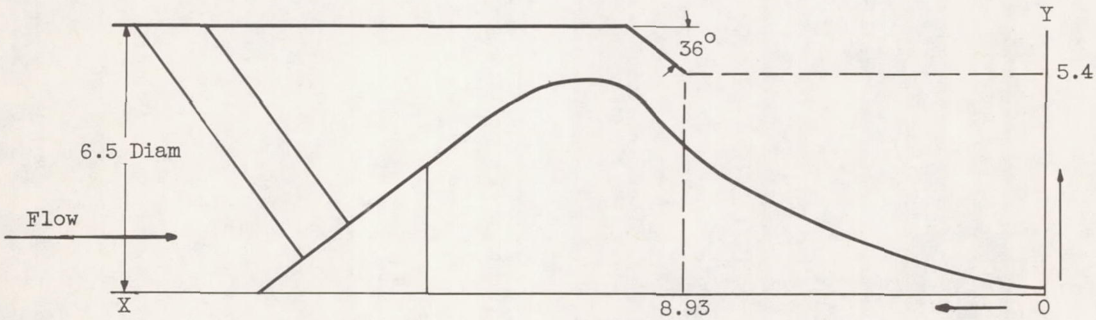
Figure 1. - Exploded view of nozzles.



(a) Isentropic plug nozzle designed for pressure ratio of 9.5.

Plug coordinates

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



(b) Isentropic nozzle designed for pressure ratio of 14.0.

Plug coordinates

X	Y	X	Y	X	Y
0	0.20	8.00	2.90	12.00	5.14
1.00	.35	8.50	3.26	13.00	4.80
2.00	.55	9.00	3.67	14.00	4.12
3.00	.83	9.50	4.15	15.00	3.36
4.00	1.13	10.00	4.67	15.31	3.12
5.00	1.48	10.50	5.03		
6.00	1.86	11.00	5.18		
7.00	2.34	11.25	5.20		

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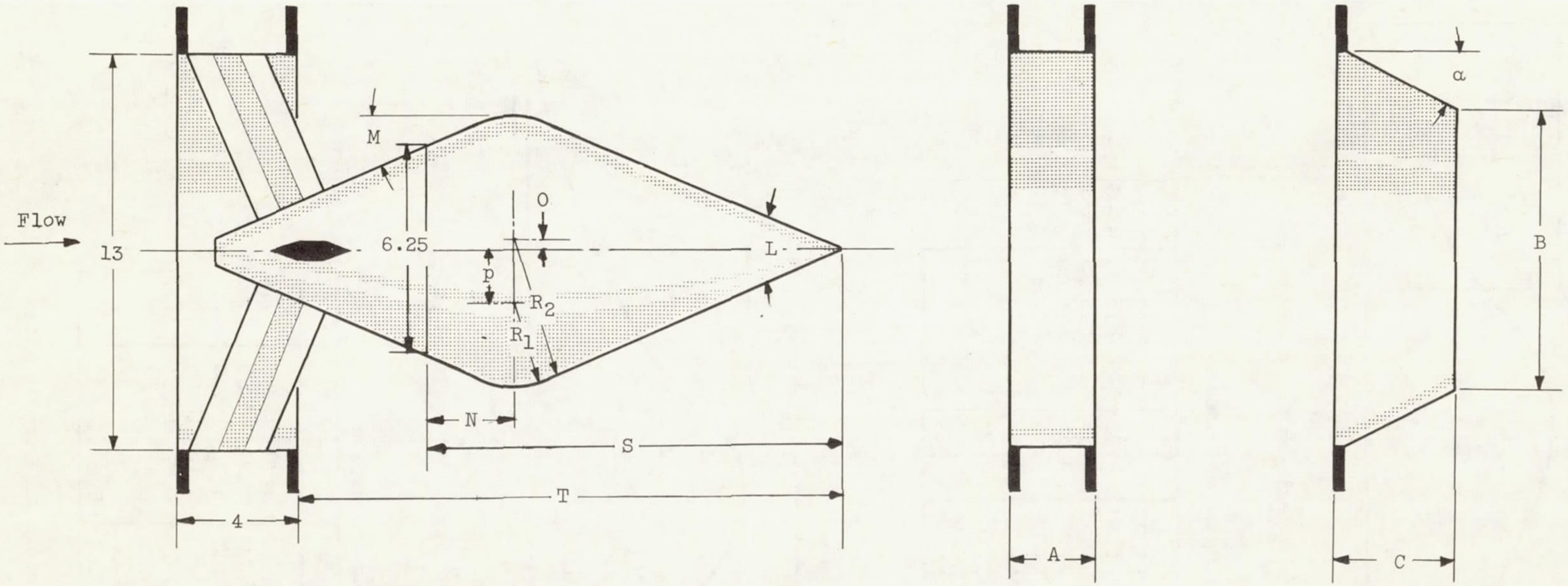
Figure 2. - Isentropic plug nozzle dimensions.



(a) Plug

(b) Spool piece.

(c) Outer shell.

Plug	L	M	N	O	P	R_1	R_2	S	T
1	40°	-	1.31	-	-	3.38	-	11.09	14.45
2	40°	30°	4.00	-	0.81	4.00	-	17.87	21.20
3	50°	-	1.30	.53	-	-	3.88	7.98	12.64
4	50°	26°	4.17	-	1.84	2.98	-	15.12	18.38
5	60°	-	1.35	-	0.22	3.20	-	8.07	11.42
6	60°	26°	4.16	-	2.36	2.52	-	13.25	16.70
7	80°	$23\frac{1}{2}$°	2.2	-	0.88	2.94	-	7.80	11.09
8	80°	35°	3.78	-	2.7	2.51	-	10.84	14.05

Spool piece	A
1	2.52
2	2.63
3	2.81
4	3.46
5	3.95
6	7.57
7	7.69
8	7.73

Outer shell	α	B	C
1	37° 12'	11.02	1.30
2	30° 36'	8.16	4.08
3	26° 42'	8.86	4.13
4	18° 6'	10.66	3.58

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Figure 3. - Conical nozzle component parts and dimensions. (All dimensions are in inches unless otherwise noted; all diameters are inside.)

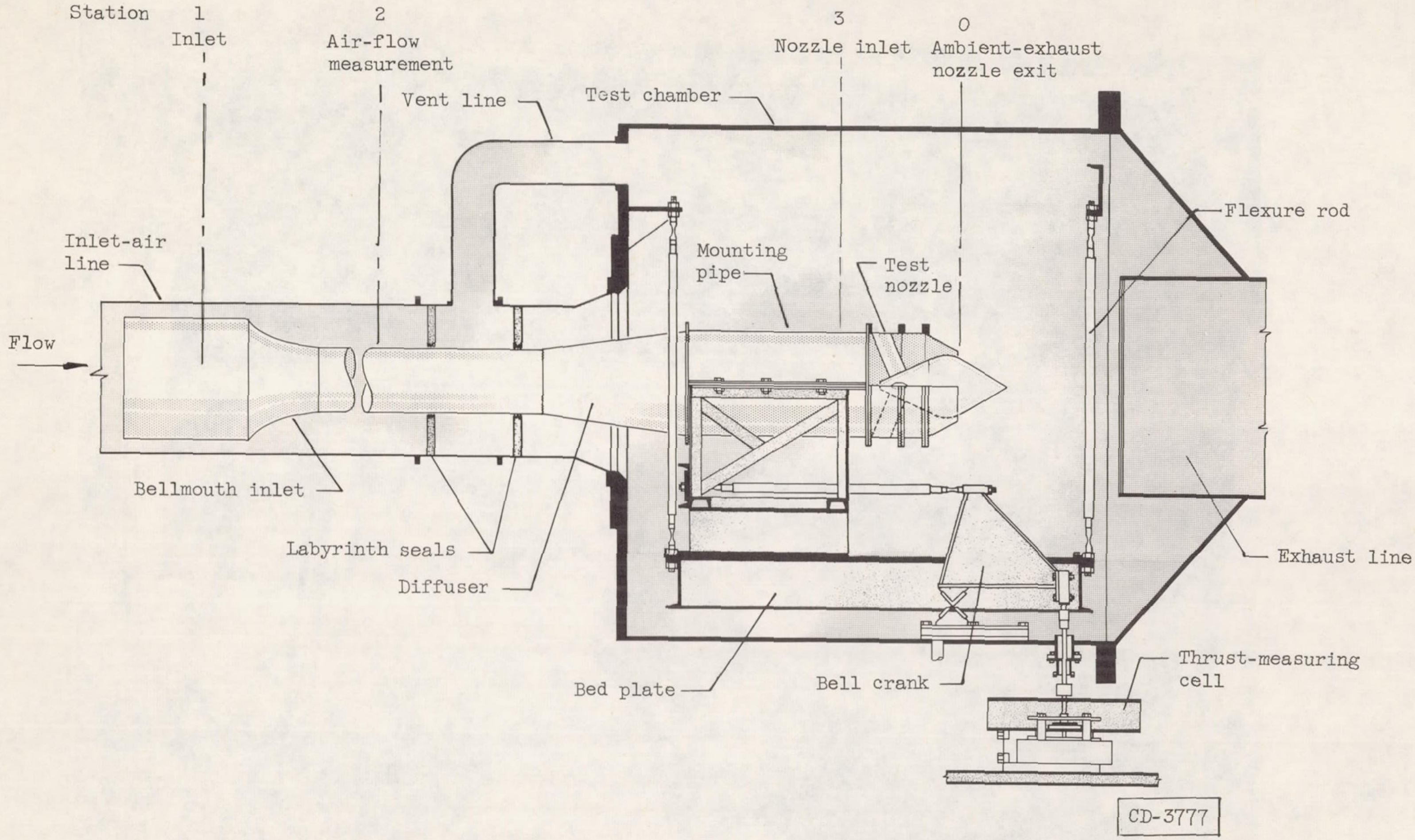


Figure 4. - Schematic drawing of nozzle in test chamber.

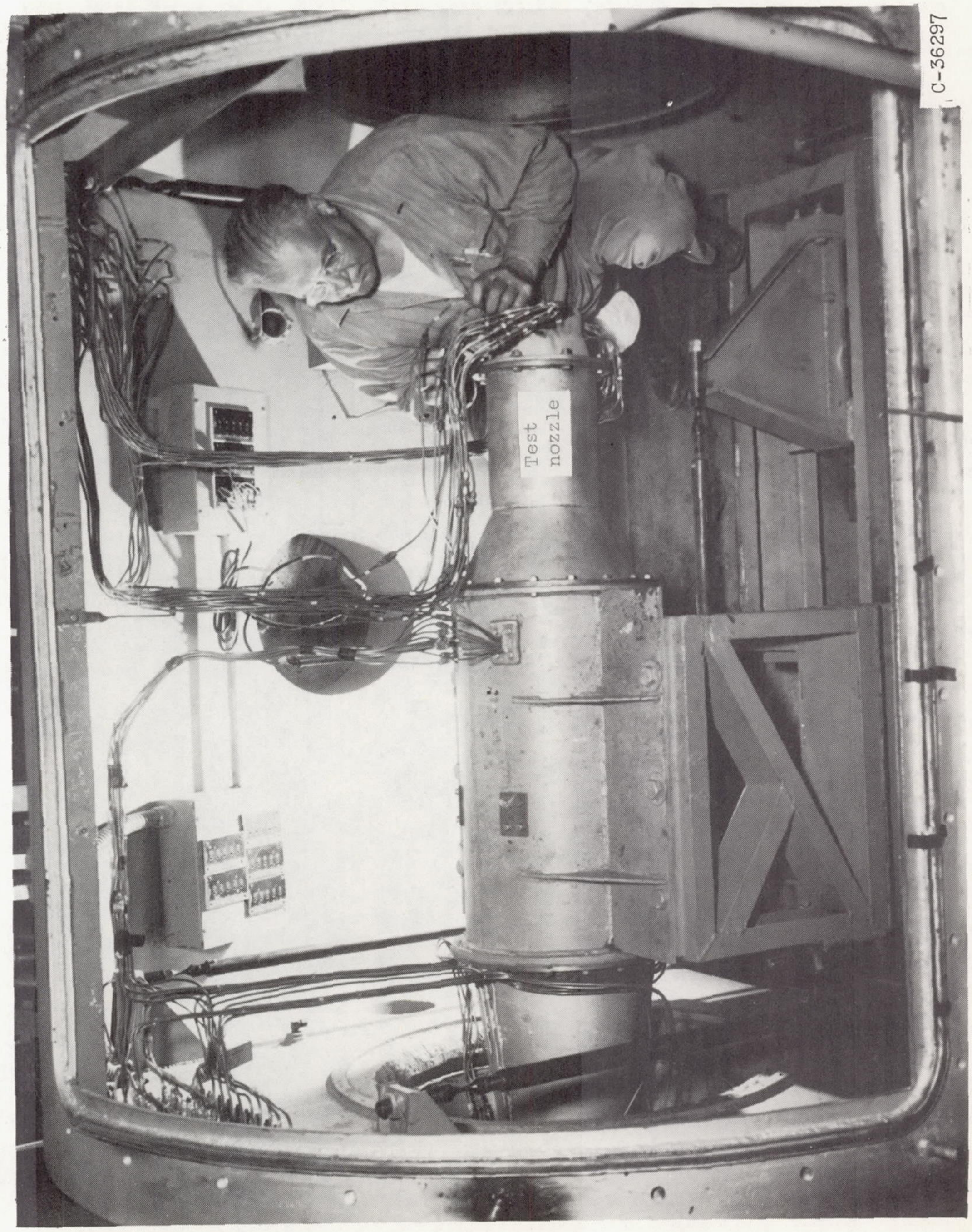


Figure 5. - Installation of nozzle in test chamber.

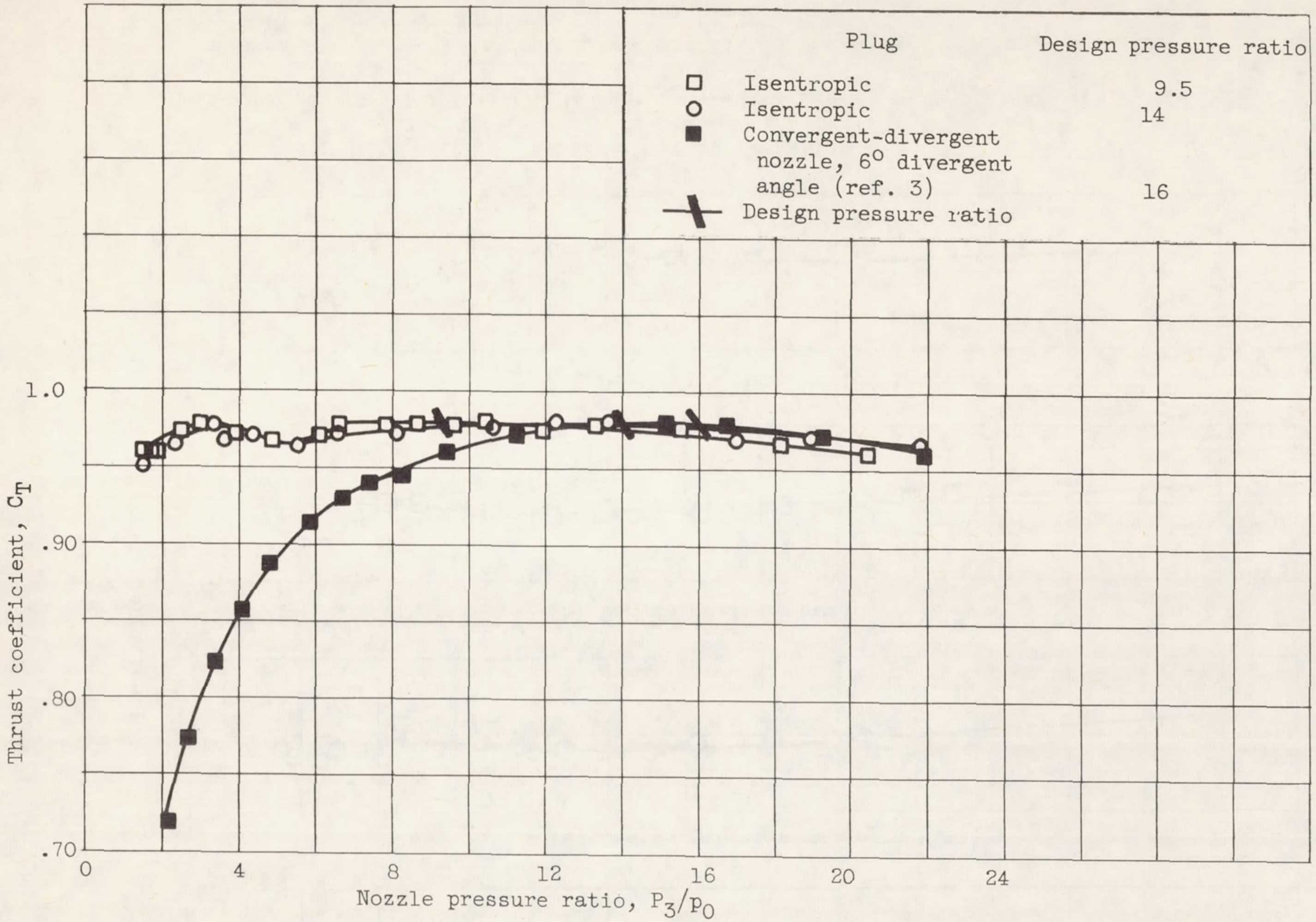
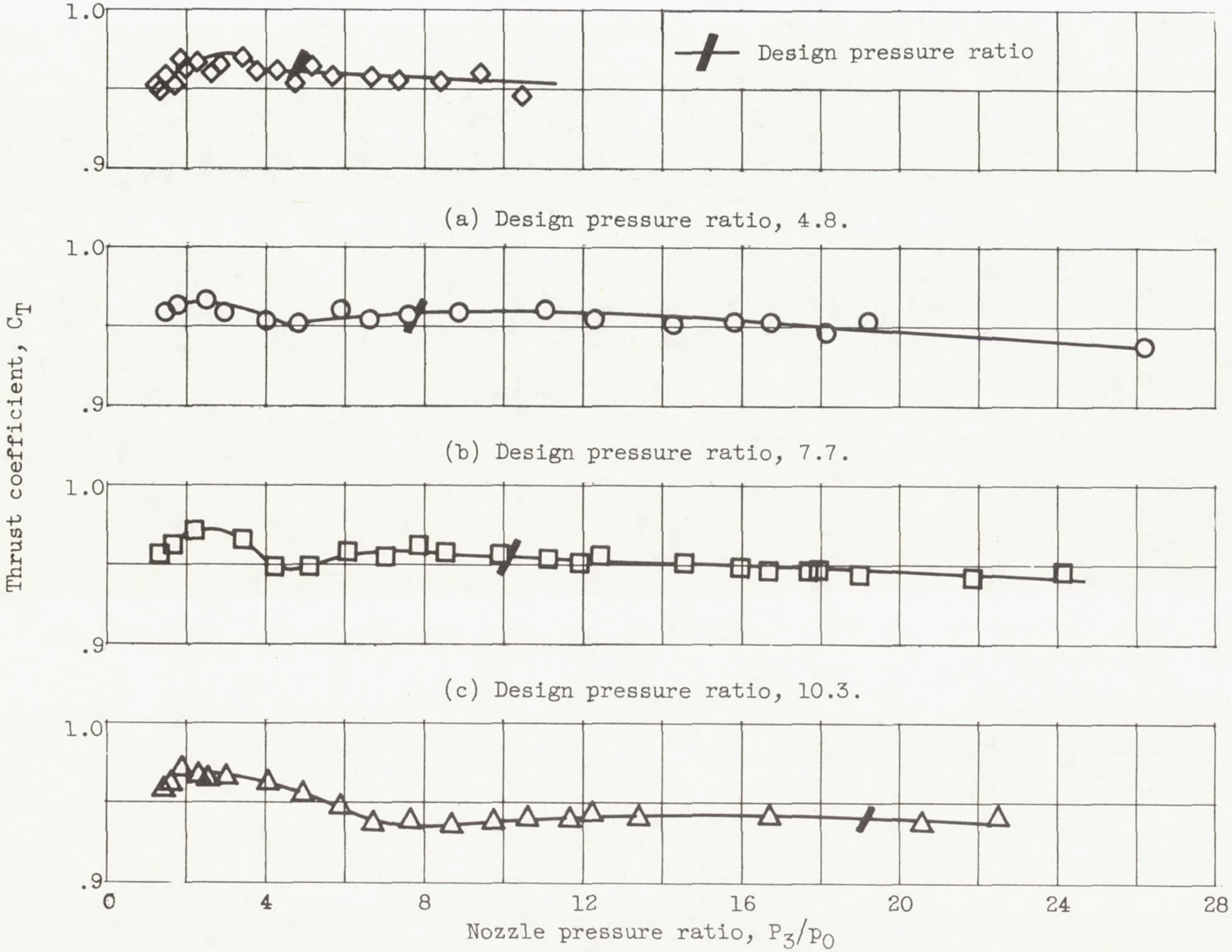


Figure 6. - Comparison of thrust coefficients over range of nozzle pressure ratios for isentropic plug nozzles designed for pressure ratios of 9.5 and 14 and conical convergent-divergent nozzle designed for pressure ratio of 16.



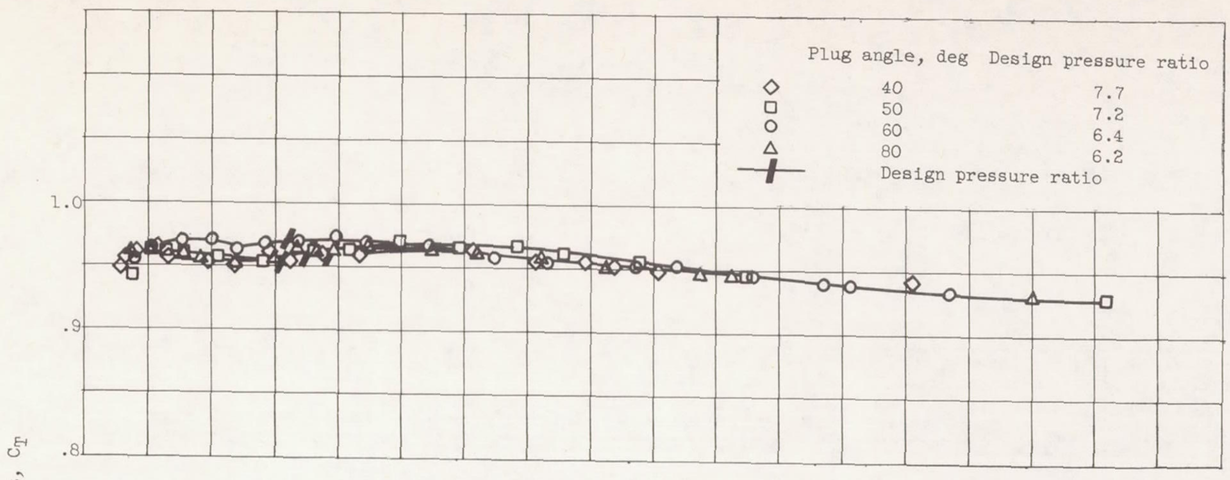
(a) Design pressure ratio, 4.8.

(b) Design pressure ratio, 7.7.

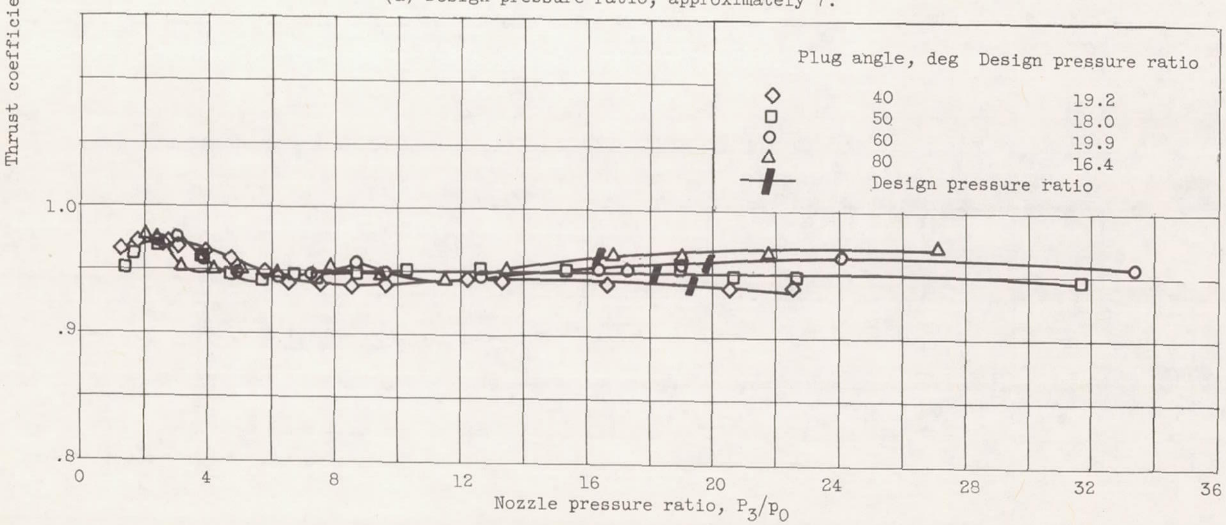
(c) Design pressure ratio, 10.3.

(d) Design pressure ratio, 19.2.

Figure 7. - Comparison of thrust coefficients over range of nozzle pressure ratios for 40° conical plug nozzle.

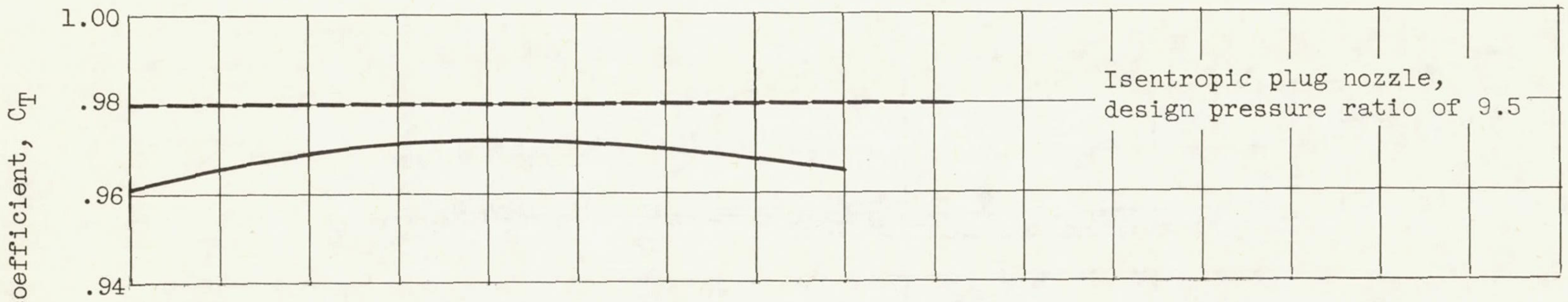


(a) Design pressure ratio, approximately 7.

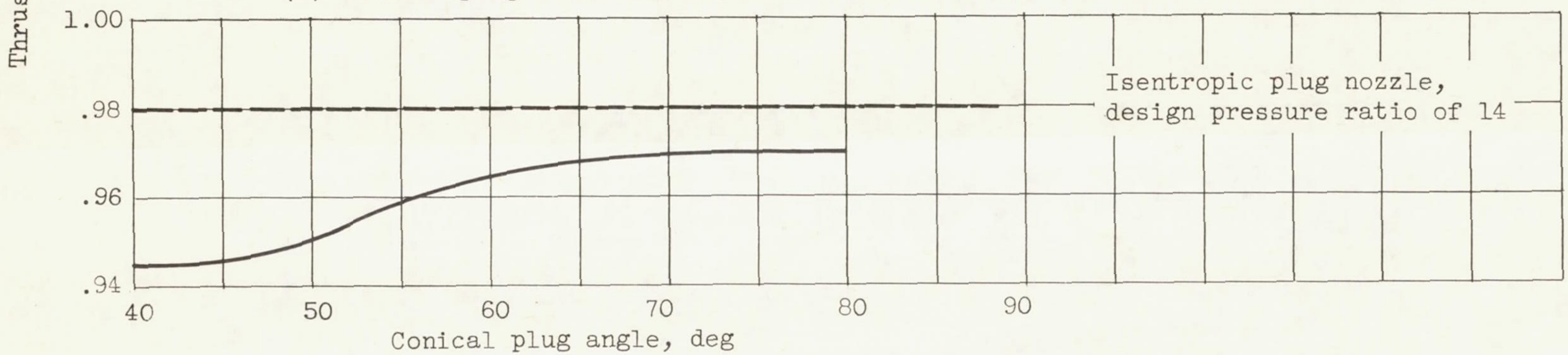


(b) Design pressure ratio, approximately 18.5.

Figure 8. - Comparison of thrust coefficients over range of nozzle pressure ratios for 40°, 50°, 60°, and 80° conical plug angle nozzles.



(a) Conical plug nozzles designed for pressure ratio of approximately 7.



(b) Conical plug nozzles designed for pressure ratio of approximately 18.5.

Figure 9. - Comparison of peak thrust coefficients of isentropic plug nozzles and conical plug nozzles over a range of conical plug angles.

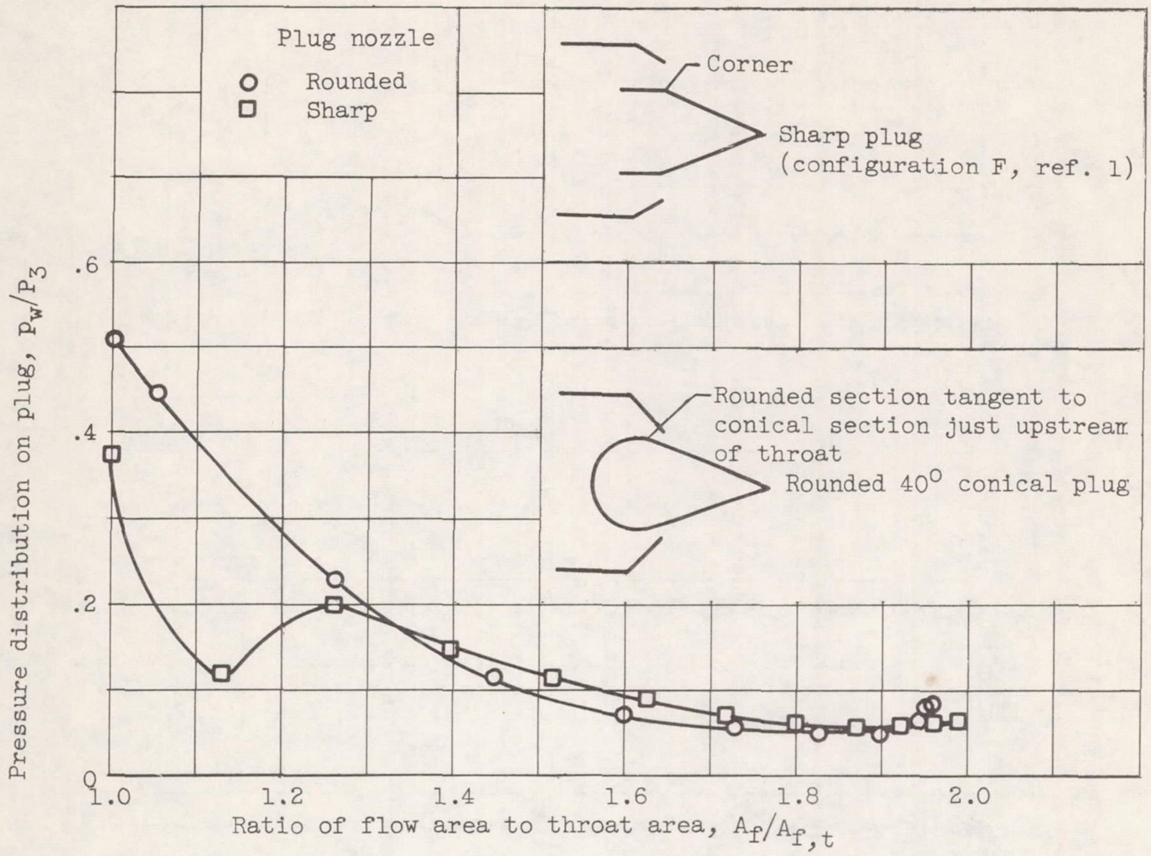


Figure 10. - Comparison of plug pressure distributions at nozzle pressure ratio of 20 for sharp and rounded conical plug nozzles designed for pressure ratio of 10.

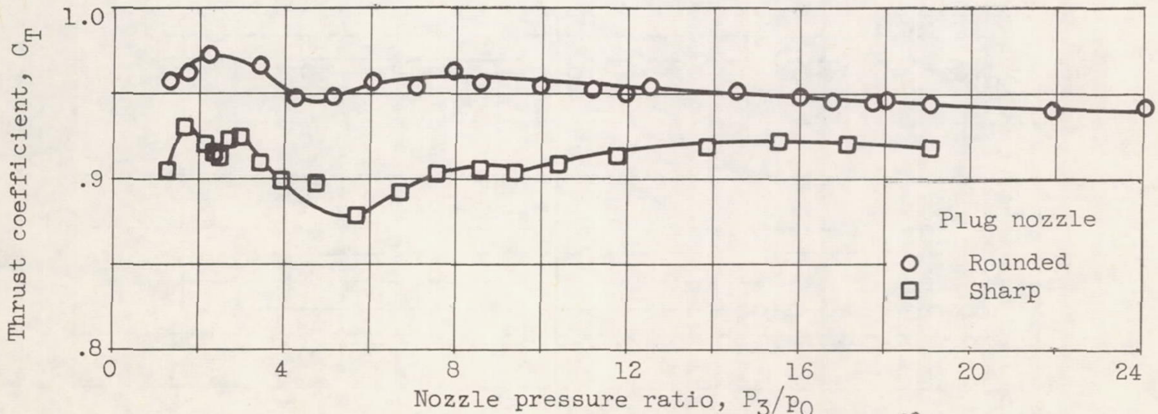


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Figure 11. - Comparison of thrust coefficients over range of nozzle pressure ratios for sharp and rounded plug nozzles designed for nozzle pressure ratio of 10.

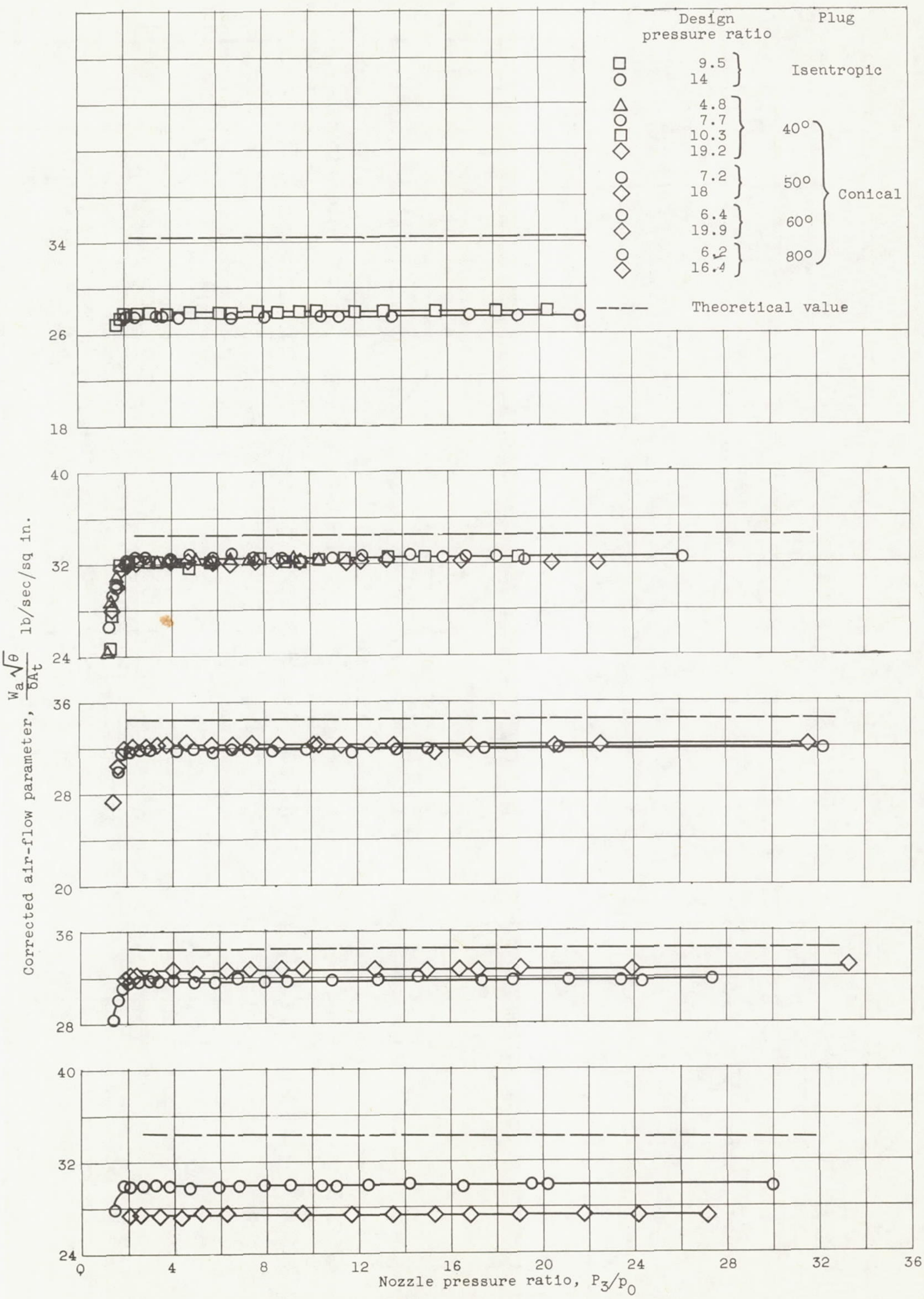

Figure 12. - Variation of air flow parameter with nozzle pressure ratio for isentropic plug nozzles designed for pressure ratios of 9.5 and 14 and 40°, 50°, 60° and 80° conical plug nozzles designed for nozzle pressure ratios from approximately 7 to 18.5.