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CALIBRATION OF THREE VENTURI AIRFLOW METERING SYSTEMS WITH STING-MOUNTED CENTERBODIES AT CRITICAL AND SUBCRITICAL FLOW CONDITIONS

H. E. Wolff
ARO, Inc.

May 1966

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FOREWORD

The work reported herein was done as a part of the TF37-GE-1A Military Qualification Test which was requested by the Aeronautical Systems Division (ASD), Air Force Systems Command (AFSC), for the General Electric Company under Program Element 62405214, Project 3066.

The results of the test presented were obtained by ARO, Inc. (a subsidiary of Sverdrup and Parcel, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract AF 40(600)-1200. The test was conducted in Propulsion Engine Test Cell (T-2) of the Rocket Test Facility (RTF) from October 25 to 28, 1965, under ARO Project No. RB0411, and the manuscript was submitted for publication on February 16, 1966.

The assistance received from Mr. R. J. Matz of the Research Branch, Rocket Test Facility, AEDC, contributed significantly to the technical quality of information obtained from this test program.

This technical report has been reviewed and is approved.

Ralph W. Everett
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ABSTRACT

An experimental investigation was conducted to determine the discharge coefficient of a venturi airflow meter with various diameter centerbodies installed. A critical flow venturi for which a theoretical discharge coefficient had been experimentally verified was used as the calibration standard. The discharge coefficients for the test venturi without centerbody and with centerbodies of two different diameters were determined over a range of venturi throat Reynolds numbers from 0.32 to 3.20 x 10^6 at a constant inlet air total temperature of 70°F. The experimentally determined coefficients were in good agreement with the theoretical value for all configurations tested. Maximum deviation (0.3 percent) of discharge coefficient from the theoretical value occurred with the venturi without centerbody operating at critical flow conditions.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

A	Area, ft^2, in.^{2}
C_f	Discharge coefficient
g	Dimensional constant, 32.174 lb$_m$-ft/lb$_f$-sec^2
M	Mach number
P	Total pressure, psfa
p	Static pressure, psfa
R	Gas constant for air, 53.34 ft-lb$_f$/lb$_m$-°R
Re	Reynolds number
T	Total temperature, °R
V	Velocity, ft/sec
W	Flow rate, lb$_m$/sec
γ	Ratio of specific heats
μ	Viscosity, lb$_f$-sec/ft^2
ρ	Density, lb$_m$/ft^3

SUBSCRIPTS

1, 2, 3, etc.	Instrumentation stations
a	Air
cr	Critical
i	Indicated
s	Standard
t	Venturi throat

SECTION I
INTRODUCTION

In performance tests of air-breathing propulsion systems, accurate measurement of airflow is a prime requirement. Venturi flowmeters designed to operate at critical flow conditions have been employed for the past several years at the Rocket Test Facility as a means of obtaining accurate airflow measurements.

Because of the large range of airflows over which air-breathing propulsion systems operate, multiple venturi flow measuring systems are required in order to ensure critical flow conditions in the flowmeter throughout the range of propulsion system flow rates. Test installations do not, however, readily permit changing venturis during a particular test program without large expenditures of time and effort.

A method was developed at the Rocket Test Facility whereby the flow area of a particular venturi is varied by insertion of a centerbody. The test program discussed in this report was conducted to determine the validity of theoretical discharge coefficients for venturis operating with centerbodies installed.

SECTION II
APPARATUS

2.1 TEST ARTICLE

Details of the test venturi are shown in Fig. 1. The venturi throat diameter was 10.096 in., giving a throat area of 80.049 in.^{2}. The test venturi was a modification of an existing venturi which had a cylindrical throat section. The modification consisted of machining the cylindrical section to produce a minimum diameter section with a continuous circular arc wall contour. As a result of this modification, the diffuser section of the venturi consisted of two separate half-angles of divergence downstream of the minimum diameter section (throat) as shown in Fig. 1.

Details of the three venturi flowmeter configurations calibrated are presented in the following table:

Configuration	Venturi Throat Diameter, in.	Centerbody Diameter, in.	Throat Annulus Height, in.	Throat Flow Area		Equivalent Diameter, in.
				ft^2	$in.^2$	
1	10.096	(None)	10.096	0.5569	80.049	—
2	10.096	6.249	1.923	0.3430	49.387	7.929
3	10.096	7.855	1.120	0.2194	31.592	6.342

A detailed schematic of the centerbody installation is presented in Fig. 2.

All configurations of the test venturi were calibrated using a standard venturi designed according to the criteria presented in Ref. 1. The discharge coefficient for the standard venturi operating at critical flow conditions had been experimentally determined as described in Ref. 1. A schematic showing design details of the standard venturi is presented in Fig. 3.

2.2 INSTALLATION

A schematic of the test installation is presented in Fig. 4. The standard venturi was mounted in a flange attached to the test cell inlet plenum and exhausted into the test venturi inlet plenum chamber. The test venturi was installed on the downstream bulkhead of the venturi inlet plenum and exhausted into the test cell. The test venturi centerbodies were attached to a centerbody mounting bracket fixed to the venturi inlet mounting flange. The test cell inlet plenum and the test venturi inlet plenum were 72 in. in diameter. A photograph showing the test cell inlet flow-straightening grid and the standard venturi inlet is presented in Fig. 5a. A photograph showing the test venturi inlet with a centerbody installed is presented in Fig. 5b.

2.3 INSTRUMENTATION

Pressure and temperature measurements were made at the stations shown in Fig. 4. Details of instrumentation are presented in Fig. 6. All pressures were indicated on manometers and photographically recorded. Temperatures were obtained by manually recording the millivolt output of iron-constantan thermocouples on a null-balance indicator.

SECTION III
PROCEDURE

Air was supplied to the test cell with a moisture content of less than 4 grains/lb. Inlet air total temperature was maintained at 70°F, and inlet pressure was set at the value required to establish the desired Reynolds number in the test venturi throat. The test cell pressure (test venturi exit) was maintained at a level required to produce the desired total pressure ratio across the test venturi. The standard venturi was operated at critical flow conditions for all calibration points.

A minimum of two data samples was recorded at each steady-state operating condition to minimize random error in the data averages. Methods of calculation are presented in Appendix I. Tabulated data are presented in Appendix II.

SECTION IV
RESULTS AND DISCUSSION

The venturi calibration test yielded discharge coefficient data over a range of test venturi inlet total pressures from 2 to 12 psia at an air inlet total temperature of 70°F. Venturi throat Reynolds number varied from 0.32 to 3.2 million.

Discharge coefficients were determined for three test venturi configurations at both critical and subcritical flow conditions. Venturi configuration 1 consisted of the basic test venturi with a 10.096-in.-diam throat section, configuration 2 was the basic venturi with a 6.249-in.-diam centerbody installed, and configuration 3 was the basic venturi with a 7.855-in.-diam centerbody.

The theoretical coefficients presented were mathematically obtained by using the Tucker technique for determining turbulent boundary layer growth in compressible flow (Ref. 2) and the techniques of Ref. 3 for determining centrifugal force effects on flow at the venturi throat. Perfect gas behavior was assumed for all analyses and test results presented in this discussion.

4.1 VENTURI OPERATING AT CRITICAL FLOW CONDITIONS

The discharge coefficients determined for the three test venturi configurations operating at critical flow conditions are presented in Fig. 7. The experimentally determined discharge coefficient for configuration 1 was approximately 0.3 percent lower than the theoretical value throughout the Reynolds number range from 0.5 to 3.1×10^6. A trend of decreasing discharge coefficient is noted as venturi throat Reynolds numbers go above 2.0×10^6.

The test data for configuration 2 in the Reynolds number range from 1.0 to 2.45×10^6 are in good agreement with the theoretically determined value. The experimental coefficient ranged from 0.991 at a Reynolds number of 1.45×10^6 to 0.988 at a Reynolds number of 2.45×10^6 as compared to the theoretical value of 0.9887. As Reynolds number decreases below 1.0×10^6, the discharge coefficient begins to decrease significantly because of the transition from turbulent to laminar boundary layer conditions along the venturi wall.

The discharge coefficient for configuration 3 is also in good agreement with the theoretical levels above Reynolds numbers of 1.0×10^6. As expected, the coefficients begin to decrease significantly below Reynolds numbers of 1.0×10^6. For example, the coefficient is 1.1 percent lower at a Reynolds number of 0.32×10^6 than the value at a Reynolds number of 1.0×10^6.

Generally, excellent agreement with the theoretical discharge coefficients was obtained for all configurations in the Reynolds number range between 1.0 and 3.2×10^6; therefore, in the region where a fully developed turbulent boundary layer exists, a high degree of confidence can be placed in the theoretically determined discharge coefficients for venturis with sting-mounted centerbodies as well as for those without centerbodies.

The discharge coefficient in the Reynolds number range from 1.0 to 3.2×10^6 decreases as the venturi centerbody diameter increases. This is as expected since the annular height between centerbody surface and venturi throat inner wall becomes less as centerbody diameter increases, and with a smaller annulus height, the relative effect of boundary layer becomes larger.

4.2 VENTURI OPERATING AT SUBCRITICAL FLOW CONDITIONS

The discharge coefficients for the three venturi configurations operating at subcritical flow conditions are presented in Fig. 8 as a function of venturi indicated throat wall static-to-total pressure ratio and Mach number for two Reynolds number ranges. As expected, the coefficients for the venturi configuration with centerbodies are slightly higher than those obtained for the venturi without centerbody because the centrifugal effects are less. For example, at an indicated throat wall static-to-total pressure ratio of 0.7, the discharge coefficients for the centerbody configurations are approximately 0.5 percent higher than the configuration without centerbody. The discharge coefficients in the range of throat static-to-total pressure ratios from 0.57 to 0.60 are not significantly affected by venturi configuration.

A theoretical discharge coefficient for each of the three venturi configurations is also presented in Fig. 8 for comparison with the experimental. The theoretical coefficient calculations were made in accordance with the methods presented in Refs. 2 and 3 for subcritical flow conditions, applying the axisymmetric procedures to the venturi without centerbody, and the two-dimensional procedures to the venturi with centerbody installation.

As venturi throat wall Mach number was decreased, the theoretical discharge coefficient for venturi configuration 1 decreased more rapidly than the experimental discharge coefficient. In the range of throat wall Mach numbers from approximately 0.73 to 1.00, the deviation of experimental from theoretical ranged from -0.5 to +0.5 percent. The deviation became much larger as throat wall Mach number decreased below 0.73.

For the venturi configurations with centerbodies installed, the experimental discharge coefficients were lower than the theoretical throughout the wall Mach number range investigated. Deviation of the experimental discharge coefficients from the theoretical ranged from approximately -0.2 to -0.4 percent in the wall Mach number range from 0.70 to 0.90.

When operating in the subcritical range, venturi discharge coefficients are not significantly affected by Reynolds number in the range of indicated throat static-to-total pressure ratios from 0.57 to 0.60. As the indicated throat static-to-total pressure ratio increases, however, the effect of Reynolds number becomes significant. For example, at a pressure ratio of approximately 0.93 (Fig. 8), the discharge coefficient for configuration 1 ranged from 0.933 to 0.943 at a Reynolds number of approximately 0.47×10^6, whereas, at Reynolds numbers greater than 0.9×10^6, the discharge coefficient was approximately 0.955.

4.3 INDICATED VENTURI THROAT CRITICAL PRESSURE RATIO

The indicated test venturi critical throat pressure ratios for the various configurations are compared to theoretical values in Fig. 9 as a function of test venturi inlet total pressure for Reynolds numbers in the range from 1.0 to 3.2 x 10^6. The measured critical pressure ratio for each configuration was lower than the corresponding theoretical value throughout the range of venturi inlet total pressures investigated. The greatest deviation from theoretical occurred with the venturi having the largest diameter centerbody, and the best agreement was obtained for the configuration without centerbody. For example, at an inlet pressure of 570 psfa, the theoretical critical pressure ratio for the configuration with the largest centerbody (configuration 3) was approximately 5 percent higher than the experimental; whereas, for configuration 1 (no centerbody), this value was only 1 percent. The variation between theoretical and measured critical pressure ratio is the result of the inability to precisely locate the venturi throat static pressure ports.

The experimental data show a significant increase in the indicated throat static-to-total critical pressure ratio when a centerbody is installed in the venturi. For example, at a venturi inlet total pressure of 1000 psfa, the critical pressure ratio for the venturi without centerbody was 0.473. When the 6.25-in.-diam (configuration 2) centerbody was installed, the indicated critical pressure ratio increased to 0.484, and with the 7.86-in.-diam centerbody, the ratio was 0.488.

This variation in indicated critical pressure ratio is the result of throat velocity profile variation between configurations. It will also be noted from Fig. 9 that the indicated critical pressure ratio increases slightly as venturi inlet total pressure increases. The reason for this increase is not known but is perhaps again a result of changing boundary layer displacement thickness in the venturi throat region.

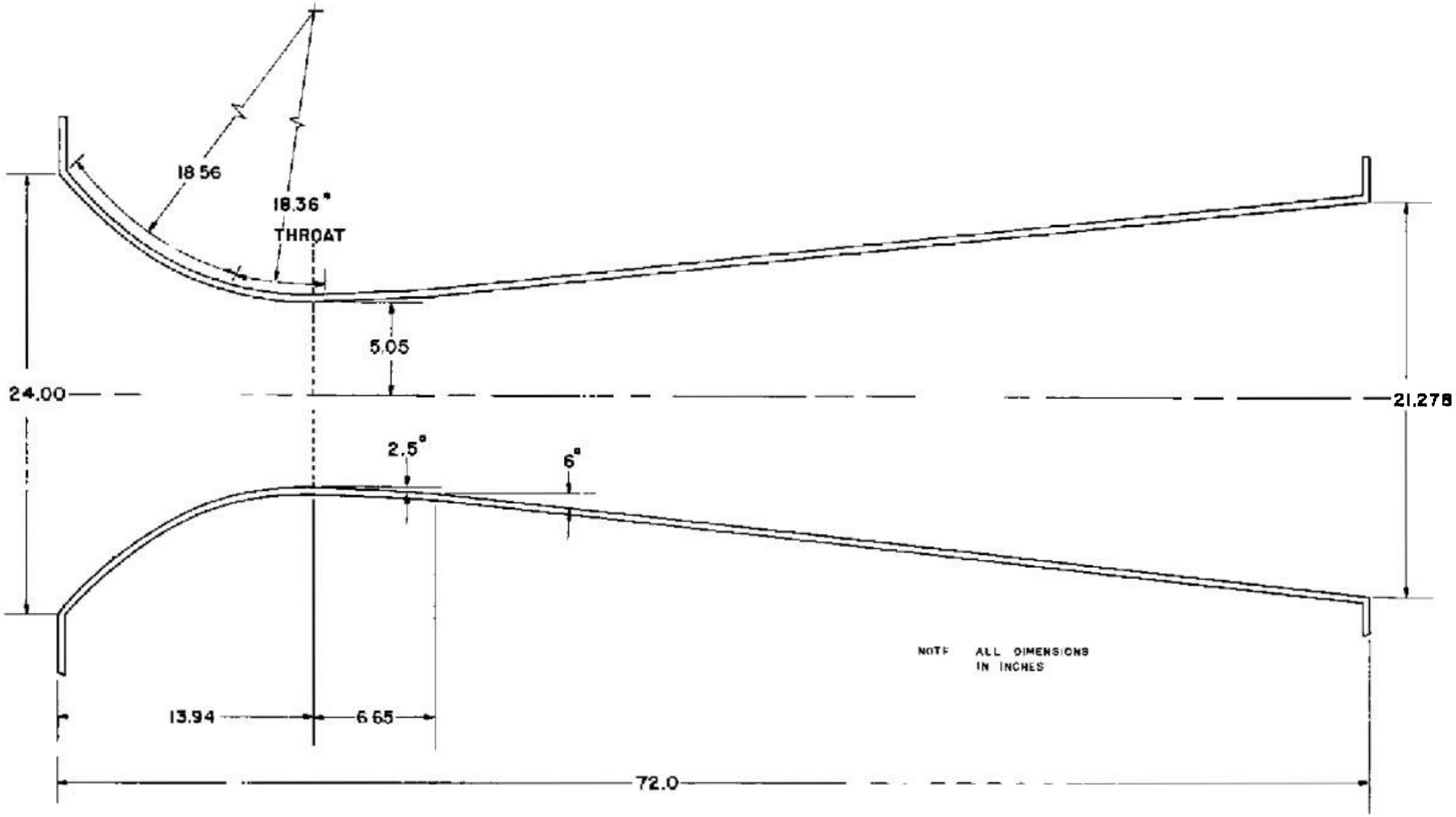
SECTION V
SUMMARY OF RESULTS

The results obtained from a flow calibration to determine the effect of installing a sting-mounted venturi centerbody on venturi discharge coefficients are summarized as follows:

1. Experimentally determined discharge coefficients for the test venturi without a centerbody and operating at critical flow conditions agreed within 0.3 percent of the theoretical value throughout the throat Reynolds number range from 0.5 to 3.1 x 10^6.
2. The discharge coefficients determined from the test venturi with sting-mounted centerbodies were slightly lower than those for the venturi without centerbody but agreed within 0.1 percent of the theoretically determined value.
3. The discharge coefficients for a venturi with centerbody and operating at critical flow conditions decreased as centerbody diameter was increased.
4. At subcritical venturi flow conditions, the discharge coefficient increased as much as 0.5 percent at a throat static-to-total pressure ratio of 0.70 when a centerbody was installed in the venturi. The difference in discharge coefficient obtained for a venturi with and without centerbody decreases as the throat pressure ratio approaches critical.
5. Discharge coefficients for a venturi operating at critical flow conditions with a sting-mounted centerbody can be theoretically determined to within 0.1 percent of the experimentally determined mean value.

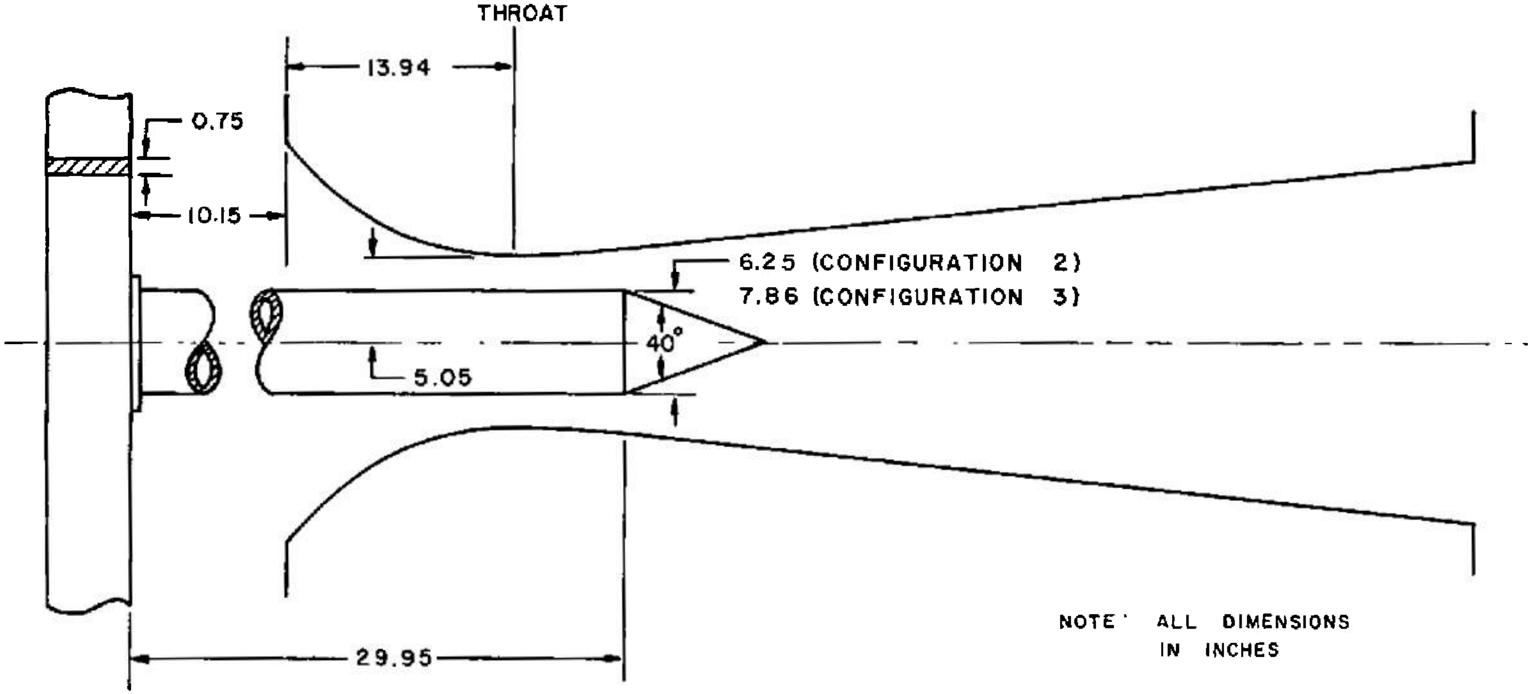
REFERENCES

1. Smith, Robert E., Jr. and Matz, Roy J. "Verification of a Theoretical Method of Determining Discharge Coefficients for Venturis Operating at Critical Flow Conditions." AEDC-TR-61-8 (AD263714), September 1961.
2. Tucker, Maurice. "Approximate Calculation of Turbulent Boundary-Layer Development in Compressible Flow." NACA-TN-2337, April 1951.
3. Oswatitsch, K. and Rothstein, W. "Flow Pattern in a Converging-Diverging Nozzle." NACA-TM-1215, March 1942.



* RADIUS VALID ONLY IN VICINITY OF THROAT

Fig. 1 Test Venturi Design Details



NOTE: ALL DIMENSIONS IN INCHES

Fig. 2 Test Venturi Centerbody Installation

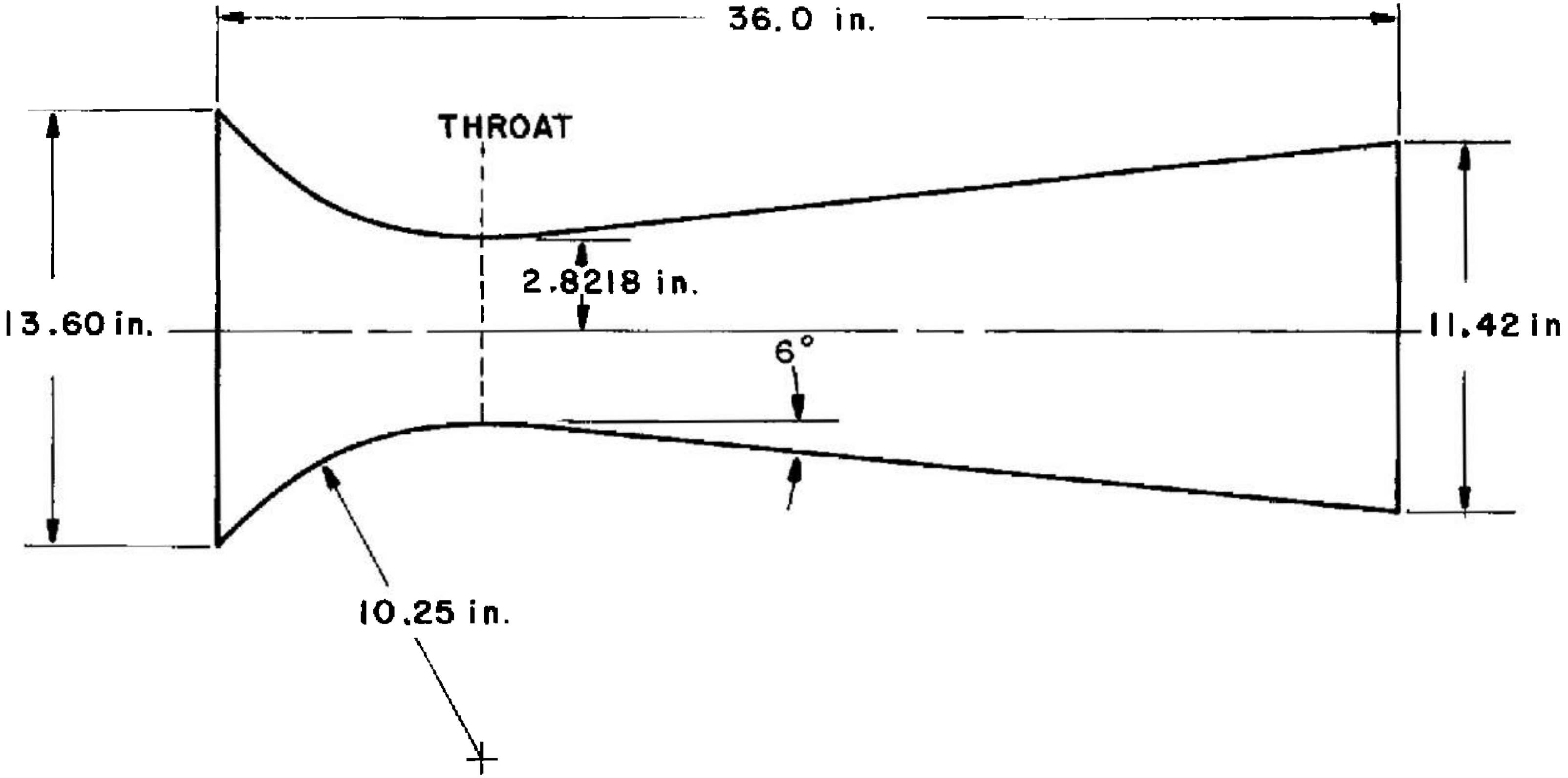


Fig. 3 Standard Venturi Design Details

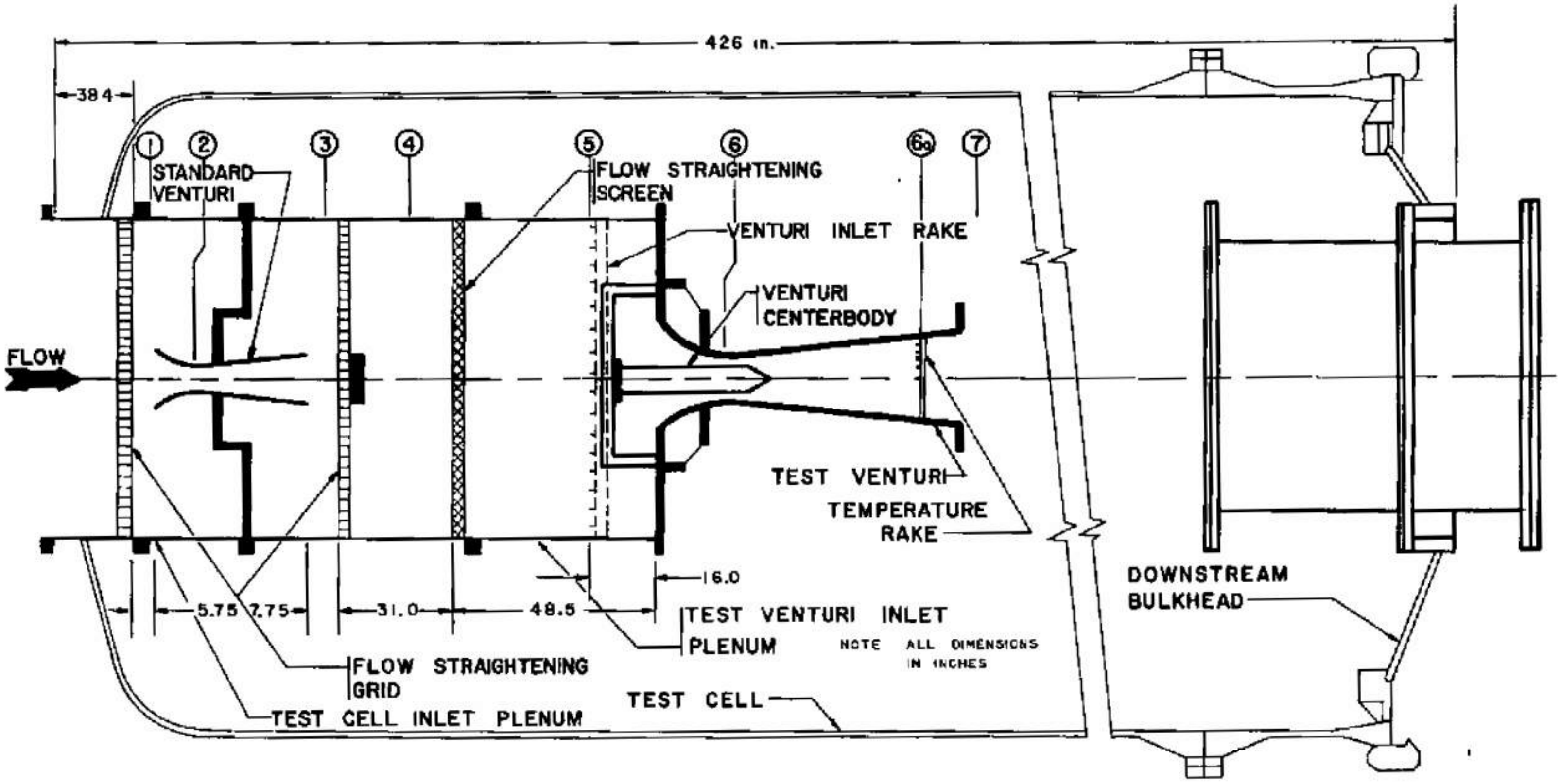
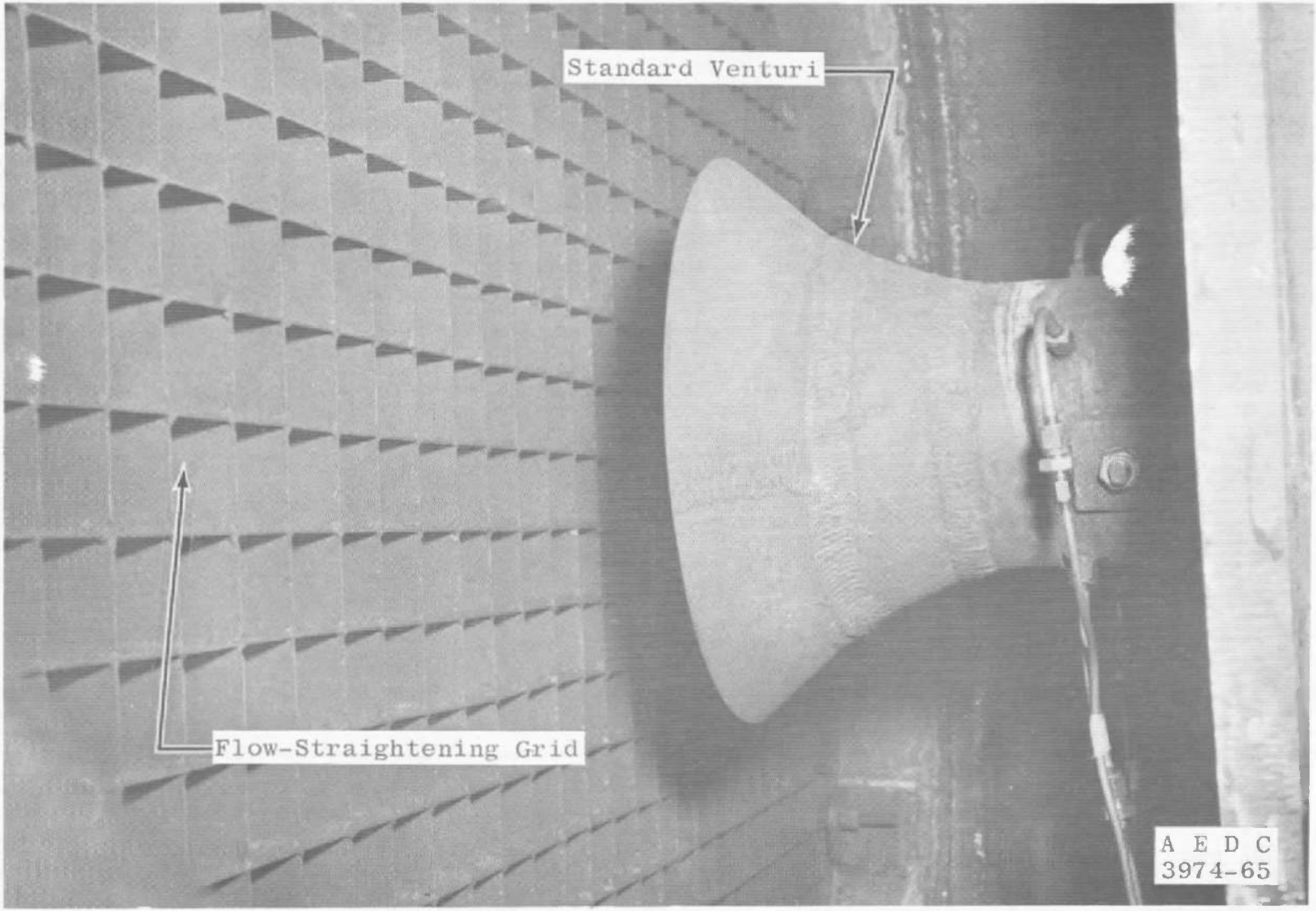
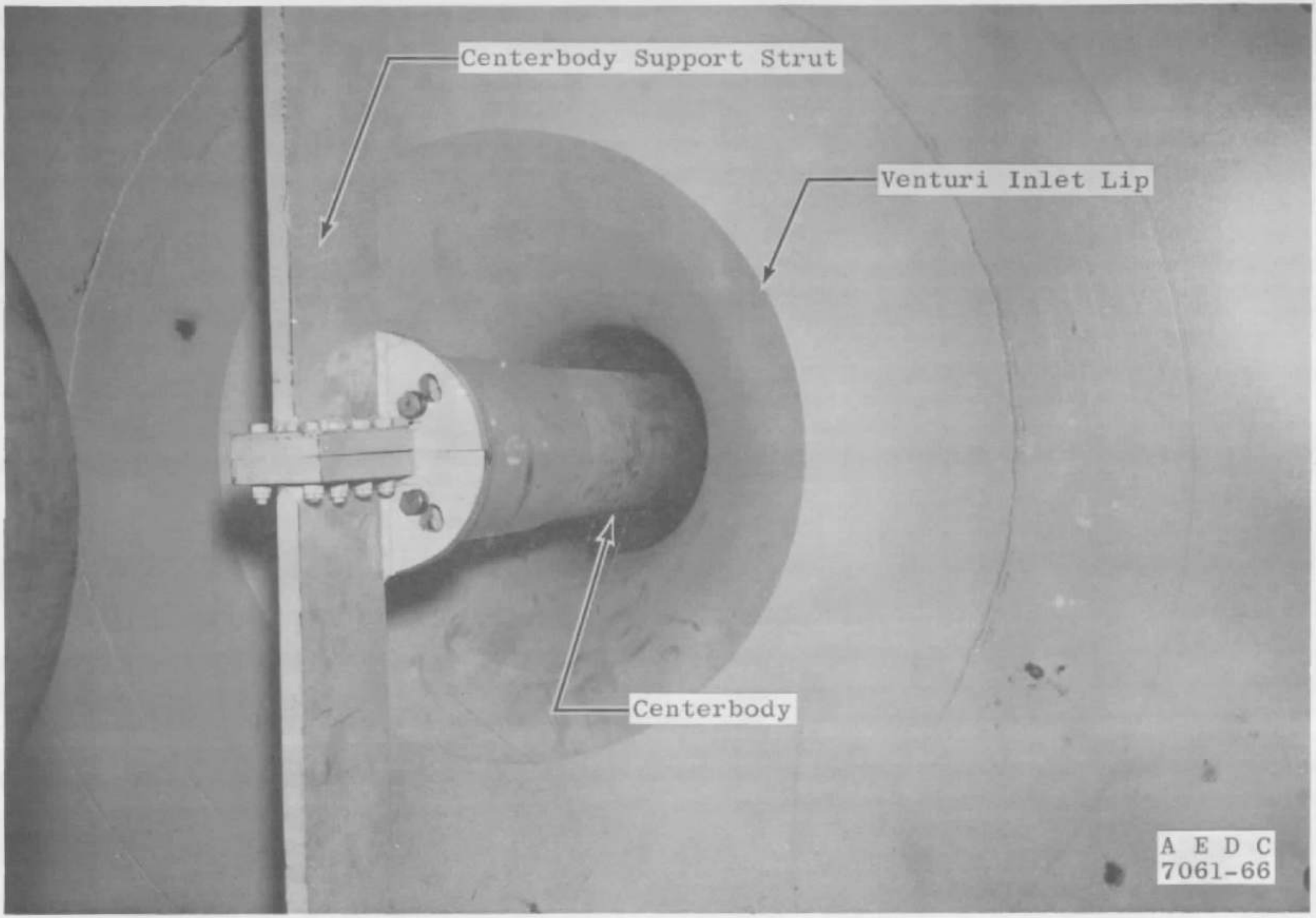


Fig. 4 Test Article Installed in Propulsion Engine Test Cell (T-2)



a. Standard Venturi Inlet Region
Fig. 5 Venturi Installation Photographs



b. Test Venturi with Centerbody Installed
Fig. 5 Concluded

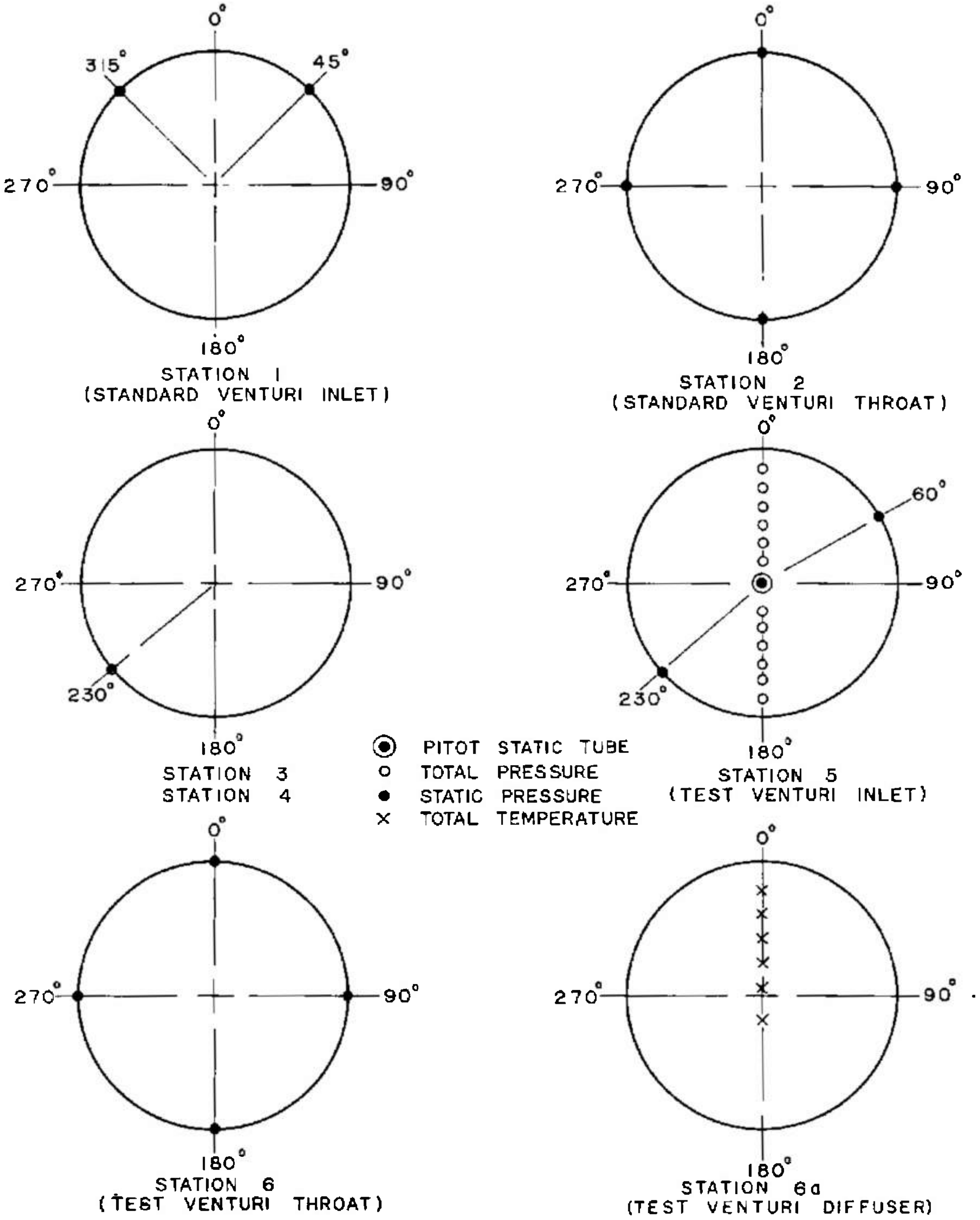


Fig. 6 Instrumentation Details (Looking Upstream)

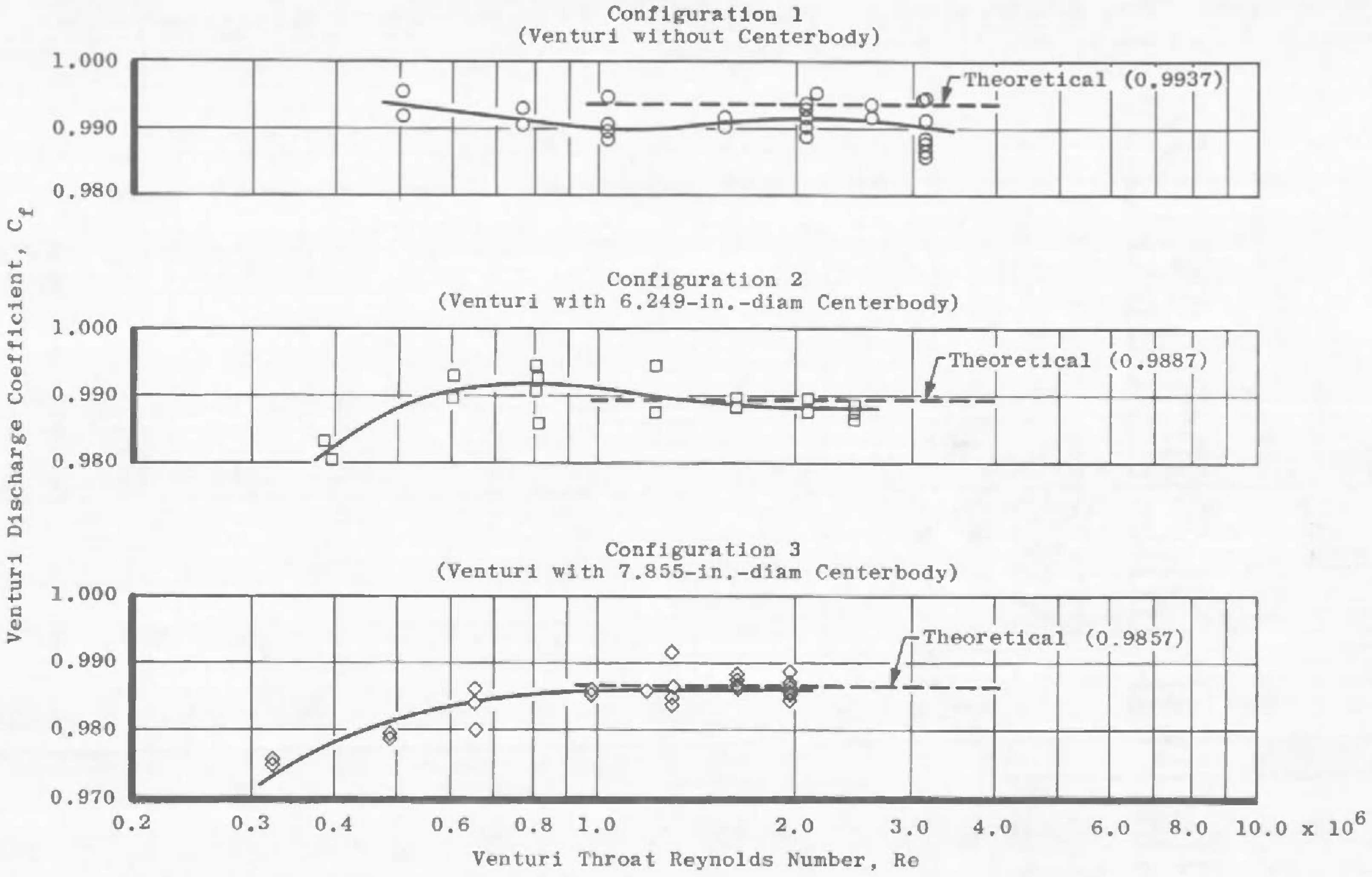


Fig. 7 Test Venturi Discharge Coefficient for Various Configurations Operating at Critical Flow Conditions

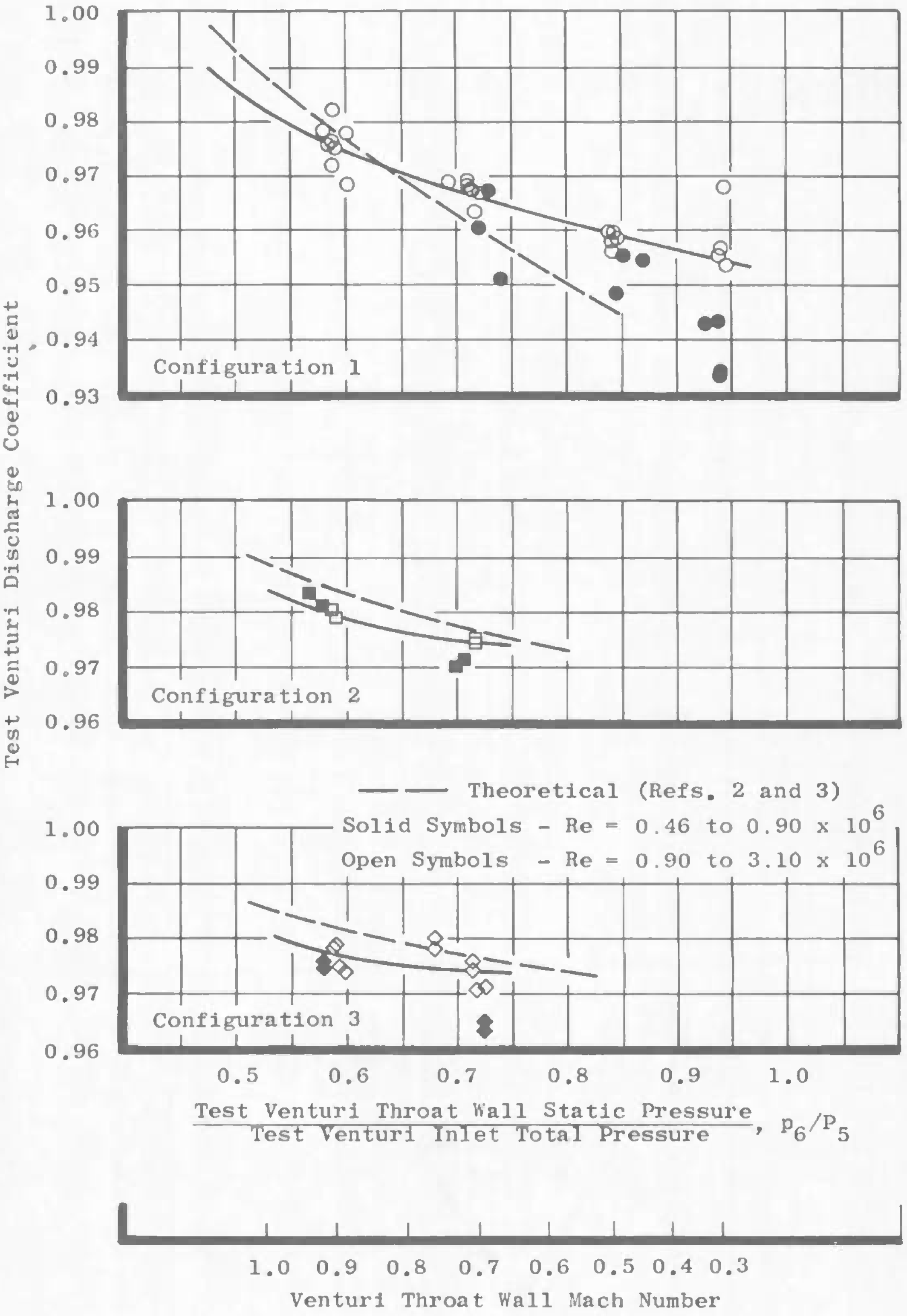


Fig. 8 Test Venturi Discharge Coefficient for Various Configurations at Subcritical Flow Conditions

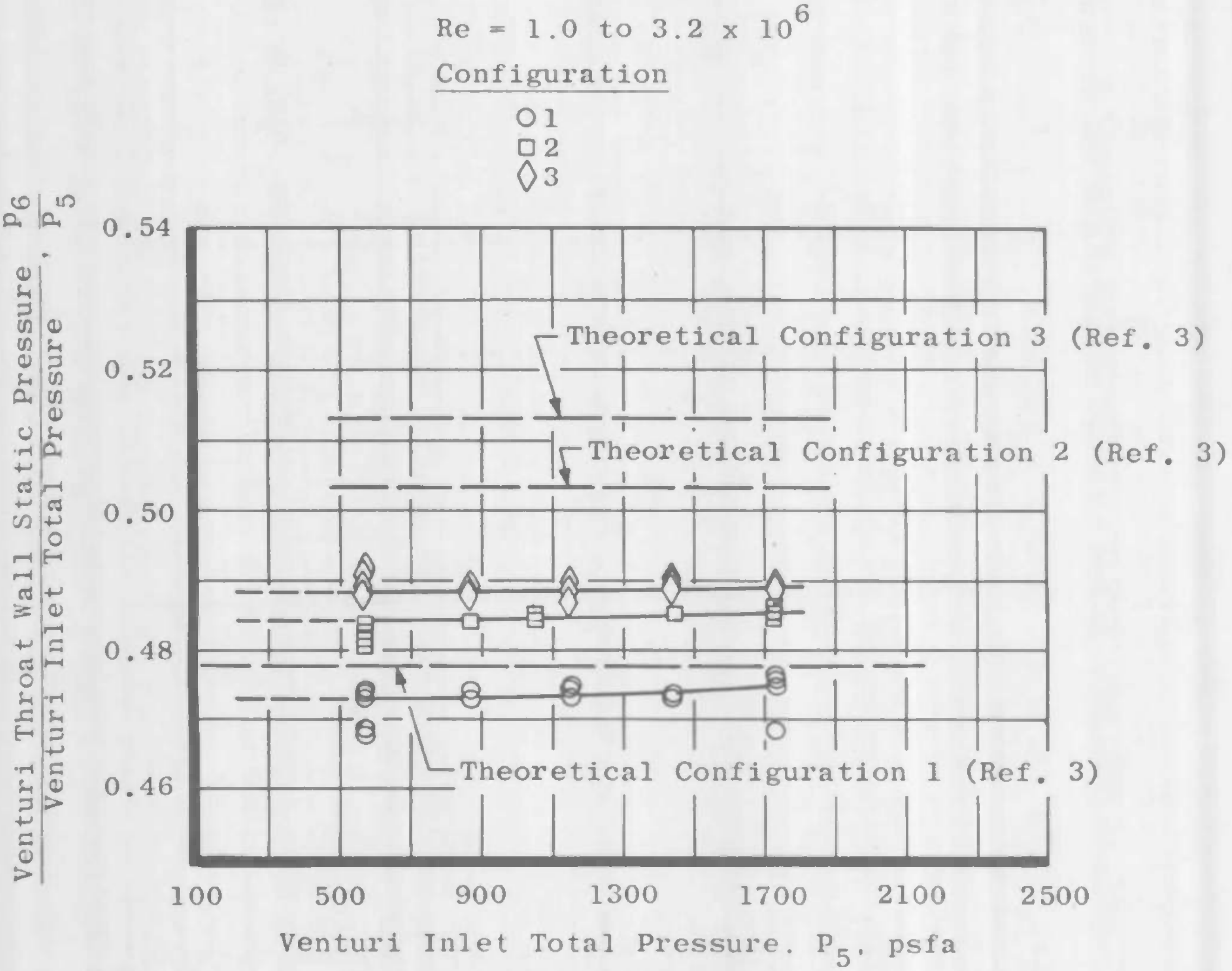


Fig. 9 Venturi Throat Indicated Critical Pressure Ratio as a Function of Venturi Centerbody Configuration

APPENDIX I
METHODS OF CALCULATION

General methods and equations employed to compute the steady-state parameters presented are given below. Where applicable, arithmetic averages of the pressures and indicated temperatures were used.

RATIO OF SPECIFIC HEATS

The ratio of specific heats, γ, was assumed to be 1.4 at all measuring stations.

AIRFLOW

1. Airflow at station 2 (standard venturi throat) was calculated from the following critical flow equation:

$$W_{a_s} = P_1 A_2 C_{f_2} \sqrt{\frac{\gamma g}{RT_2}} \left[\left(\frac{2}{\gamma + 1}\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

and $C_{f_2} = 0.9935$. C_{f_2} is an experimentally determined flow coefficient (Ref. 1).

2. Indicated airflow at station 6 (test venturi throat) was calculated from the following equations:

(1) Subcritical Operation

$$W_{a_{6_i}} = \frac{p_6 A_6}{\left(\frac{p_6}{P_5}\right)^{\frac{\gamma-1}{\gamma}}} \sqrt{\frac{2\gamma g}{RT_{6_a}(\gamma-1)} \left[1 - \left(\frac{p_6}{P_5}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

(2) Critical Operation

$$W_{a_{6_i}} = P_5 A_6 \sqrt{\frac{\gamma g}{RT_{6_a}}} \left[\left(\frac{2}{\gamma + 1}\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

DISCHARGE COEFFICIENT

The discharge coefficient of the test venturi was determined from the equation

$$C_{f_6} = \frac{W_{a_s}}{W_{a_{6_i}}}$$

MACH NUMBER

Mach number was obtained from the equation

$$M = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

REYNOLDS NUMBER

Reynolds number was obtained from the equation

$$Re = \frac{\rho V \ell}{\mu}$$

where the characteristic length, ℓ, was taken as the diameter of the test venturi throat for configuration 1 and as an equivalent diameter (based on the throat flow area) for configurations 2 and 3.

APPENDIX II

TABULATED STEADY-STATE DATA

Values given are the four significant digits, positive or negative sign, and the power of ten, e.g., .1237 + 01 = $0.1237 \times 10^{+1}$ = 1.237, .9755 + 00 = 0.9755×10^{0} = 0.9755

RB0411 VENTURI TEST 01 TEST DATE 10-25-65 COMPUTED DATE 11-11-65

POINT NO.	$\frac{P_5}{P_7}$	$\frac{P_6}{P_5}$	W_{a_s}, lb/sec	P_1	P_2	P_5	P_{5_r}	P_6	T_{6a}, °R	M_6	R_{e_t}	C_{f_6}
				←		psfa		→				
1.00	.1247+01	.4761+00	.2191+02	.5521+04	.2707+04	.1724+04	.1712+04	.8208+03	.5352+03	.1000+01	.3118+01	.9941+00
2.00	.1250+01	.4751+00	.2190+02	.5521+04	.2707+04	.1724+04	.1713+04	.8191+03	.5353+03	.1000+01	.3118+01	.9941+00
3.00	.1251+01	.4736+00	.1835+02	.4596+04	.2251+04	.1439+04	.1425+04	.6813+03	.5285+03	.1000+01	.2602+01	.9917+00
4.00	.1254+01	.4737+00	.1839+02	.4603+04	.2251+04	.1439+04	.1422+04	.6815+03	.5278+03	.1000+01	.2602+01	.9933+00
5.00	.1253+01	.4746+00	.1465+02	.3682+04	.1794+04	.1150+04	.1138+04	.5459+03	.5318+03	.1000+01	.2081+01	.9936+00
6.00	.1239+01	.4729+00	.1466+02	.3682+04	.1793+04	.1149+04	.1151+04	.5432+03	.5317+03	.1000+01	.2077+01	.9951+00
7.00	.1255+01	.4741+00	.1104+02	.2761+04	.1340+04	.8656+03	.8528+03	.4104+03	.5273+03	.1000+01	.1566+01	.9901+00
8.00	.1250+01	.4729+00	.1100+02	.2754+04	.1337+04	.8621+03	.8522+03	.4076+03	.5283+03	.1000+01	.1559+01	.9916+00
9.00	.1246+01	.4685+00	.7280+01	.1825+04	.8825+03	.5696+03	.5585+03	.2669+03	.5293+03	.1000+01	.1030+01	.9946+00
10.00	.1237+01	.4679+00	.7280+01	.1825+04	.8816+03	.5696+03	.5593+03	.2665+03	.5293+03	.1000+01	.1030+01	.9946+00
11.00	.1274+01	.4664+00	.5413+01	.1361+04	.6366+03	.4254+03	.4112+03	.1984+03	.5323+03	.1000+01	.7694+00	.9929+00
12.00	.1222+01	.4673+00	.5399+01	.1357+04	.6557+03	.4254+03	.4250+03	.1988+03	.5323+03	.1000+01	.7694+00	.9903+00
13.00	.1176+01	.4680+00	.3596+01	.8986+03	.4260+03	.2813+03	.2818+03	.1317+03	.5262+03	.1000+01	.5087+00	.9918+00
14.00	.1176+01	.4606+00	.3581+01	.8951+03	.4245+03	.2792+03	.2836+03	.1286+03	.5265+03	.1000+01	.5049+00	.9954+00
15.00	.1086+01	.5826+00	.7192+01	.1806+04	.8740+03	.5752+03	.5625+03	.3351+03	.5312+03	.9134+00	.1028+01	.9812+00
16.00	.1066+01	.6006+00	.6997+01	.1756+04	.8494+03	.5646+03	.5542+03	.3391+03	.5310+03	.8854+00	.9992+00	.9773+00
17.00	.1052+01	.7275+00	.6399+01	.1605+04	.7747+03	.5682+03	.5620+03	.4134+03	.5303+03	.6897+00	.8790+00	.9669+00
18.00	.1052+01	.7383+00	.6217+01	.1560+04	.7536+03	.5682+03	.5571+03	.4195+03	.5303+03	.6728+00	.8649+00	.9508+00
19.00	.1032+01	.8683+00	.4840+01	.1211+04	.5815+03	.5674+03	.5611+03	.4927+03	.5273+03	.4537+00	.6472+00	.9539+00
20.00	.1012+01	.9370+00	.3494+01	.8733+03	.4135+03	.5745+03	.5742+03	.5383+03	.5263+03	.3064+00	.4677+00	.9428+00
21.00	.1029+01	.9263+00	.3716+01	.9296+03	.4374+03	.5692+03	.5590+03	.5272+03	.5272+03	.3325+00	.4989+00	.9423+00

RB0411 VENTURI TEST 02 TEST DATE 10-26-65 COMPUTED DATE 01-03-66

1.00	.1237+01	.4849+00	.1350+02	.3382+04	.1645+04	.1723+04		.8356+03	.5285+03	.1000+01	.2448+01	.9873+00
2.00	.1243+01	.4857+00	.1352+02	.3387+04	.1649+04	.1728+04		.8391+03	.5292+03	.1000+01	.2454+01	.9864+00
3.00	.7009+00	.4852+00	.1129+02	.2833+04	.1376+04	.1441+04		.6990+03	.5302+03	.1000+01	.2047+01	.9894+00
4.00	.7008+00	.4853+00	.1129+02	.2827+04	.1374+04	.1441+04		.6992+03	.5283+03	.1000+01	.2047+01	.9874+00
5.00	.1231+01	.4849+00	.9018+01	.2259+04	.1094+04	.1150+04		.5578+03	.5288+03	.1000+01	.1634+01	.9882+00
6.00	.1228+01	.4844+00	.9013+01	.2256+04	.1109+04	.1148+04		.5559+03	.5282+03	.1000+01	.1630+01	.9893+00
7.00	.1230+01	.4842+00	.6809+01	.1708+04	.8258+03	.8642+03		.4184+03	.5302+03	.1000+01	.1228+01	.9944+00
8.00	.1227+01	.4842+00	.6755+01	.1692+04	.8183+03	.8621+03		.4174+03	.5285+03	.1000+01	.1225+01	.9874+00
9.00	.1214+01	.4833+00	.4486+01	.1122+04	.5372+03	.5724+03		.2766+03	.5267+03	.1000+01	.8131+00	.9859+00
10.00	.1214+01	.4805+00	.4501+01	.1126+04	.5377+03	.5710+03		.2743+03	.5277+03	.1000+01	.8111+00	.9927+00
11.00	.2095+01	.4806+00	.3315+01	.8325+03	.3941+03	.4233+03		.2034+03	.5315+03	.1000+01	.6014+00	.9896+00
12.00	.1192+01	.4796+00	.3320+01	.8339+03	.3934+03	.4226+03		.2027+03	.5317+03	.1000+01	.6004+00	.9929+00
13.00	.1174+01	.4858+00	.2199+01	.5509+03	.2609+03	.2820+03		.1370+03	.5290+03	.1000+01	.4006+00	.9831+00
14.00	.1178+01	.4795+00	.2200+01	.5513+03	.2605+03	.2806+03		.1345+03	.5290+03	.1000+01	.3986+00	.9887+00
15.00	.1302+01	.4781+00	.4436+01	.1114+04	.5309+03	.5660+03		.2706+03	.5318+03	.1000+01	.8041+00	.9907+00
16.00	.1313+01	.4791+00	.4455+01	.1119+04	.5321+03	.5667+03		.2715+03	.5313+03	.1000+01	.8051+00	.9932+00
17.00	.1082+01	.5639+00	.4414+01	.1105+04	.5260+03	.5674+03		.3200+03	.5283+03	.9429+00	.8031+00	.9831+00
18.00	.1085+01	.5769+00	.4392+01	.1100+04	.5245+03	.5674+03		.3274+03	.5283+03	.9224+00	.7991+00	.9805+00
19.00	.1060+01	.6990+00	.4103+01	.1027+04	.4873+03	.5717+03		.3996+03	.5282+03	.7340+00	.7222+00	.9693+00
20.00	.1047+01	.7029+00	.4061+01	.1017+04	.4829+03	.5667+03		.3983+03	.5283+03	.7280+00	.7124+00	.9710+00
21.00	.1245+01	.4852+00	.1355+02	.3405+04	.1655+04	.1733+04		.8407+03	.5318+03	.1000+01	.2461+01	.9887+00
22.00	.1241+01	.4859+00	.1360+02	.3405+04	.1657+04	.1735+04		.8428+03	.5282+03	.1000+01	.2464+01	.9875+00
23.00	.1245+01	.4863+00	.1361+02	.3406+04	.1657+04	.1736+04		.8442+03	.5277+03	.1000+01	.2466+01	.9871+00
24.00	.1496+01	.4866+00	.1364+02	.3413+04	.1662+04	.1738+04		.8457+03	.5275+03	.1000+01	.2469+01	.9880+00
25.00	.1503+01	.4842+00	.1364+02	.3413+04	.1661+04	.1739+04		.8419+03	.5273+03	.1000+01	.2470+01	.9876+00
26.00	.1101+01	.5830+00	.1334+02	.3339+04	.1624+04	.1726+04		.1006+04	.5283+03	.9129+00	.2423+01	.9804+00
27.00	.1105+01	.5880+00	.1333+02	.3338+04	.1625+04	.1730+04		.1018+04	.5285+03	.9051+00	.2424+01	.9785+00
28.00	.1068+01	.7147+00	.1231+02	.3079+04	.1497+04	.1729+04		.1236+04	.5273+03	.7097+00	.2139+01	.9746+00
29.00	.1067+01	.7136+00	.1232+02	.3081+04	.1499+04	.1729+04		.1234+04	.5272+03	.7114+00	.2143+01	.9742+00

RB0411 VENTURI TEST 03 TEST DATE 10-27-65 COMPUTED DATE 12-27-65

POINT NO.	$\frac{P_5}{P_7}$	$\frac{p_6}{P_5}$	W_{a_s},	P_1	p_2	P_5	P_{5_r}	p_6	T_{6_a},	M_6	R_{e_t}	C_{f_6}
			lb/sec	psfa					°R			
1.00	.2503+01	.4887+01	.7238+01	.1808+04	.8738+03	.1443+04		.7058+03	.5260+03	.5447+00	.1190+01	.9859+00
2.00	.2503+01	.4888+00	.7237+01	.1807+04	.8729+03	.1441+04		.7046+03	.5253+03	.1000+01	.1638+01	.9861+00
3.00	.1658+01	.4893+00	.7215+01	.1810+04	.8750+03	.1442+04		.7057+03	.5302+03	.1000+01	.1639+01	.9872+00
4.00	.1656+01	.4896+00	.7223+01	.1813+04	.8752+03	.1443+04		.7064+03	.5308+03	.1000+01	.1639+01	.9884+00
5.00	.1244+01	.4884+00	.7210+01	.1807+04	.8733+03	.1441+04		.7037+03	.5293+03	.1000+01	.1637+01	.9866+00
6.00	.1247+01	.4890+00	.7230+01	.1812+04	.8752+03	.1444+04		.7059+03	.5293+03	.1000+01	.1640+01	.9874+00
7.00	.1104+01	.6821+00	.6757+01	.1693+04	.8163+03	.1437+04		.9803+03	.5293+03	.7600+00	.1482+01	.9799+00
8.00	.1108+01	.6788+00	.6786+01	.1701+04	.8225+03	.1444+04		.9799+03	.5294+03	.7650+00	.1495+01	.9775+00
9.00	.1237+01	.4895+00	.8658+01	.2172+04	.1050+04	.1732+04		.8477+03	.5303+03	.1000+01	.1968+01	.9865+00
10.00	.1239+01	.4891+00	.8661+01	.2173+04	.1051+04	.1733+04		.8474+03	.5304+03	.1000+01	.1969+01	.9864+00
11.00	.1242+01	.4897+00	.7226+01	.1813+04	.8768+03	.1444+04		.7069+03	.5307+03	.1000+01	.1640+01	.9881+00
12.00	.1242+01	.4893+00	.7227+01	.1811+04	.8764+03	.1444+04		.7063+03	.5293+03	.1000+01	.1640+01	.9870+00
13.00	.1224+01	.4907+00	.5761+01	.1442+04	.6931+03	.1144+04		.5612+03	.5278+03	.1000+01	.1299+01	.9917+00
14.00	.1234+01	.4870+00	.5754+01	.1441+04	.6975+03	.1152+04		.5610+03	.5283+03	.1000+01	.1309+01	.9837+00
15.00	.1229+01	.4881+00	.4319+01	.1082+04	.5191+03	.8634+03		.4214+03	.5293+03	.1000+01	.9810+00	.9861+00
16.00	.1227+01	.4883+00	.4315+01	.1081+04	.5199+03	.8634+03		.4216+03	.5293+03	.1000+01	.9810+00	.9852+00
17.00	.1212+01	.4914+00	.2867+01	.7186+03	.4473+03	.5744+03		.2823+03	.5294+03	.1000+01	.6527+00	.9840+00
18.00	.1205+01	.4891+00	.2868+01	.7193+03	.3406+03	.5737+03		.2806+03	.5302+03	.1000+01	.6519+00	.9862+00
19.00	.1196+01	.4935+00	.2126+01	.5322+03	.2533+03	.4278+03		.2111+03	.5283+03	.1000+01	.4861+00	.9786+00
20.00	.1195+01	.4886+00	.2126+01	.5322+03	.2531+03	.4275+03		.2089+03	.5283+03	.1000+01	.4857+00	.9794+00
21.00	.1178+01	.4948+00	.1408+01	.3522+03	.1687+03	.2840+03		.1405+03	.5272+03	.1000+01	.3227+00	.9755+00
22.00	.1205+01	.4908+00	.1406+01	.3515+03	.1680+03	.2837+03		.1392+03	.5269+03	.1000+01	.3223+00	.9748+00
23.00	.1305+01	.4878+00	.2849+01	.7158+03	.3420+03	.5723+03		.2792+03	.5317+03	.1000+01	.6503+00	.9837+00
24.00	.1309+01	.4897+00	.2848+01	.7158+03	.3417+03	.5744+03		.2813+03	.5322+03	.1000+01	.6527+00	.9801+00
25.00	.1144+01	.5795+00	.2822+01	.7098+03	.3378+03	.5758+03		.3337+03	.5332+03	.9185+00	.6478+00	.9754+00
26.00	.1143+01	.5785+00	.2823+01	.7094+03	.3378+03	.5755+03		.3329+03	.5322+03	.9199+00	.6477+00	.9753+00
27.00	.1096+01	.7235+00	.2567+01	.6433+03	.3065+03	.5758+03		.4166+03	.5292+03	.6960+00	.5629+00	.9646+00
28.00	.1097+01	.7245+00	.2558+01	.6405+03	.3053+03	.5751+03		.4167+03	.5285+03	.6944+00	.5614+00	.9625+00
33.00	.1239+01	.4885+00	.8638+01	.2164+04	.1047+04	.1730+04		.8450+03	.5290+03	.1000+01	.1965+01	.9842+00
34.00	.1239+01	.4889+00	.8660+01	.216[illegible]+04	.1049+04	.1730+04		.8461+03	.5283+03	.1000+01	.1966+01	.9857+00
35.00	.1139+01	.5926+00	.8489+01	.2126+04	.1047+04	.1731+04		.1026+04	.5283+03	.8979+00	.1934+01	.9748+00
36.00	.1130+01	.5996+00	.8466+01	.2120+04	.1026+04	.1733+04		.1039+04	.5283+03	.8870+00	.1927+01	.9737+00
37.00	.1098+01	.7193+00	.7797+01	.1954+04	.9503+03	.1730+04		.1245+04	.5292+03	.7025+00	.1702+01	.9707+00
38.00	.1099+01	.7228+00	.8005+01	.1948+04	.9492+03	.1731+04		.1251+04	.4992+03	.6971+00	.1694+01	.9709+00
43.00	.1230+01	.4882+00	.5786+01	.1450+04	.7010+03	.1156+04		.5645+03	.5292+03	.1000+01	.1314+01	.9863+00
44.00	.1224+01	.4860+00	.5751+01	.1441+04	.6984+03	.1151+04		.5594+03	.5292+03	.1000+01	.1300+01	.9848+00
45.00	.1134+01	.5906+00	.5679+01	.1422+04	.6852+03	.1153+04		.6811+03	.5282+03	.9007+00	.1289+01	.9788+00
46.00	.1127+01	.5879+00	.5672+01	.1420+04	.6861+03	.1151+04		.6767+03	.5282+03	.9053+00	.1289+01	.9783+00
47.00	.1090+01	.7144+00	.5243+01	.1313+04	.6290+03	.1151+04		.8723+03	.5282+03	.7102+00	.1140+01	.9755+00
48.00	.1097+01	.7143+00	.5250+01	.1315+04	.6386+03	.1155+04		.8246+03	.5282+03	.7104+00	.1143+01	.9738+00

R80411 VENTURI TEST 04 TEST DATE 10-28-65 COMPUTED DATE 01-03-66

POINT NO.	$\frac{P_5}{P_7}$	$\frac{P_6}{P_5}$	W_{a_s}', lb/sec	P_1	P_2	P_5	P_{5_r}	P_6	T_{6a}', °R	M_6	R_{e_t}	C_{f_6}
				← psfa				→				
16.00	.1237+01	.4742+00	.2193+02	.5511+04	.2705+04	.1731+04		.8209+03	.5322+03	.1000+01	.3131+01	.9884+00
17.00	.1237+01	.4685+00	.2196+02	.5515+04	.2704+04	.1727+04		.8092+03	.5315+03	.1000+01	.3124+01	.9912+00
18.00	.1226+01	.4731+00	.1462+02	.3668+04	.1787+04	.1147+04		.5426+03	.5302+03	.1000+01	.2074+01	.9928+00
19.00	.1224+01	.4742+00	.1460+02	.3670+04	.1789+04	.1149+04		.5449+03	.5323+03	.1000+01	.2078+01	.9916+00
20.00	.1213+01	.4741+00	.7284+01	.1827+04	.8837+03	.5731+03		.2717+03	.5300+03	.1000+01	.1036+01	.9896+00
21.00	.1213+01	.4741+00	.7267+01	.1822+04	.8830+03	.5724+03		.2714+03	.5297+03	.1000+01	.1035+01	.9882+00
22.00	.1297+01	.4732+00	.7284+01	.1824+04	.8830+03	.5717+03		.2705+03	.5283+03	.1000+01	.1034+01	.9906+00
23.00	.1305+01	.4745+00	.7283+01	.1824+04	.8810+03	.5717+03		.2712+03	.5283+03	.1000+01	.1034+01	.9904+00
24.00	.1045+01	.5849+00	.7085+01	.1774+04	.8573+03	.5681+03		.3323+03	.5283+03	.9099+00	.1015+01	.9765+00
25.00	.1042+01	.6003+00	.7014+01	.1756+04	.8538+03	.5699+03		.3421+03	.5285+03	.8859+00	.1009+01	.9682+00
26.00	.1045+01	.6919+00	.6721+01	.1684+04	.8151+03	.5752+03		.3980+03	.5292+03	.7449+00	.9333+00	.9687+00
27.00	.1032+01	.7188+00	.6470+01	.1620+04	.7842+03	.5724+03		.4114+03	.5283+03	.7033+00	.8965+00	.9598+00
28.00	.1038+01	.7149+00	.6554+01	.1641+04	.7939+03	.5759+03		.4117+03	.5283+03	.7094+00	.9069+00	.9626+00
29.00	.1022+01	.8438+00	.5232+01	.1305+04	.6321+03	.5741+03		.4845+03	.5245+03	.4986+00	.7052+00	.9479+00
30.00	.1020+01	.8508+00	.5186+01	.1294+04	.6270+03	.5752+03		.4893+03	.5247+03	.4861+00	.6928+00	.9554+00
31.00	.1013+01	.9380+00	.3427+01	.8582+03	.4134+03	.5752+03		.5395+03	.5283+03	.3037+00	.4645+00	.9327+00
32.00	.1020+01	.9377+00	.3455+01	.8652+03	.4117+03	.5752+03		.5393+03	.5283+03	.3045+00	.4657+00	.9380+00
33.00	.1231+01	.4733+00	.1463+02	.3662+04	.1784+04	.1148+04		.5434+03	.5278+03	.1000+01	.2077+01	.9901+00
34.00	.1230+01	.4729+00	.1463+02	.3657+04	.1784+04	.1148+04		.5430+03	.5265+03	.1000+01	.2077+01	.9887+00
35.00	.1059+01	.5779+00	.1430+02	.3585+04	.1746+04	.1145+04		.6615+03	.5293+03	.9209+00	.2051+01	.9777+00
36.00	.1062+01	.5821+00	.1430+02	.3585+04	.1746+04	.1149+04		.6688+03	.5300+03	.9143+00	.2055+01	.9752+00
37.00	.1041+01	.7106+00	.1321+02	.3314+04	.1612+04	.1152+04		.8184+03	.5302+03	.7161+00	.1825+01	.9678+00
38.00	.1041+01	.7132+00	.1316+02	.3302+04	.1606+04	.1152+04		.8215+03	.5302+03	.7119+00	.1818+01	.9667+00
39.00	.1019+01	.8401+00	.1069+02	.2676+04	.1298+04	.1152+04		.9676+03	.5282+03	.5051+00	.1429+01	.9596+00
40.00	.1022+01	.8372+00	.1077+02	.2695+04	.1309+04	.1152+04		.9642+03	.5282+03	.5104+00	.1440+01	.9595+00
41.00	.1008+01	.9375+00	.7041+01	.1763+04	.8540+03	.1149+04		.1077+04	.5282+03	.3051+00	.9321+00	.9549+00
42.00	.1009+01	.9391+00	.6978+01	.1747+04	.8487+03	.1151+04		.1081+04	.5282+03	.3010+00	.9222+00	.9562+00
43.00	.1244+01	.4753+00	.2206+02	.5511+04	.2703+04	.1733+04		.8236+03	.5257+03	.1000+01	.3134+01	.9872+00
44.00	.1240+01	.4757+00	.2211+02	.5507+04	.2702+04	.1733+04		.8244+03	.5227+03	.1000+01	.3134+01	.9866+00
45.00	.1054+01	.5869+00	.2159+02	.5388+04	.2643+04	.1735+04		.1018+04	.5245+03	.9067+00	.3095+01	.9718+00
46.00	.1051+01	.5880+00	.2157+02	.5388+04	.2645+04	.1731+04		.1018+04	.5257+03	.9051+00	.3087+01	.9741+00
47.00	.1039+01	.7085+00	.1985+02	.5001+04	.2453+04	.1733+04		.1228+04	.5350+03	.7193+00	.2753+01	.9687+00
48.00	.1036+01	.7202+00	.1957+02	.4929+04	.2415+04	.1731+04		.1247+04	.5347+03	.7011+00	.2706+01	.9668+00
49.00	.1022+01	.8413+00	.1596+02	.4005+04	.1958+04	.1732+04		.1457+04	.5303+03	.5031+00	.2143+01	.9578+00
50.00	.1020+01	.8437+00	.1584+02	.3973+04	.1940+04	.1729+04		.1459+04	.5303+03	.4987+00	.2124+01	.9581+00
51.00	.1006+01	.9437+00	.9973+01	.2517+04	.1220+04	.1726+04		.1629+04	.5368+03	.2888+00	.1332+01	.9534+00
52.00	.1008+01	.9422+00	.1030+02	.2598+04	.1261+04	.1733+04		.1633+04	.5362+03	.2929+00	.1354+01	.9678+00
53.00	.2000+01	.4746+00	.2212+02	.5523+04	.2709+04	.1737+04		.8242+03	.5252+03	.1000+01	.3141+01	.9873+00
54.00	.2006+01	.4745+00	.2221+02	.5530+04	.2715+04	.1740+04		.8258+03	.5227+03	.1000+01	.3147+01	.9866+00
55.00	.1491+01	.4761+00	.2217+02	.5492+04	.2697+04	.1730+04		.8235+03	.5170+03	.1000+01	.3128+01	.9856+00
56.00	.1497+01	.4759+00	.2228+02	.5512+04	.2706+04	.1736+04		.8262+03	.5157+03	.1000+01	.3140+01	.9857+00
57.00	.1235+01	.4740+00	.2225+02	.5491+04	.2701+04	.1727+04		.8188+03	.5130+03	.1000+01	.3124+01	.9869+00

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY *(Corporate author)* Arnold Engineering Development Center, ARO, Inc., Operating Contractor, Arnold Air Force Station, Tennessee	2a REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b GROUP N/A

3 REPORT TITLE

CALIBRATION OF THREE VENTURI AIRFLOW METERING SYSTEMS WITH STING-MOUNTED CENTERBODIES AT CRITICAL AND SUBCRITICAL FLOW CONDITIONS

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13 ABSTRACT

An experimental investigation was conducted to determine the discharge coefficient of a venturi airflow meter with various diameter centerbodies installed. A critical flow venturi for which a theoretical discharge coefficient had been experimentally verified was used as the calibration standard. The discharge coefficients for the test venturi without centerbody and with centerbodies of two different diameters were determined over a range of venturi throat Reynolds numbers from 0.32 to 3.20 x 10^6 at a constant inlet air total temperature of 70°F. The experimentally determined coefficients were in good agreement with the theoretical value for all configurations tested. Maximum deviation (0.3 percent) of discharge coefficient from the theoretical value occurred with the venturi without centerbody operating at critical flow conditions.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
venturi flowmeters						
flow measurement						
calibration						
centerbodies						
sting-mounted						

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