JET SPREADING CHARACTERISTICS AT PRESSURE ALTITUDES OF 180,000 TO 260,000 FEET

By

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Propulsion Wind Tunnel Facility

ARO, Inc.

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ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

NOTICES

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a subsidiary of Sverdrup and Parcel, Inc.

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ABSTRACT

An investigation has been conducted to determine the effects of certain parameters on the spreading characteristics of a jet discharging from conical underexpanded nozzles into a quiescent atmosphere. Tests were conducted in low pressure chambers using both nitrogen and carbon dioxide as the nozzle fluid.

Flow visualization enabling the expanding jet to be photographed was accomplished by a glow discharge technique. Boundaries are presented for 7.5, 25.3, and 45.7 area ratio nozzles having 15-deg half-angle conical divergence. The experimental boundaries are presented and compared with contours calculated by the method-of-characteristics. Jet boundaries obtained using nitrogen as the nozzle fluid compare favorably with the theoretical boundaries. The boundaries obtained with carbon dioxide nozzle flow were expanded much more than predicted by the method-of-characteristics because of condensation in the jet.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

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DCS/Research

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CONTENTS

TABLES

ILLUSTRATIONS

NOMENCLATURE

A	Cross-sectional area, in.^{2}
H_c	Model chamber pressure, psi
M	Mach number
p	Static pressure, torr
r	Radius normal to nozzle axis, in.
T	Temperature, °F
x	Axial distance aft of nozzle exit, in.
γ	Ratio of specific heats
θ_n	Nozzle divergence half angle, deg

SUBSCRIPTS

c	Stagnation
e	Nozzle exit
∞	Ambient conditions in test chamber

SUPERSCRIPT

*	Nozzle throat

1.0 INTRODUCTION

A problem of concern to designers of rocket propelled aircraft and missiles is the effect of the jet exhaust on adjacent vehicle components. Jet effects may alter vehicle stability or result in undesirable heating and corrosion. Numerous theoretical studies have been conducted in an effort to predict the jet boundaries, and, in general, they compare favorably with experimental results. Although some experimental data are available at the low jet exit to ambient pressure ratios, data to validate these theories at high pressure ratios are very limited. For the purpose of theoretical calculations, it may be assumed that the flow goes through a Prandtl-Meyer expansion at the nozzle lip. The flow in the jet can then be calculated using the method-of-characteristics with appropriate jet boundary conditions. Jet flow fields calculated using this method appear in Refs. 1, 2, and 3. Simplified methods for calculating the jet boundary are presented in Refs. 4, 5, and 6.

The investigations reported herein were conducted to obtain the variation of jet plume contours, in a quiescent atmosphere, as a function of jet exit to ambient pressure ratio by varying jet total pressure and pressure altitude. Data were obtained with a 7.5 area ratio conical nozzle using carbon dioxide as the nozzle fluid and with 7.5, 25.3, and 45.7 area ratio conical nozzles using nitrogen as the nozzle fluid. Boundaries, obtained from photographs of the jet, were made visible by use of a glow discharge phenomenon. These investigations were conducted at the Propulsion Wind Tunnel Facility (PWT) under the sponsorship of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC). Tests were conducted in the 18-in. Test Cell and the PWT Cold Wall Vacuum Chamber at pressure altitudes from 180,000 to 260,000 ft using both nitrogen and carbon dioxide as the nozzle fluid. Plume contours were obtained by both schlieren and glow techniques at identical test conditions, using a sonic nozzle to determine if the electrical discharge used in producing the glow phenomena was affecting the jet expansion. Pressure measurements were obtained in the divergent section of a 48.5 area ratio nozzle to determine nozzle flow characteristics with carbon dioxide as the test fluid.

Manuscript received April 1964.

2.0 APPARATUS

2.1 TEST FACILITY

Tests using nitrogen as the nozzle fluid were conducted in the 18-in. Test Cell. Basic dimensions of the 18-in. Test Cell are shown in Fig. 1. The cell was designed to attach directly to a six-stage steam ejector used to pump the jet exhaust. The cell was equipped with a 6-in. -diam viewing port which was also used for model access. The model installation in the 18-in. Test Cell is shown in Fig. 2.

Tests using carbon dioxide as the nozzle fluid were conducted in the PWT Cold Wall Vacuum Chamber. The location of the model in the Cold Wall Vacuum Chamber is shown in Fig. 3. The vacuum chamber is 38 in. in diameter and 155 in. long. It is of double wall construction, and approximately 130 ft^2 of surface area can be cooled with liquid nitrogen to cryopump the jet exhaust. The vacuum chamber is equipped with two 16-in. -diam windows to view the model and to provide access to the models. A more complete description of the vacuum chamber and its operating characteristics is presented in Ref. 7. The model installation in the vacuum chamber is shown in Fig. 4.

To produce the glow phenomena, an anode was immersed in the jet exhaust aft of the nozzle exit as shown in Figs. 1 and 3. The nozzle was maintained at ground potential while 40, 000 volts were impressed upon the anode, which "excited" the nozzle fluid and thereby caused it to glow. The boundaries were obtained from photographs of the "excited" flow.

A secondary gas was bled into the upstream end of the test chamber to regulate the upstream pressure. The secondary gas selected produced a glow of different color than the glow of the nozzle fluid and thereby increased the definition of the plume boundary. Nitrogen was used as the secondary gas when carbon dioxide was used as the nozzle fluid, and carbon dioxide was used as the secondary gas when nitrogen was used as the nozzle fluid. The "excited" carbon dioxide produced a dense blue glow in contrast to the pinkish glow of the "excited" nitrogen.

2.2 MODELS

Jet spreading data were obtained with convergent-divergent conical nozzles having area ratios of 7. 5, 25. 3, and 45. 7. Basic dimensions of these models are presented in Fig. 5. The nozzles had a nominal throat diameter of 0.1 in. and divergence half angles of 15 deg. The 7.5 area ratio nozzle was constructed with a long slender chamber to prevent the base from interfering with the jet expansion. A 2.5-in. chamber extension (shown in Fig. 4) was used with the 25.3 and 45.7 area ratio nozzles to position all nozzle exits at the same cell location for viewing purposes. A photograph of the models is presented as Fig. 6.

A 48.5 area ratio nozzle having static pressure orifices in the divergent section was used to determine the fluid dynamic characteristics of the nozzle flow. Details of the instrumented nozzle are presented in Fig. 7.

2.3 INSTRUMENTATION

Model instrumentation consisted of a pressure orifice located in the model chamber for measuring jet total pressure and a thermocouple in the inlet line for measuring the temperature of the nozzle fluid. Five pressure orifices were located in the divergent section of the 48.5 area ratio nozzle to obtain static pressure measurements. An Alphatron was used to determine test cell pressure, which was measured at an orifice located forward of the nozzle as shown in Figs. 1 and 3.

The oscillator power supply used for producing the glow visualization was rated at 40 KV-RF at 18 milliamps. The unit operated at a frequency of one megacycle and had a damped waveform with maximum peak occurring at a frequency of 30 kilocycles.

Thermocouples located in the liquid-nitrogen panels of the Cold Wall Vacuum Chamber were used to monitor chilldown and to ensure that an adequate liquid-nitrogen flow rate was maintained during testing.

3.0 PROCEDURE

3.1 GENERAL

Data were obtained in the 18-in. Test Cell at pressure altitudes from 215,000 to 235,000 ft using nitrogen as the nozzle fluid. A six-stage steam ejector was used to pump the nozzle exhaust during this portion of the tests. The nitrogen was passed through a resistance heater where it was heated to obtain a model stagnation temperature of 1000°F. After the cell was evacuated using the steam ejector, nitrogen flow was established and regulated by a pneumatically-operated control valve. Carbon dioxide was then bled into the upstream end of the cell to establish the desired cell pressure and to aid in the visualization of the jet boundary.

Data were obtained in the PWT Cold Wall Vacuum Chamber at pressure altitudes from 180, 000 to 260, 000 ft using carbon dioxide as the nozzle fluid. Before testing, the carbon dioxide was heated to a temperature of 600°F in a 60-ft^3 conditioning vessel. This resulted in a model chamber temperature of from 245 to 310°F, depending upon the temperature loss in the carbon dioxide supply line. Chilldown was initiated approximately 1. 5 hours before testing and was monitored by thermocouples located in the liquid-nitrogen panels. The vacuum chamber was evacuated to a pressure of 0. 02 torr by two mechanical pumps having a combined pumping capacity of 550 cfm. After chilldown, the desired carbon dioxide flow rate was established by use of a pneumatically-operated control valve. Gaseous nitrogen was bled into the upstream end of the cell to regulate cell pressure and to aid in the visualization of the jet boundary.

3.2 GLOW TECHNIQUE

Since the test cell pressures were below those required for conventional flow visualization methods (shadowgraph, schlieren, etc.), another means of flow visualization was necessary. A method developed for use in low density wind tunnels, in which an electrical charge was used to excite the flow producing a glow, was investigated and proved successful. Developers of the flow visualization method (Refs. 8, 9, and 10) produced the glow either by exciting the flow upstream of the model or by charging the model itself. During the present investigations, the best results were obtained by charging an anode which was immersed in the expanding jet aft of the nozzle exit. The anode was positioned 5 and 7 in. aft of the nozzle exit during tests in the 18-in. Test Cell and Cold Wall Vacuum Chamber, respectively. These anode positions were found to give the best jet boundary definitions for the respective test configurations. The nozzles were maintained at ground potential while a 40-KV one-megacycle oscillator power supply was used to charge the anode. The electrical charge excited the flow, causing carbon dioxide to give off a dense blue glow in contrast to the pinkish glow of nitrogen. Using one gas to simulate the rocket exhaust and the other to serve as a background increased the boundary definition. With both gases excited, the plume was photographed using 7257 ER, Index 160 Eastman Kodak colored film. The boundaries were obtained from measurements taken from projections of the photographic film.

During these investigations, definite boundaries could not be determined below a cell ambient pressure of approximately 0.035 and 0.01 torr when using nitrogen and carbon dioxide, respectively, as the nozzle fluid. No data were presented below these pressures because of this poor boundary definition.

4.0 RESULTS AND DISCUSSION

Jet spreading data are presented up to a maximum pressure ratio p_e/p_∞ = 6,600 and 20,400 using nitrogen and carbon dioxide, respectively, as the test fluid. A summary of the test conditions is presented in Tables 1 and 2.

Jet boundaries were obtained from photographs of the expanding jet. A typical photograph of the jet plume is presented in Fig. 8a, and an explanation of the photograph in Fig. 8b. The jet boundary is assumed to be the dividing line determined by the color contrast between the pink nitrogen glow and the blue carbon dioxide glow. Close observation of the photograph reveals a faint, light blue-pink band at the boundary periphery which could be a mixing region. No efforts were made to distinguish this blue-pink band from the exhaust flow, and the jet boundary was assumed to be the outer edge of this mixed color region. To determine if the electrical discharge used in producing the glow was affecting the jet boundary, plume contours were obtained using both schlieren and glow techniques at similar test conditions. A sonic nozzle was used to obtain the highest pressure ratio (p_e/p_∞) possible (therefore the greatest plume expansion) and still permit good definition in the schlieren photographs. The lowest cell ambient pressure at which boundary definition could be obtained using the schlieren system was 20 torr, which resulted in a value of p_e/p_∞ = 563. The data, presented in Fig. 9, show good agreement between boundaries obtained by glow and schlieren techniques and indicate that the boundaries are not affected by the electrical discharge, at least at the lower pressure ratios.

Nitrogen used in these investigations was heated to obtain a chamber temperature of 1000°F in an endeavor to prevent condensation in the nozzle and that portion of the plume from which measurements were obtained. Figure 10, obtained from Ref. 11, shows the maximum amount of supercooling that can be expected as a function of pressure. The curve represents a compilation of data obtained for the condensation threshold of air in hypersonic wind tunnels. The region of possible condensation in the subject tests is presented in Fig. 11 as a function of stagnation conditions and cell ambient pressure. The condensation boundary was obtained using the criteria of Fig. 10 and assuming a stagnation temperature of 1000°F. The symbols represent conditions at which the experimental boundaries reported herein were obtained.

All theoretical boundaries presented herein were calculated by the method-of-characteristics presented in Ref. 3. The required input constants for the theoretical solutions are nozzle divergence half angle θ_n, ratio of specific heats γ, nozzle exit Mach number M_e, and ratio of test cell ambient pressure to model chamber pressure p_∞/H_c. The calculations assume a perfect gas with isentropic flow in the nozzle. Jet exit to ambient pressure ratios were calculated assuming an isentropic expansion in the nozzle at an average γ between those values of γ for the nozzle stagnation and exit conditions.

Experimental boundaries obtained using nitrogen as the nozzle fluid are compared with theoretical boundaries for the 7.5, 25.3, and 45.7 area ratio nozzles (Fig. 12). A value of $\gamma = 1.38$ was used in determining nozzle exit Mach number, and $\gamma = 1.40$ was used for the theoretical calculations of the boundary. The variation of γ with pressure and temperature is presented in Fig. 13 (obtained from Ref. 12), which shows $\gamma = 1.36$ for nitrogen at a temperature of 1000°F, which corresponds to the stagnation temperature, and increases to $\gamma = 1.40$ at nozzle exit temperature and pressure. The value of $\gamma = 1.38$ was, therefore, the average γ in the nozzle between stagnation conditions and nozzle exit conditions. The experimental data shown in Fig. 12 agree favorably with theoretical data calculated by the method-of-characteristics, with the greatest deviation being less than two exit radii for the range of data presented. The experimental contours show a greater initial expansion and therefore a greater initial plume radius than predicted. However, at $x/r_e > 3$ the experimental and theoretical boundaries appear to be converging. The condensation criteria presented in Fig. 11 indicate that some of the data of Fig. 12 were obtained in the region of possible condensation. Referring to the test conditions of Table 1 and to the condensation criteria of Fig. 11, it can be seen that the test conditions of $p_e/p_\infty = 6600$ and 5500 for the 7.5 area ratio nozzle are in the region of possible condensation. However, the boundaries do not appear to be affected by condensation when compared with the other boundaries obtained with the same nozzle. Data from Ref. 13 indicate that the degree of supercooling increases as the scale of the experiment is decreased, that is, as (1) nozzle length is decreased, (2) throat area is decreased, and/or (3) the nozzle divergence angle is increased. Data reported herein were obtained from nozzles and plumes having combined lengths of less than 6 in., which are an order of magnitude smaller in scale than most hypersonic wind tunnel nozzles. Since the condensation criteria presented in Figs. 10 and 11 are from hypersonic wind tunnel nozzles, it is believed that no condensation occurred in either the nozzles or portion of the plume in which measurements were obtained in the investigation reported herein.

A comparison of the boundary obtained with the 25.3 area ratio nozzle with data of Ref. 14 is presented in Fig. 14. The jet contour of Ref. 14 was obtained using air as the nozzle fluid. These experimental boundaries agree favorably, with each showing a greater initial expansion than predicted by the method-of-characteristics.

Experimental boundaries obtained with carbon dioxide as the test fluid are shown in Fig. 15. The variation of jet expansion with pressure ratio, p_e/p_∞, is presented for the 7.5 area ratio nozzle. The comparison of an experimental boundary with theoretical boundaries calculated by the method-of-characteristics (Ref. 3) is shown in Fig. 16. The experimental boundary of Fig. 16 is expanded much more than the theoretical boundary calculated for $\gamma = 1.39$ and $M_e = 3.44$, which are the anticipated values at the nozzle exit. The exit Mach number ($M_e = 3.44$) was obtained for isentropic flow conditions using an average specific heat ratio ($\gamma = 1.34$) between nozzle stagnation conditions and nozzle exit conditions. The values of γ were obtained from Fig. 13, which shows $\gamma = 1.28$ at nozzle stagnation conditions (T_c = 310°F, H_c = 301 psi) and $\gamma = 1.39$ at nozzle exit conditions. The data shown in Fig. 13, obtained from Ref. 12, do not extend to pressures below 0.15 psi; however, data in the vicinity of 0.15 psi indicate that γ does not vary significantly with pressure at the lower pressures. Therefore, it is assumed that the variation of γ with temperature at a pressure of 0.15 psi is valid for pressures down to 0.10 torr. The measured boundary shown in Fig. 16 lies between the theoretical contours calculated for $\gamma = 1.20$ and 1.39. It should be remembered, however, that the value of γ would increase from $\gamma = 1.28$, at stagnation conditions, as the fluid expands isentropically in the nozzle and plume.

To determine if condensation were causing the increased spreading shown in Fig. 16, static pressure measurements were obtained in the divergent section of a 48.5 area ratio nozzle. The data presented in Fig. 17 show what appears to be the onset of condensation between an area ratio of 12.4 and 19.1. Condensation results in a higher pressure and lower Mach number at the nozzle exit than predicted by an isentropic expansion from stagnation conditions for $\gamma = 1.28$. An isentropic expansion for $\gamma = 1.15$ was found to more nearly match the measured pressures; however, as seen from Fig. 13, γ cannot be less than 1.28, which corresponds to the value of γ at stagnation conditions. It is quite probable that condensation is not occurring in the 7.5 area ratio nozzle but may be occurring in the free expansion region aft of the nozzle exit, which will cause a greater expansion than predicted.

On the basis of the data obtained using nitrogen as the nozzle fluid, it appears that the method-of-characteristics is a valid method for predicting jet boundaries at high nozzle exit to ambient pressure ratios and low ambient pressures, provided the assumptions used in the theoretical calculations are applicable to the nozzle fluid.

The jet boundaries obtained with carbon dioxide nozzle flow are expanded much more than predicted by the method-of-characteristics because of the occurrence of condensation in the jet exhaust. The data indicate that caution should be exercised in using theoretical methods for predicting rocket exhaust boundaries for practical applications. Many propellant combinations will have exhaust products which will be subject to condensation, recombination, after-burning, or a combination of these, all of which will result in jet plumes larger than predicted by theory.

5.0 CONCLUSIONS

1. Jet boundaries obtained using nitrogen as the nozzle fluid agree favorably with boundaries obtained by the method-of-characteristics; however, the experimental data show a greater initial expansion than predicted.
2. Jet boundaries obtained using carbon dioxide as the nozzle fluid were expanded much more than predicted by the method-of-characteristics. The greater spreading is believed to be the result of condensation occurring in the expanding jet.
3. Care should be exercised in using theoretical methods for predicting jet boundaries for a practical application where condensation, recombination, and/or after-burning may occur.
4. Comparison of boundaries obtained using both schlieren and glow techniques shows favorable agreement.
5. The glow technique appears to be a promising method for obtaining jet boundaries at ambient pressures down to 0.035 and 0.01 torr when using nitrogen and carbon dioxide, respectively, as the nozzle fluid.

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TABLE 1

SUMMARY OF TEST CONDITIONS WITH NITROGEN AS THE NOZZLE FLUID

A/A*	p_∞, torr	H_c, psi	T_c, °F	p_e/p_∞
7.5	0.038	100	1000	1605
7.5	0.063	300	975	2910
7.5	0.045	300	995	4070
7.5	0.055	501	1000	5550
7.5	0.037	400	980	6600
25.3	0.082	398	980	505
25.3	0.045	400	985	925
45.7	0.089	500	990	245
45.7	0.065	500	995	335

TABLE 2

SUMMARY OF TEST CONDITIONS WITH CARBON DIOXIDE AS THE NOZZLE FLUID

A/A^*	p_∞, torr	H_c, psi	T_c, °F	p_e/p_∞
7.5	0.250	22	245	65
7.5	0.096	22	245	160
7.5	0.330	102	275	215
7.5	0.100	101	275	700
7.5	0.042	102	290	1670
7.5	0.100	300	310	2200
7.5	0.020	202	300	6960
7.5	0.021	301	310	9650
7.5	0.010	301	310	20400

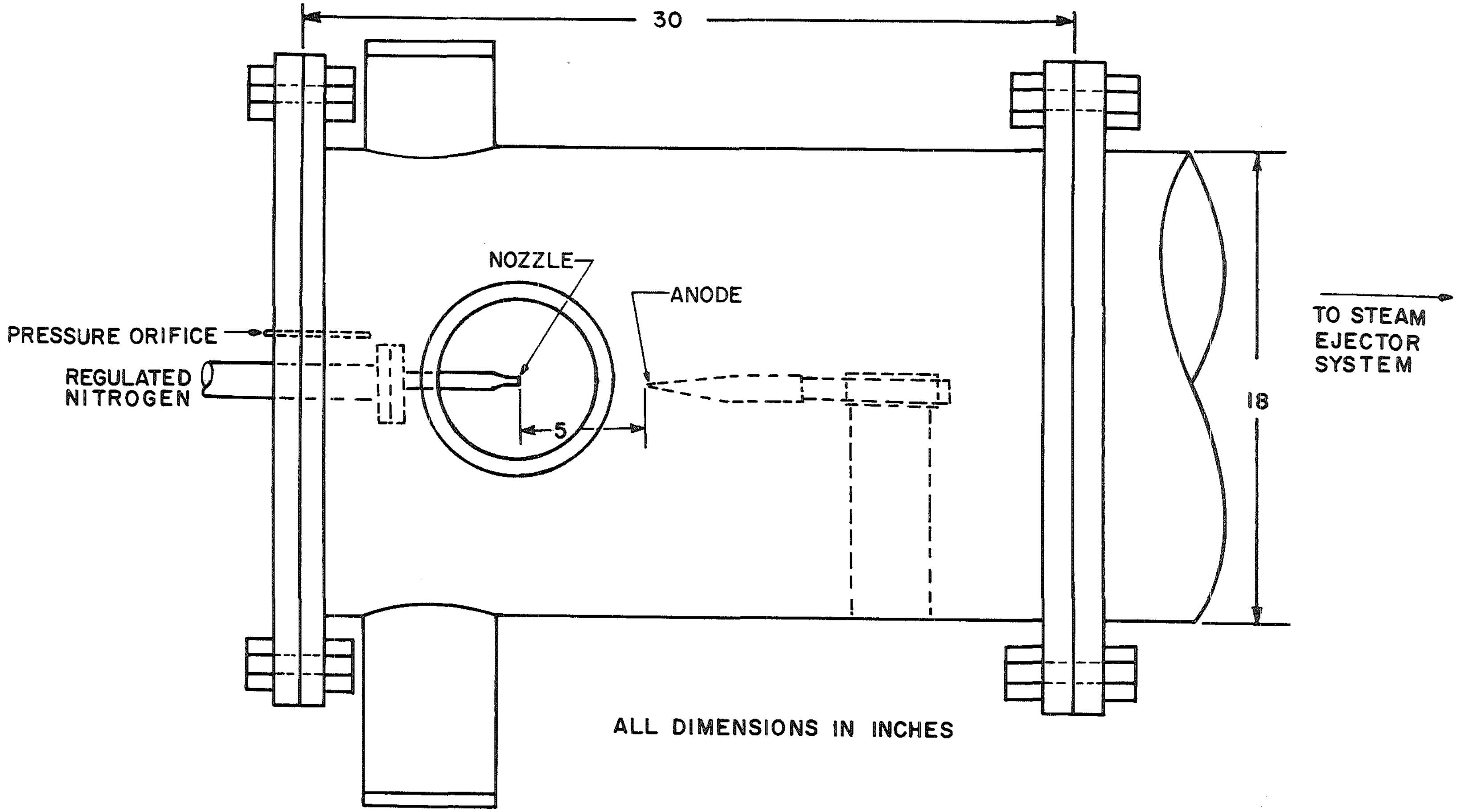

Fig. 1 Basic Dimensions of 18-in. Test Cell

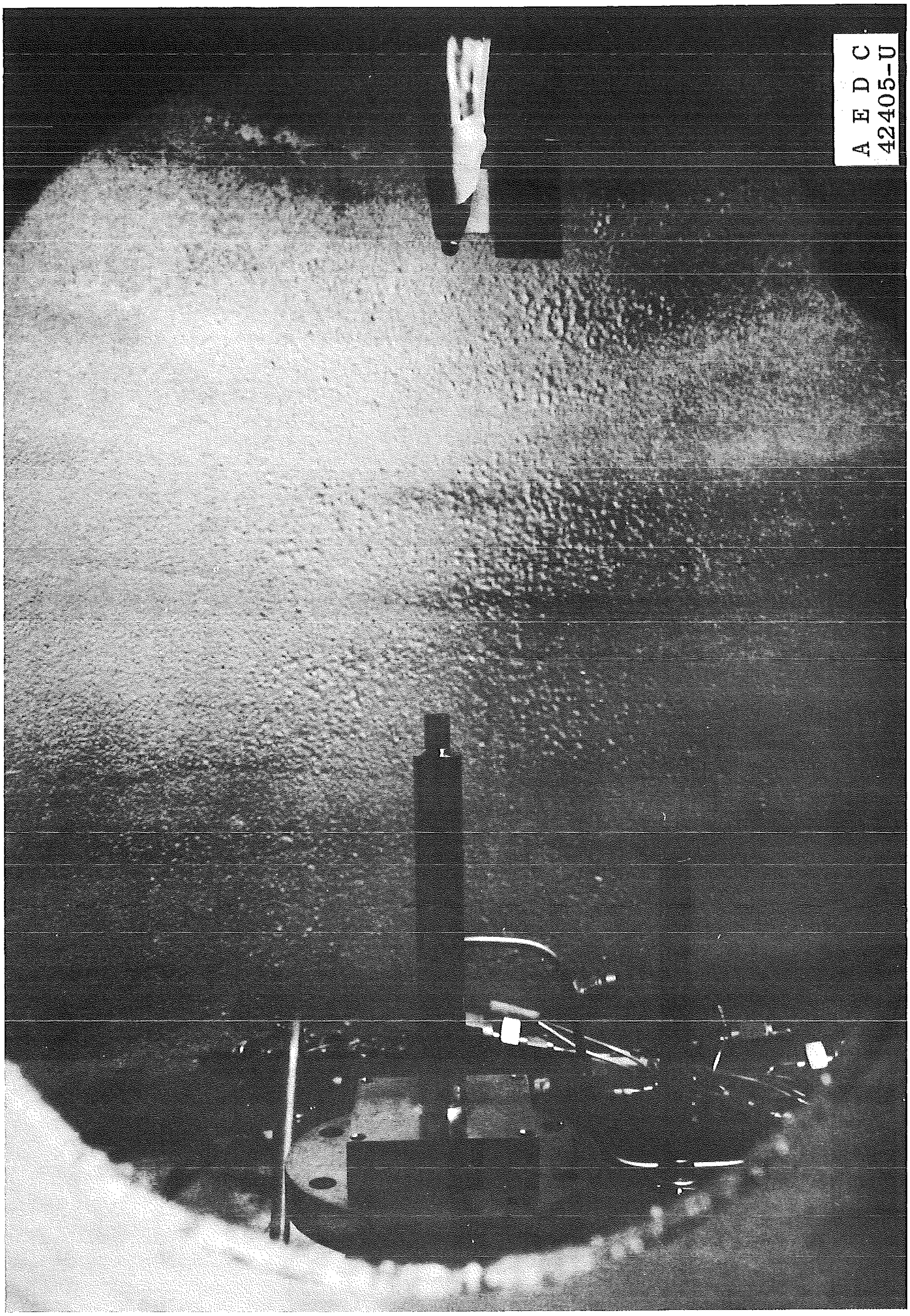

Fig. 2 Model Installation in 18-in. Test Cell

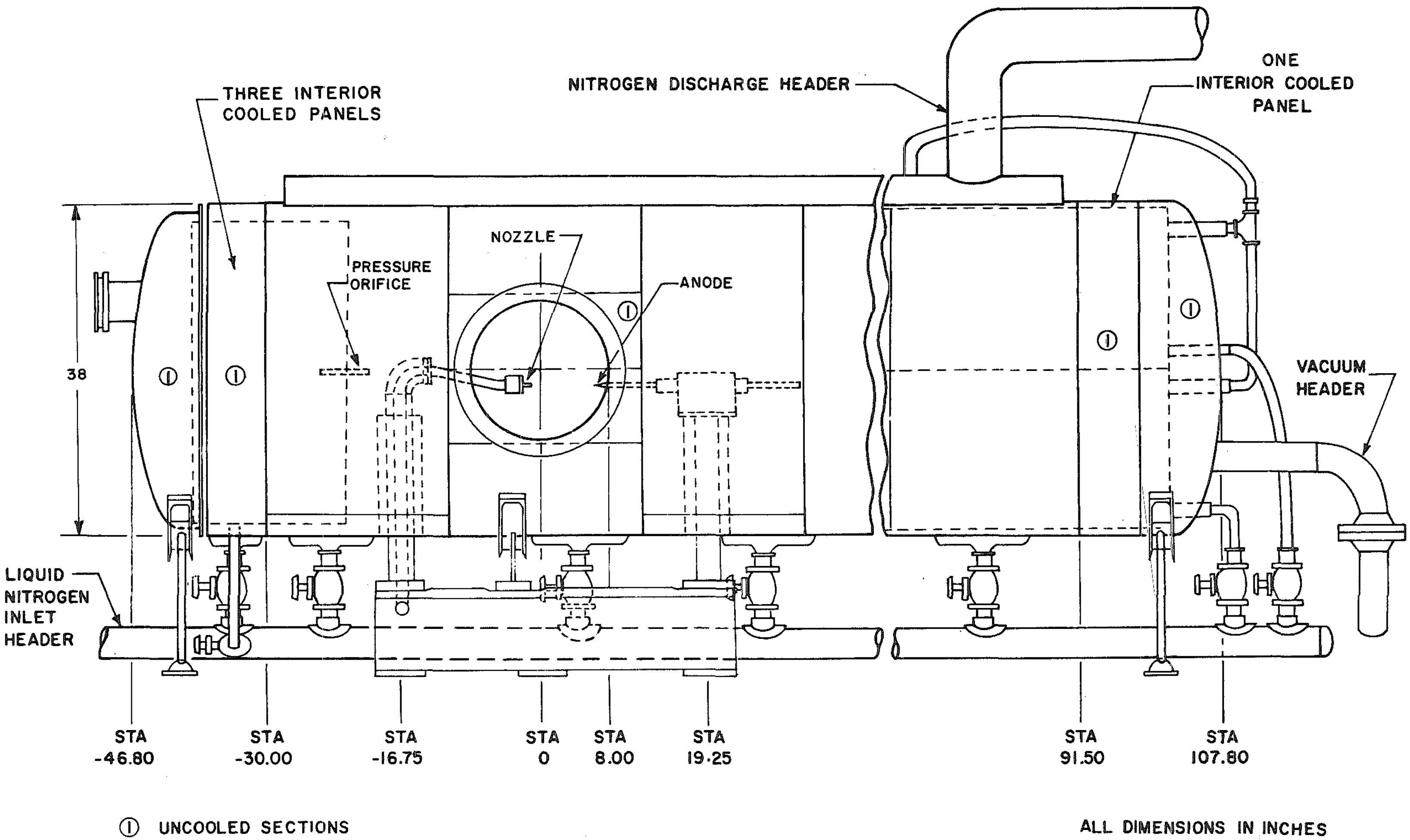

Fig. 3 Location of Model in PWT Cold Wall Vacuum Chamber

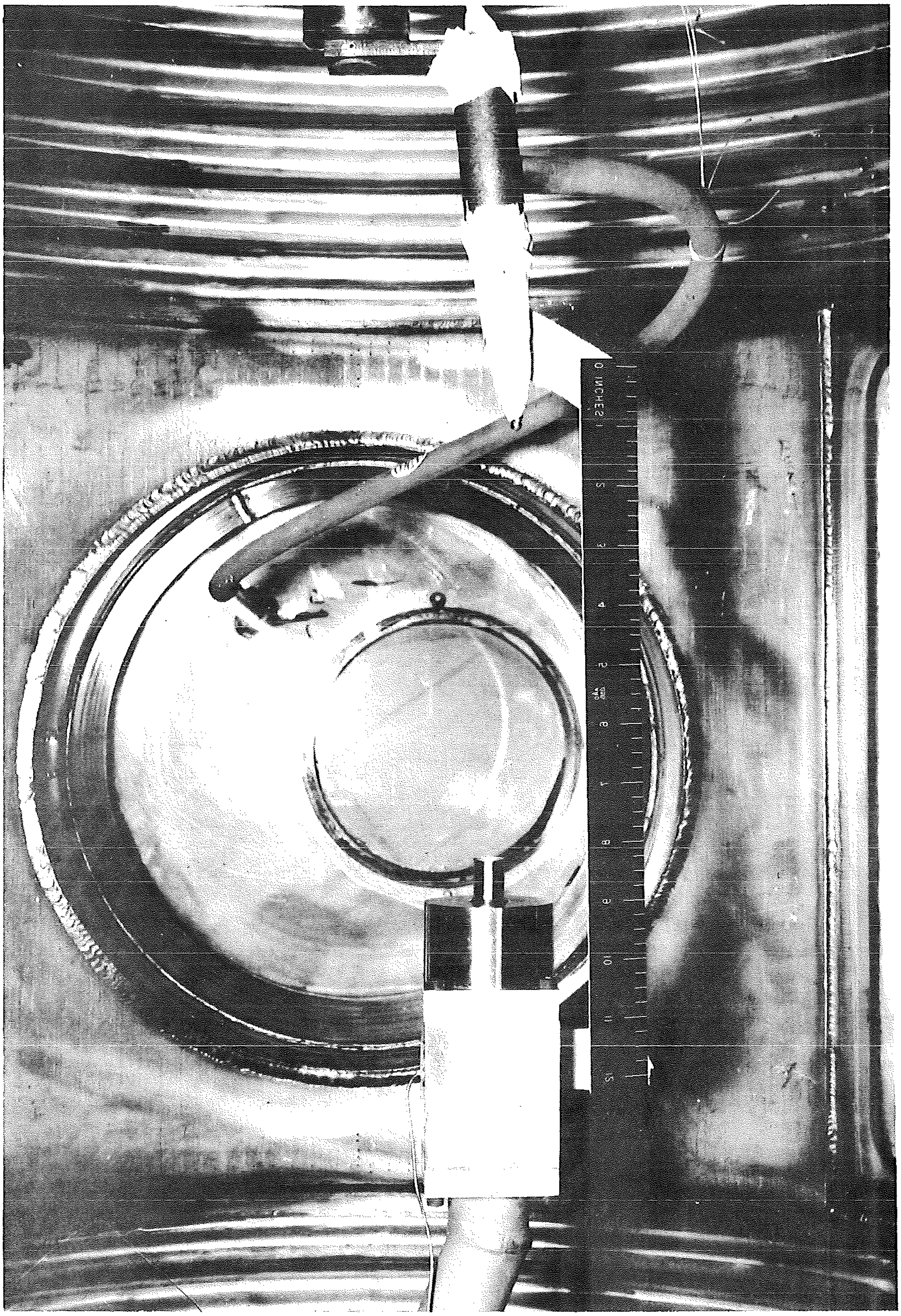

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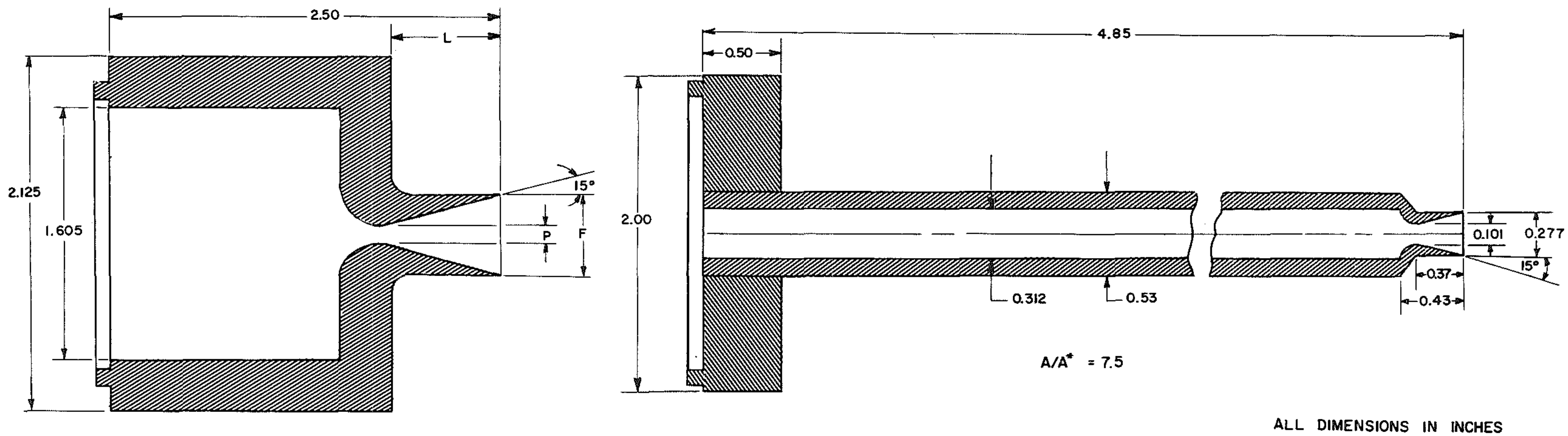
Fig. 4 Model Installation in PWT Cold Wall Vacuum Chamber



A/A*	L	F	P
25.3	.706	.503	.100
45.7	1.096	.663	.098

Fig. 5 Basic Dimensions of Models

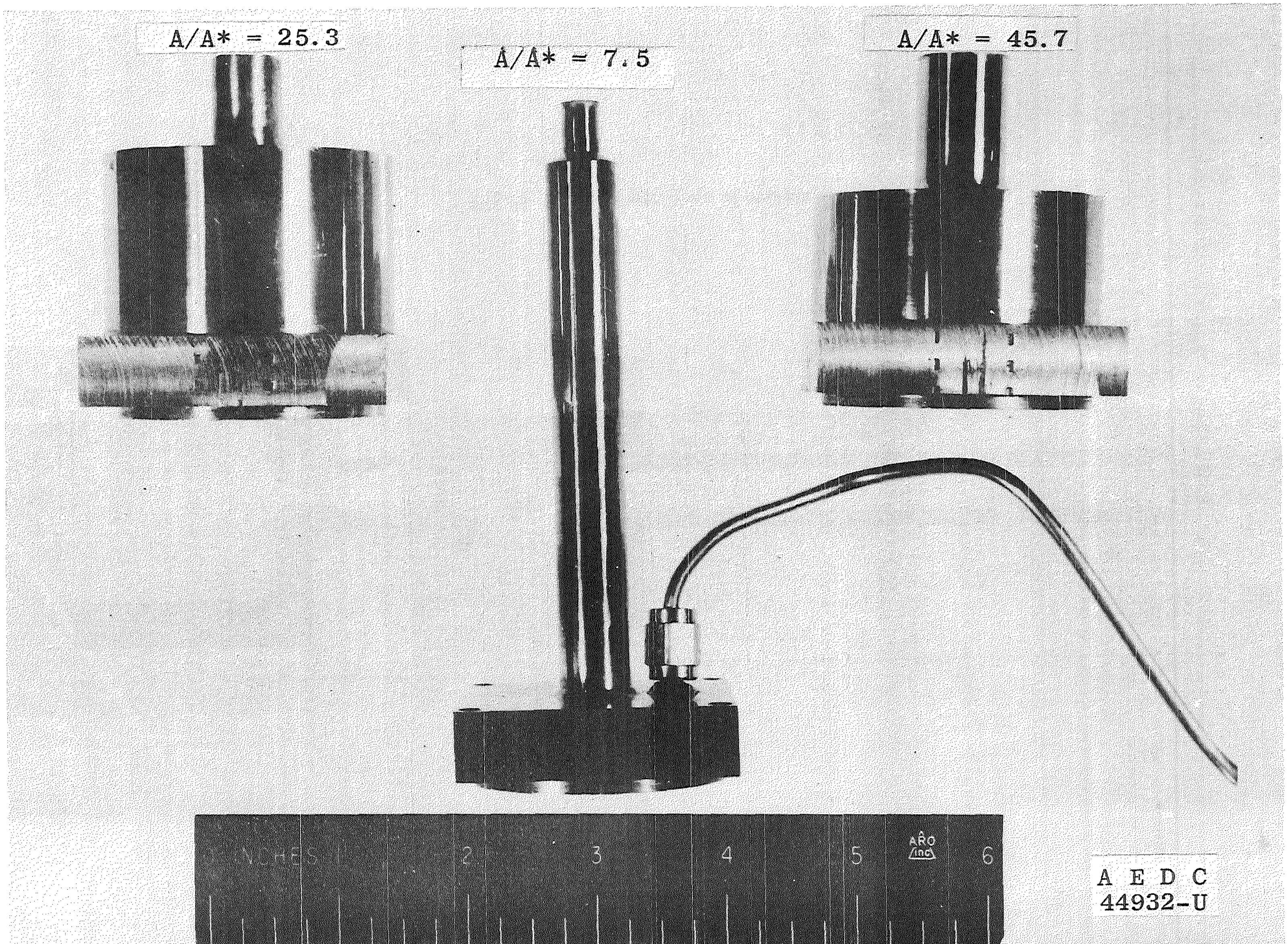
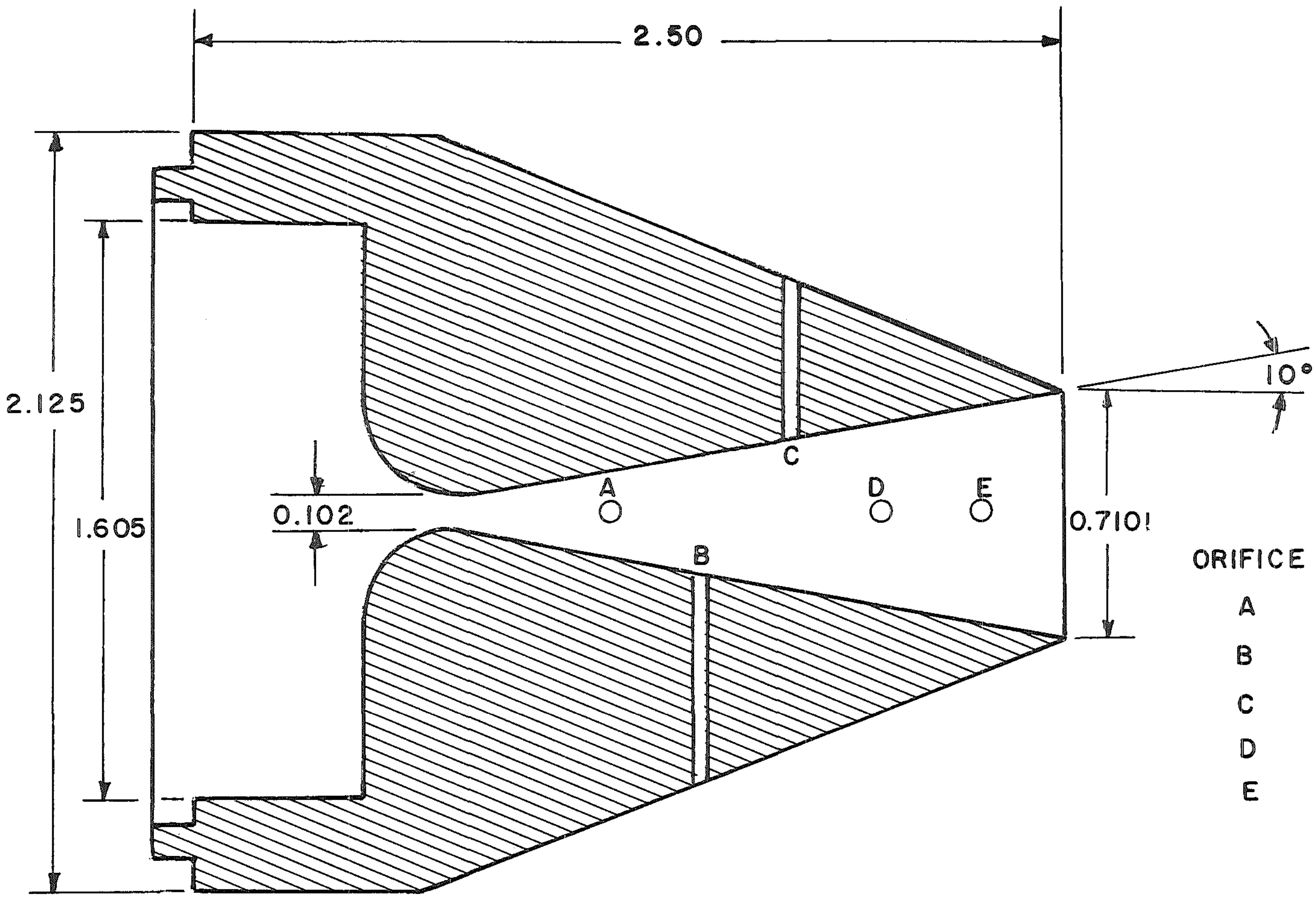


Fig. 6 Photograph of Models



ORIFICE	A/A*
A	7.03
B	12.40
C	19.10
D	26.60
E	36.50

ALL DIMENSIONS IN INCHES

Fig. 7 Basic Dimensions of Instrumented Nozzle

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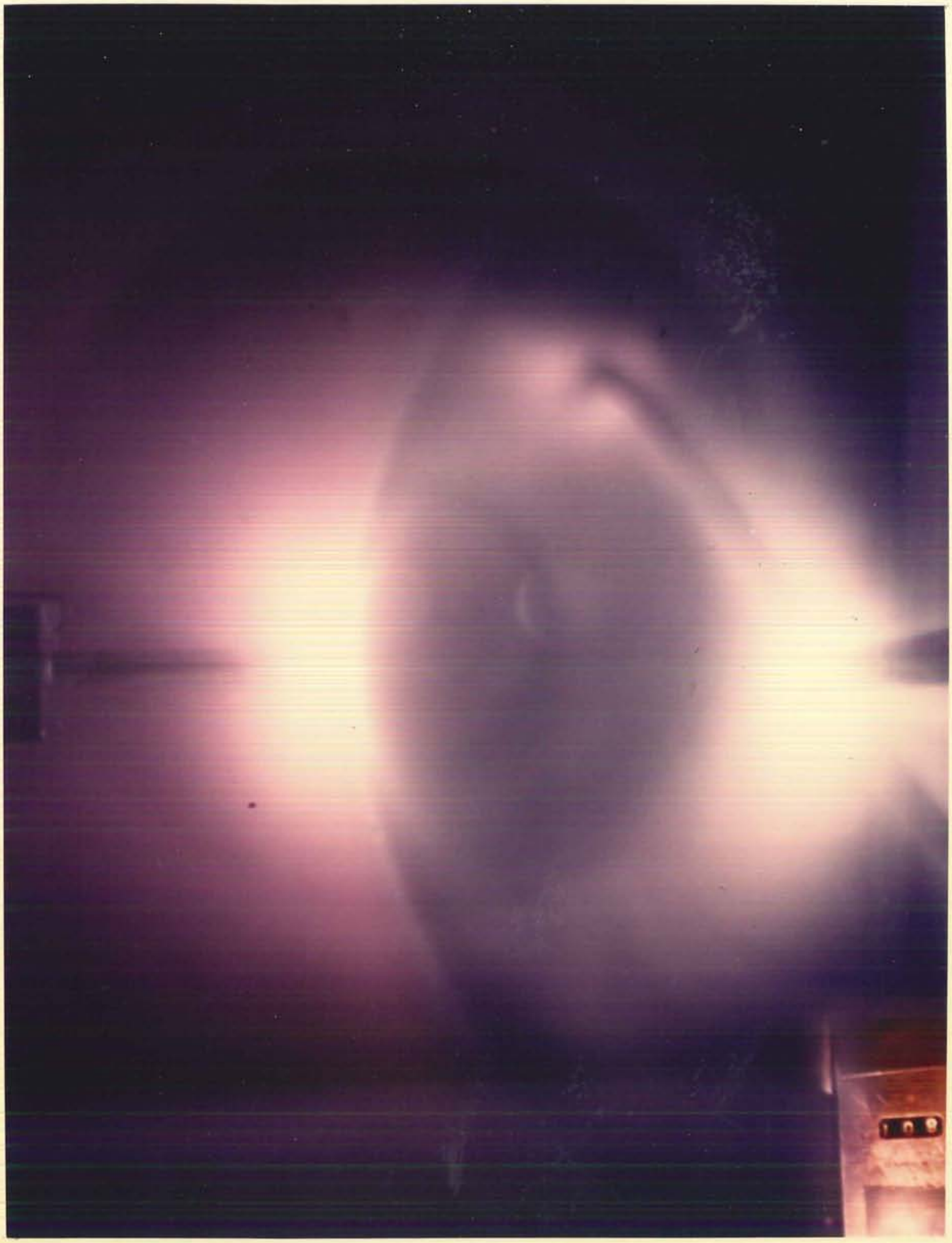

a. Photograph

Fig. 8 Typical Photograph of Jet Plume

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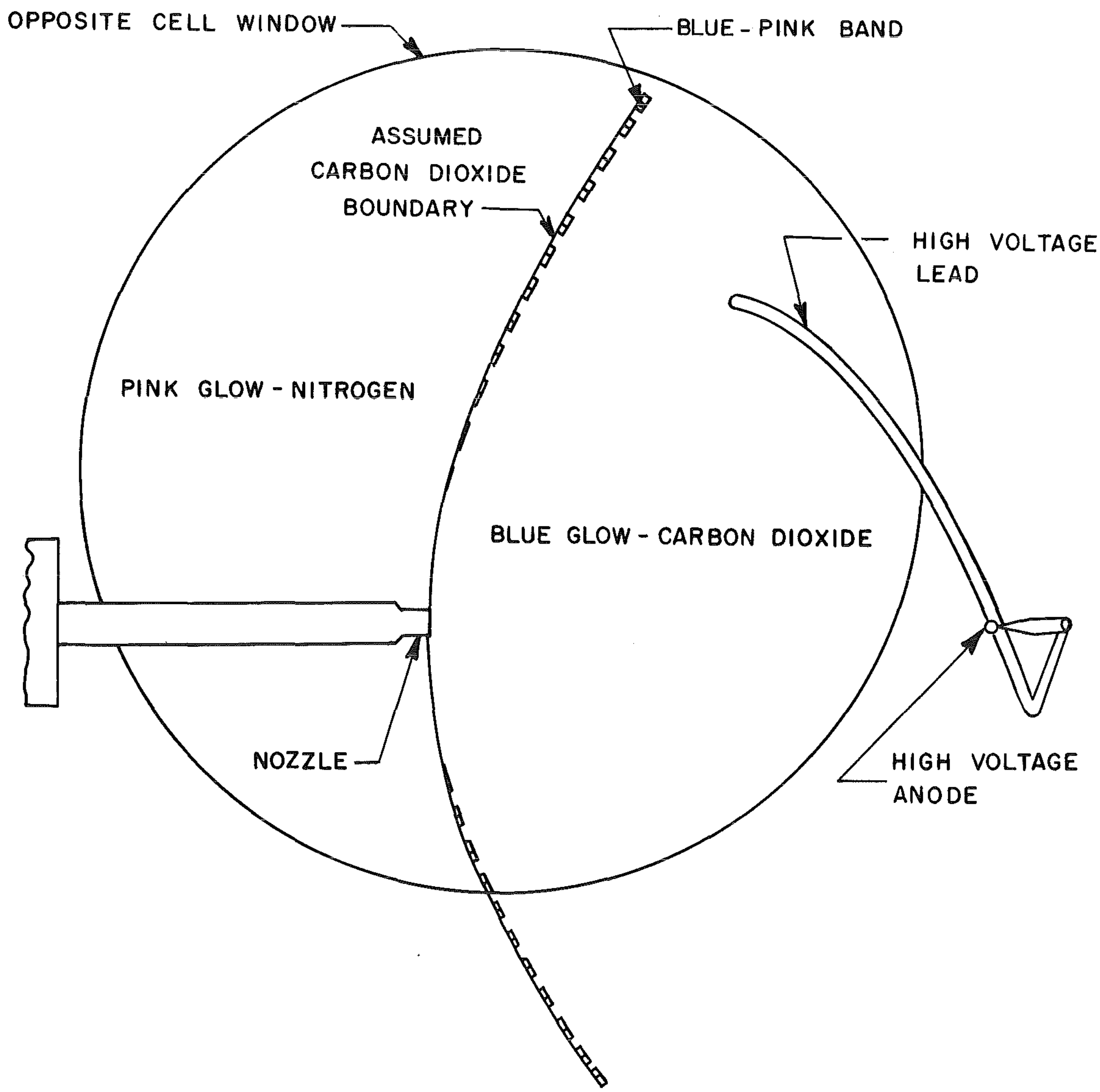


b. Explanation of Photograph

Fig. 8 Concluded

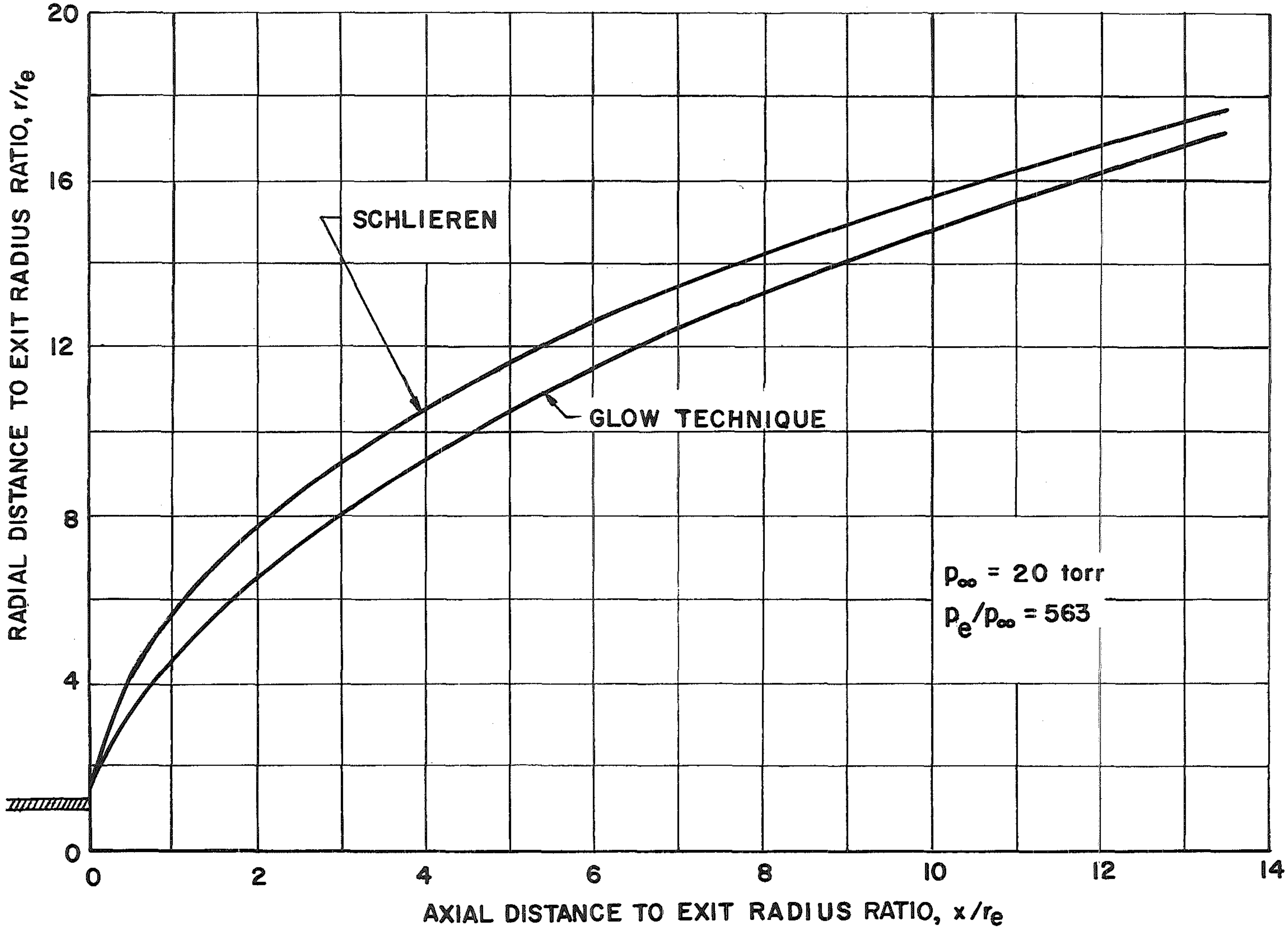


Fig. 9 Comparison of Boundaries Obtained by Schlieren and Glow Techniques, $A/A^* = 1.0$

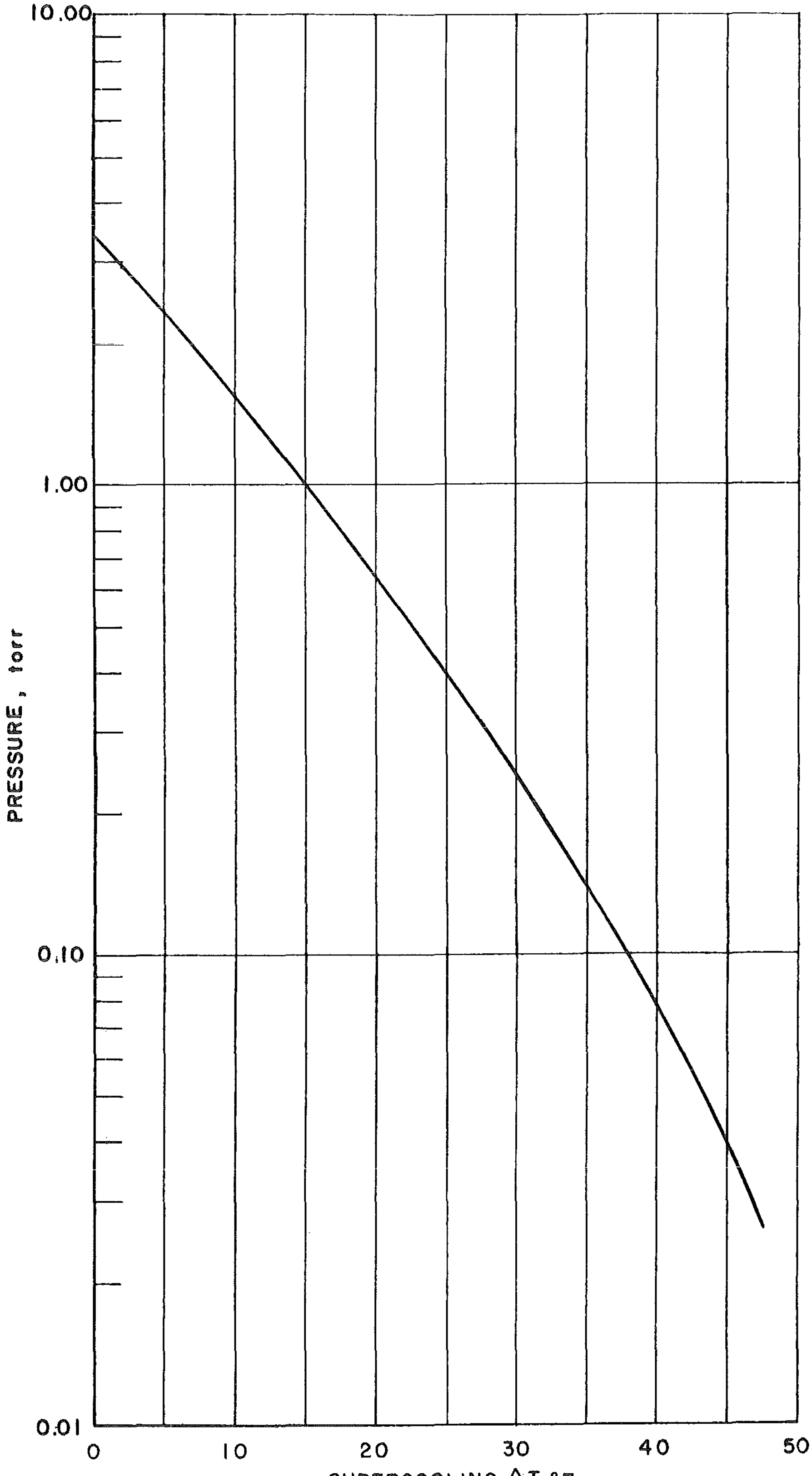


Fig. 10 Variation of Air Supercooling with Pressure (Ref. 11)

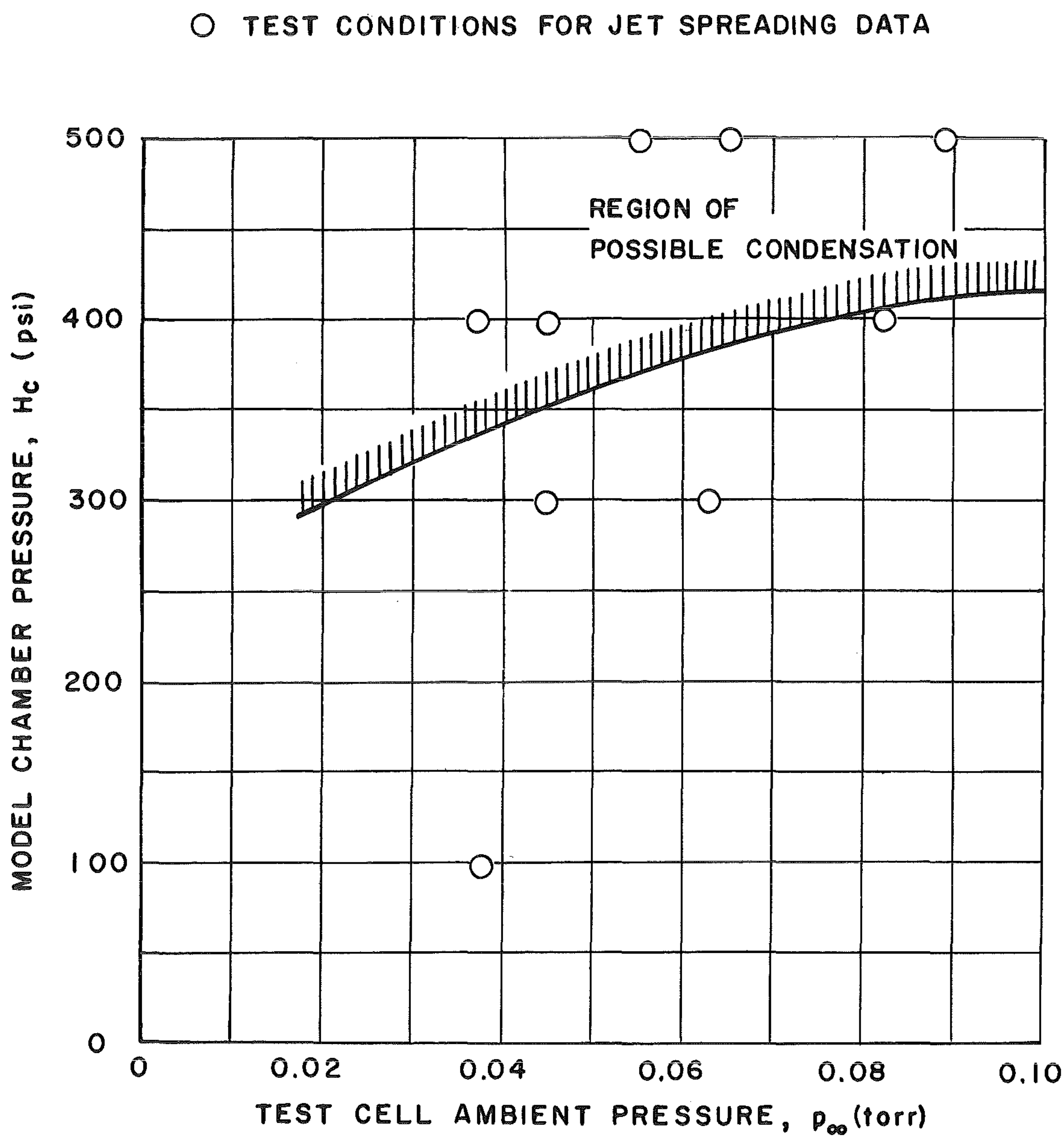
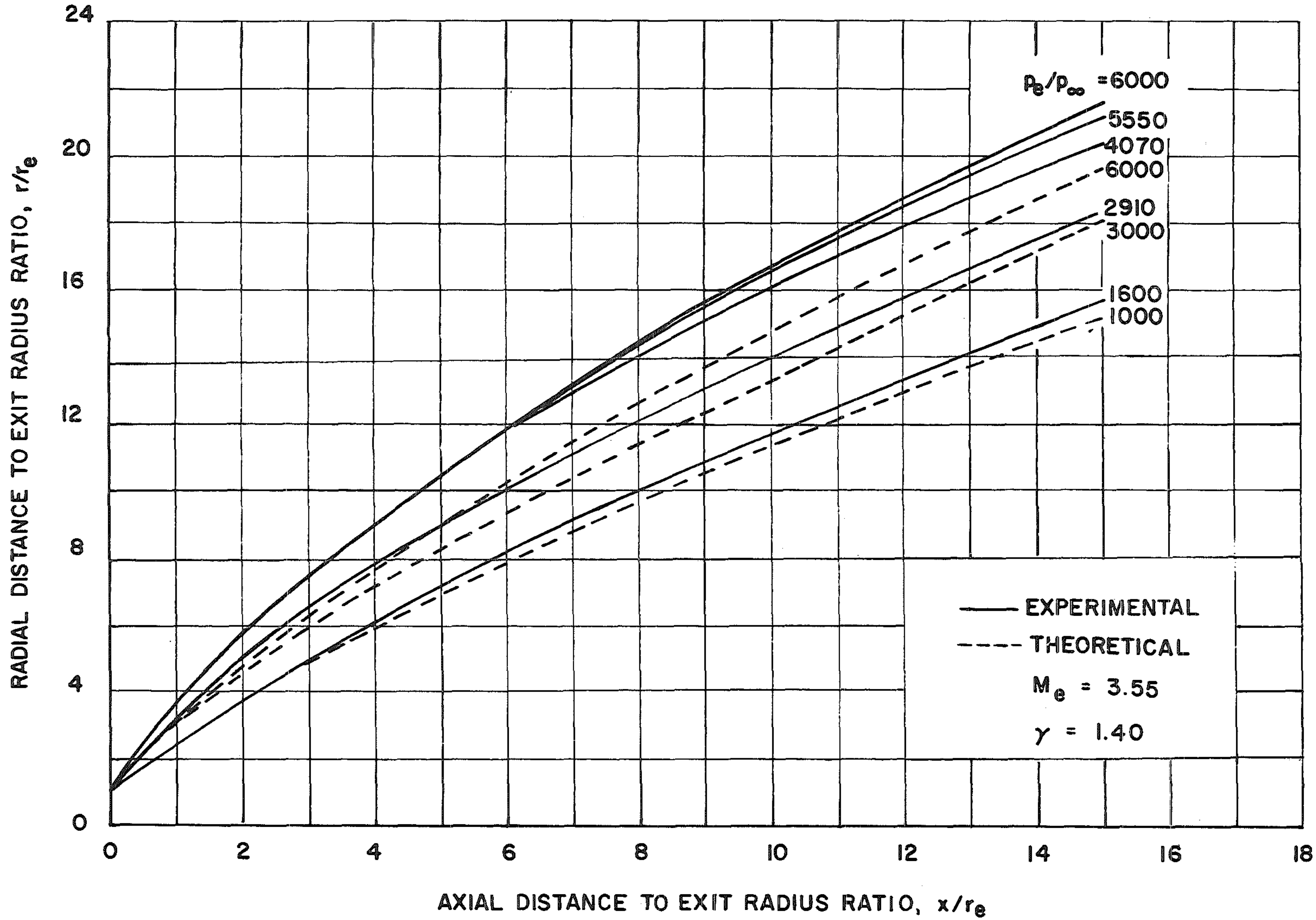
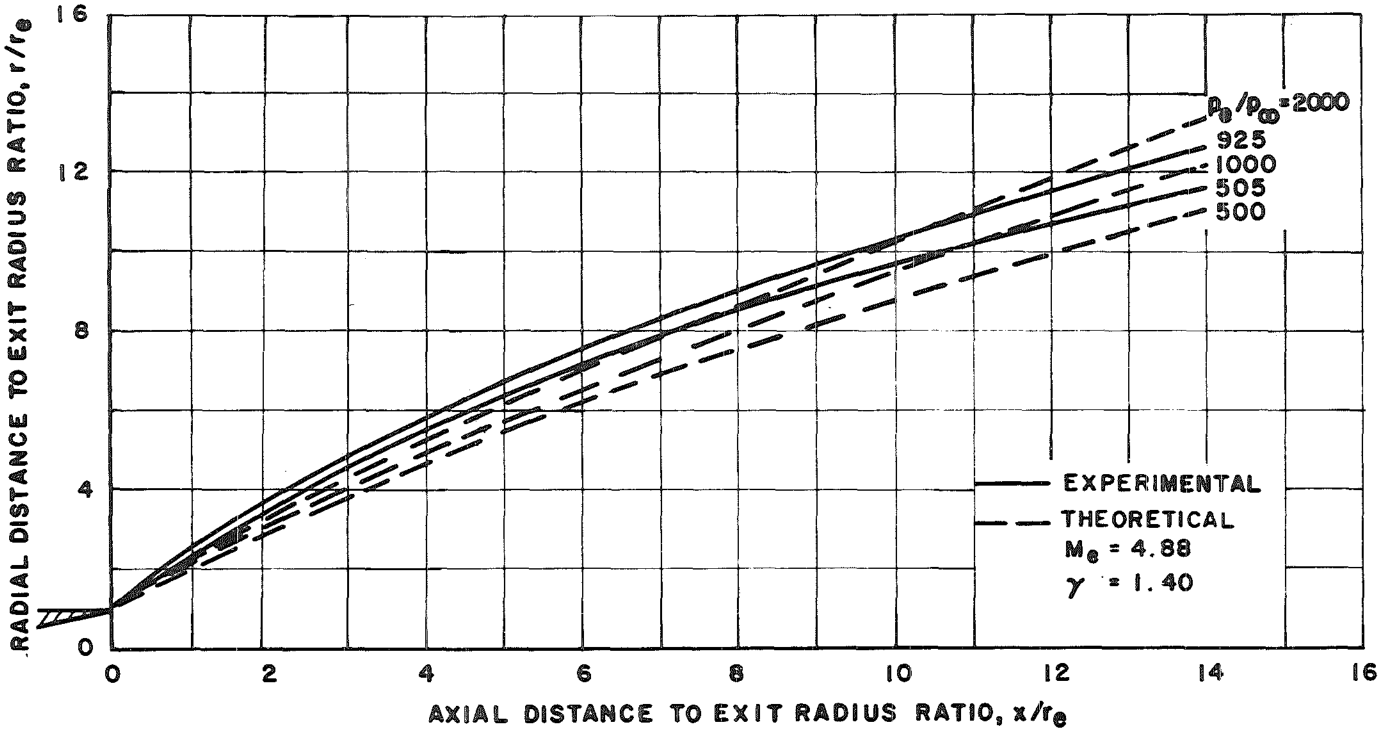


Fig. 11 Variation of Probable Nitrogen Condensation Line with Test Pressures Assuming a Stagnation Temperature of 1000°F



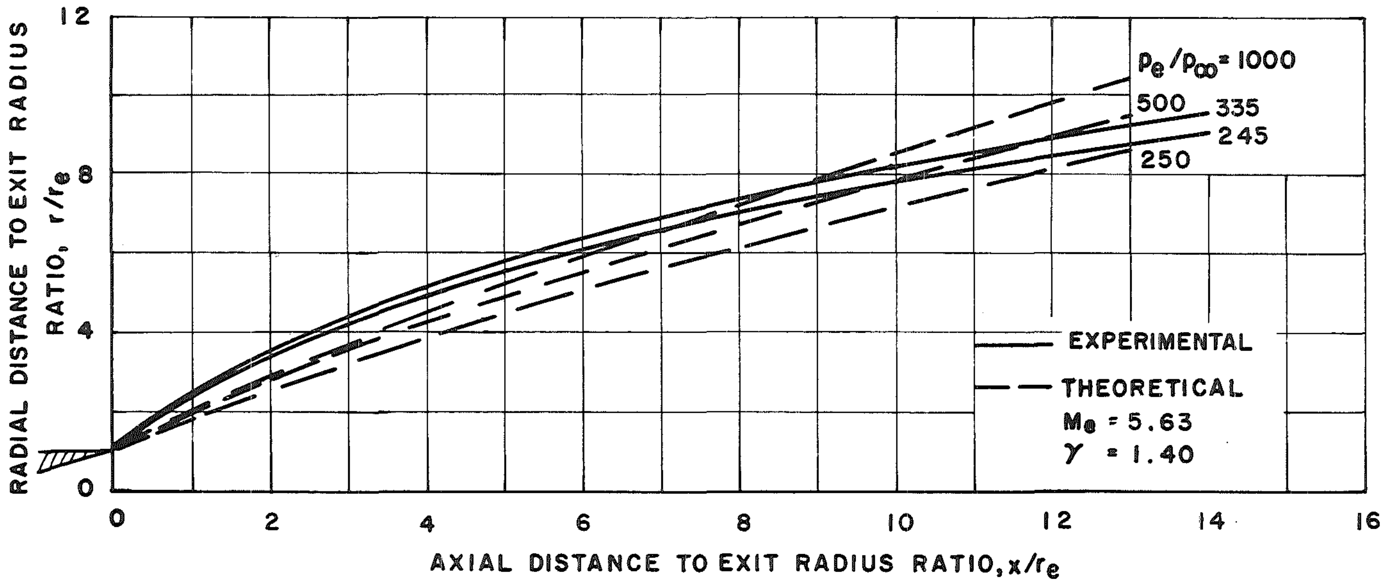
a. $A/A^* = 7.5$

Fig. 12 Comparison of Boundaries Obtained Using Nitrogen as the Nozzle Fluid with Theoretical Boundaries Calculated by the Method-of-Characteristics, $\theta_n = 15$ deg



b. A/A* = 25.3

Fig. 12 Continued



c. A/A* = 45.7

Fig. 12 Concluded

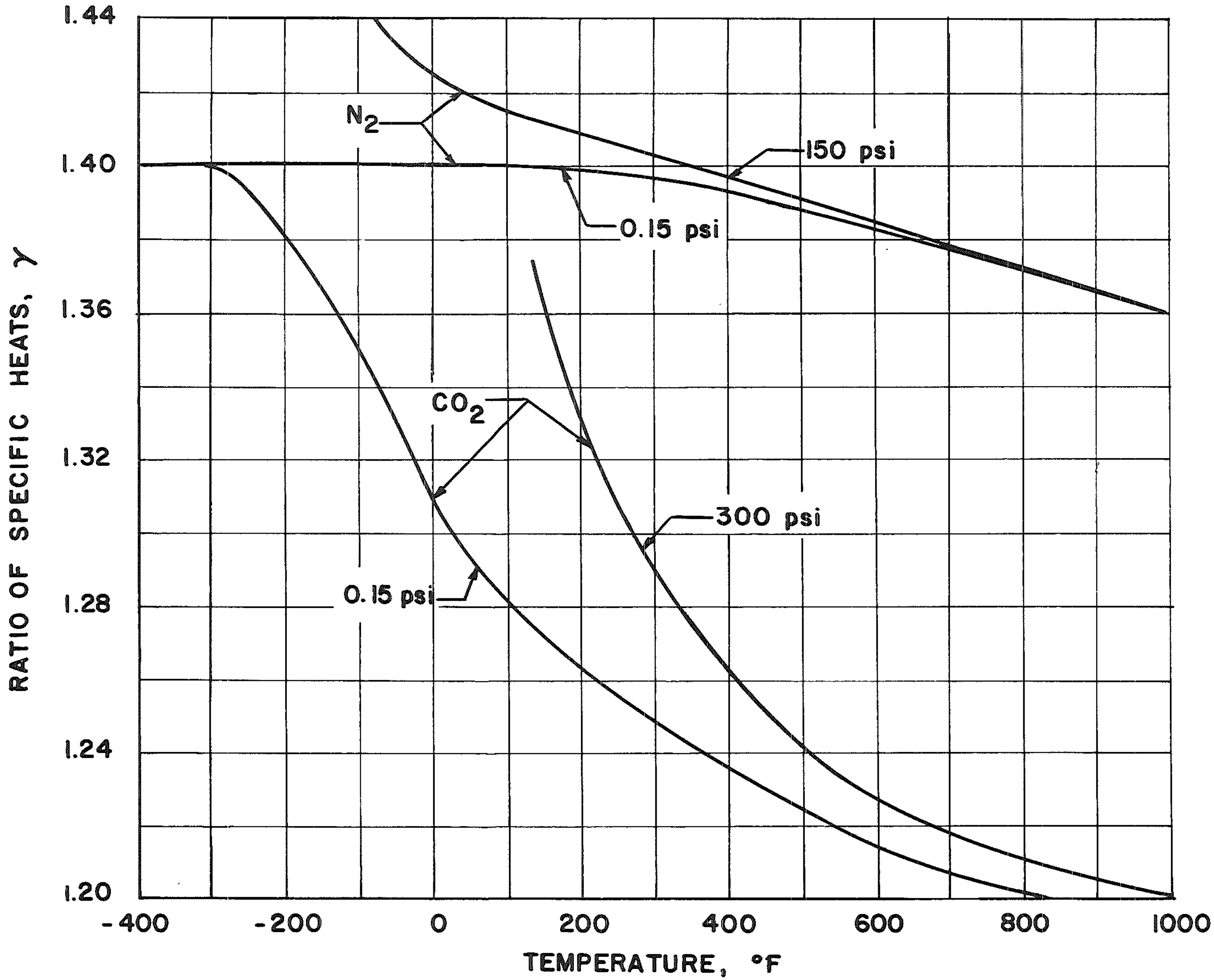


Fig. 13 Effect of Temperature and Pressure on Specific Heat Ratio

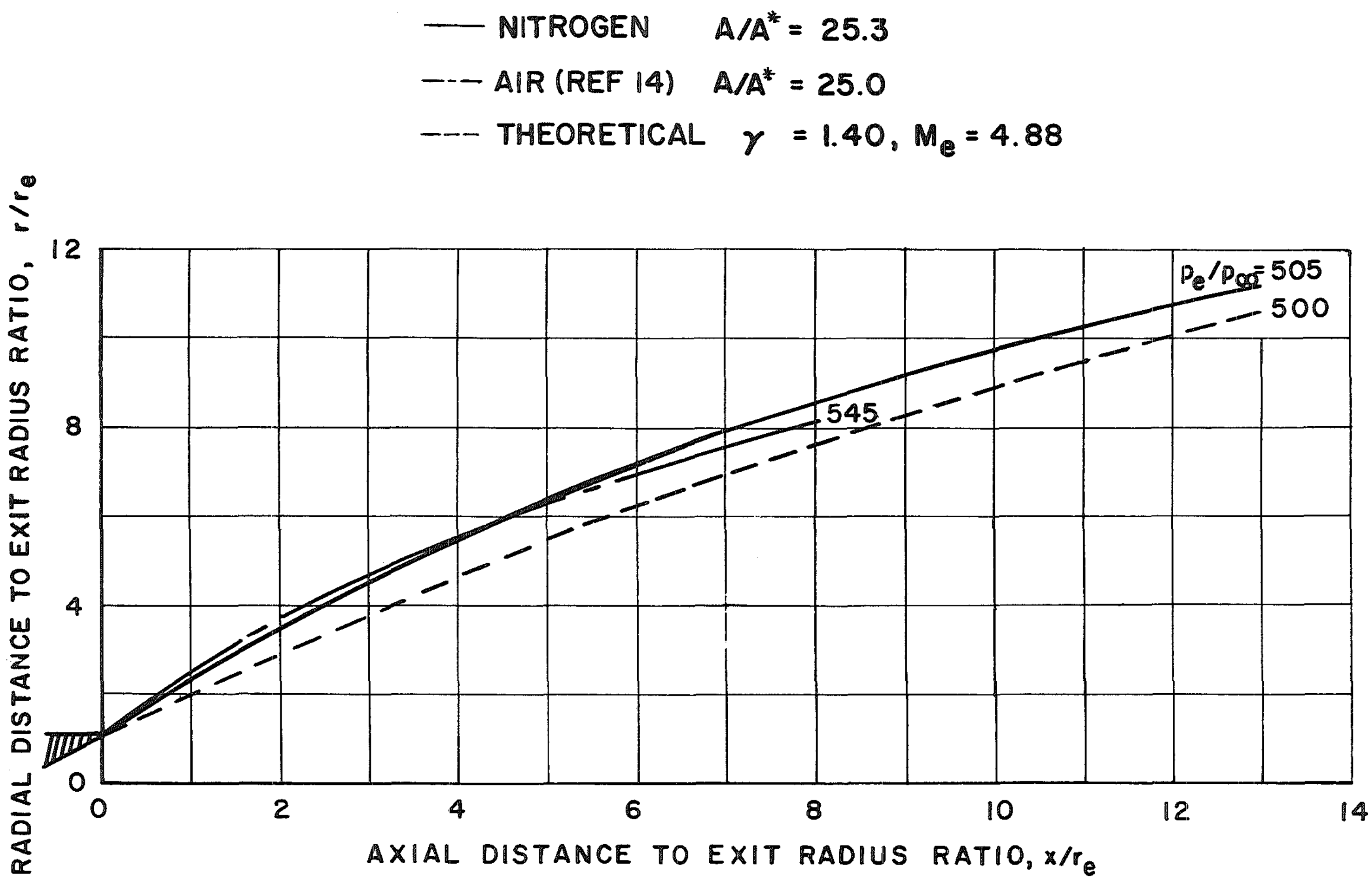


Fig. 14 Comparison with Experimental Boundary of Ref. 14, $\theta_n = 15$ deg

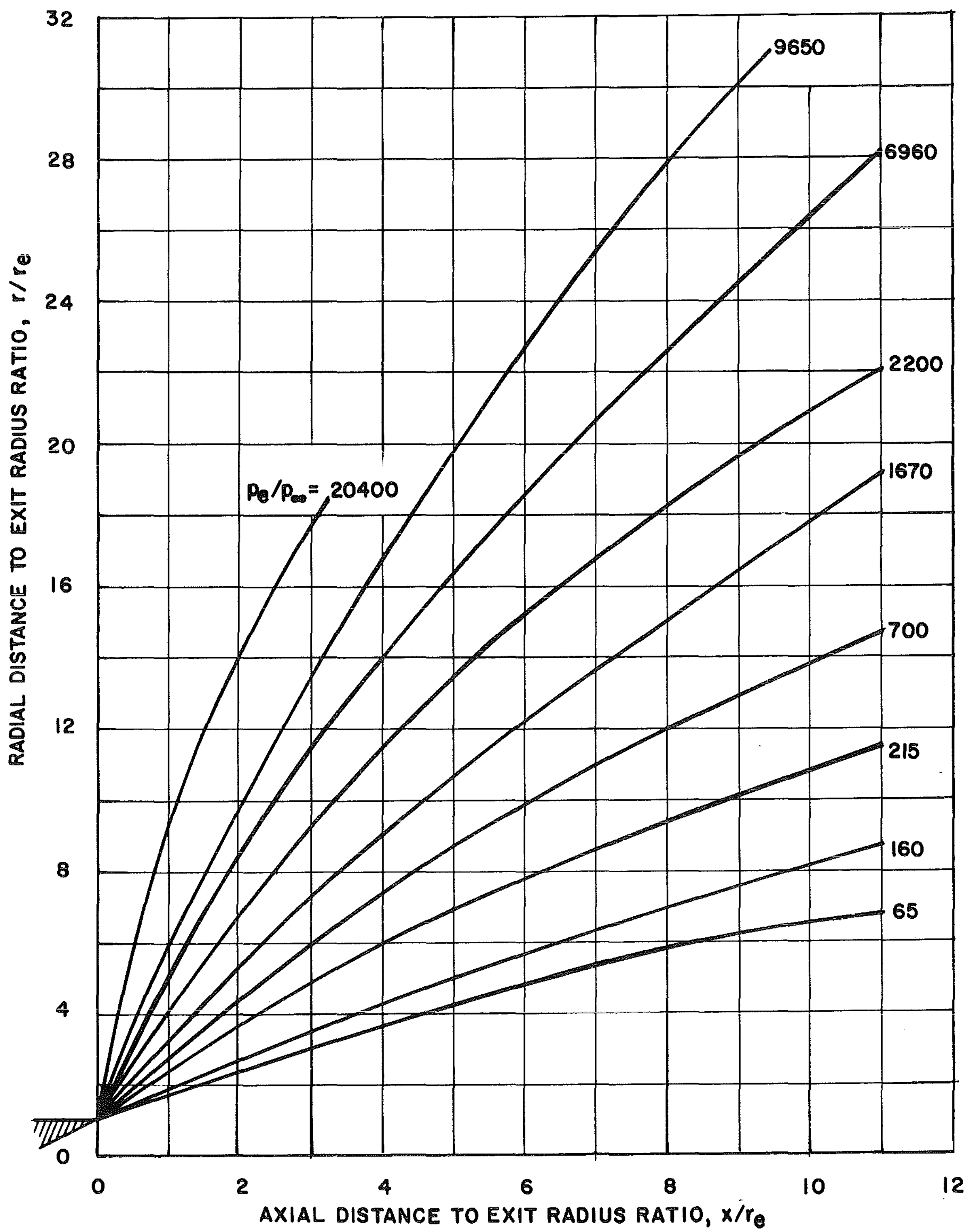


Fig. 15 Variation of Boundary Growth with Pressure Ratio, Carbon Dioxide as the Nozzle Fluid, $A/A^* = 7.5$, $\theta_n = 15$ deg

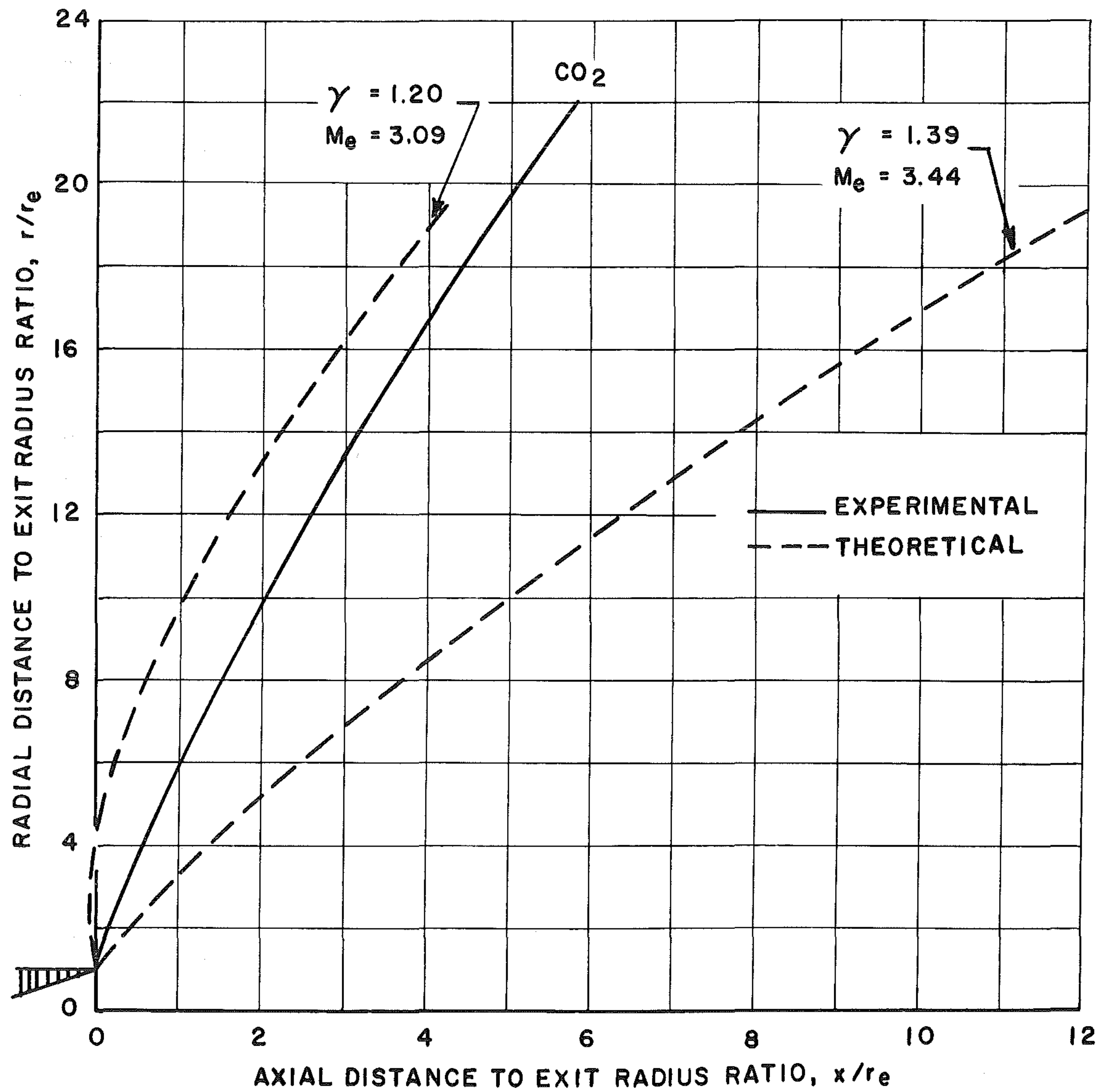


Fig. 16 Comparison of Experimental Results Obtained Using Carbon Dioxide with Boundaries Calculated by the Method-of-Characteristics, $A/A^* = 7.5$, $\theta_n = 15$ deg, $p_e/p_\infty = 9650$

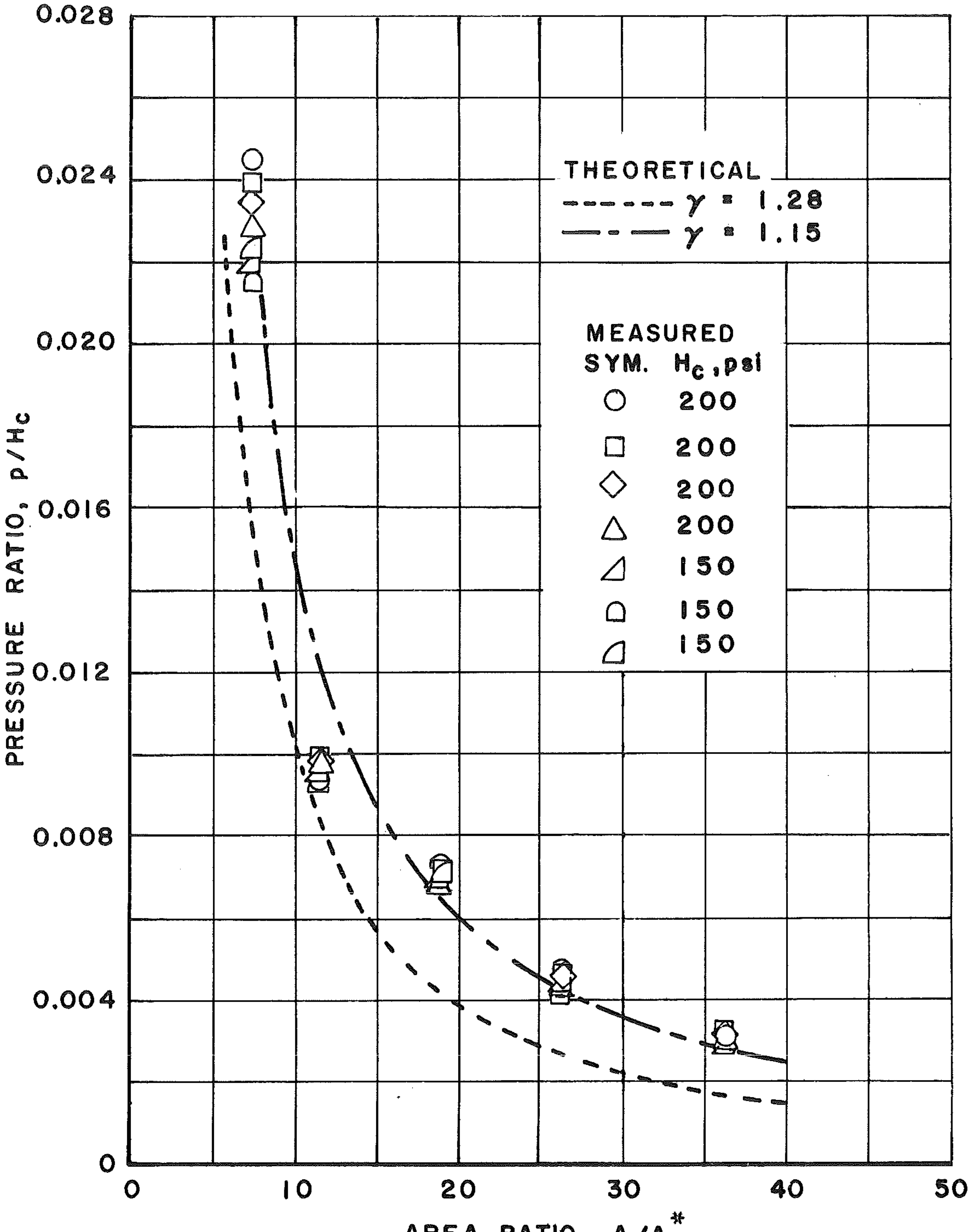


Fig. 17 Comparison of Measured and Theoretical Isentropic Pressure Ratio Variation through Nozzle Divergent Section with Carbon Dioxide Nozzle Flow