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AN EXPERIMENTAL METHOD FOR LOCATING STREAMTUBES IN A FREE JET EXPANSION TO NEAR VACUUM

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AEROSPACE ENVIRONMENTAL FACILITY
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NOTICES

AN EXPERIMENTAL METHOD FOR LOCATING STREAMTUBES IN A FREE JET EXPANSION TO NEAR VACUUM

Frederick Arnold
ARO, Inc.

Per A.F. letter dated 1 Aug. 1973 Signed William C. Cole.

FOREWORD

The research reported herein was sponsored by Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element Nos. 65401F and 62302F, Project 5730, Task 04.

The results of the research were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, under Contract F40600-69-C-0001. The work was performed under ARO Project Nos. SW3809 and SW3902 during the period from January through November 1968. The manuscript was submitted for publication on December 16, 1968.

The work reported herein has also been used as a thesis for partial fulfillment of the requirements for the degree of Master of Science from the University of Tennessee.

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This technical report has been reviewed and is approved.

Eules L. Hively Research Division Directorate of Plans and Technology	Edward R. Feicht Colonel, USAF Director of Plans and Technology

ABSTRACT

Experimental investigations of free jet expansions into near vacuum conditions have in the past been generally limited to pressure, temperature, and force measurements. This investigation concerned a method of experimentally defining the streamtubes in a free jet expansion by splitting the flow along streamtubes with a series of diffusers operating in a cryogenically pumped vacuum chamber. Conditions necessary for shock attachment at the diffuser inlet were analyzed and streamtubes in a CO_2 free jet expansion were experimentally determined. The procedure was found to be applicable for up to 98 percent of the plume mass flow if suitable diffuser inlet design is used. The method is ideally suited for streamtube definition in flows with entrained solids, for condensing flows, or for gaseous mixtures. For the free jet expansion investigated, qualitative information was derived concerning the effect of nozzle boundary layer on the plume expansion, the degree of condensation in the plume, and the applicability of method of characteristics solutions to the expansion process.

Per A. F. Letter dated 7 Aug, 1973 signed William O. Cole

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NOMENCLATURE

A	Area
D	Diameter
f	Mass fraction
F	Flow meter correction factor
g_c	Gravitational constant
h	Specific enthalpy
J	Mechanical energy heat equivalent
K	Dimensional constant for flow meter
$\dot{m}$	Mass flow rate
M	Mach number
P	Pressure
q	Quality or vapor fraction in a mixture
r	Radial position in the plume
r_e	Nozzle exit radius
R	Gas constant
S	Specific entropy
T	Temperature
v	Specific volume
V	Velocity
x	Nozzle-diffuser separation distance
z	Flow meter scale reading
θ	Angle
θ_N	Nozzle half angle
γ	Specific heat ratio

Subscripts

C	Test chamber conditions
D	Plenum chamber conditions
e	Nozzle exit conditions
O	Nozzle stagnation conditions
P	Pitot tube data
S	Carbon dioxide supply conditions
T	4 × 6 foot conditions
*	Nozzle throat conditions

CHAPTER I

INTRODUCTION

I. STATEMENT OF THE PROBLEM

One of the important parameters in experimental investigations of free jet expansions is the definition of streamlines or streamtubes. Usually, this has been accomplished by integrating pitot and static pressure data taken in the flow field after determining the directions of the streamlines by maximum pitot pressure response or through use of small vanes (1)[1]. For ideal gases with accurately known stagnation conditions, such procedures are adequate. However, in the low density outer edge of the expansion plume, pitot pressure data must be corrected for viscous effects. In addition, if the flow is of uncertain or changing composition (as in a rocket exhaust), or if the fluid is not described by ideal gas relations (as in vapor expansions or solid rockets with metal additives), the pitot pressure data cannot be accurately translated to velocity data and velocities cannot be meaningfully integrated to define streamtubes.

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[1]Numbers in parentheses correspond to similarly numbered references listed in the bibliography.

This investigation was undertaken to provide an experimental method for directly determining the streamtubes in a free jet expansion. Recent work participated in by the author in connection with development of high altitude rocket test facilities suggested this investigation.

II. BACKGROUND

Most current high altitude rocket test facilities utilize a diffuser to recover as much as possible of the rocket stagnation pressure, thus reducing the volumetric pumping capacity required for boosting the exhaust products to atmospheric pressure. Test cell altitude is maintained by the ejector action of the rocket firing into the diffuser. Test altitude is generally limited to approximately 150,000 feet, corresponding to a background pressure of 1 mm. Hg., but large rockets (up to 500,000 lbs. thrust) can be tested in existing facilities (2). This type of testing is shown schematically in Figure 1.

As a result of needs for small rocket testing at much higher altitudes (up to 500,000 feet or 10^{-5} mm. Hg. background pressure), a concept for a cryogenically pumped rocket test chamber was developed and tested at the Aerospace Environmental Facility (3). This method, shown schematically in Figure 2, obtained the required high

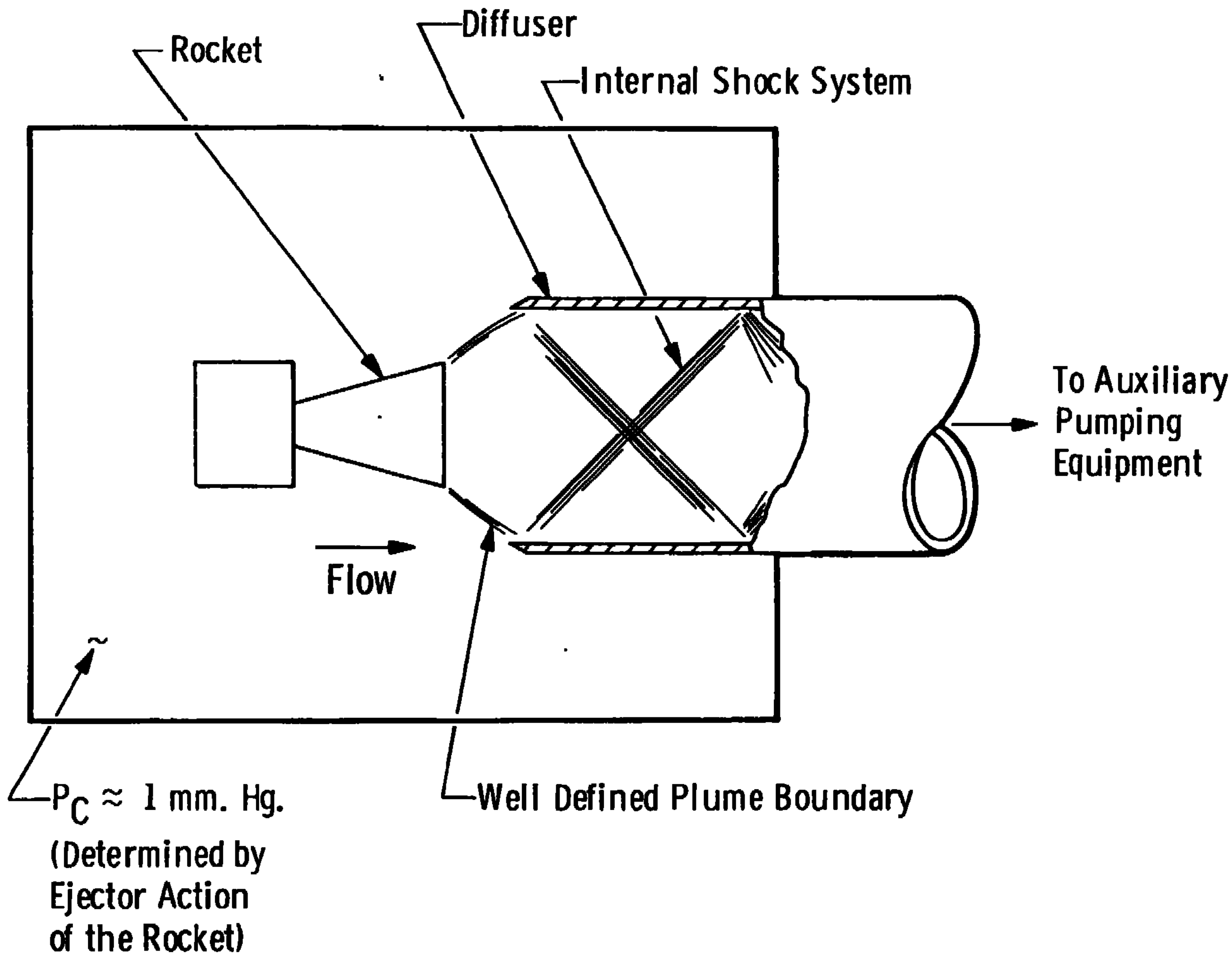


Figure 1. Schematic of conventional rocket test chamber.

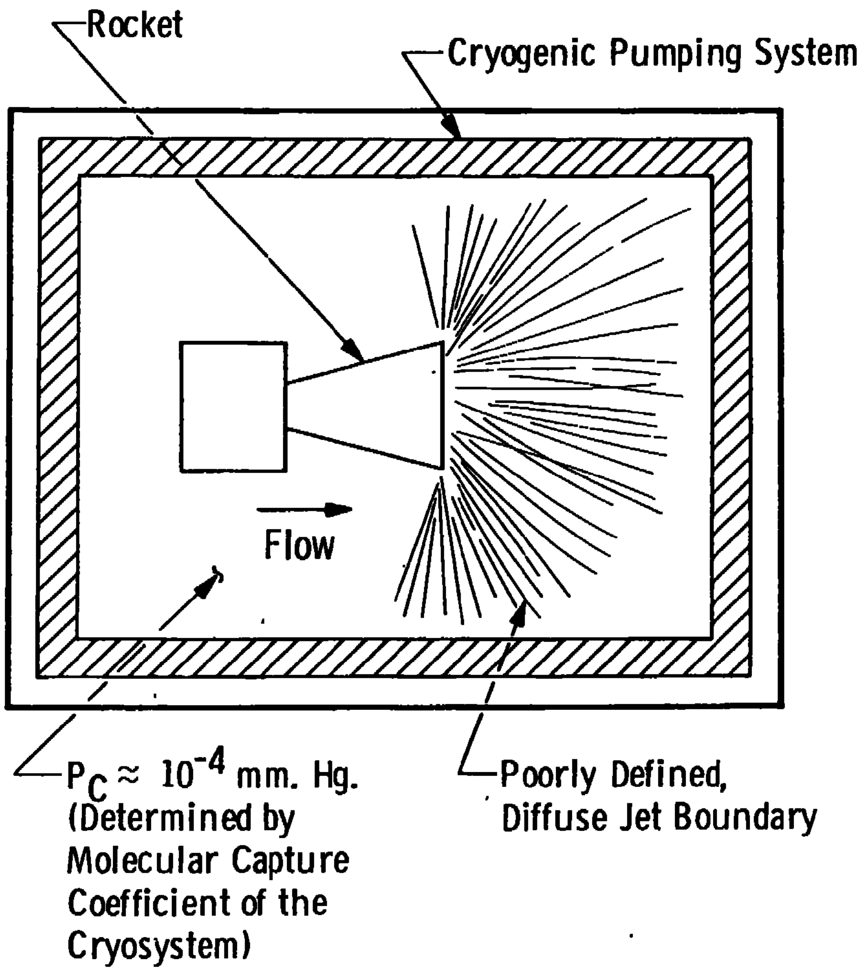


Figure 2. Schematic of plume test chamber.

altitudes but was limited to small rockets because of the large heat loads imposed on the cryogenic system.

Subsequently, an investigation was initiated to determine the feasibility of combining these two types of facilities. The combination as shown in Figure 3 would consist of a cryogenically pumped test chamber equipped with a diffuser and auxiliary pumping system to remove the bulk of the rocket exhaust. A test program was initiated using carbon dioxide as the test gas because of the availability of liquid nitrogen for cryopumping. Initial experiments showed the feasibility of the approach and also suggested its applicability for experimental determination of the streamtubes of the jet expansion. Each diffuser inlet location defines one point on a streamtube provided the respective flows can be measured and that the disturbance caused by the diffuser inlet is not propagated upstream (i.e., the shock structure caused by the diffuser is attached to the diffuser inlet).

III. SCOPE OF THE INVESTIGATION

The objectives of this investigation were as follows:

1. Determine theoretical diffuser inlet requirements for attached flow and verify experimentally.
2. Using one plume (i.e., one nozzle with constant stagnation conditions), map the streamtubes by

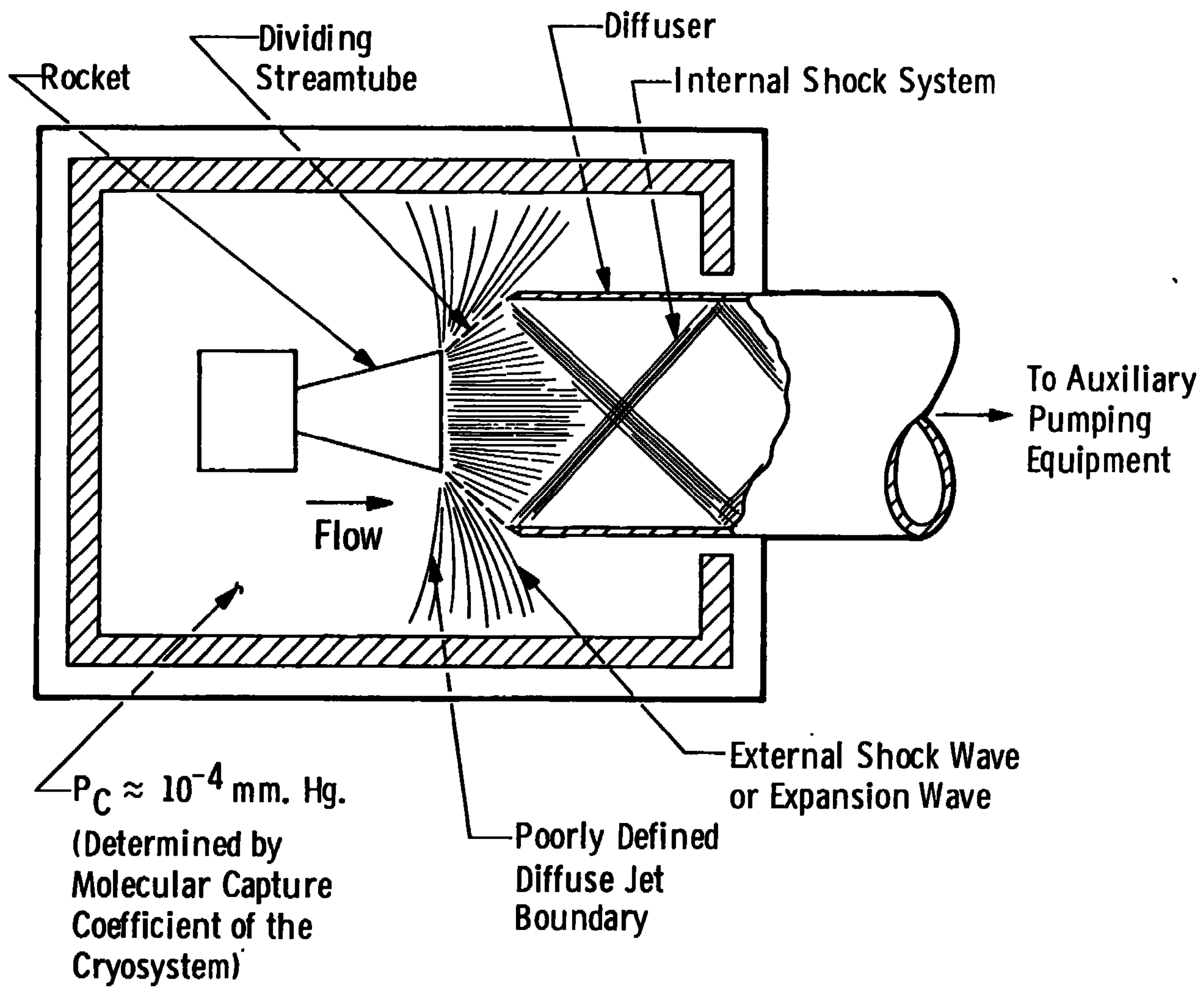


Figure 3. Schematic of combined test chamber.

using several diffusers at various locations in the plume.

3. Compare the measured results with theoretical nozzle flow and method of characteristics solutions of the free jet expansion.
4. Analyze the results to obtain information regarding the degree of condensation in the nozzle and the effect of nozzle boundary layer and condensation on the free jet expansion.

CHAPTER II

APPARATUS

I. BASIC TEST EQUIPMENT

The test equipment is represented schematically in Figure 4 and includes two vacuum chambers, each equipped with liquid nitrogen cooled cryogenic pumping systems and interconnected with a 6 inch duct and isolation valve.

The main test chamber, Figure 5, was a 2 × 3 foot Research Vacuum Chamber equipped with a finned cryopump and a 6 inch oil diffusion pump. Development of the cryopump is described by Heald, et al. (3), and its pumping performance with CO_2 as the test gas is shown in Figure 6. The chamber was also equipped with an axially moveable probe mounted on the centerline which served as the CO_2 nozzle supply and nozzle mount. The diffusers were mounted in the opposite end of the test chamber on the removeable end flange and discharged into the 6 inch plenum chamber. Changing of diffusers required removal of the 6 inch plenum chamber, with alignment of diffuser and nozzle accomplished visually for each diffuser by shifting the diffuser on its mounting flange prior to final tightening of the flange bolts and installation of the plenum chamber. Alignment is estimated to have been within 1/16 inch eccentricity.

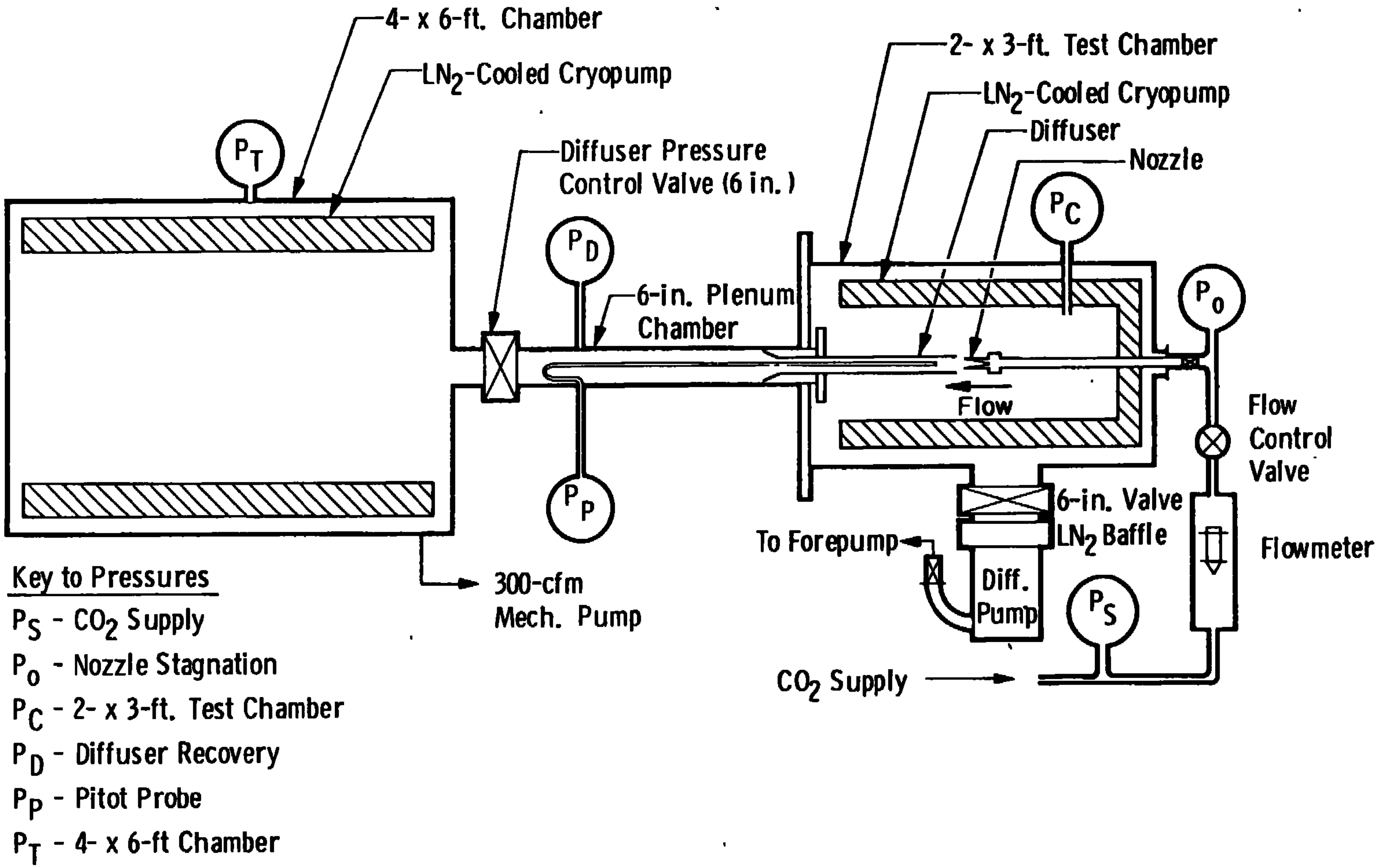


Figure 4. Schematic of test apparatus.

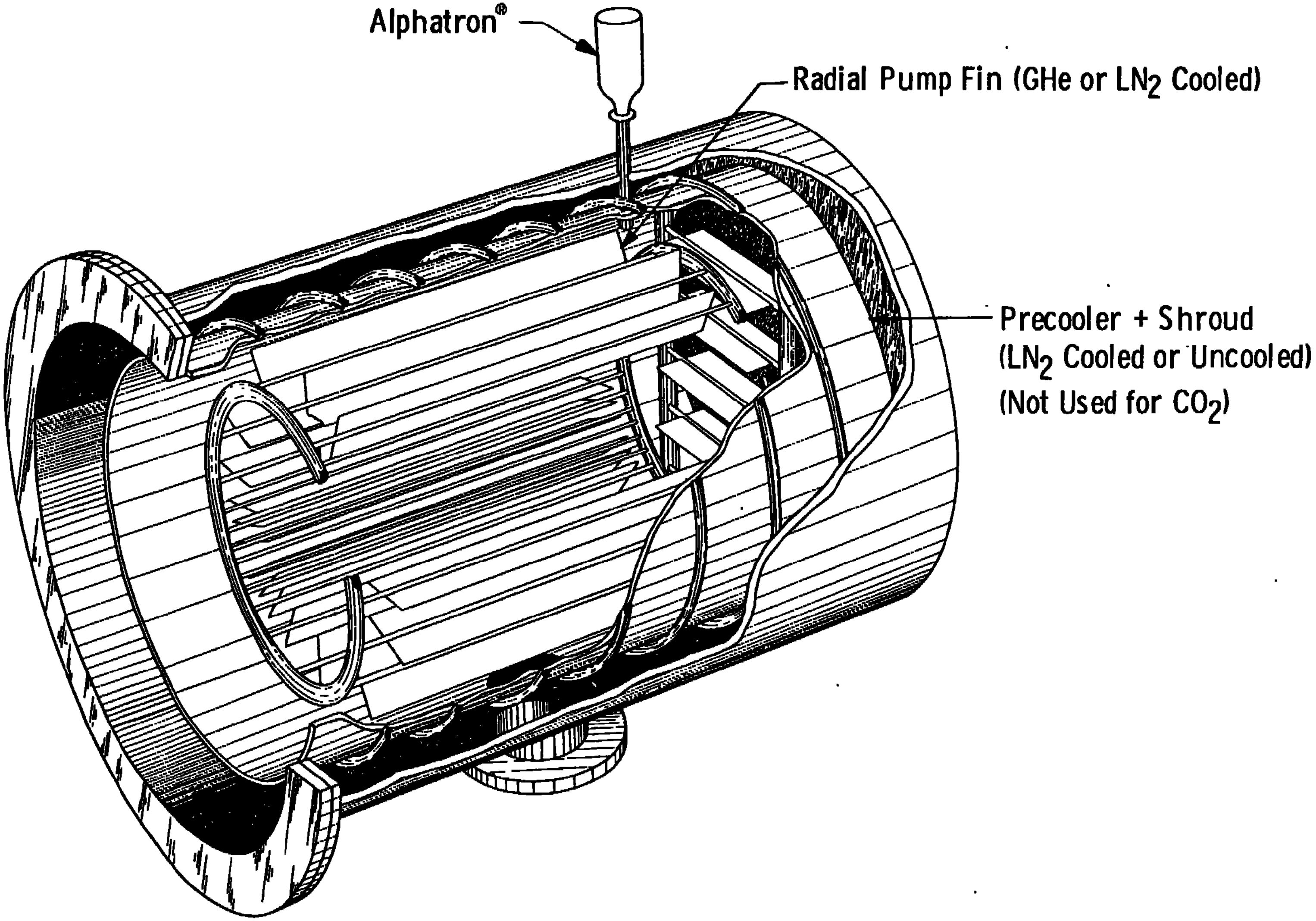


Figure 5. 2 × 3 foot research vacuum chamber with cryogenic pumping system.

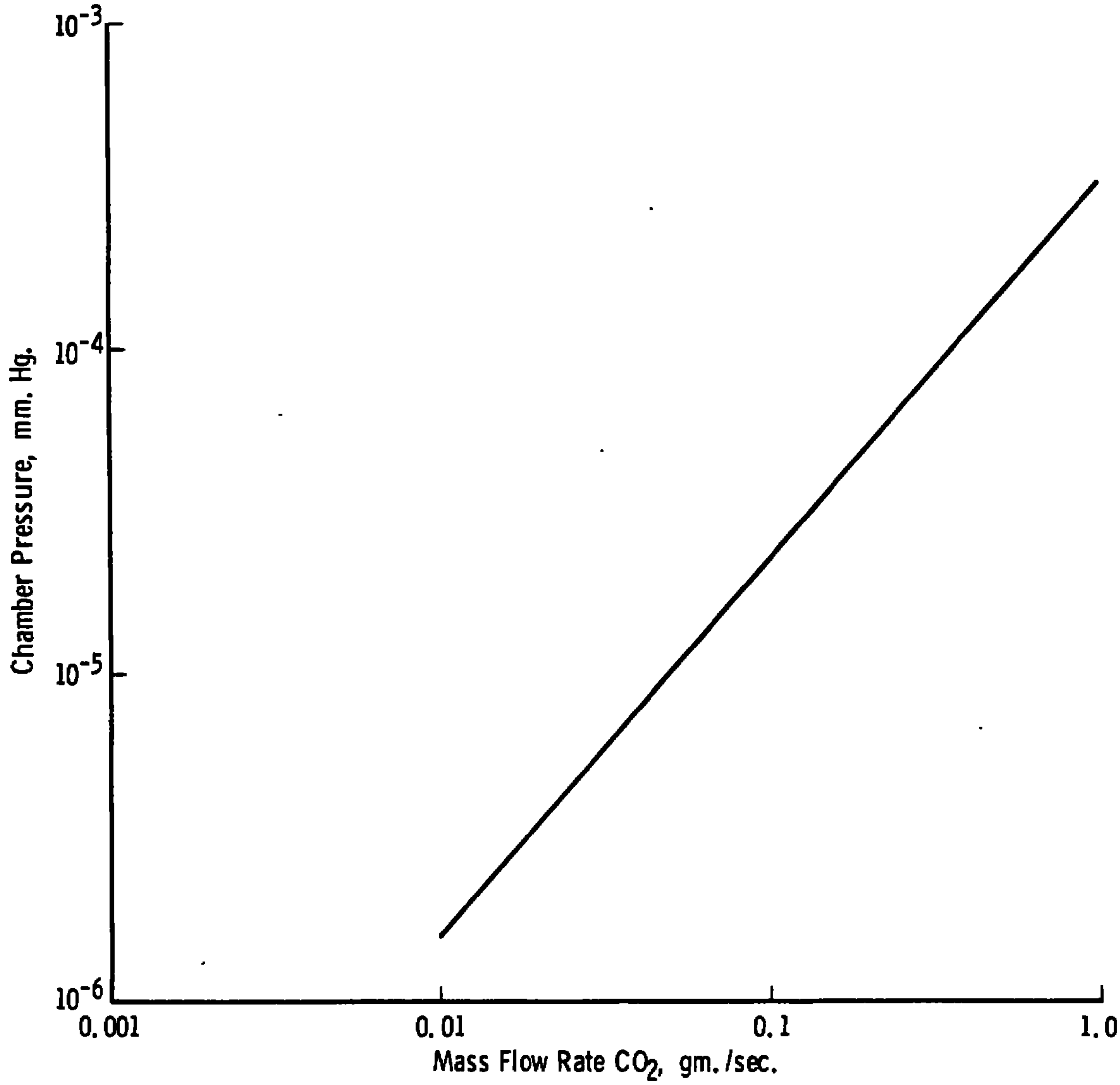


Figure 6. Test chamber operating pressure versus mass flow rate of CO_2.

The plenum chamber discharged through a 6 inch valve into the 4 × 6 foot Research Vacuum Chamber which was equipped with a liquid nitrogen cooled cryopump for CO_2 pumping and a 300 CFM mechanical vacuum pump used for initial pumpdown and for removing non-condensable gases during operation. This chamber with its 6 inch inlet valve was analogous to the auxiliary mechanical pumping equipment normally used in conventional rocket test facilities.

Carbon dioxide supply was from four 50 lb. liquid storage bottles through a heated manifold and pressure regulator. The manifold heater consisted of heater tape wrapped around the manifold with power supplied from a variable transformer. The heater was added after initial difficulties with frozen water vapor in the CO_2 flow meter and unacceptably low stagnation temperatures. Manifold heat was used to maintain the supply temperature at room temperature. In addition to the flow control valve shown in Figure 4, page 9, a vacuum quality isolation valve was required on the external end of the tubular feedthrough since most of the CO_2 supply system was not vacuum tight.

II. NOZZLE

Dimensions of the nozzle used in this investigation are shown in Figure 7. The throat area was chosen to give

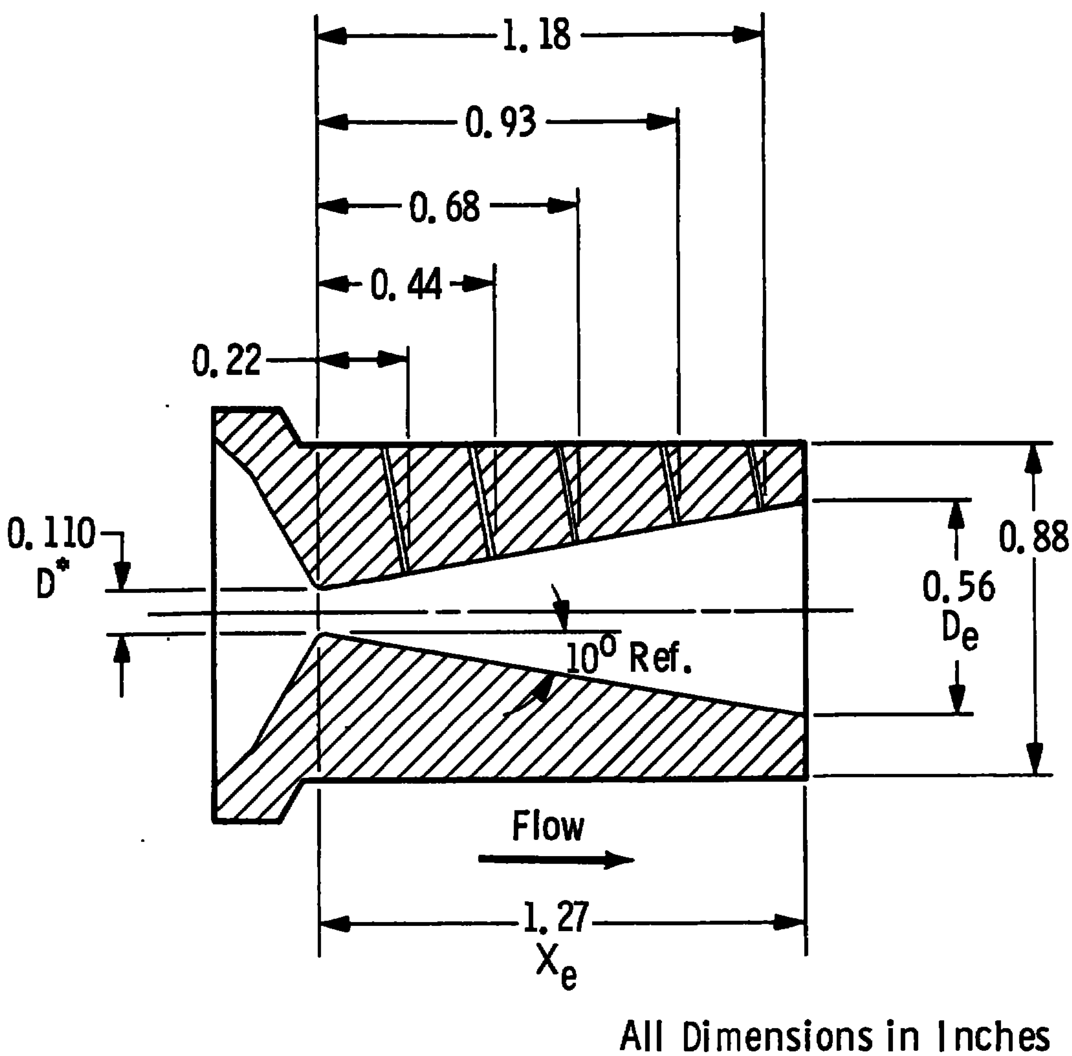


Figure 7. Nozzle details.

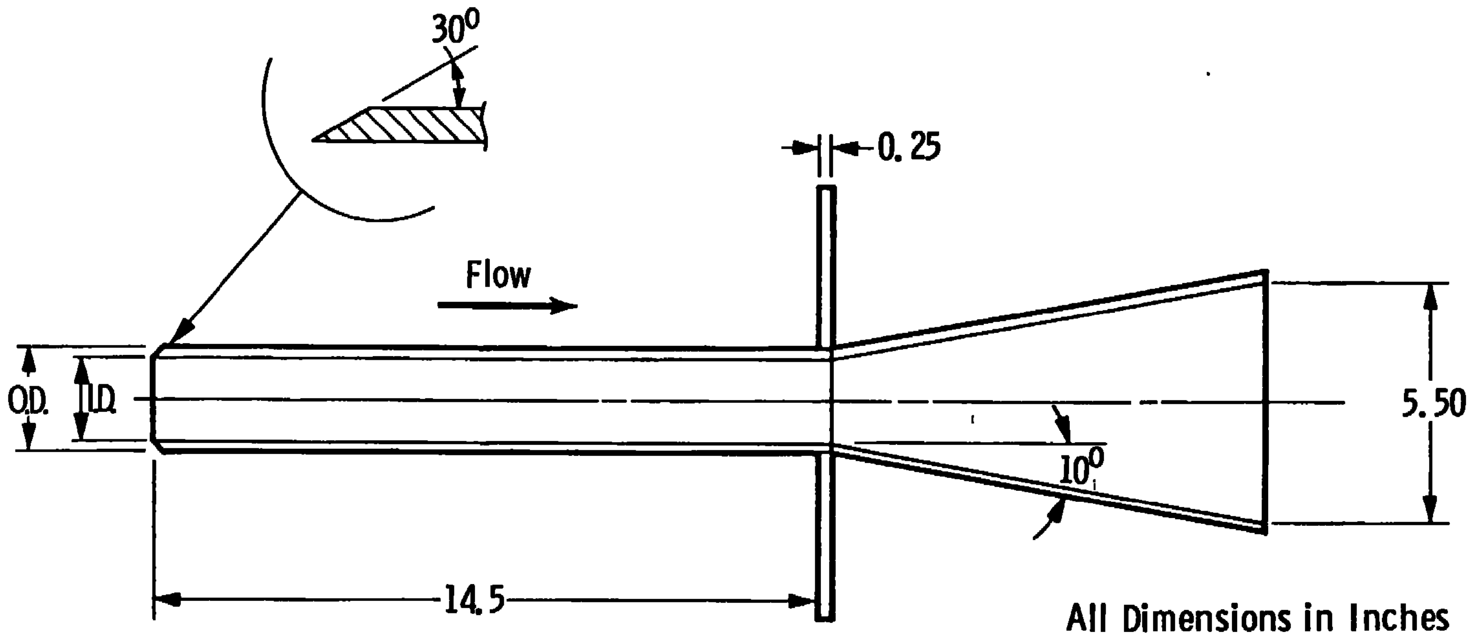
approximately 5 gm/sec CO_2 flow at 40 psia stagnation pressure and 60°F stagnation temperature. The divergence angle and area ratio are similar to existing small control rockets.

At the conclusion of the backflow experiments, five .02 inch static pressure taps were drilled perpendicular to the nozzle wall at the axial positions shown. These taps were equally spaced around the nozzle to minimize effects of disturbances propagated by the taps. Connections for the pressure taps were soldered to the outside of the nozzle.

III. DIFFUSERS

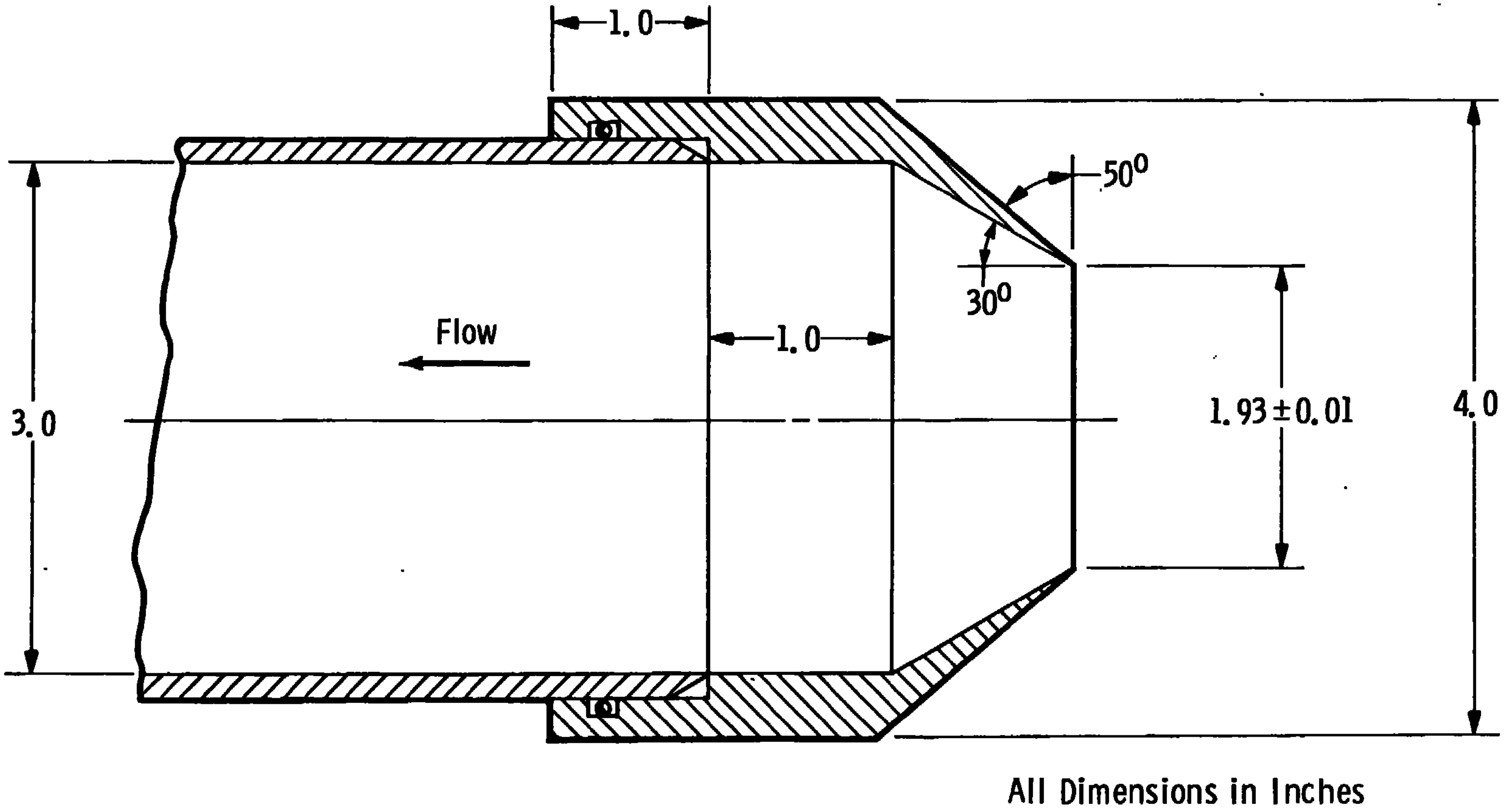
Dimensions of the straight duct diffusers are shown in Figure 8. All were equipped with conical diverging downstream sections and the leading edges were beveled to 30°. The length was chosen to place the leading edge of the diffuser directly opposite the single viewport in the side of the 2 × 3 foot test chamber.

The two conical diffuser inlets used are shown in Figure 9. These inlets were designed to attach to the largest of the straight diffusers. The smaller conical diffuser inlet has the same inlet diameter (1.93 inch) as the No. 3 straight diffuser so that a direct comparison



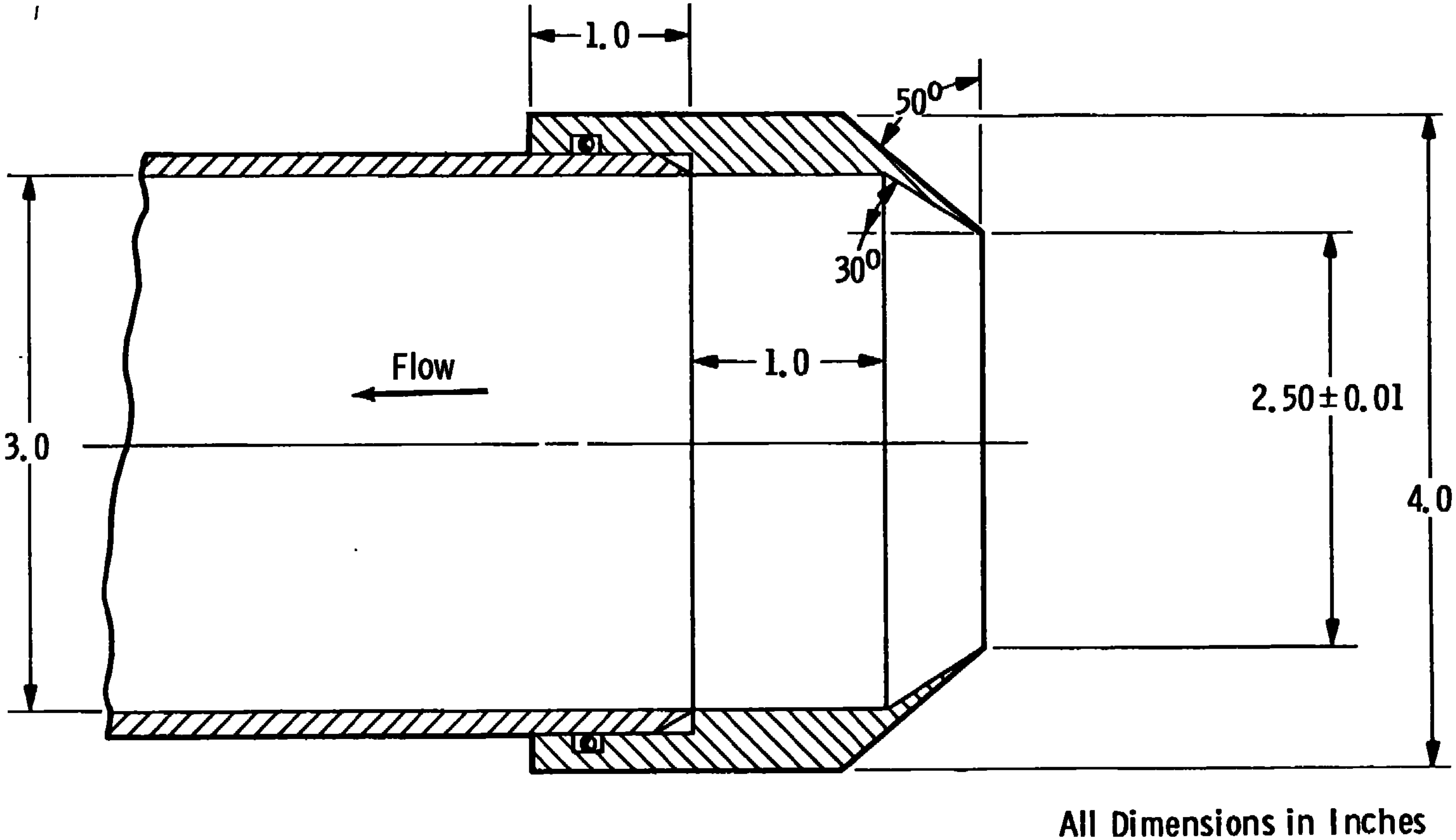
Diffuser No.	Outside Diam., in.	Inside Diam., in.
1	1.00	0.90
2	1.50	1.41
3	2.00	1.93
4	2.375	2.25
5	3.25	3.00

Figure 8. Straight duct diffuser details.



a. Conical diffuser no. 1

Figure 9. Conical diffuser details.



b. Conical diffuser no. 2

Figure 9. (continued)

could be made. Based on preliminary analysis, the inlet angles were chosen to allow shock attachment throughout most of the flow field.

IV. FLOW VISUALIZATION

Flow visualization was accomplished by inducing afterglow (glow discharge) in the test gas by means of RF (radio frequency) excitation. The technique is described by Hurlbut (4) and its application to CO_2 flows is described by Prunty (5).

The output of a 400 volt, 3 megacycle oscillator power supply was impressed between the nozzle and the grounded diffuser inlet. Electrical isolation of the nozzle was accomplished by using a Teflon bushing.

As observed by Prunty (5), the CO_2 glow was pastel blue while air produced a pink glow. Thus, large air leaks or incomplete pumpdown resulted in pink glow throughout the test volume.

V. INSTRUMENTATION

Carbon dioxide supply and nozzle stagnation pressures were measured by Kollsman absolute pressure gauges with 0.1 psi resolution. Supply and stagnation temperatures were measured with copper-constantan thermocouple probes inserted in the flow.

Nozzle flow rate was measured with a rotameter. The tube and float used were calibrated to read percent of full scale flow, which was 6.25 CFM of air at 14.7 psia and 70°F, or 3.54 gm/sec of air at standard temperature and pressure. Corrections for different flowmeter conditions were made by the following relation:

$$F = \frac{\dot{m}_{full\ scale}}{\dot{m}_{cal}} = \left(\frac{P_s}{P_{std}}\right) \left(\frac{T_{std}}{T_s}\right) \left(\frac{R_{air}}{R_{CO_2}}\right) ,$$

where P, R, and T are pressure, gas constant, and temperature respectively. Thus $\dot{m}$ (gm/sec) = 3.54 Fz or $\dot{m} = Kz\ P_s^{1/2}/T_s^{1/2}$ where K is a constant determined by units and type of gas and z is the scale reading.

Test chamber pressures were measured with an Alphatron gage which opened into the test volume above and slightly upstream of the nozzle, an ionization gage upstream of the nozzle facing to the rear, and a calibrated absolute pressure gage with a resolution of 1 mm. Hg. The plenum chamber pressure was monitored with an Alphatron gage, and a thermocouple gage was used in the 4 × 6 foot chamber. Diffusion pump foreline pressure, which gives a qualitative indication of the flow through the diffusion pump, was monitored with a thermocouple gage.

CHAPTER III

PROCEDURES

I. BASIC CHAMBER OPERATION AND FLOW VISUALIZATION

Normally, the 300 CFM pump, the diffusion pump with its forepump, and liquid nitrogen flow to the 4 × 6 foot chamber were started simultaneously to save time, although at the expense of collecting some water vapor in the 4 × 6 foot chamber and diffusion pump oil in the 2 × 3 foot chamber. This was done with the 6 inch isolation valve open so that both chambers pumped down together. Flow of liquid nitrogen to the 2 × 3 foot chamber was delayed until the diffusion pump was operative in order to prevent collection of water and residual CO_2. After pumpdown, the 2 × 3 foot test chamber was isolated so that base pressure could be monitored as indication of leakage. Pressures higher than 10^{-5} mm. Hg. with a cold cryogenic system were considered evidence of leakage; however, leaks occurred on only two occasions.

Reference for measuring nozzle-diffuser separation distance was established visually by placing the nozzle exit even with the diffuser inlet and marking this reference on the axial probe. By reflecting light off the opposite chamber wall, very close (approximately ± 0.01

inch) determination of the reference point was possible. Nozzle position was then measured with a scale (1/64 inch resolution) on the external portion of the probe.

After setting the desired nozzle-diffuser separation distance, nozzle flow was then initiated at the desired stagnation conditions.

For experiments involving flow visualization, difficulty of initiation of glow discharge was encountered, necessitating very slow establishment of flow. At times, the only successful method was to bleed air into the chamber raising the background pressure. Initiation usually occurred at approximately 10^{-1} mm. Hg., after which flow could be slowly started. Using this method, the discharge was required to travel back into the nozzle. This usually occurred suddenly, after which flow conditions and nozzle separation distance could be changed as rapidly as desired without stopping the glow discharge. Apparently, initiation of the glow discharge is an order of magnitude more pressure dependent than maintaining it.

II. BACKFLOW MEASUREMENTS

As will be noted from Figure 4, page 9, all flow captured by the diffuser was pumped in the 4 × 6 foot chamber while the remainder of the total nozzle flow was pumped in the 2 × 3 foot test chamber. For this investigation <u>the percent of total nozzle flow captured in the 2 × 3 foot test chamber is termed backflow.</u>

The backflow measurement was an especially critical part of this investigation since it is in most instances a small percentage of the nozzle flow; and since by the nature of the experiment, it must be allowed to expand fully into the 2 × 3 foot test chamber. Measurement of the diffuser flow could have been accomplished by means of orifices since downstream pressures can be allowed to rise to the 10 - 20 mm. Hg. range without breaking down the diffuser flow. However, backflow determined by the difference between the diffuser flow and total nozzle flow would not provide sufficient accuracy.

It was therefore decided to measure backflow directly since all backflow was cryopumped in the 2 × 3 foot chamber. For a particular diffuser and nozzle-diffuser separation distance, CO_2 flow at the desired stagnation conditions was established for a measured time period. On termination of nozzle flow, the test chamber was isolated and the cryosystem and chamber allowed to warm up to room temperature. Total accumulated mass is calculated from the final pressure achieved on warmup and the known test chamber volume. Backflow is then the ratio of the captured mass to the total mass flowed through the nozzle during the test. Because of the extremely large pumping capacity of liquid nitrogen cooled surfaces for CO_2, the only limitation on run time was that the final test chamber pressure after warmup must be slightly less than atmospheric pressure. This limitation was necessary because the test chamber automatically vented on reaching atmospheric pressure. Run time was generally made as long as possible within this limitation in order to reduce the transient effects of startup, shutdown, and fluctuations of nozzle stagnation conditions. An average run was approximately one-half hour.

Isolation of the test chamber at completion of a run was accomplished with the 6 inch plenum discharge valve, the diffusion pump foreline valve, and the 1/2 inch vacuum valve in the CO_2 supply line. The test volume thus included the plenum duct, the 2 × 3 foot test chamber, the diffusion pump, and the diffusion pump baffle. Although a valve was available to exclude the diffusion pump, it was desirable to include its liquid nitrogen cooled optically tight baffle in the test volume in case a portion of the backflow might cryopump there.

Volume of the system was measured by bleeding a known volume of atmospheric air into the evacuated test cell using a wet test gas meter (resolution 0.1 liter). Volume was then calculated using final chamber pressure after standing overnight, ambient temperature, and barometric pressure at the time of the repressurization. The possibility of temperature gradients and of premature release of chamber flanges prevented a direct measurement by repressurizing to atmospheric pressure.

III. STATIC PRESSURE PROFILE

After completing all backflow experiments, a static pressure profile was obtained in order to gain additional information on the degree of condensation in the nozzle. The pressures were measured with a Baratron differential pressure gage (resolution 0.01 mm. Hg.) referenced to the 4 × 6 foot chamber. Since the pressure at the tap nearest the nozzle throat was slightly above the instrument's normal range of 100 mm. Hg., a Kollsman absolute pressure gage (resolution 0.1 inch Hg.) was used for that point.

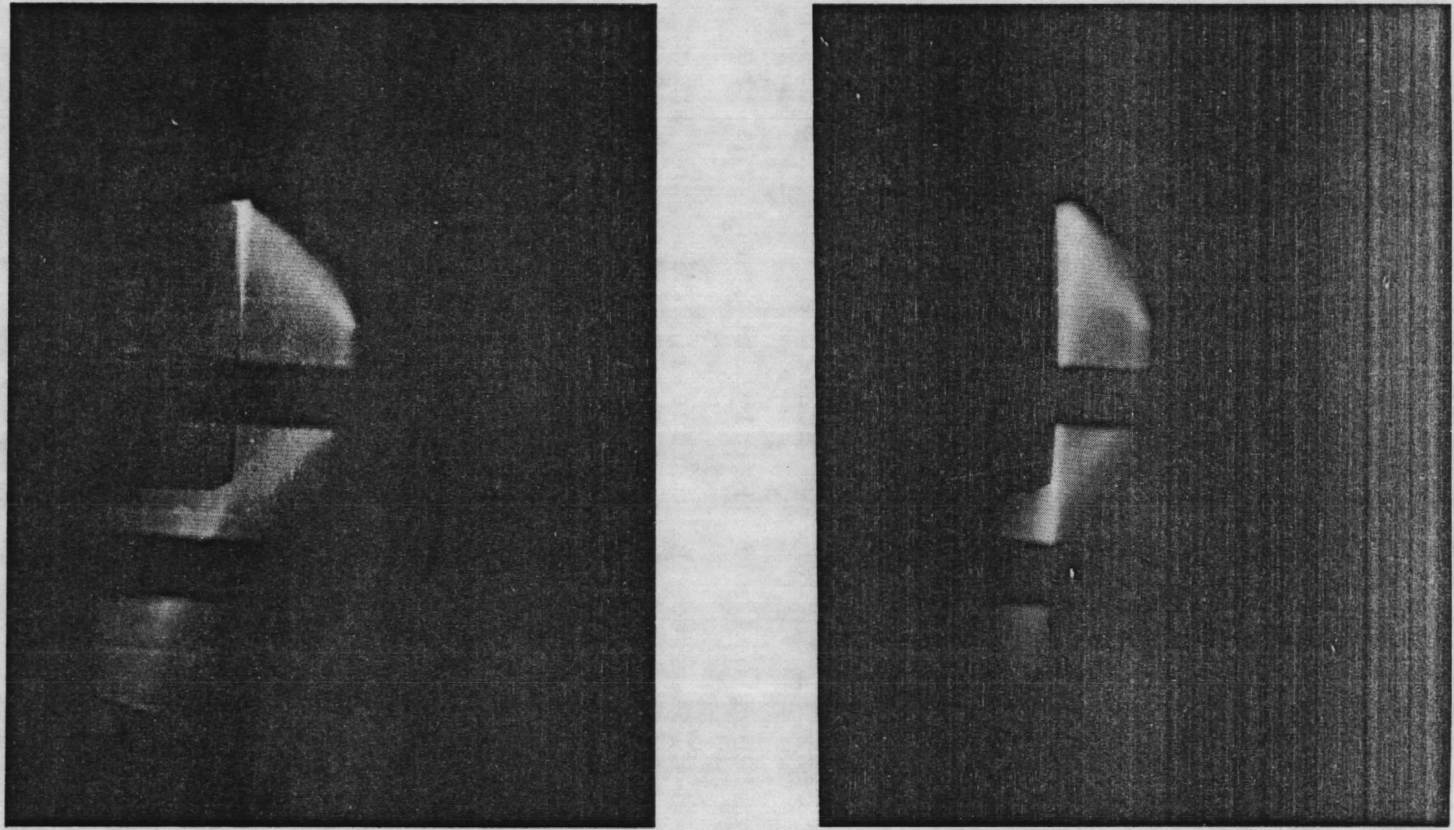
CHAPTER IV

EXPERIMENTAL RESULTS AND DISCUSSION

I. FLOW VISUALIZATION

Figure 10 shows typical plume-diffuser interactions for a 3.0 inch I.D. straight duct diffuser, using the RF glow-discharge flow visualization technique. The series of photographs shows the changes in external flow as the nozzle was moved toward the diffuser. At large separation distances, the conical shock wave formed at the lip of the diffuser was well defined and clearly attached. As the nozzle was moved closer to the diffuser inlet, the shock wave folded back toward the nozzle and detached from the diffuser inlet. As separation distance was further decreased, the shock wave became diffuse and poorly defined. Finally, for zero separation, the diffuser simply turned the outer edges of the plume back toward the nozzle. The backflow for this diffuser was 1.62% for the zero separation shown in Figure 10(d).

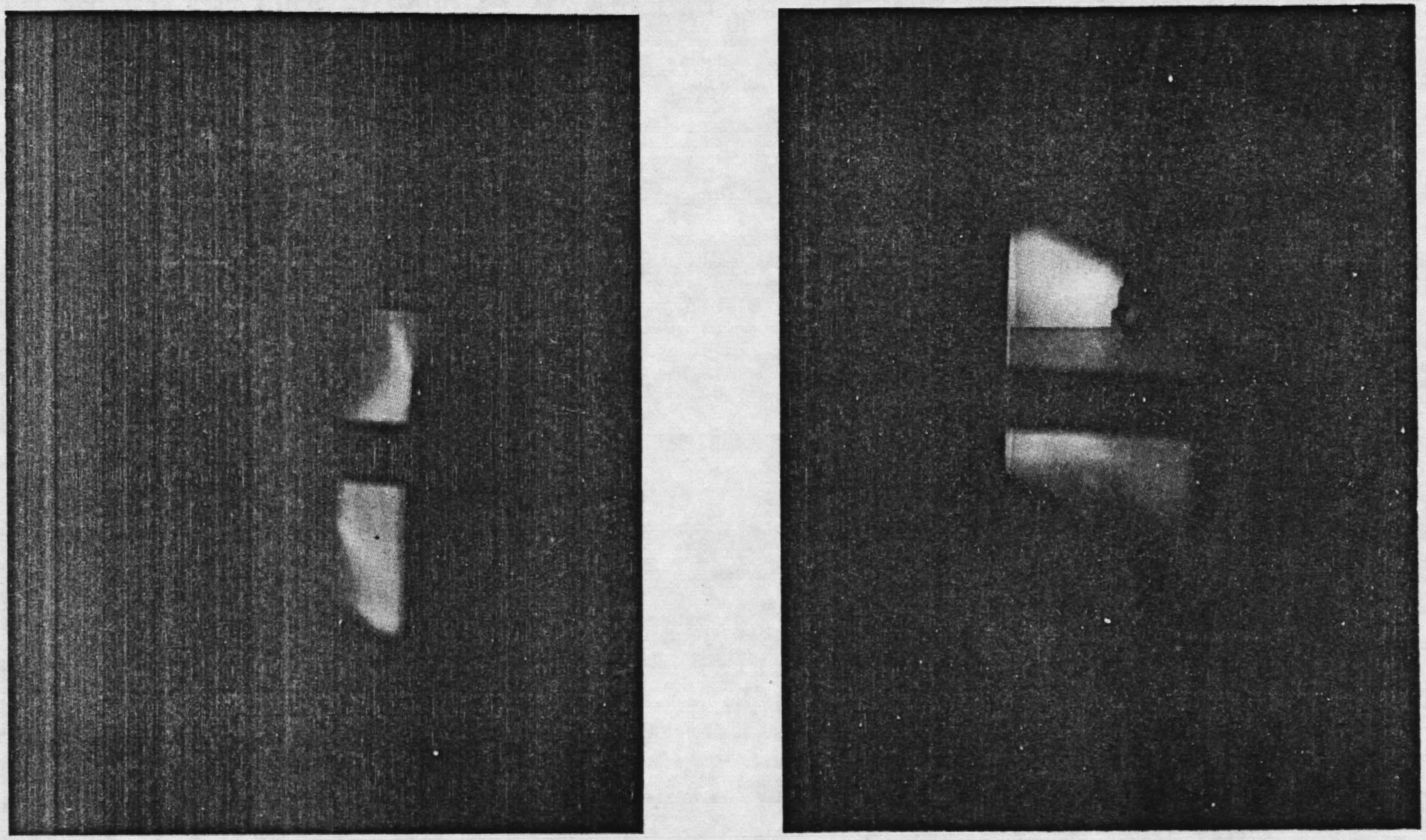
Similar results were observed for a 1.93 inch I.D. conical diffuser, as shown in Figure 11. In this case, however, the nozzle was moved much closer to the diffuser inlet before separation occurred. In addition, the change



a. 3.0-in.-I.D. Diffuser-
1-1/2-in. Separation
(x/r_e = 5.35)

b. 3.0-in.-I.D. Diffuser-
1-1/4-in. Separation
(x/r_e = 4.46)

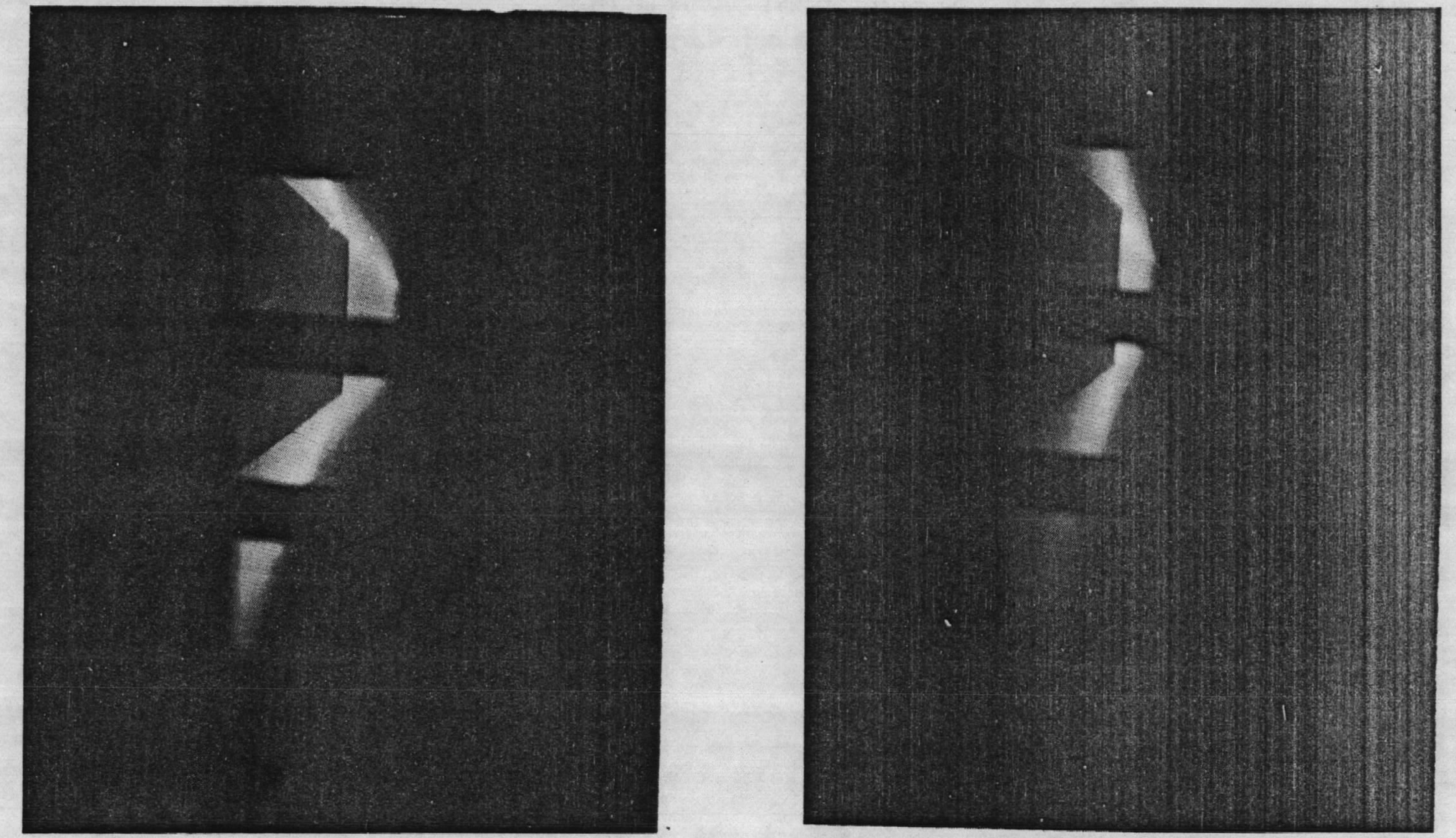
Figure 10. Photographs of plume-diffuser interaction (straight diffuser).



c. 3.0-in.-I.D. Diffuser-
1-in. Separation
(x/r_e = 3.57)

d. 3.0-in.-I.D. Diffuser-
Zero Separation
(x/r_e = 0)

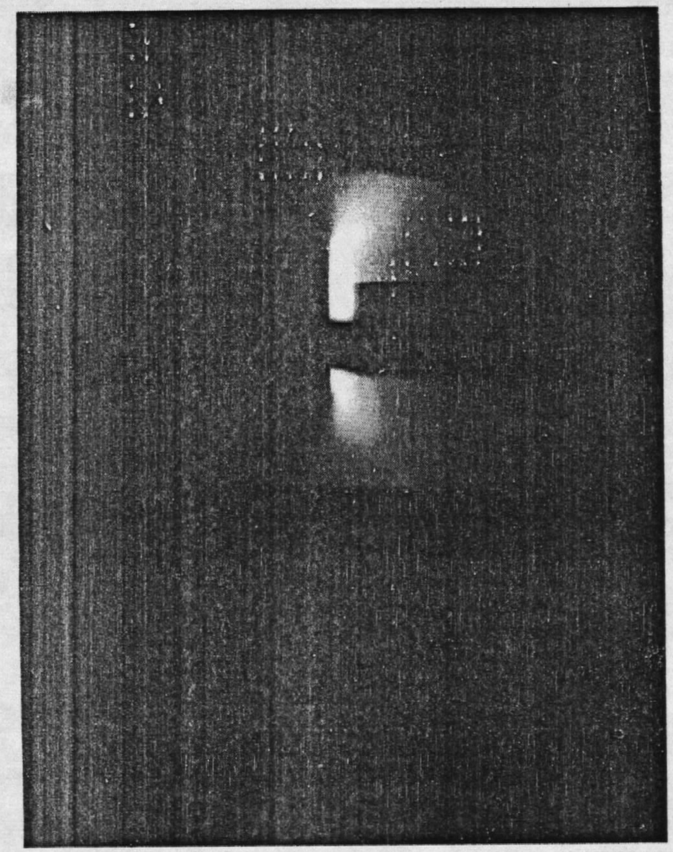
Figure 10. (continued)



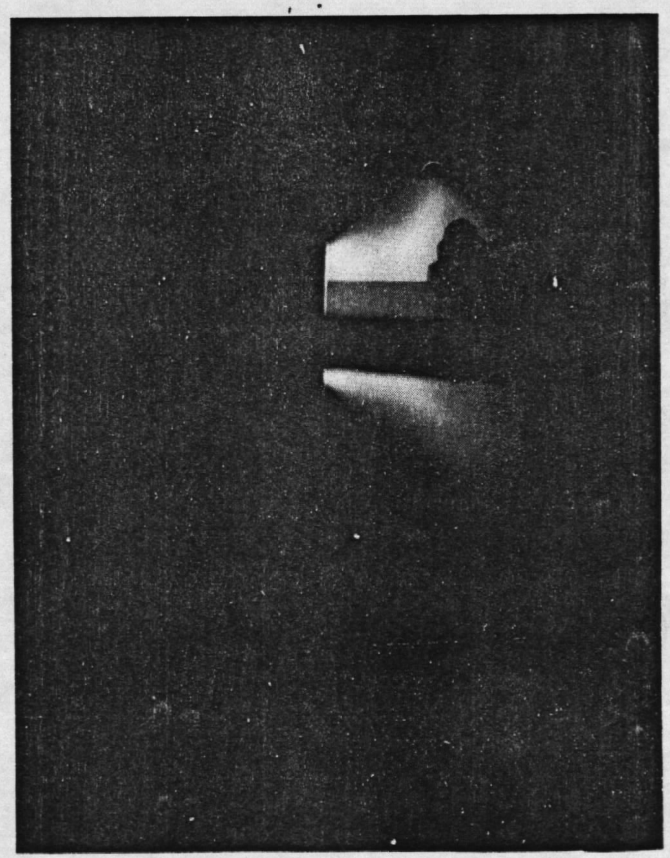
a. 1.93-in.-I.D. Conical Diffuser-3/4-in. Separation (x/r_e = 2.68)

b. 1.93-in.-I.D. Conical Diffuser-1/2-in. Separation (x/r_e = 1.79)

Figure 11. Photographs of plume-diffuser interaction (conical diffuser).



c. 1.93-in.-I.D. Conical Diffuser-1/4-in Separation ($x/r_e = 0.89$)



d. 1.93-in.-I.D. Conical Diffuser-Zero Separation ($x/r_e = 0$)

Figure 11. (continued)

from attached, well defined shock wave to diffuse reverse flow at zero separation occurred over a much smaller range of positions.

Based on the flow visualization results, it must be concluded that definition of streamtubes by measuring the flow division would not be accurate in the low density outer edges of the plume. However, use of a conical inlet diverging in the direction of flow would allow streamline definition closer to the plume boundaries than straight diffusers.

II. BACKFLOW RESULTS

Figures 12 and 13 show the primary experimental results of this investigation. Backflow results for the straight duct diffusers are shown in Figure 12. For large separation distances, there is a near-linear relationship of backflow to position. As would be expected, the larger the diffuser, the smaller the backflow for a given separation distance since the streamtubes are divergent in a free jet expansion. However, at small separation distances, this is not true and smaller diffusers capture more of the flow. Obviously, shock detachment and spillage of diffuser flow underneath the bow shock must occur for these diffusers at backflows larger than 1.5 percent. Thus the 98 percent streamtube represents a preliminary estimate of the upper limit for streamtube definition

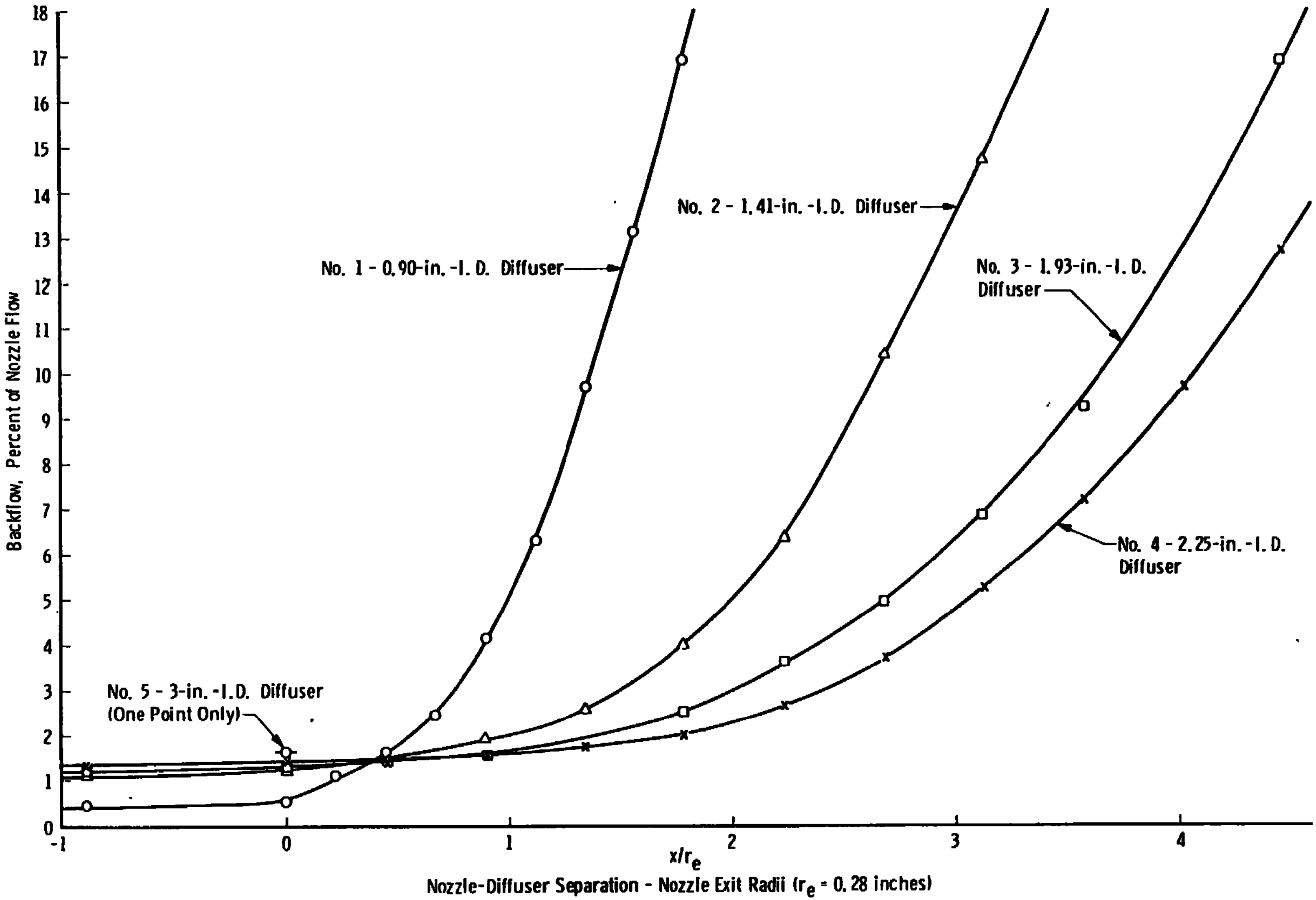


Figure 12. Backflow versus nozzle-diffuser separation for straight duct diffusers.

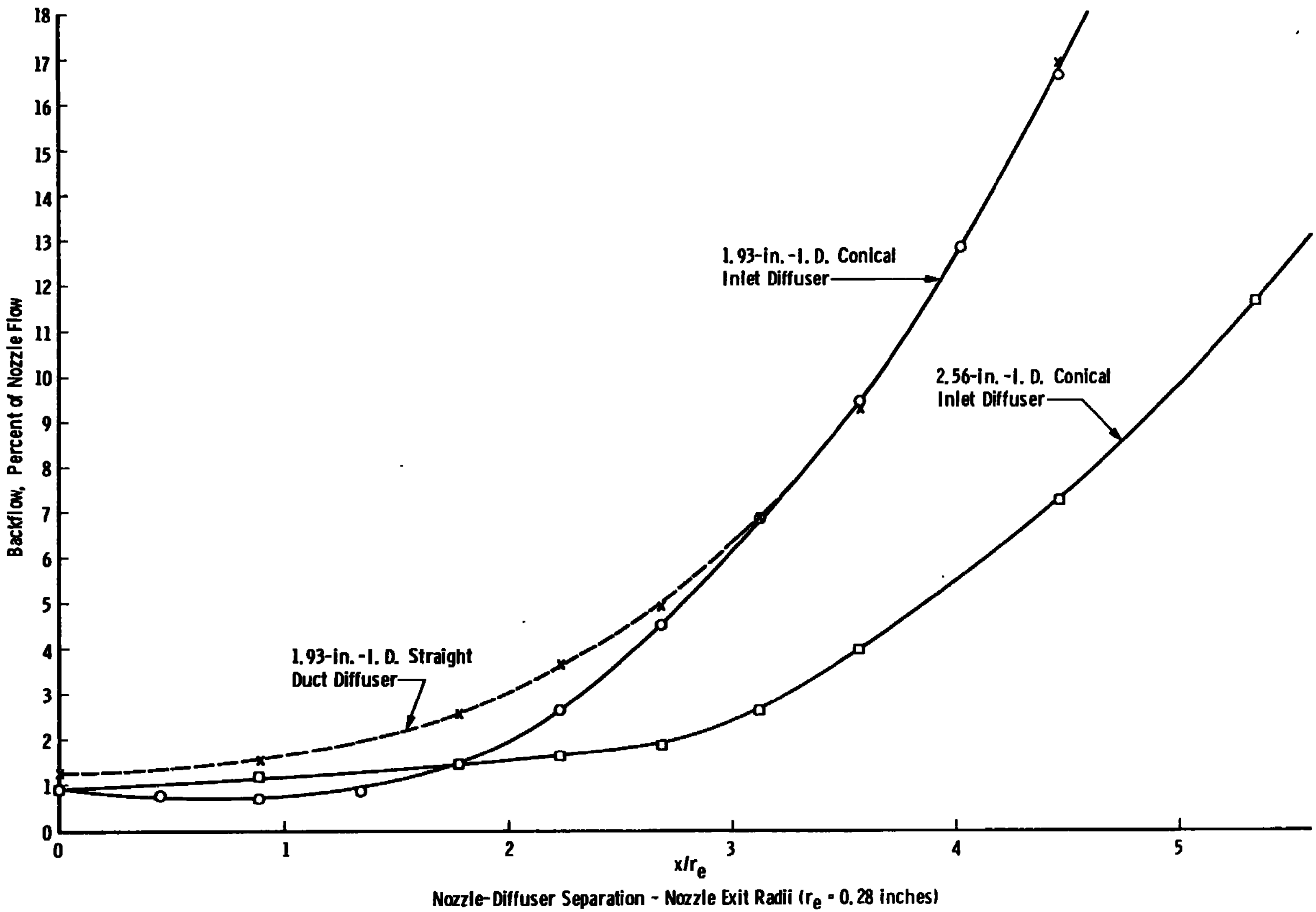


Figure 13. Backflow versus nozzle-diffuser separation for conical diffusers.

by this method. It should be noted that the conspicuously small minimum backflow for the 0.90 inch straight diffuser results from the small annular clearance between the diffuser inside diameter (0.90 inches) and the nozzle outside diameter (0.87 inches).

Figure 13 shows backflow results for the two conical diffuser inlets used in this investigation. As with the straight diffusers, the crossover point occurs at approximately 1.5 percent backflow. Also included on Figure 13 is the curve for the 1.93 inch straight diffuser. For backflow values above 7 percent, there is no difference in measured backflow. Thus, the 1.93 inch straight diffuser can be used to define streamtubes containing less than 93 percent of the nozzle flow (backflow greater than 7 percent) while the conical diffuser can be used for streamtubes of somewhat higher percentages.

III. ANALYSIS OF CONDITIONS FOR INLET SHOCK ATTACHMENT

The streamtubes of a free jet expansion are in general divergent when the jet is expanding into very low ambient pressures. With reference to Figure 1, page 3, the diffuser inlet may be represented in cross-section as a wedge in supersonic flow, turning the flow radially inward toward the diffuser centerline. As the diffuser is moved closer to the nozzle exit, the deflection angle or wedge angle θ becomes larger, eventually exceeding the maximum deflection angle allowed by the gas at its local Mach number. Beyond this condition, the shock wave detaches and forms a bow shock with flow underneath from the relatively high pressure diffuser to the low pressure test chamber. Kuethe and Schetzer (6, pages 175-185) derive relationships for the attached shock angle as a function of deflection angle and Mach number and the results are presented in graphical form. Figure 14 shows maximum deflection angle as a function of Mach number for a specific heat ratio of 1.4. It is seen that if the streamtubes and Mach number can be estimated, then the maximum deflection angle at any given position in the plume can be estimated. Since the maximum deflection angle is relatively insensitive to Mach numbers above 6 and since Mach numbers greater than 6 are achieved in most free jet expansions very close to the nozzle exit, a maximum turning angle of between 42° and 45° is seen to be valid throughout most of the plume. Thus, only the streamtube angle relative to centerline is required to verify shock attachment and since these angles are precisely the object of this investigation, the streamtube plot must be obtained first from the backflow data and evaluated afterward as to range of validity for the particular diffusers used.

The preceding analysis is based on plane oblique shock waves. The deflection angle θ is also valid for

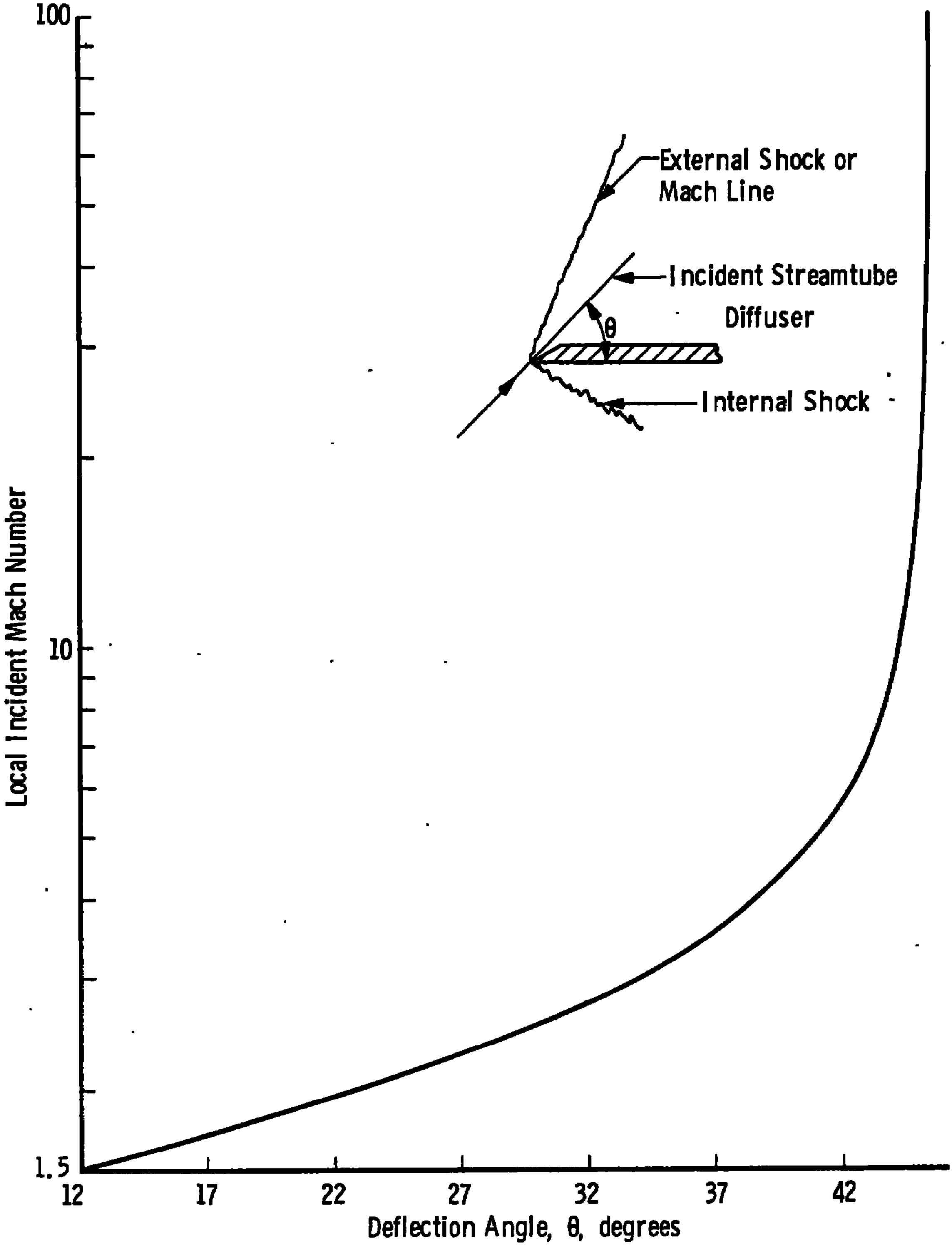


Figure 14. Maximum turning angle for supersonic flow.

axisymmetric flows but the wedge or cone angle is no longer equal to the deflection angle. For a cone, the deflection angle at the oblique shock will be less than the cone half angle, while for the case considered here, it will be greater. Therefore, shock detachment may occur at slightly smaller incident angles than indicated above. The two-dimensional analysis is believed to be sufficient for the present application however.

IV. STREAMTUBE PLOT

By crossplotting from the backflow plots, each diffuser contributes one data point toward definition of each streamtube. Figure 15 shows the streamtubes obtained for the jet used in this investigation. The dashed line portions are estimated between the 0.90 inch diffuser points and the nozzle exit; and the 80 percent streamtube is based on extrapolations from Figures 11 and 12, pages 28 and 31.

A check on the accuracy of the previous separation analysis can now be made. From Figure 13, page 32, the data for the 1.93 inch straight diffuser and the 1.93 inch conical diffuser diverged at approximately 7 percent backflow. From the streamtube plot, Figure 15, the 93 percent streamtube makes a deflection angle of 44.5° with the straight diffuser wall. This agrees well with Figure 14

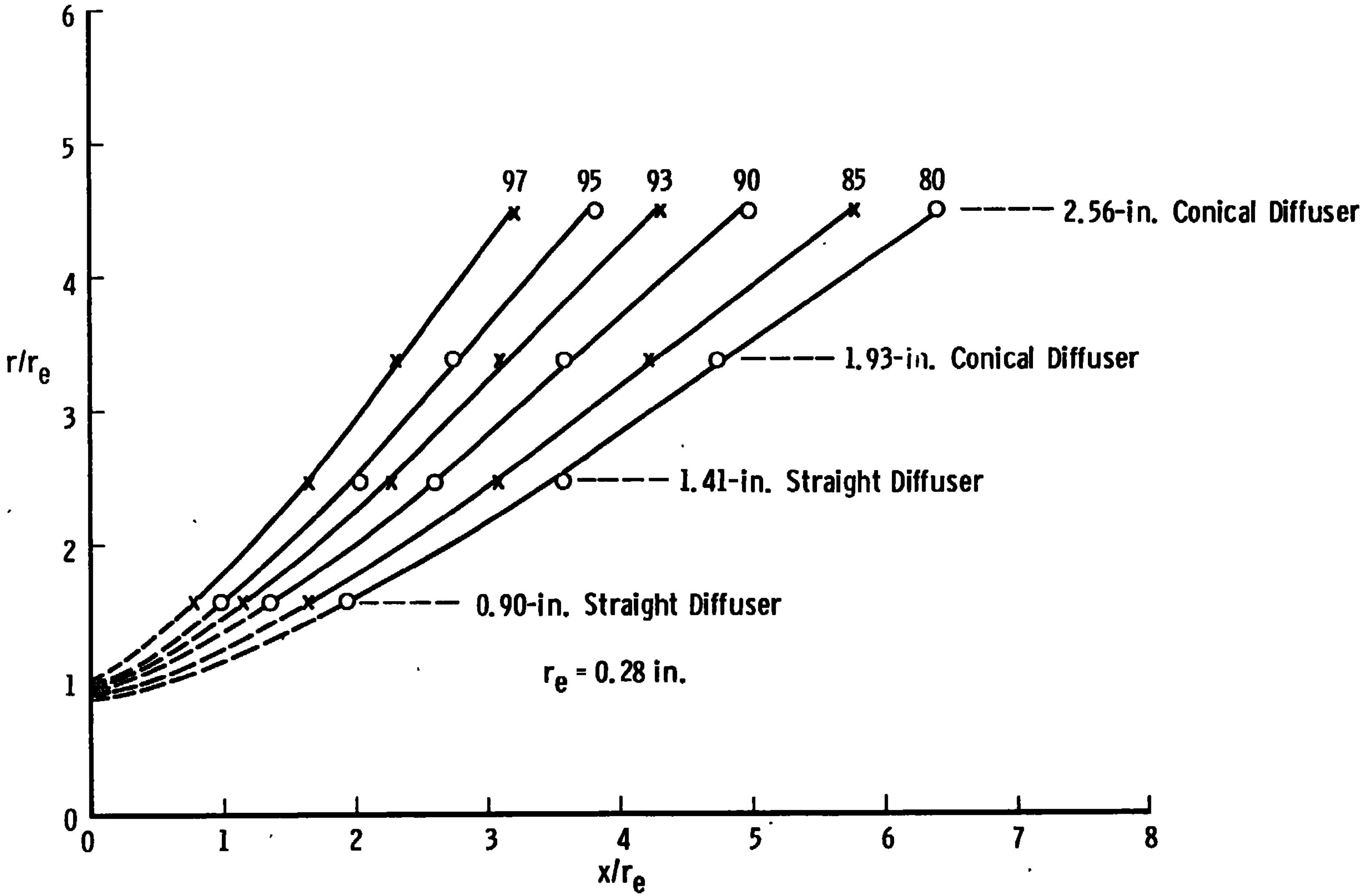


Figure 15. Experimental streamtubes.

for high Mach numbers. Further examination of Figure 15 in this manner shows that the 0.90 inch straight diffuser should yield attached inlet shock waves for all streamtubes plotted. The 1.41 inch diffuser shows possible shock detachment for the 95 percent and 97 percent streamtubes; but continuity of the curves suggests it is negligible. No separation is theoretically possible with either of the conical inlets for the streamtubes shown on Figure 15; as these inlets should allow shock attachment for streamlines up to 72° from horizontal (30° diffuser inlet angle plus 42° deflection angle). To check this limit, a 72° angle with the nozzle exit places the 1.93 inch conical diffuser approximately at 0.25 inches separation. Reference to Figures 11(c) and 13, pages 29 and 32, reveals that the shock appears to be detached at this position, however, possibly because the extreme low density in the outer edges of the plume may result in a transition flow regime. A second possibility is that the flow in the outer edges of the plume may be at lower Mach number than expected due to the effect of the nozzle boundary layer. In view of the above, the 98 percent streamtube appears to be a practical upper limit for this experimental method even if conical diffuser inlets are used exclusively.

V. DISCUSSION OF ERROR

In addition to the inaccuracies associated with curve fitting and cross-plotting to obtain streamlines, there were several probable sources of experimental error. These are as follows:

1. Errors in flow rate measurement.
2. Non-repeatability of the free jet expansion.
3. Errors in accumulated backflow measurement.
4. Nozzle position errors.
5. Nozzle-diffuser alignment errors.

Flow rate measurement depended on the accuracies of the flow meter, the supply pressure, and the supply temperature. The flow meter accuracy is believed to have been ± 1 percent while the supply pressure measurements were approximately ± 0.2 psi or ± 0.2 percent for the normal 100 psia supply pressure. Temperature measurements of ± 2°F or ± 0.4 percent can reasonably be expected from the thermocouple data. The basic equation relating the variables is:

$$\dot{m} = KzP_s^{1/2}\,T_s^{-1/2} ,$$

where $\dot{m}$, z, P_s, and T_s are mass flow rate, flow meter scale reading, supply pressure, and supply temperature, respectively. From Schenk (7), the error $\Delta\dot{m}$ is given by:

$$\Delta\dot{m}^2 = \left(\frac{\partial\dot{m}}{\partial z}\right)^2 \Delta z^2 + \left(\frac{\partial\dot{m}}{\partial P}\right)^2 \Delta P^2 + \left(\frac{\partial\dot{m}}{\partial T}\right)^2 \Delta T^2 ,$$

$$\Delta\dot{m}^2 = \left(\frac{\dot{m}}{z}\right)^2 \Delta z^2 + \left(\frac{\dot{m}}{2P}\right)^2 \Delta P^2 + \left(\frac{\dot{m}}{2T}\right)^2 \Delta T^2 ,$$

$$\left(\frac{\Delta\dot{m}}{\dot{m}}\right)^2 = \left(\frac{\Delta z}{z}\right)^2 + 1/4\left(\frac{\Delta P}{P}\right)^2 + 1/4\left(\frac{\Delta T}{T}\right)^2 ,$$

$$\frac{\Delta\dot{m}}{\dot{m}} = 1.025 \times 10^{-2} = 1.02 \text{ percent} .$$

As might be expected the resolution of the flow meter is the primary error.

Non-repeatability of the free jet expansion was possible because of differences between runs of stagnation pressure, stagnation temperature, and ambient test chamber pressure. No analytical estimate of these errors can be made other than the repeatability of the backflow results. However, stagnation pressure was closely controlled (± 0.1 psia at 40 psia or ± 0.25 percent) and temperature, which was held to 60°F ± 10°F, has little effect on streamtube location.

Sources of error in accumulated backflow measurement were generally the measurement of the final chamber equilibrium pressure (± 1 mm. Hg. at 500 mm. Hg. or ± 0.2 percent) and the final equilibrium temperature. This temperature was taken to be room temperature after forced warmup of the cryosystem using heated gaseous nitrogen. Temperatures on the cryosystem were monitored and when all cryosystem temperatures were near room temperature, the forced flow through the cryosystem was switched to room temperature gaseous nitrogen for approximately one-half hour. Such warmup procedures were necessary to reduce the overall time required per data point. By comparing chamber pressures immediately following this procedure with the pressure after standing overnight, it is estimated that the temperature error was equivalent to pressure errors of less than 5 mm. Hg. or 1 percent. This would result in an estimated maximum error of 1 percent for the accumulated backflow measurement or 1.4 percent for the percent backflow.

Nozzle position was measured to an accuracy of ± 1/16 inch. However an additional error was discovered near the completion of the investigation. The nozzle and diffuser were mounted on opposite ends of the chamber; and any temperature changes in the nozzle probe and the diffuser relative to the room temperature chamber wall caused an error in the reference point for measuring nozzle-diffuser separation distance. The largest change is caused by the highly expanded, low temperature CO_2 flowing through the 16 inch long diffuser section. No temperature measurements were taken but an average temperature of -100°F is possible. For the stainless steel diffusers, this would result in nozzle-diffuser separation measurements 0.015 inch longer than the actual value with correspondingly higher indicated backflows.

In addition to axial position, a second probable positional error results from nozzle-diffuser misalignment. In the first experimental data taken, differences of backflow as large as 1 percent (i.e., errors in streamtube definition of 1 percent) were recorded under apparently identical conditions but with a re-installed diffuser. By paying close attention to alignment on following diffuser installations, eccentricities of less than 1/16 inch were achieved. This problem would easily be eliminated by a design change in any future work. It should be noted, however, that while axial errors transfer directly to the streamtube plot since they affect the solid angle intercepted by the diffuser, the effect of misalignment is not as great. This is because if the diffuser is moved to one side of the plume and misses flow it should capture, the effect is partially offset by the additional flow intercepted on the other side; however, the added flow is in a less dense region of the plume and there is a net higher backflow than should be recorded.

CHAPTER V

FLOW ANALYSIS AND COMPARISON WITH EXPERIMENTAL RESULTS

I. METHOD OF CHARACTERISTICS SOLUTIONS

Ideal gas solutions for the streamtubes in a free jet expansion were obtained using a method of characteristics program developed by Lockheed Missile and Space Company (8). Matching of experimental streamtubes to theoretical streamtubes was attempted by two methods. The first method involved using the nozzle stagnation conditions and nozzle dimensions with an ideal gas analysis of both the nozzle and the plume, selecting the value of specific heat ratio γ which gave the best match to the experimental streamtubes. The second method involved a more detailed analysis of the nozzle flow to obtain nozzle exit conditions so that the starting line for the method of characteristics solution was the nozzle exit.

The second method is obviously preferable provided sufficient information to define the nozzle exit conditions is available. Since this is not always the case, it was believed worthwhile to make a preliminary comparison of ideal gas solutions.

II. COMPARISON BASED ON IDEAL GAS NOZZLE FLOW

Method of characteristics solutions were obtained for specific heat ratios (γ) of 1.2, 1.3, and 1.4 and are shown in Figures 16, 17, and 18 respectively, with the experimental streamtubes superimposed. Matching of the experimental streamtubes requires a γ of approximately 1.17. Prunty (5) observed comparable values of γ required to match observed jet boundaries and concluded that condensation was reducing the exit Mach number and causing greater spread of the jet than could be calculated using acceptable values of γ. Reference to Figure 19 shows that values of γ of less than 1.28 are not justifiable for CO_2 in a nozzle expansion from room temperature. Further, any tendency to freeze the existing degrees of freedom in the rapid plume expansion could only account for increases in the value of γ (9, pages 80-86). If, however, it is reasoned that condensation provides many additional degrees of freedom, then there is some justification for use of low values of γ, although such a procedure must be considered empirical.

III. ANALYSIS OF NOZZLE FLOW

Newitt et al. (10) includes a temperature entropy diagram extending to -140°C. Using this chart, the known stagnation conditions of 60°F and 40 psia, and the nozzle

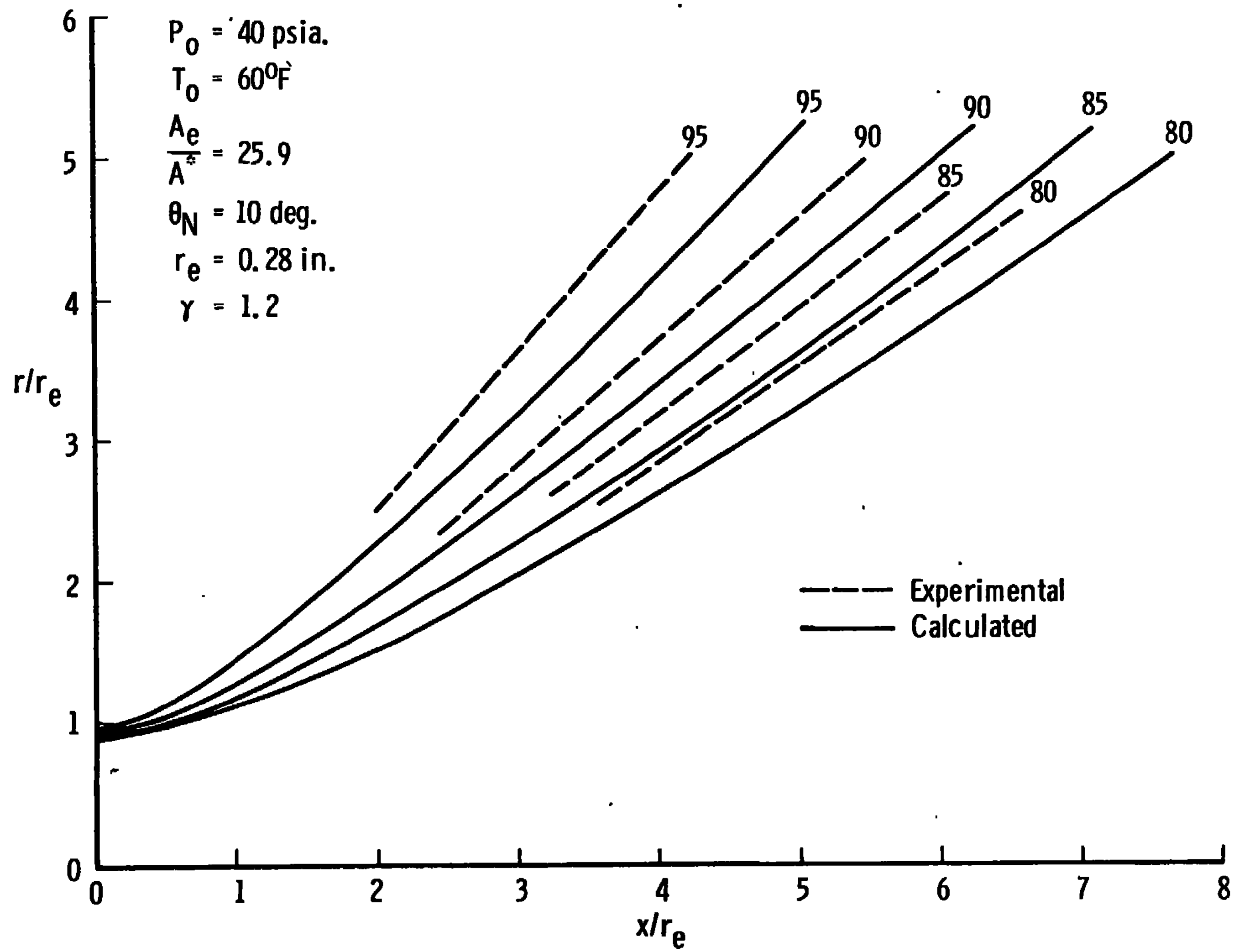


Figure 16. Method of characteristics solution for γ = 1.2.

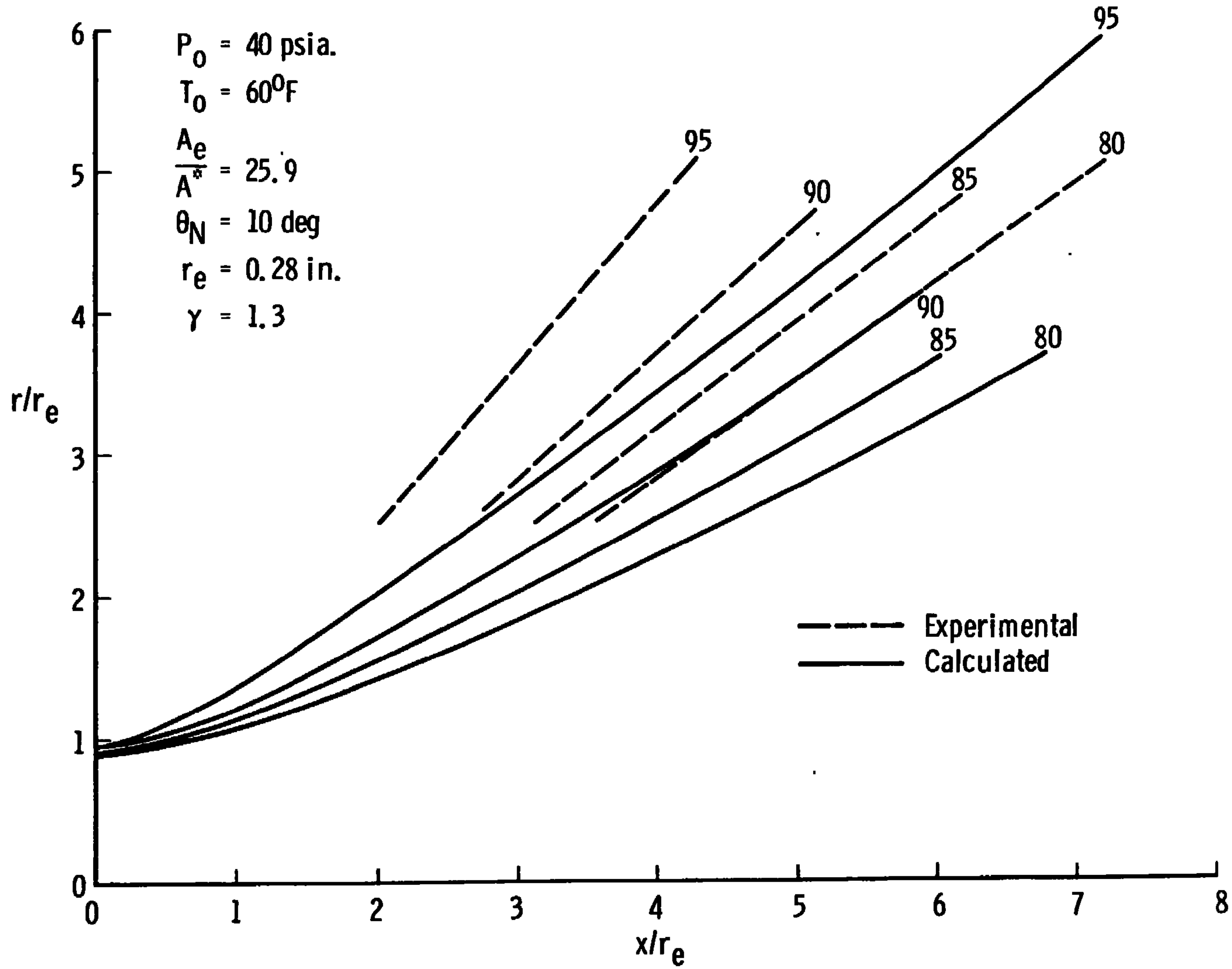


Figure 17. Method of characteristics solution for $\gamma = 1.3$.

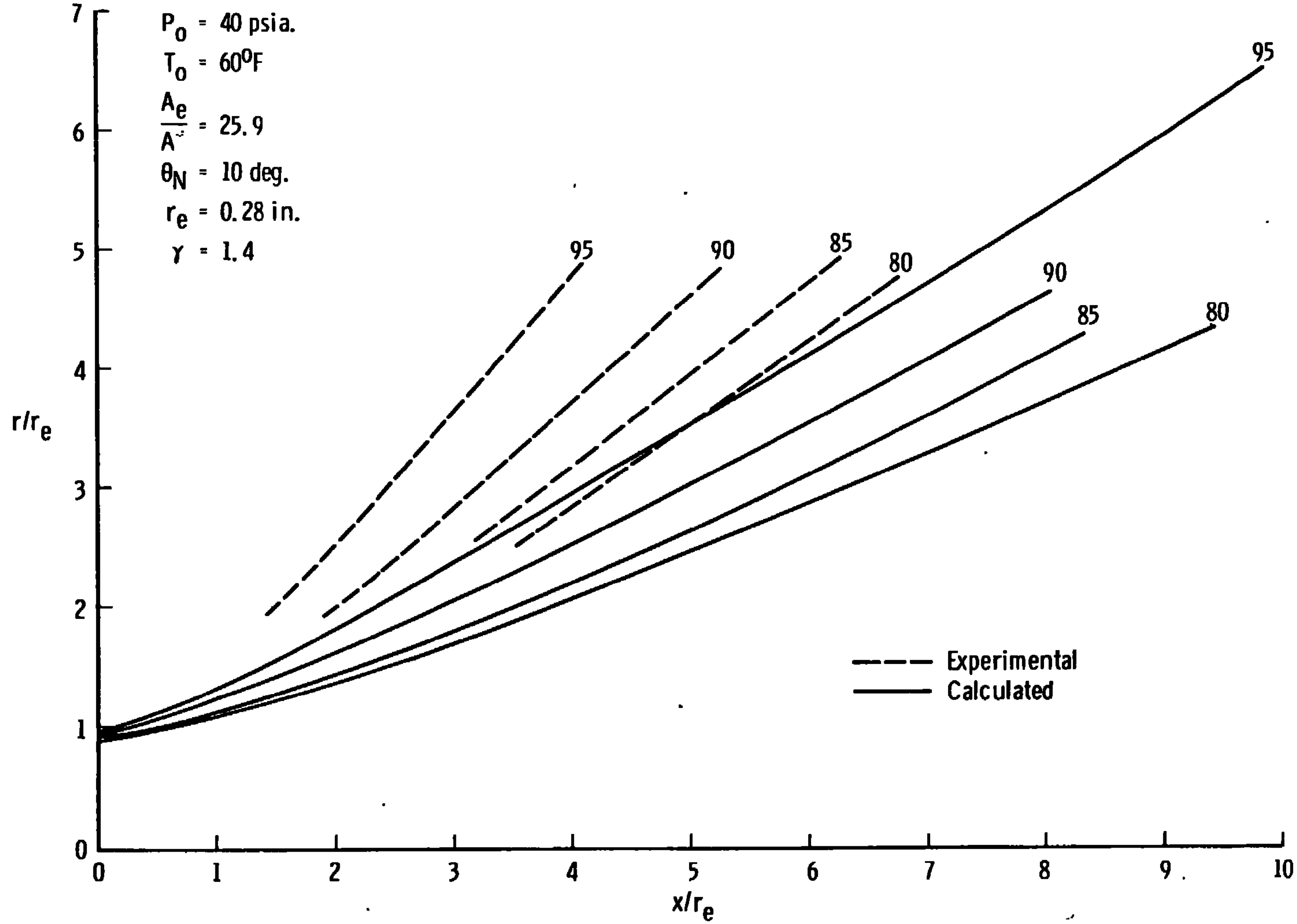


Figure 18. Method of characteristics solution for $\gamma = 1.4$.

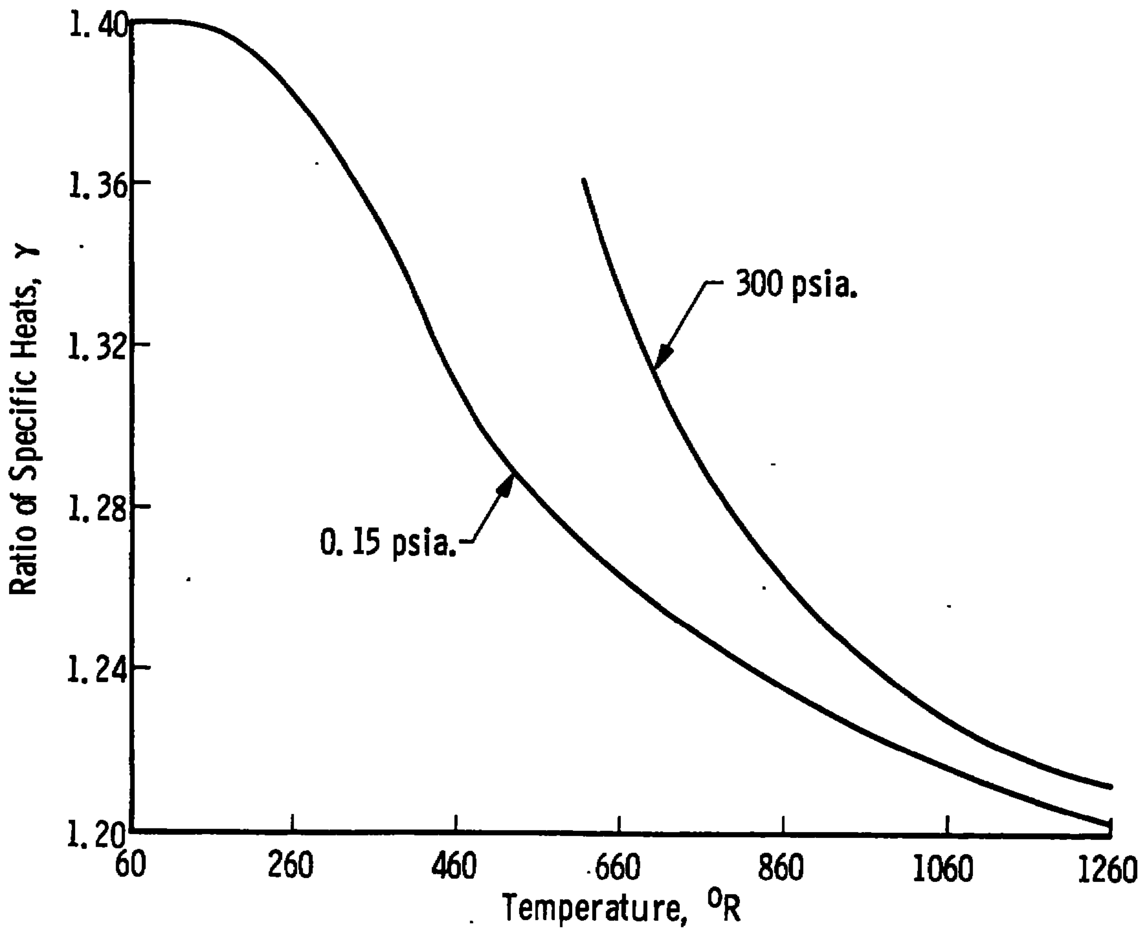


Figure 19. Specific heat ratio of CO_2.

dimensions, flow conditions through the nozzle were calculated assuming an isentropic process.

The procedure for calculating isentropic flow properties was as follows:

1. Locate the stagnation point on the T-S chart, record enthalpy, entropy, and specific volume.
2. In order to accomplish accurate and fast interpolation, plot specific volume versus enthalpy for convenient points along the stagnation entropy.
3. Select a convenient value of enthalpy below the stagnation enthalpy, calculate the flow velocity from the first law equation $V = \sqrt{2Jg_c(h_o-h)}$.
4. Using the specific volume corresponding to the enthalpy selected at the stagnation entropy, calculate nozzle area $A = \dot{m}\, v/V$ where $\dot{m}$ is the measured mass flow rate. The corresponding local temperature and pressure may be read directly from the T-S diagram.
5. From the known nozzle dimensions, calculate the axial position relative to the throat corresponding to the calculated flow area.
6. Repeat steps 3 through 5 for decreasing values of enthalpy until the nozzle exit area is exceeded. Each property may then be plotted as

a function of axial position and the nozzle exit conditions determined graphically. Explicit solutions for nozzle exit properties are not possible for vapor expansions.

The results of the calculations for static pressure are shown in Figure 20, along with measured static pressures in the nozzle. Also included are static pressure profiles using standard ideal gas relationships (11) (12) for specific heat ratios of 1.2 and 1.3. It is seen that a value of γ of approximately 1.15 would match both the measured results and the expanding vapor calculations. It should be noted that the measured static pressures near the nozzle exit are slightly higher than the calculated pressures for isentropic vapor expansion.

A comparison of nozzle exit conditions calculated by the two methods is shown below with the specific heat ratio selected to match the exit pressure of .17 psia calculated for the isentropic vapor expansion.

Ideal Gas (γ = 1.15)		Isentropic Vapor Expansion
P_e (psia)	.17	.17
T_e (°R)	257	276
V_e (ft/sec)	2120	1990
v_e (ft^3/lbm)	347	288
M_e	3.68	3.02 (gas only)
Quality	——	85 percent Saturated Vapor

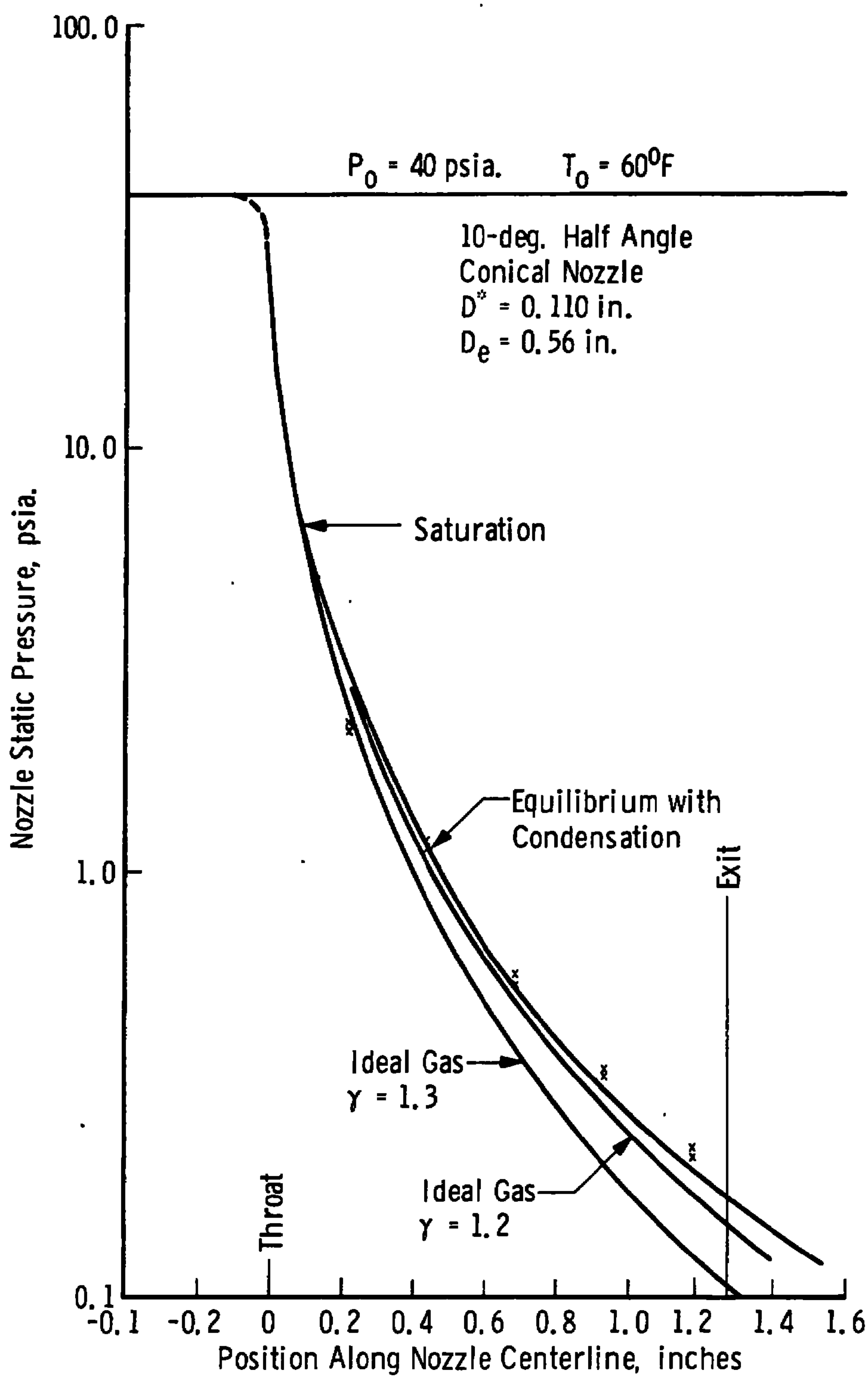


Figure 20. Nozzle static pressure profile.

The isentropic vapor expansion results will be used as the starting point for further examination of the plume. However, the effects of nozzle boundary layer and local supersaturation should be discussed.

IV. NOZZLE IRREVERSIBILITIES

Inherent in the isentropic vapor expansion is the assumption that the flow remained in phase equilibrium throughout the nozzle. While the measured static pressures indicate that this was a reasonable assumption, there are two possible effects of supersaturation. If the flow is supersaturated throughout the nozzle, then measured static pressures would be lower than the corresponding equilibrium pressures since condensation would not be keeping up with the expansion. A more likely occurrence is supersaturation immediately downstream of the nozzle location where the saturation curve is crossed, followed by a condensation shock wave with equilibrium condensation through the remainder of the nozzle. This would explain the relatively low static pressure of 0.23 psia shown in Figure 20 at the first static pressure tap downstream of the throat. Occurrence of a condensation shock would cause higher exit static pressure and temperature, and lower exit velocity than would result from isentropic flow.

A second cause of lower exit velocities than expected is the boundary layer in the nozzle. The displacement thickness associated with the boundary layer would in effect lower the area ratio of the nozzle and would lower the exit velocity even though the core flow were isentropic. Further, the flow contained in the boundary layer would leave the nozzle with velocities ranging from zero at the wall to that of the isentropic core at the inner edge of the boundary layer. This would preclude the well defined plume boundary predicted by the Prandtl-Meyer ideal gas expansion at the nozzle exit. In fact, the subsonic portion of the boundary layer can expand around the nozzle exit and flow back up the outside of the nozzle; though it will become supersonic and approach the free-molecular flow regime immediately after making the turn. The effects of the nozzle boundary layer may be summarized as follows:

1. Lower effective nozzle area ratio with corresponding lower exit velocity and higher static pressure.
2. Lower Mach number through the outer edges of the plume than predicted by isentropic expansion.
3. A diffuse and poorly defined plume boundary with some of the subsonic portion reversing itself and flowing backward along the outside of the nozzle.

4. A spreading of the outer streamtubes of the plume, compared to the calculated results without the boundary layer.

Therefore, the experimentally determined plume should be generally more divergent than a calculated plume based on isentropic nozzle flow since both boundary layer and condensation shock effects lower the exit velocity and Mach number. Second, even if the exit Mach number and specific heat ratio used for the method of characteristics solution of the plume were correct, the outer experimental streamtubes would still be more divergent than the calculated streamtubes due to the boundary layer expansion.

V. COMPARISON BASED ON CONDENSING FLOW NOZZLE EXIT CONDITIONS

In carrying out additional method of characteristics solutions, it was necessary to distinguish between the effect of lower than expected exit Mach number and the effect of additional condensation in the plume. Specifically, a match with experimental plume streamtubes can be made either by holding exit Mach number constant and varying specific heat ratio or by holding specific heat ratio constant and varying exit Mach number. It was decided to try the latter method first since the rapid expansion to very low densities in the plume seemed likely to preclude additional condensation. For that assumption, the specific heat ratio must be nearly 1.4, (Figure 19, page 48), and the solution will represent the gaseous expansion only, with the solid particles remaining close to the centerline. Figures 21, 22, and 23 show method of characteristics solutions for exit Mach numbers of 2.0, 3.0, and 4.0 respectively. It is seen that the streamtubes match well for an exit Mach number of 3.0, however, the experimental streamtubes include the solid CO_2, whereas the theoretical solutions do not.

It should be noted that in the outer regions of the plume, the streamtubes are linear and may be closely approximated by straight lines from a common origin slightly inside the nozzle. Taking advantage of this fact, the experimental streamtubes may be corrected to represent percent of saturated vapor in the flow and the calculated streamtubes at constant γ may be interpolated for intermediate values of Mach number. The procedure used was to correct the experimental streamtubes to represent the gaseous portion of the plume using the exit quality; then, using a plot of angle of divergence versus streamtube percent, determine the gas only experimental streamtubes for 80, 85, 90, and 95 percent streamtubes. For the calculated plume solutions, a graph of divergence or expansion angle versus Mach number for the streamtubes of

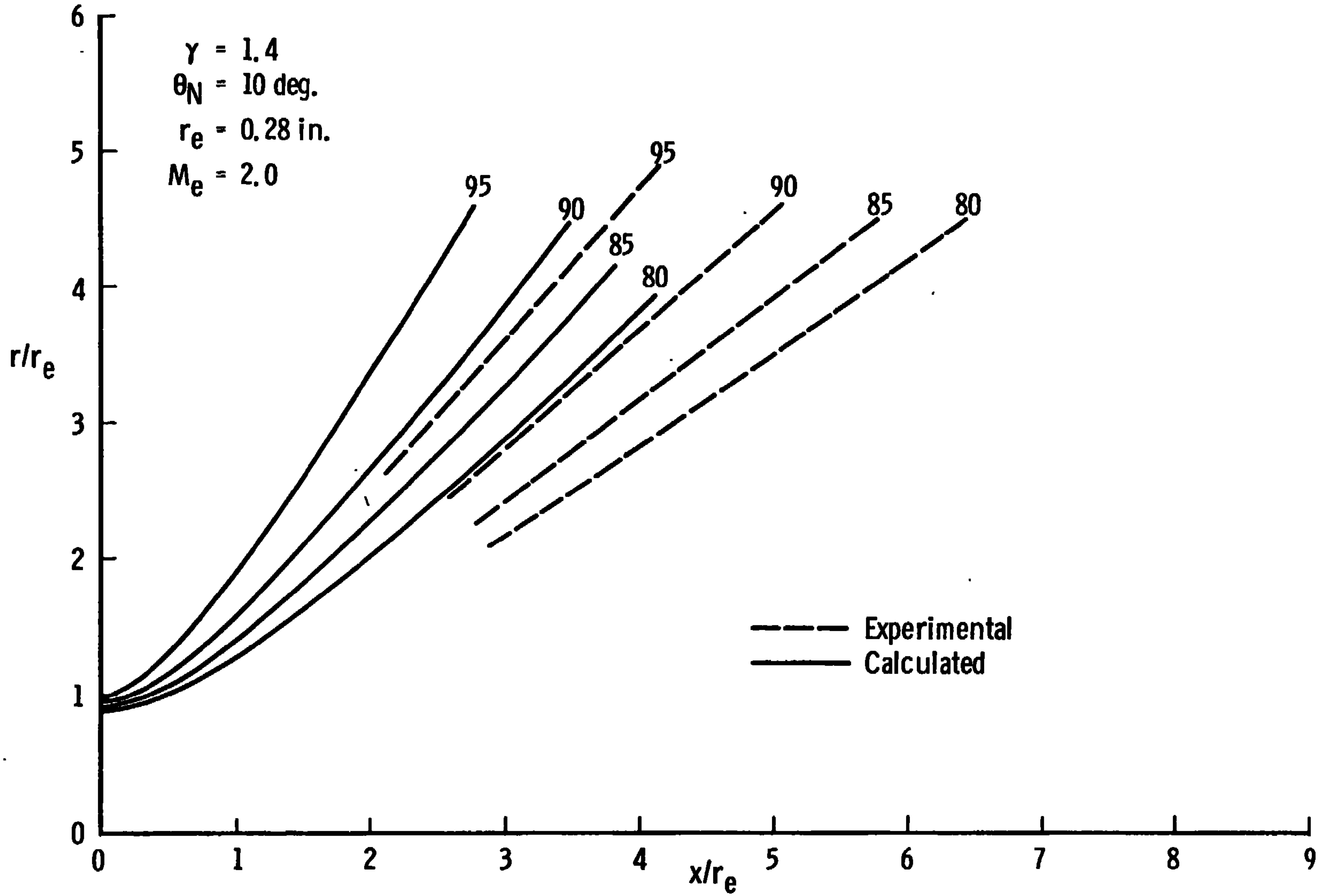


Figure 21. Method of characteristics solution for $M_e = 2.0$.

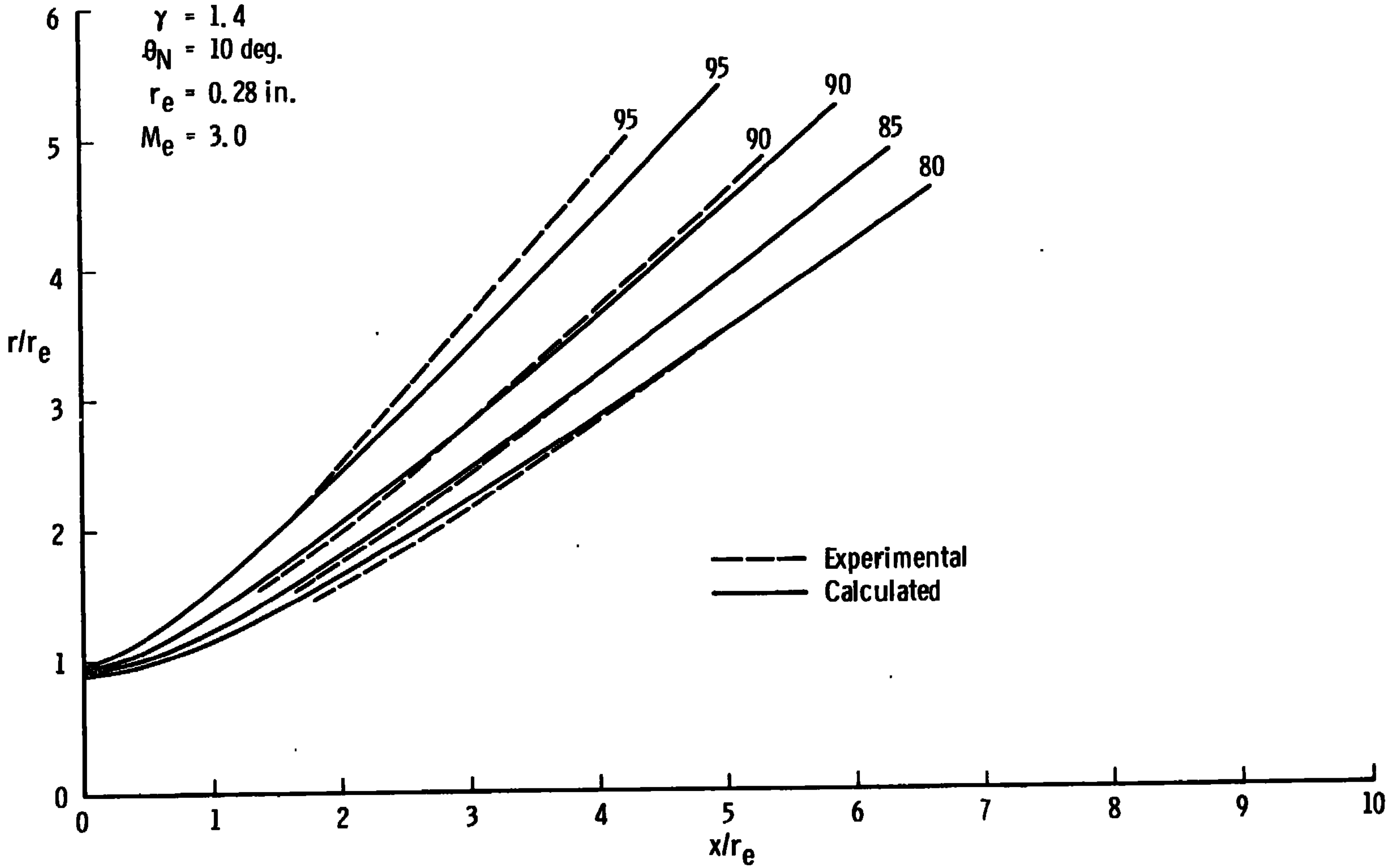


Figure 22. Method of characteristics solution for M_e = 3.0.

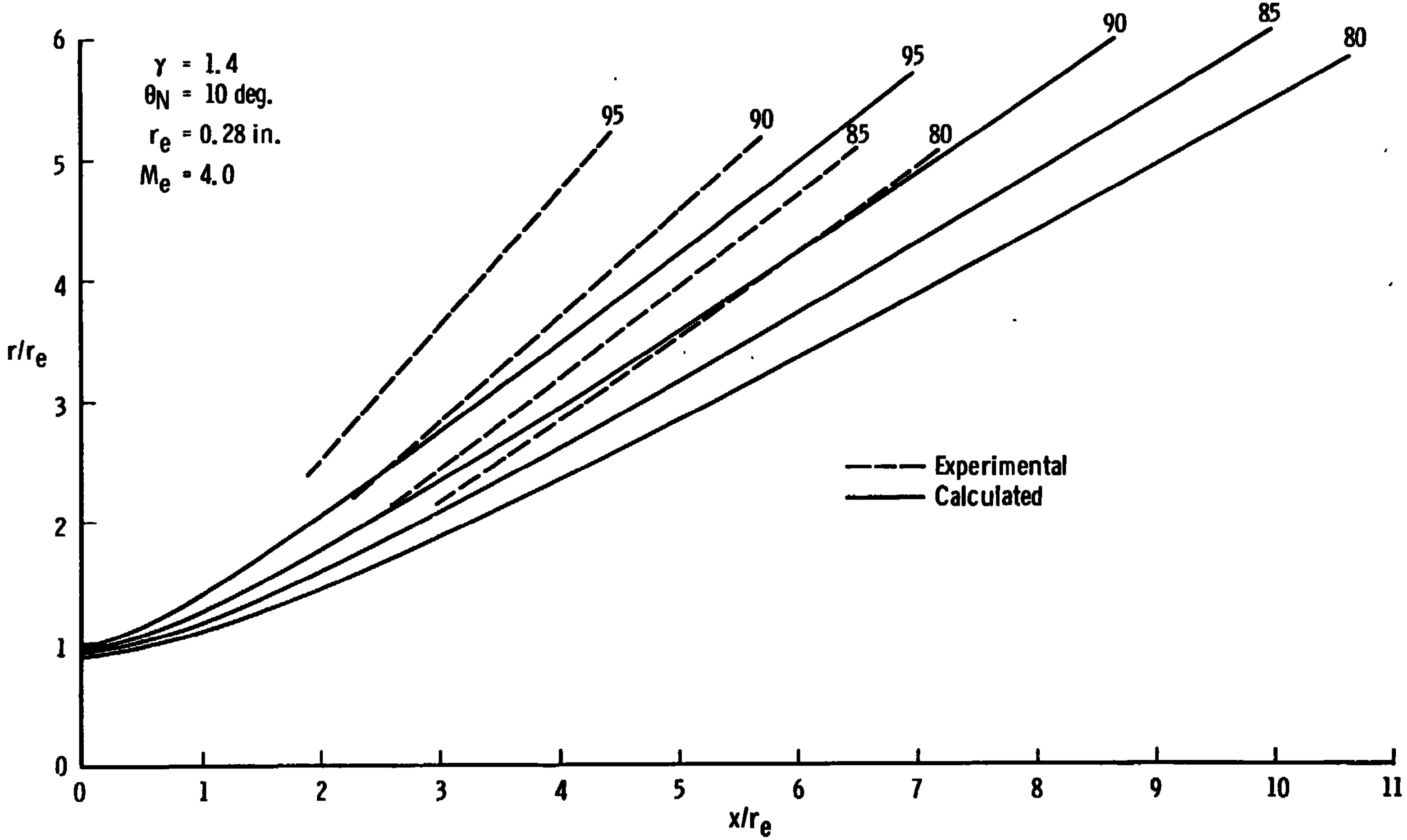


Figure 23. Method of characteristics solution for $M_e = 4.0$.

interest allows the interpolation for intermediate values of Mach number in order to match the corrected experimental streamtubes.

If all solids are along the centerline, the mass flow within any streamtube ($\dot{m}_{str}$) is the fraction of the gas included (f_{gas}) times the mass flow of gas ($\dot{m}_{gas}$) plus the mass flow rate of solid.

$$\dot{m}_{str} = f_{gas}\,\dot{m}_{gas} + \dot{m}_{solid}\ .$$

Define the quality (q) as the percent vapor, and f_{tot} as the percent of total flow in the streamtube.

$$\dot{m}_{str} = qf_{gas}\,\dot{m}_{tot} + (1-q)\dot{m}_{tot}$$

$$f_{tot} = qf_{gas} + 1-q = 1-q(1-f_{gas})$$

Thus, the following total experimental percentages correspond to the gas percentages used in the method of characteristics solutions, and θ_{exp} are the experimental expansion angles from Figure 24:

f_{gas}	f_{tot}	θ_{exp}
.80	.830	35.3
.85	.872	38.3
.90	.915	42.7
.95	.958	49.5

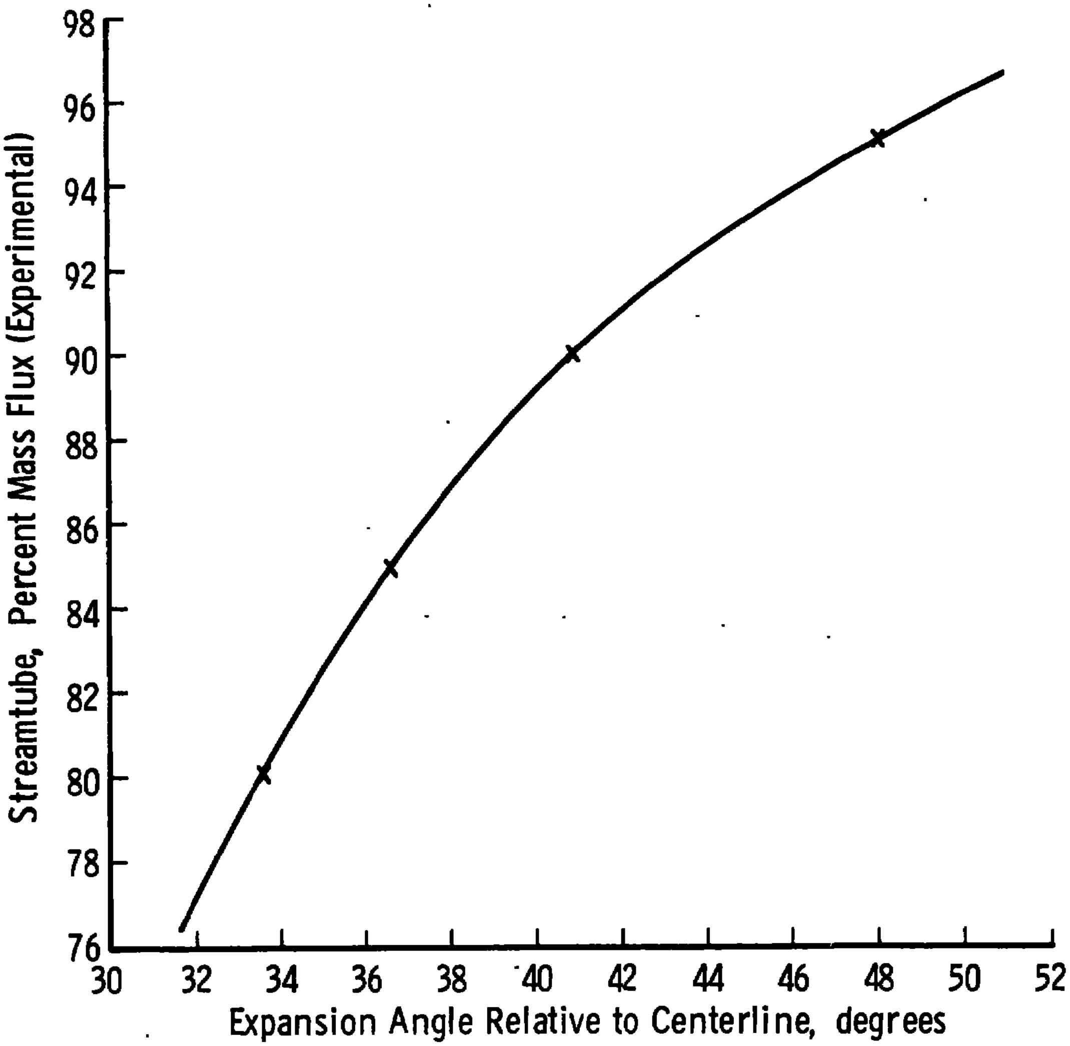


Figure 24. Expansion angle for experimental streamtubes.

Using the experimental expansion angles, Figure 25 allows interpolation for the exit Mach number giving the best match with the experimental data. The value of 2.75 is slightly less than the calculated value of 3.0; but the difference can be reasonably accounted for by nozzle irreversibilities. Based on the preceding analysis, the assumption of no condensation in the plume expansion appears reasonable; and no attempt was made to match the experimental plume using the exit Mach number of 3.0 while varying specific heat ratio.

Figure 26 shows a comparison of experimental streamtubes with calculated streamtubes for an exit Mach number of 2.75. All except the 95 percent streamtube match, with the 95 percent experimental streamtube more divergent. This would be expected as the result of the nozzle boundary layer flow.

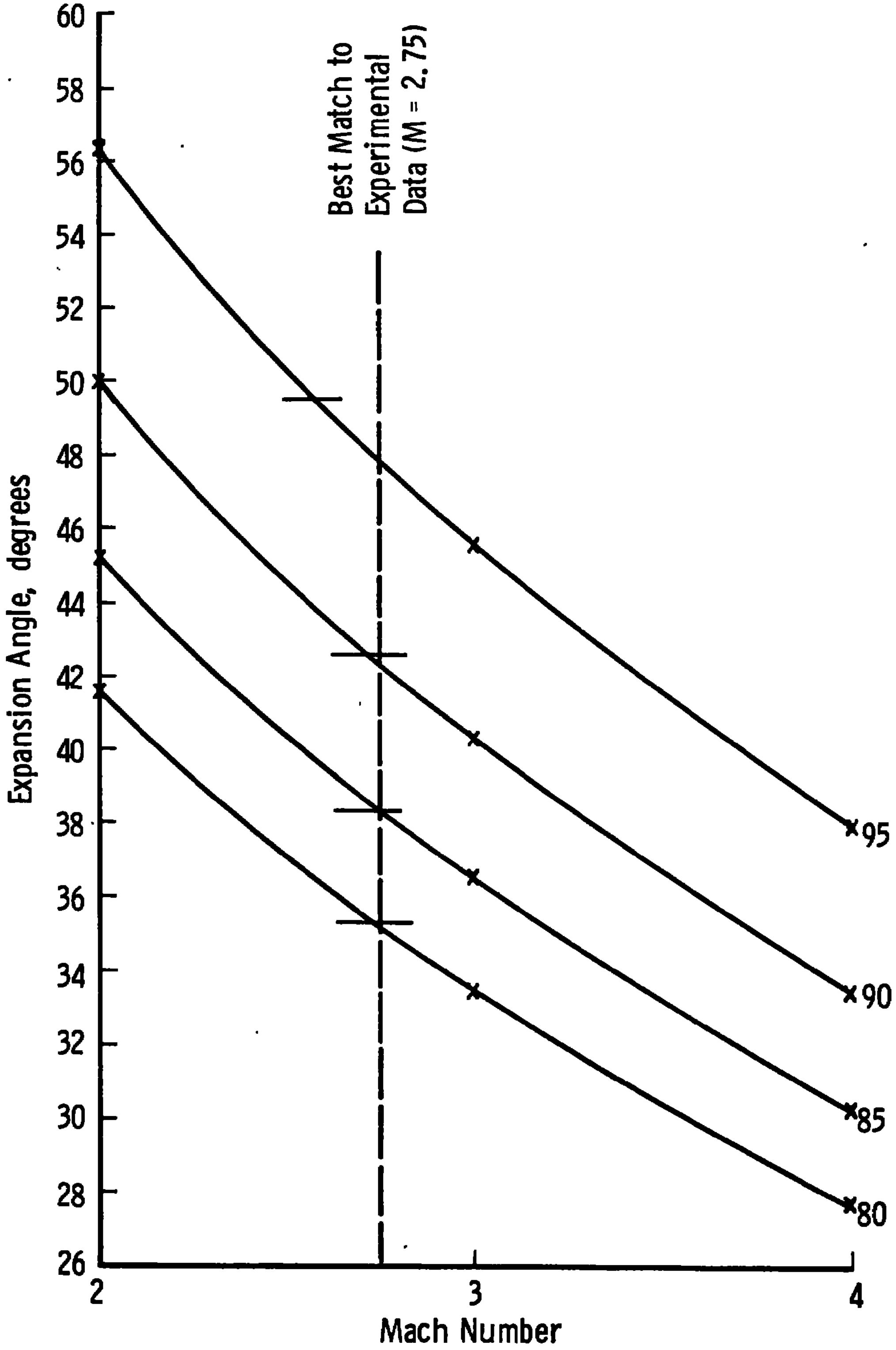


Figure 25. Expansion angle versus Mach number for method of characteristics solutions.

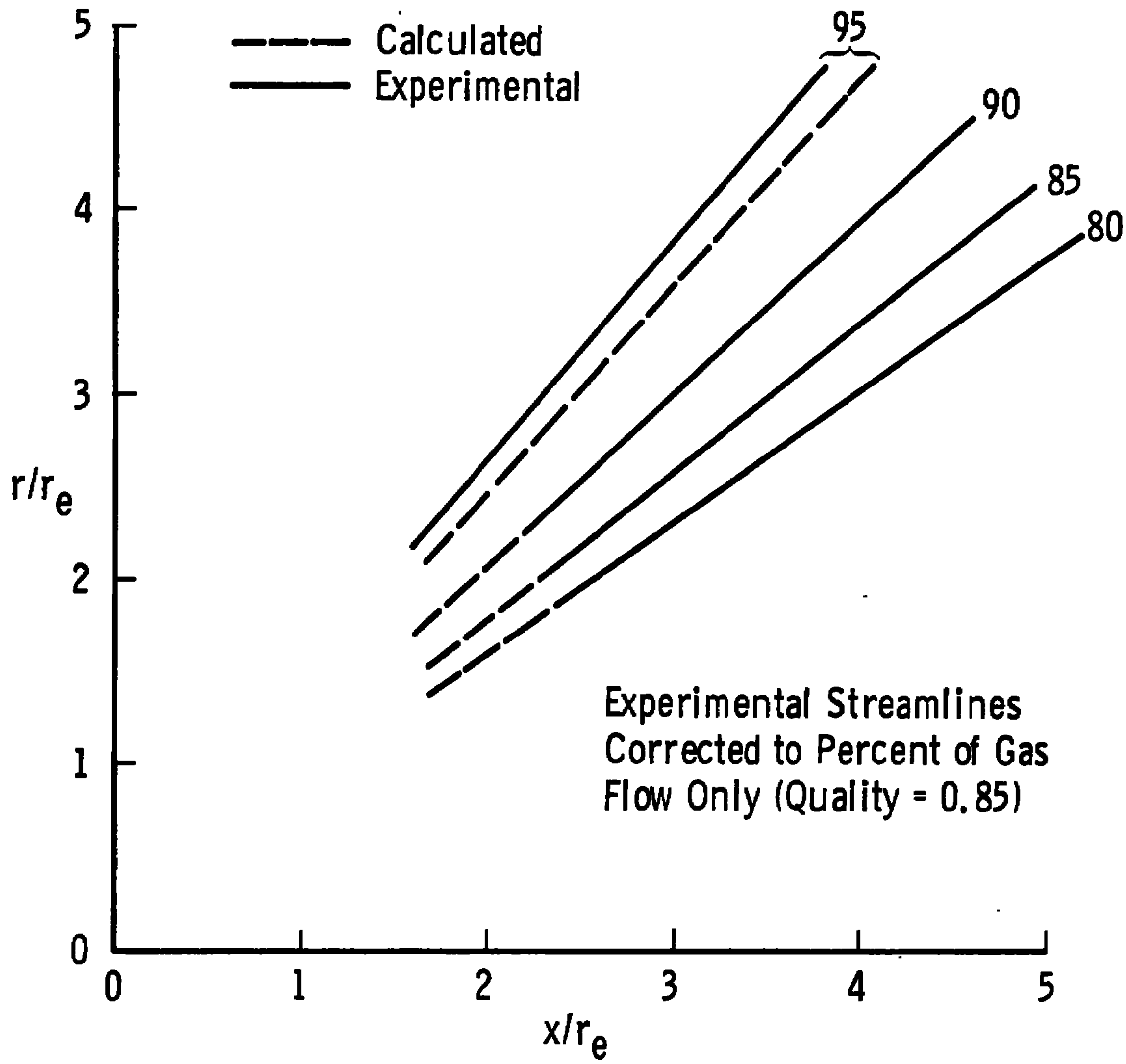


Figure 26. Comparison of experimental versus calculated streamtubes for $M_e = 2.75$.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The use of a diffuser in conjunction with a cryogenically pumped test chamber to experimentally determine the streamtubes in a free jet expansion has been shown to be feasible. The procedure was found to be applicable for up to 98 percent of the plume mass flow, provided conical sharp edged diffuser inlets divergent in the direction of flow were used.

Although the method is believed to be accurate to within less than 2 percent of the mass flow rate in a streamtube, its chief disadvantage is the length of time required for each data point. If an extensive flow expansion research project is undertaken using this method, some faster means of taking data must be found. Suggested improvements in the equipment and procedures are as follows:

1. For the lower percentage streamtubes, measure the diffuser flow by means of an orifice or other flow measurement technique downstream of the diffuser, rather than measuring backflow. With this procedure, most of the data for a particular diffuser could be taken during one pumpdown and cooldown.

2. Retain the test chamber warmup technique for low backflow rates but provide rapid warmup equipment for the cryosystem.
3. The nozzle support should be designed to provide fast and more accurate nozzle-diffuser alignment.
4. The nozzle-diffuser separation distance measurement should be refined to obtain better accuracy.

With the preceding improvements, the method can provide a direct and accurate method of determining streamtubes and is ideally suited for use in condensing flows as well as flows containing other types of solids. In addition, plumes involving mixtures can be examined to determine the extent to which the lighter gas is expanded to the outer edges of the plume leaving the heavier gas in the center.

Locations of the streamtubes can be used to obtain information regarding the degree of condensation in a free jet expansion from a nozzle, the effect of nozzle boundary layer on the plume expansion, and the percent of nozzle flow contained in the nozzle boundary layer. When used in conjunction with other measurement techniques, a clearer analysis of free jet expansion processes should be made possible.

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13. ABSTRACT Experimental investigations of free jet expansions into near vacuum conditions have in the past been generally limited to pressure, temperature, and force measurements. This investigation concerned a method of experimentally defining the streamtubes in a free jet expansion by splitting the flow along streamtubes with a series of diffusers operating in a cryogenically pumped vacuum chamber. Conditions necessary for shock attachment at the diffuser inlet were analyzed and streamtubes in a CO_2 free jet expansion were experimentally determined. The procedure was found to be applicable for up to 98 percent of the plume mass flow if suitable diffuser inlet design is used. The method is ideally suited for streamtube definition in flows with entrained solids, for condensing flows, or for gaseous mixtures. For the free jet expansion investigated, qualitative information was derived concerning the effect of nozzle boundary layer on the plume expansion, the degree of condensation in the plume, and the applicability of method of characteristics solutions to the expansion process.

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