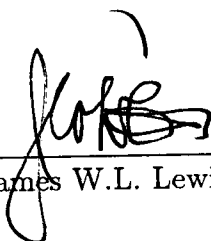
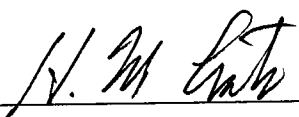


To the Graduate Council:

I am submitting herewith a thesis written by Lisa M. McGee entitled "Case Study of a Flowfield Using a Pentode." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Physics.


James W.L. Lewis, Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council:


Vice Provost
and Dean of The Graduate School

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Master's degree at The University of Tennessee, Knoxville, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of the source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the Head of Interlibrary Services when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature Lisa M. McLee

Date April 26, 1991

CASE STUDY OF A FLOWFIELD
USING A PENTODE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

LISA M. MCGEE

May 1991

To Terry and Jake, my sweetest blessings

ACKNOWLEDGEMENTS

In the course of thesis research, a number of scholars have assisted me generously. In particular, I would like to express my sincere appreciation to Dr. J.W.L. Lewis, whose consultation, criticism, encouragement, and patience have enabled me to achieve results otherwise impossible. Working with Dr. Lewis has inspired a sense of admiration and a desire to continue my studies. I wish to thank him for the excellent teaching I have received as his student, both in course work and in life. Dr. Crater and Dr. Mason, who served on my committee, provided much appreciated suggestions and support. Dr. Parigger aided me greatly in setting up the data acquisition system. I am thankful to Mr. James Hornkohl and Mr. Newt Wright for their expertise in electronics. For the building and maintenance of my experimental system, I owe much gratitude to Mr. Fred Schwartz and Mr. Bruce Hill. The entire staff of the Center for Laser Applications has been most helpful during the completion of this thesis and I am very thankful. Lastly, I have been inspired and supported by my husband and my son throughout this endeavor. I am grateful to them both for their patience and understanding during this work.

ABSTRACT

A pentode vacuum-tube, used as a fast-response pressure-gauge, was found to be well suited for measuring gas pulses into a vacuum chamber through a sonic orifice. Static and dynamic calibration curves with fitted equations are presented for nitrogen and carbon dioxide. Placement of a skimmer between the pentode and nozzle provided the means by which a certain portion of the plume could be observed, but the skimmer also produced the possibility of shock interference. The gauge was used to characterize the flowfield, and the axial and radial results compared well with Ashkenas and Sherman results. A theoretical model of the pressure within the skimmer as a function of time was also developed and compared to the pentode results.

TABLE OF CONTENTS

SECTION	PAGE
I. INTRODUCTION	1
Definition of Fast Response	1
Possible Gauges	2
Previous Pentode Work	4
II. VACUUM CHAMBER	5
Chamber Description	5
Chamber Performance	5
Instrumentation	11
III. FLOWFIELD SOURCE	15
Pulsed Source	15
Theory for Flowfield Parameters	15
Flowfield Prediction for Chamber	28
IV. DESCRIPTION OF PENTODE GAUGE STUDIES	30
Gauge Choice	30
Static Calibration	37
Dynamic Calibration	41
V. RESULTS	46
Dynamic Calibration	46
Axial Data	50
Radial Data	56
Time of Flight	56
VI. ANALYSIS OF RESULTS	60
Comparison with Predictions	60
Analysis of Flowfield	74
VII. CONCLUSION	79
VIII. RECOMMENDATIONS FOR FUTURE WORK	80
LIST OF REFERENCES	81
APPENDIXES	84
APPENDIX A. General Pumping Equations	85
APPENDIX B. Pressure Curve Fit Equations	87
APPENDIX C. Isentropic Expansion Equations	92
VITA	94

LIST OF FIGURES

FIGURE	PAGE
II-1. Vacuum chamber system	6
II-2. Pumpdown time: roughing pump	8
II-3. Pumpdown time: cryopump	8
II-4. Generalized pumping equation [Eqn. (2.1)]	10
II-5. Non-dimensionalized generalized pumping equation	12
II-6. Ionization gauge detector calibration	14
II-7. Thermocouple gauge calibration	14
III-1. Lasertechnics pulsed valve diagram (from Lasertechnics Manual) . . .	16
III-2. Radial flow geometry (from Reference [2])	18
III-3. $\frac{P}{P_o}$: axial variation	20
III-4. $\frac{T}{T_o}$: axial variation	21
III-5. Mach number: axial variation	22
III-6. $\frac{P}{P_o}$: radial variation ($\frac{r}{D} = 2$)	23
III-7. $\frac{P}{P_o}$: radial variation ($\frac{r}{D} = 10$)	23
III-8. Flux: radial variation	24
III-9. Mean free path: axial variation	26
III-10 Knudsen number: axial variation	26
III-11. Translational freezing surface location	27
III-12. Pumping equation with Ashkenas and Sherman value for $\dot{m}_i$	29
IV-1. Electrical schematic for pentode circuit	31
IV-2. Pentode characteristics: E_{g2}	33

IV-3. Pentode characteristics: E_p	33
IV-4. Pentode characteristics: I_{g2}	34
IV-5. Pentode characteristics: $I_{g2}(E_p)$	34
IV-6a. Pentode signal without operational amplifier	35
IV-6b. Pentode signal with operational amplifier	35
IV-7. Electrical schematic of operational amplifier	36
IV-8. Pentode Calibration: N_2 pentode 24 set 1	38
IV-9. Pentode Calibration: N_2 pentode 24 set 2	38
IV-10. Pentode Calibration: N_2 pentode 22 set 1	39
IV-11. Pentode Calibration: N_2 pentode 22 set 2	39
IV-12. Pentode Calibration: CO_2 pentode 23 set 1	40
IV-13. Pentode Calibration: CO_2 pentode 26 set 1	40
IV-14. Plume portion viewed with skimmer	42
IV-15. Illustration of an attached shock	42
IV-16. Diagram of pentode-skimmer apparatus	43
V-1. Raw axial data CO_2 and N_2 ($\frac{x}{D} = 2$)	47
V-2. Raw axial data CO_2 ($\frac{x}{D} = 4$)	48
V-3. Raw axial data CO_2 ($\frac{x}{D} = 6$)	48
V-4. Raw axial data CO_2 ($\frac{x}{D} = 8$)	49
V-5. Raw axial data CO_2 ($\frac{x}{D} = 10$)	49
V-6. CO_2 axial profile: signal ratios	51
V-7. CO_2 axial profile: pressure ratios ($P_o = 10$ psi, $P_o = 20$ psi)	52
V-8. CO_2 axial profile: pressure ratios ($P_o = 30$ psi, $P_o = 40$ psi)	52

V-9. N_2 axial profile: signal ratios	54
V-10. CO_2 radial profile: pressure ratios ($\frac{x}{D}=2$)	55
V-11. CO_2 radial profile: pressure ratios ($\frac{x}{D}=5$)	57
V-12. CO_2 radial profile: pressure ratios ($\frac{x}{D}=10$)	57
V-13. Trigger signal	58
VI-1. Axial profile: comparison of pressure, number density, and flux ratios with CO_2 and N_2 data	62
VI-2. CO_2 pentode pulse compared with theory ($\frac{x}{D}=2$)	65
VI-3. CO_2 pentode pulse compared with theory ($\frac{x}{D}=4$)	66
VI-4. CO_2 pentode pulse compared with theory ($\frac{x}{D}=6$)	66
VI-5. CO_2 pentode pulse compared with theory ($\frac{x}{D}=8$)	67
VI-6. CO_2 pentode pulse compared with theory ($\frac{x}{D}=10$)	67
VI-7. N_2 pentode pulse compared with theory ($\frac{x}{D}=2$)	68
VI-8. CO_2 pentode variation with age ($\frac{x}{D}=3$)	70
VI-9. CO_2 pentode variation with age ($\frac{x}{D}=5$)	71
VI-10. CO_2 axial profile: Ashkenas-Sherman flow through expansion	73
VI-11. CO_2 shock determination	75
VI-12. CO_2 locus of saturation and condensation	77

SECTION I

INTRODUCTION

The need for a fast response, non-optical monitor of pulsed flowfields is the result of the frequency with which such flowfields were and still are encountered. Not only do these flowfields occur in satellite attitude-control-system thrusters, but the space station may utilize pulsed thrusters for attitude control, as well. Pulsed-plasma accelerators and arcjets provide still further additions to the realm of pulsed flowfields. Perhaps, the largest use of such flowfields comes in the area of research facilities and the numerous experiments performed to gain insight into the behavior of the expanding gas in regard to collision processes, chemical reactions, condensation, and relaxation of internal modes. Even a study of the time development of a flowfield, which occurs frequently in aerodynamical research and development, could employ this type of flowfield detector.

Often a non-optical monitor of the flowfield is necessary due to the nature of the experiment. For example, observation of pure gas, such as helium, flowfields requires a non-optical monitor, unless the flow is seeded with a readily fluorescing element. Due to the rapid changes introduced into the flowfield with each pulse, the need for a fast response time is intrinsic. While a fast response, non-optical monitor has a variety of uses, it may also serve as a comparison for optically acquired results.

Definition of Fast Response

The response time of a detector indicates the resolution ability of the detector. To resolve individual pulses produced at a high repetition-rate, the detector must

have a response time that is faster than the pulse rate. In some ways, the effectiveness of a gauge is measured by its response time. The necessary response time depends on the duration and frequency of the flowfield pulse.

A definition of the response time can be obtained through the utilization of the Fourier transform. A plot of the pulsed signal as a function of time can be Fourier transformed into a signal versus frequency graph. Comparison of the time dependence of the observed signal with that of the gauge, then, indicates whether the gauge response time is sufficient. As an example, consider a signal of $100\mu\text{sec}$ pulsewidth. To obtain 100 points across the pulsewidth, requires that the time per point is $1\mu\text{sec}$. The frequency dependence of this signal, obtained through transform, is $\omega_o = 2\pi f_o$, where the subscript o denotes the value corresponding to maximum signal peak. Thus, in order to obtain a resolution of $1\mu\text{sec}/\text{point}$, the necessary frequency is $f_o = 1\text{MHz}$, which implies a response time, for the detector, of $1\mu\text{sec}$. A fast response gauge has f_o values of 100kHz to 1MHz .

Possible Gauges

Considering the many uses and advantages of a fast response, pulsed flowfield monitor, it is not surprising that much work has been done in an attempt to successfully produce a gauge of this type. The groundwork for the present gauge development was laid with the invention of the ionization-gauge detector first proposed by Buckley [3] in 1916. He cited the triode as a gauge with simplistic construction and quick response, as well as, the ability to span a larger range of pressures than was previously possible. Schulz and Phelps [11] examined the triode as a means of extending the range of pressures detectable with linear gauge response. They proposed several, different tube constructions, which varied the electron path length, in order to achieve a collection efficiency of the ion collector

close to one over a broad pressure range. These gauges were used solely in static pressure environments. As a result, no time response was given. However, Inutake and Kuriki [6] presented results from a triode study of quasisteady gas injection, in which a response time of $80\mu\text{sec}$ is estimated, but is not supported by the data presented. There is some ambiguity as to the experimental value of the rise time due to the leading edge of the gas pulse being detected. Pentode studies by Marshall [10], Valsamakis [16] and Small [13] showed the many advantages of the pentode type ion gauge. Marshall used a 6AH6 pentode, with glass envelope removed, to measure $100\mu\text{sec}$ pulses produced by a hydromagnetic plasma gun, which lead to two important discoveries, namely, the filament voltage must be kept higher than rated in order to achieve linear gauge response and the cathode must be hot enough to assure that its emission is space-charge limited. With a CK-5702 pentode tube, with the envelope removed, Valsamakis achieved a response time of $20\mu\text{sec}$, which is faster than any of the other gauge studies encountered in this research.

The tube comparison lead to the use of the pentode gauge described by Valsamakis as the detector for this work. The fast time response required for the pulsed flowfield examined could be achieved with the pentode, but the subminiature size of the CK-5702 also contributed to the tube decision. Subminiature tubes are well-suited for gas profile measurements due to the fact that the pressure is averaged over a smaller volume and the linear response of these tubes extends to higher pressures. Viscous effects caused by probe interference with the flowfield, which cause inaccurate results, as discussed by French [4], can be avoided through the use of the CK-5702, as well.

Previous Pentode Work

The pentode experiments of Valsamakis [16] and his cohorts, Small [13], Small, Lind, Connell, and Valsamakis [14] resulted in a gauge capable of measuring transient gas pressures. The CK-5702 was primarily used as a means of studying the gas profiles produced by a pulsed plasma accelerator, as it was in Marshall's work [10]. Valsamakis presented a detailed description of the preparation of the pentode, the circuit in which to use the CK-5702 and various calibration results. While these results were very useful, the range of pressures (from 1×10^{-3} to about 5×10^{-1} torr) explored with the pentode were not as extensive as herein proved allowable (from 1×10^{-6} to 5 torr). The pulses presented by Valsamakis were obtained at large distances from the orifice (greater than about 50 cm), and therefore were not well defined. The placement of the pentode in a skimmer provides: 1) a means of looking at the plume at closer proximity, by lowering the pressures measured by the pentode and 2) spatial isolation of a plume region. With the addition of an operational amplifier, well-defined pulses in a flowfield region of great interest, seldom observed by gauges, can be observed. The fast response and small size of the subminiature CK-5702 pentode met the necessary requirements for a gauge at this location.

SECTION II

VACUUM CHAMBER

Chamber Description

A vacuum chamber provided the low background pressure necessary for the experiments. The chamber was stainless steel with aluminum flanges and cylindrical in shape with an inner diameter of 19.25 inches and a height of 27.6 inches. It had three windows of ultraviolet fused silica, .25 inches thick, 2 inches in diameter at 90 degrees from each other.

The pumping system consisted of two phases. As illustrated in Figure II-1 the chamber was initially pumped down from atmosphere to about 1×10^{-3} torr with an Edwards Fore Pump (Model E2M5), which is a rotary vane, oil-sealed mechanical pump with a pumping speed of about 1.7 liters/second. The pump removes gases by compressing them to a point slightly over atmospheric pressure then expels these gases to the outside world.

The cryopump did the second phase of pumping. A Balzer cryopump (model RCP401Z) with a cryopump controller (model CRC401) brought the chamber from 1×10^{-3} torr to a theoretical limit of 1×10^{-11} torr, with a quoted speed of about 6500 liters/second for nitrogen. The basic principle of this pump is to freeze the gases, which are then captured in the pump. Cryopumps are extremely clean as they have no oils or moving parts in the vacuum and have a very high throughput.

Chamber Performance

Some preliminary experiments revealed the actual chamber system performance in the areas of pressure and pumping capabilities. Observation of

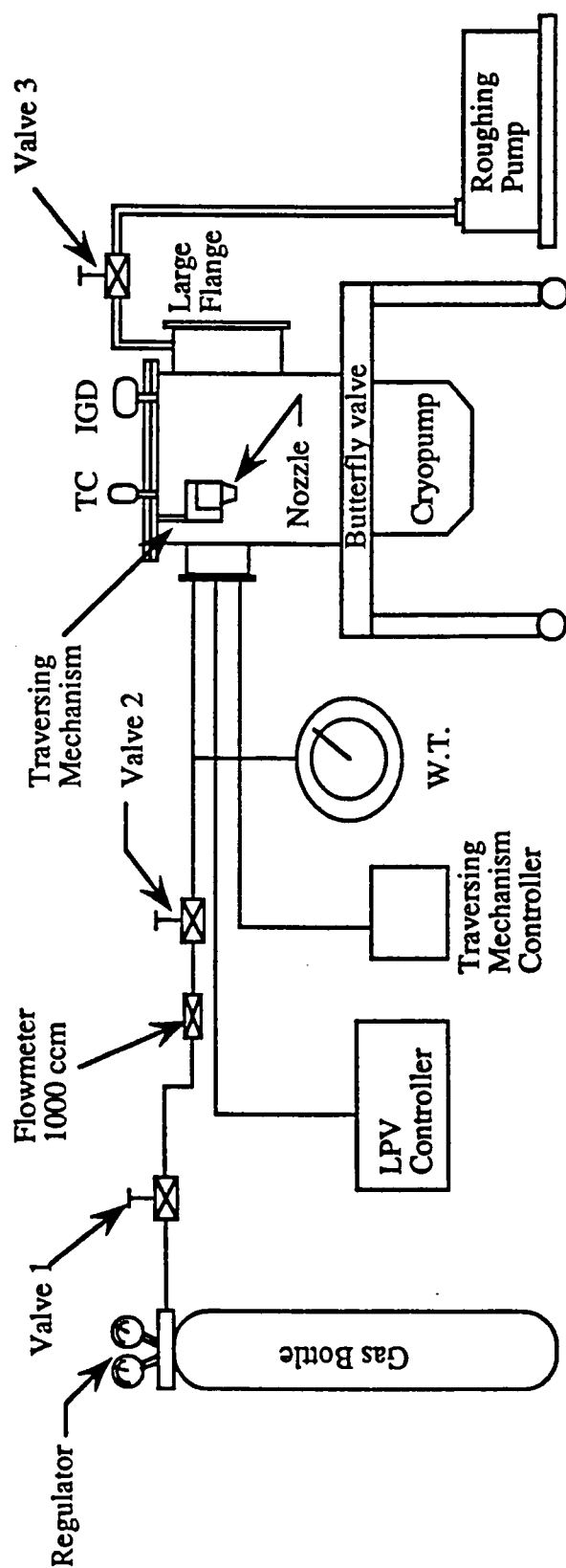


Figure II-1. Vacuum chamber system.

the pressure performance of the chamber system lead to the pumpdown time for the chamber shown in Figures II-2 and II-3. As shown in Figure II-2, the chamber was pumped from a pressure of 760 torr to 5×10^{-1} torr in about 20 minutes using the roughing pump. At that point it was possible to start the cryopump. The use of the cryopump provided a very rapid pressure decrease which slowly tapered off to 1×10^{-6} torr within about one hour. Allowing for gas clean-up in the chamber, a minimum pressure of 1×10^{-7} torr was achieved after about 12 hours. The speed at which the chamber came back up to atmosphere once the pump is stopped, that is, the leak rate, was about 0.26 liters/second. Although such a leak rate was not desirable, it was not damaging as the chamber was continually pumped during the experiments.

As stated previously, the roughing pump was quoted to have a pumping speed of about 1.65 liters/second. From the data of Figure II-2, the pumping speed can be calculated as 1.62 liters/second, which closely agrees with the quoted speed. The cryopump speed is dependent on the type of gas being pumped. The data of Figure II-3 gives a speed of 6350 liters/second for nitrogen (N_2), whereas the quoted speed is 6500 liters/second. For carbon dioxide (CO_2), the measured pumping speed was 5350 liters/second. For effusive flows, which are going into the cryopump, the pumping speed goes as the inverse square root of the molecular weight of the gas. Thus, although the Balzer manual does not quote a speed for CO_2 , the pumping speed can be compared to 5500 liters/second for Argon ($M_{Ar} = 40$), which is approximately the same molecular weight as CO_2 ($M_{CO_2} = 44$).

In order to better understand the experimental results, a model of the chamber pressure performance with time was created. The above results allowed a more accurate modelling of the pumping system. The general pumping equation is given

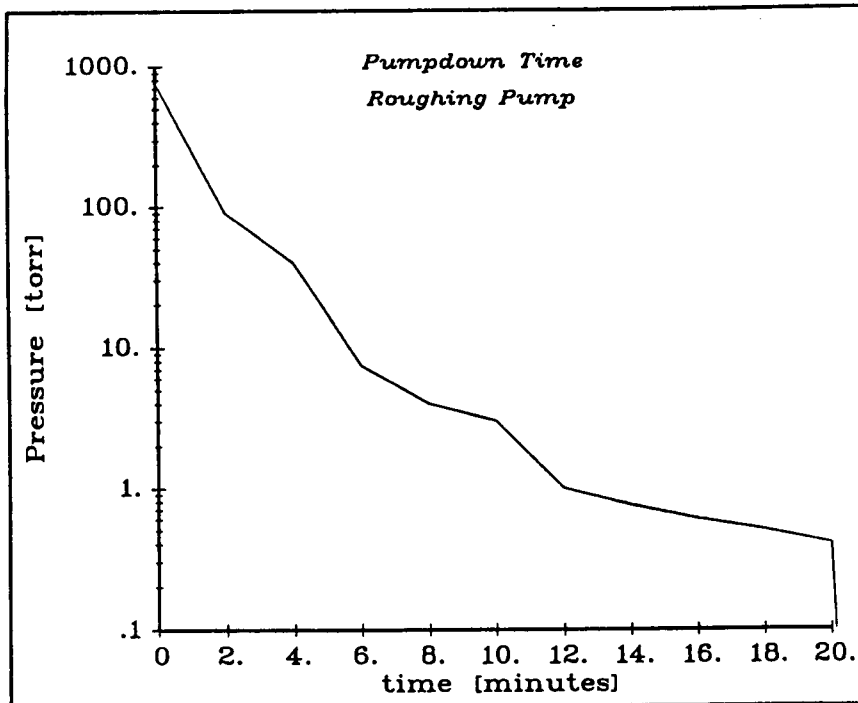


Figure II-2. Pumpdown time: roughing pump.

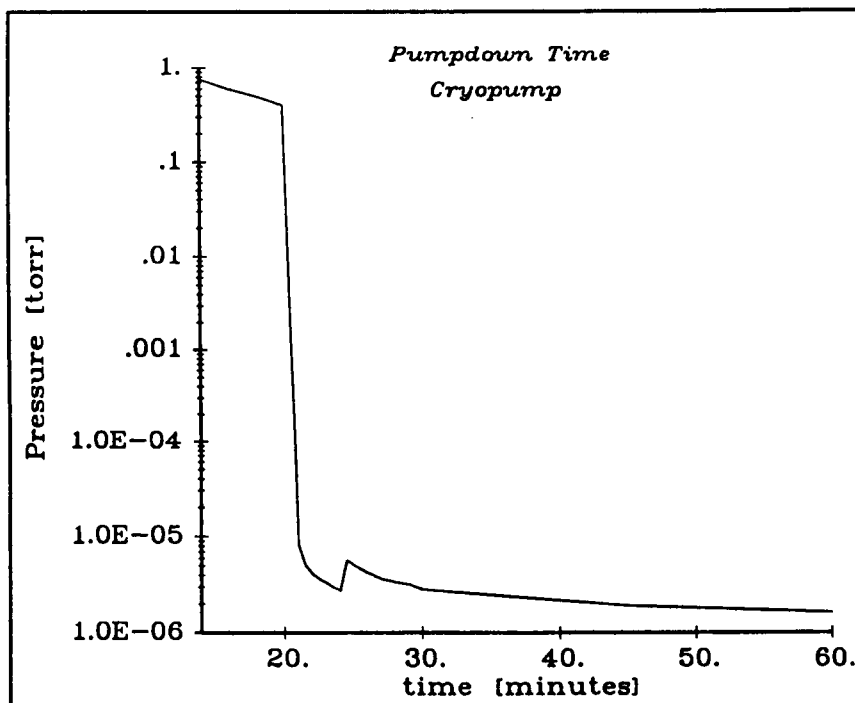


Figure II-3. Pumpdown time: cryopump.

by:

$$\frac{dP}{dt} = \frac{\dot{m}_i RT}{MV_c} + \frac{a_c A_c}{V_c} - \frac{SP}{V_c}, \quad (2.1)$$

where $\dot{m}_i$ =mass inflow, M =molecular mass, V_c =chamber volume, a_c =outgassing coefficient, and S =pumping speed. Defining the characteristic times as:

$$\text{pumping time} \equiv \tau_p = \frac{V_c}{S},$$

$$\text{fill time} \equiv \tau_i = \frac{MV_c}{\dot{m}_i RT},$$

$$\text{outgassing time} \equiv \tau_o = \frac{V_c}{a_c A_c},$$

results in the following equation:

$$\frac{dP}{dt} = \frac{1}{\tau_i} + \frac{1}{\tau_o} - \frac{P}{\tau_p}. \quad (2.2)$$

Some basic mathematics (see Appendix A) leads to the following solution:

$$P(t) = P(0)e^{-Bt} + \frac{A}{B}(1 - e^{-Bt}), \quad (2.3)$$

where $A = \frac{1}{\tau_i} + \frac{1}{\tau_o}$, and $B = \frac{1}{\tau_p}$. The properties of this solution are better shown graphically. By varying the input, $\dot{m}_i$, a corresponding set of results is obtained. For our purposes, the $\dot{m}_i$ is a function of the nozzle input values, such as, the repetition rate and the pulse width. As shown in Figure II-4, varying the repetition rate, Q , produces a peak pressure variance, as well as, new time dependence. This should be kept in mind when the experimental data are presented.

The general pumping equation can be further generalized by non-dimensionalizing it with respect to both pressure and time. (See Appendix A for further details.) Dividing the equation by the characteristic pumping time, τ_p , associated with the cryopump, provides the non-dimensionalized time. The next consideration is how to non-dimensionalize the pressure. The most general and

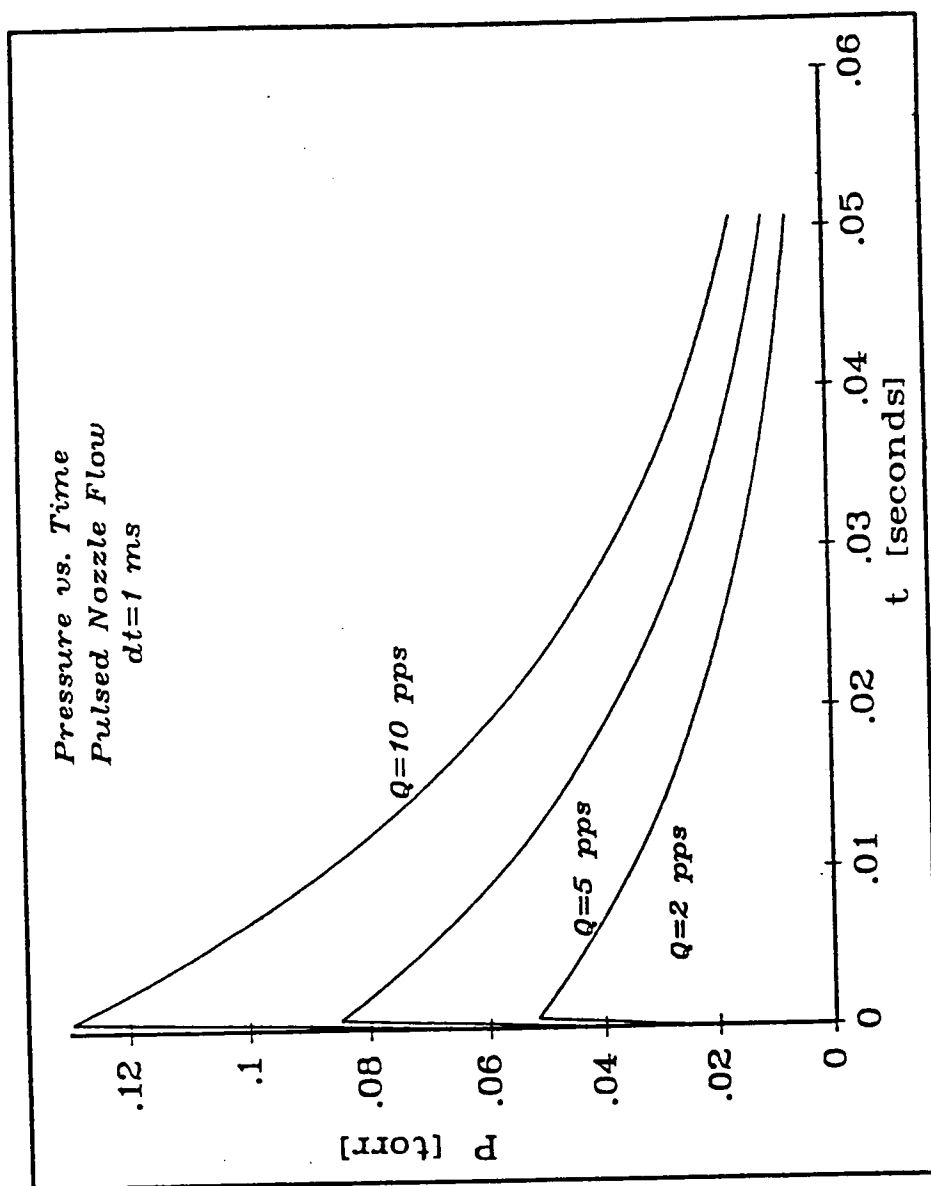


Figure II-4. Generalized pumping equation [Eqn. (2.1)].

benign value would, perhaps, be $P = 1$ atmosphere. A non-dimensional pumping equation proves to be most advantageous as it only requires one to multiply by a new τ_p in order to obtain results for a different pumping system, and multiplication by $P = 1 \text{ atm}$ allows conversion to any pressure units desired (see Figure II-5).

Instrumentation

An ionization gauge detector (IGD) and a thermocouple gauge (TC) provided pressure measurements within the chamber, while a manifold regulator and a Wallace-Tiernian (WT) gauge read the pressure of gases entering the chamber. As shown in Figure II-1, page 6, the IGD and TC were both located at the top of the chamber, in order to avoid interference with the nozzle flowfield. The regulator read the pressure of the bottled gas being let into the chamber. The WT was located just outside of the nozzle. The placement and purposes of each of these gauges will be discussed below.

The IGD and TC provided pressure measurements within the chamber but in different ranges. The IGD, which gave pressures between 1×10^{-3} and 1×10^{-10} torr, was a Granville-Phillips Bayard-Alpert type ionization gauge glass envelope tube (Model 274 003). The gauge was nitrogen calibrated and therefore required adjustment when using other gases. The gauge tube sensitivity is given by:

$$K = \frac{i_+}{i_- P}, \quad (2.4)$$

where i_+ is the positive ion current at the collector, i_- is the electron emission current from filament to grid, and P is the pressure. In this case, $K = \frac{10}{\text{torr}}$ for nitrogen. The IGD pressure was read from a needle gauge with an accuracy of $\pm 2 \times 10^n$, where n goes from 3 to 10. The TC supplied pressure measurements in the range from 760 torr to 1×10^{-3} torr. The thermocouple gauge was a Granville-Phillips (Series 260) and nitrogen calibrated. The readout was given by a Fluke

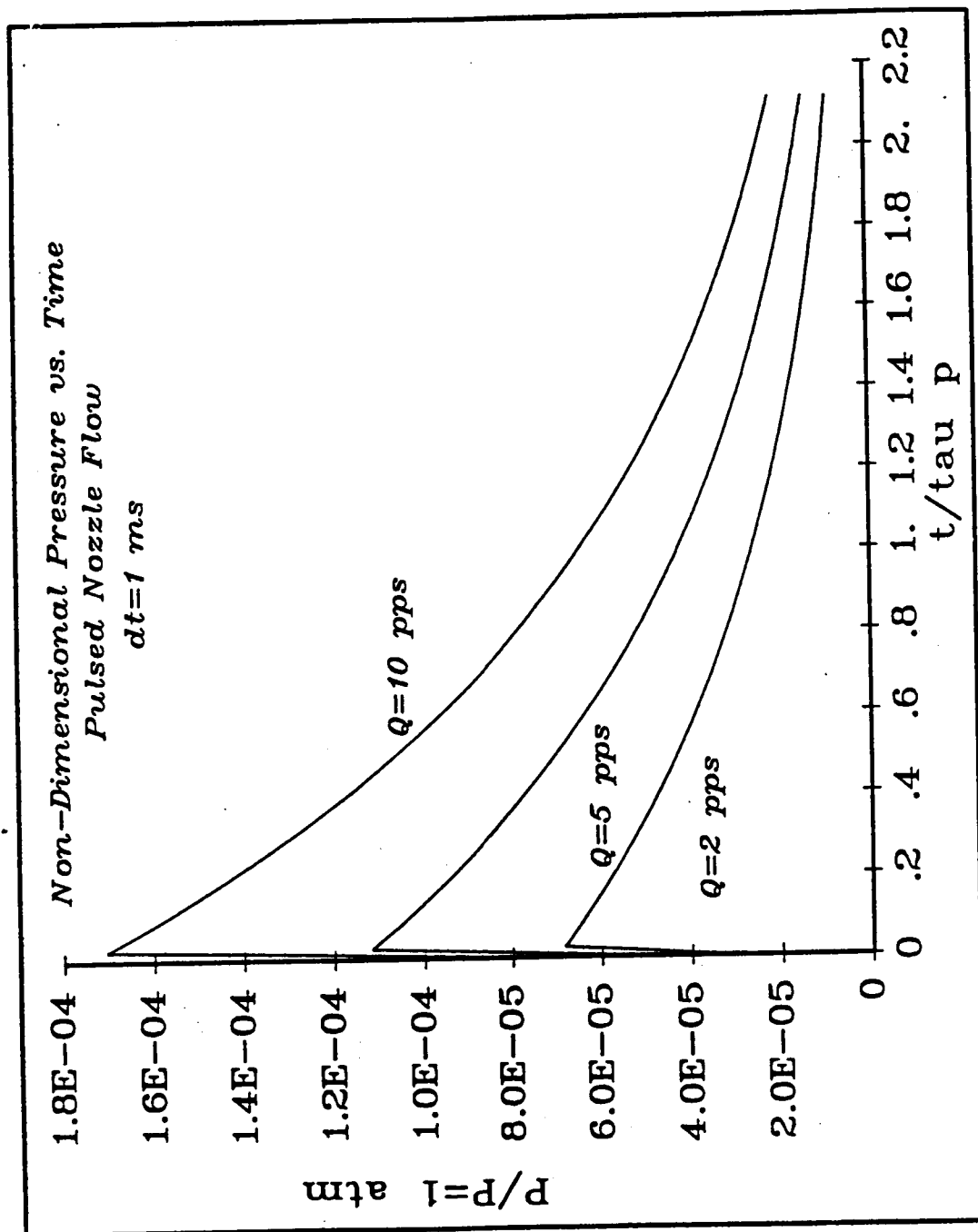


Figure II-5. Non-dimensionalized generalized pumping equation.

800A digital voltmeter, with an uncertainty of ± 0.01 on the 20 volt scale and ± 0.001 on the 2 volt scale. The voltage reading was then converted to a pressure using a curve given by the manufacturer. By fitting an equation to the curve, a simple volts-to-torr conversion was obtained (see Appendix B).

These gauges were calibrated simultaneously using a Varian controller with a digital readout. The IGD was calibrated against a similar type gauge (Bayard Alpert IGD 563) that was factory calibrated against McLeod gauge standards. The TC was calibrated against a Varian gauge (model 0531) of a similar type. The calibration procedure consisted of a systematic gas inbleed and periodic pressure readings from each of the gauges, that is, either the IGD or TC and the calibration gauge, depending on the pressure range being observed. The results of this procedure provided a means of determining true pressure values. Figures II-6 and II-7 show the IGD data and TC data for CO_2 versus calibration gauge data, respectively. A least-squares curve fit was performed for the data of each of these graphs, and the resulting equations are given in Appendix B. These equations were then used to obtain the actual pressure values from the IGD and TC data which were obtained in later experiments. The uncertainty of the resulting pressure was about 2%.

The incoming pressure was obtained using two gauges: (a) the manifold regulator and (b) a Wallace-Tiernian (WT) gauge. Due to the excessive distance between the regulator and the nozzle (about 14 feet), a WT was placed approximately four feet upstream of the nozzle, in order to provide a more accurate pressure reading (± 0.25 psi). The WT was calibrated against a factory calibrated Wallace-Tiernian gauge and was found to be accurate to within ± 0.33 psi. The WT was then used to calibrate the Matheson regulator, which proved to be accurate to ± 3 psi.

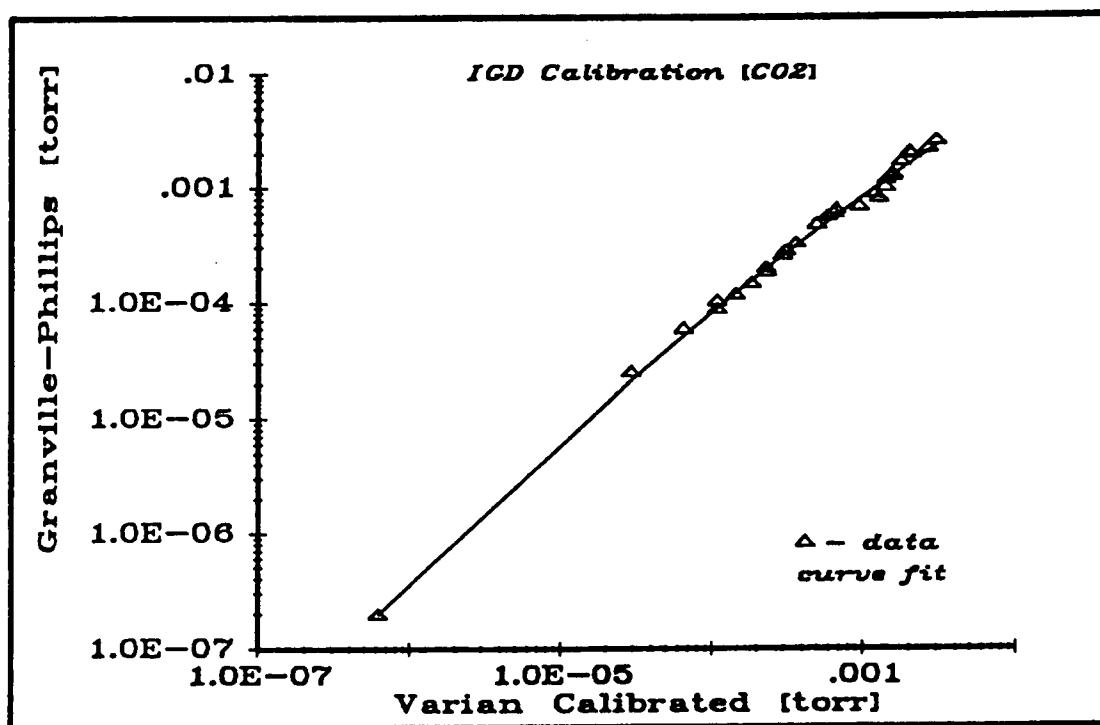


Figure II-6. Ionization gauge detector calibration.

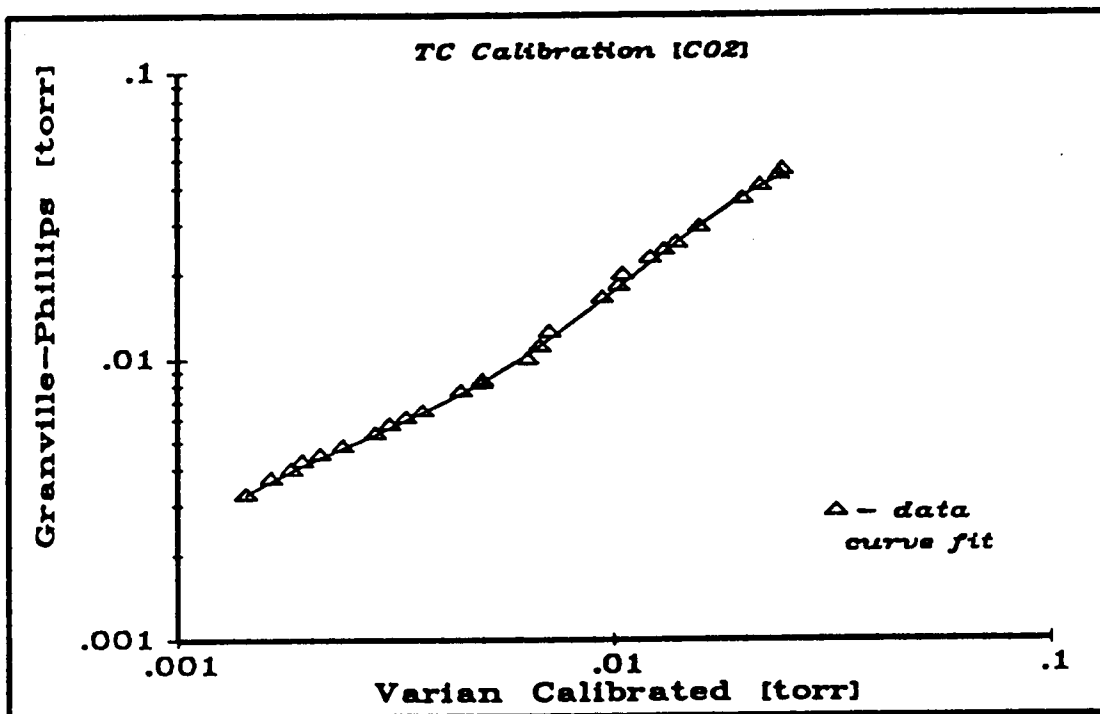


Figure II-7. Thermocouple gauge calibration.

SECTION III

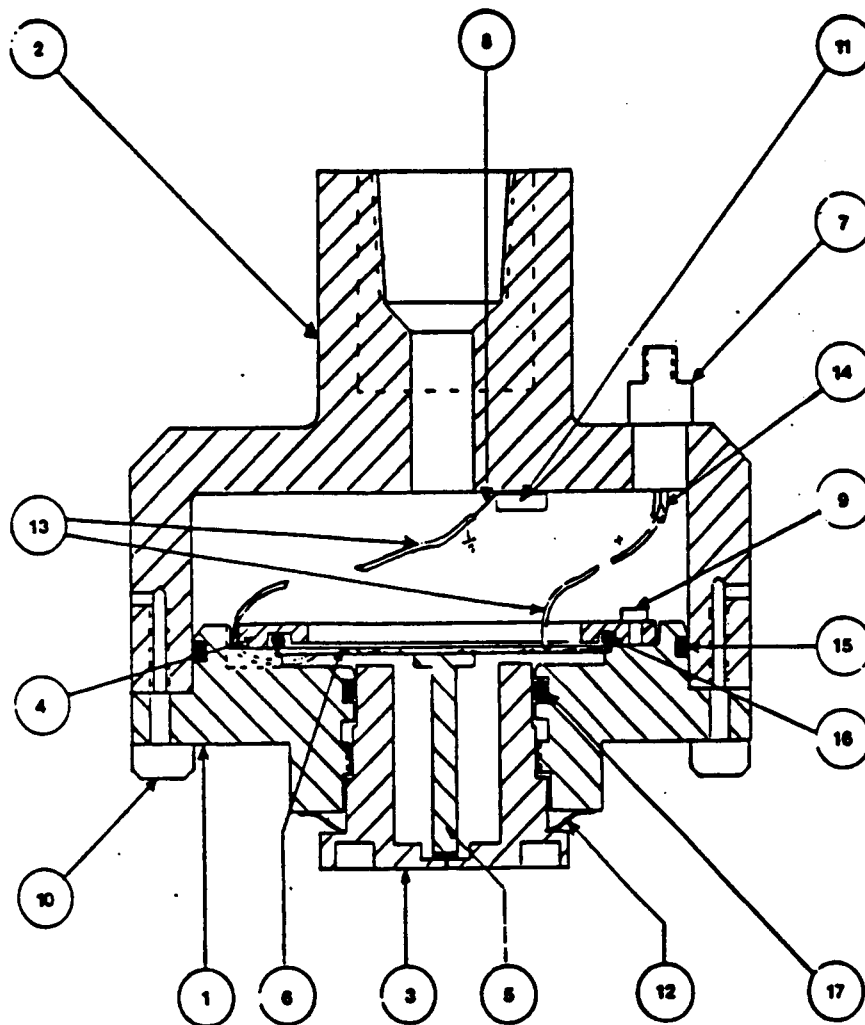
FLOWFIELD SOURCE

Pulsed Source

The flowfield was produced with a pulsed, 0.5 mm diameter nozzle. The Lasertechnics Model LPV pulsed valve, constructed of stainless steel, teflon and nickel, was controlled by a Lasertechnics Model 203 valve driver. The active element in the valve is a nickel-plated, piezoelectric, monomorph disc (see Figure III-1). The poppet, which is attached to the monomorph, is lifted when the monomorph receives a voltage pulse from the driver. The faceplate holds the monomorph actuator and allows for interchangeable nozzles. The nozzle contains an orifice sized as desired, which was, in this case, 0.5 mm diameter. The nozzle exit surface is also available in three shapes: (a) flat, (b) conical or (c) beveled designs. The flat surface, which is used in this experiment, allows for a fully developed gas expansion with a minimum amount of cluster formation. The LPV is voltage activated and can be operated in a pulsed or a continuous mode, with a maximum backing pressure of 10 atmospheres. The maximum repetition rate exceeds 500 pulses per second, and pulse widths range from 150 microseconds to continuous.

Theory for Flowfield Parameters

A substantial stride was made in describing the flowfield produced by a sonic orifice expanding into a low pressure chamber in 1966 with the work of Ashkenas and Sherman [2], who summarized the theory of free jet behavior. By considering the core region, or the "inertia-dominated" region of the free jet expansion, and



<u>ITEM</u>	<u>DESCRIPTION</u>	<u>ITEM</u>	<u>DESCRIPTION</u>
1	faceplate	10	faceplate screws
2	valve body	11	ground terminal screw
3	nozzle (flat)	12	curved spring washer
4	O-ring carrier	13	Teflon coated wire
5	poppet	14	Teflon shrink tubing
6	monomorph	15	faceplate O-ring, -032
7	feedthrough	16	monomorph O-ring, -026
8	ground terminal	17	nozzle O-ring, -017
9	O-ring carrier screws		

Figure III-1. Lasertechnics pulsed valve diagram [from Lasertechnics Manual].

using the available method-of-characteristics solutions, they discovered that in this region, the flow seemed to exhibit a "simple and self-similar development." In the inertia-dominated region, quoting Ashkenas and Sherman, "the streamlines appear to radiate from a source at a distance x_o downstream of the orifice. The variation of density from streamline to streamline (i.e., with polar angle θ , at constant distance, R , from the "source") is approximately independent of R ." One result of their experiments is a set of equations that characterizes the flowfield produced by nozzle flow into a vacuum. Table III-1 shows the experimental constants presented by Ashkenas and Sherman. Using these constants in the following equation gives the Mach number as a function of the ratio of the axial distance from the source and the orifice diameter, $\frac{x}{D}$, for three different specific heat ratios (γ)

$$M = A \left(\frac{x - x_o}{D} \right)^{\gamma-1} - \frac{1}{2} \frac{\gamma - 1}{\gamma + 1} / A \left(\frac{x - x_o}{D} \right)^{(\gamma-1)} + C \left(\frac{x - x_o}{D} \right)^{-3(\gamma-1)}, \quad (3.1)$$

where $\frac{x_o}{D}$ is the experimentally determined, effective source distance. These results fit the method-of-characteristics computations to 1%, as stated by French.

Ashkenas and Sherman provide a set of equations to characterize the radial variation of the mass density (ρ) with radial distance from the nozzle, as well. To calculate the radial variation of ρ , the constants shown in Table III-1 may be used in the following equation:

$$\frac{\rho(r, x)}{\rho(0, x)} = \cos^2 \theta \cos^2 \left(\frac{\pi \theta}{2\phi} \right), \quad (3.2)$$

where r , x , and θ are shown in Figure III-2. These results fit the method-of-

characteristics solutions to 4%, as related by French. The Mach disk location was determined by Ashkenas and Sherman to be given by:

$$\frac{x_m}{D} = 0.67 \left(\frac{P_o}{P_1} \right)^{\frac{1}{2}}, \quad (3.3)$$

where P_1 is the background or chamber pressure and P_o is the reservoir pressure.

Table III-1
Ashkenas-Sherman Constants

γ	$\frac{x_o}{D}$	A	C	$\frac{x^a}{D}_{min_{2T}}$	$\frac{x^a}{D}_{min_{3T}}$	ϕ
1.67	0.075	3.26	0.31	2.5	1.0	1.365
1.40	0.40	3.65	0.20	6.0	1.0	1.662
1.2857	0.85	3.96	b	4.0	b	1.888

x^a For values of $\frac{x}{D} > \frac{x}{D}_{min}$, the two-term fitting formulas give accuracy within the random scatter of the computer data.

x^b No third term of form $C \left(\frac{x-x_o}{D} \right)^{-3(\gamma-1)}$ seems to fit.

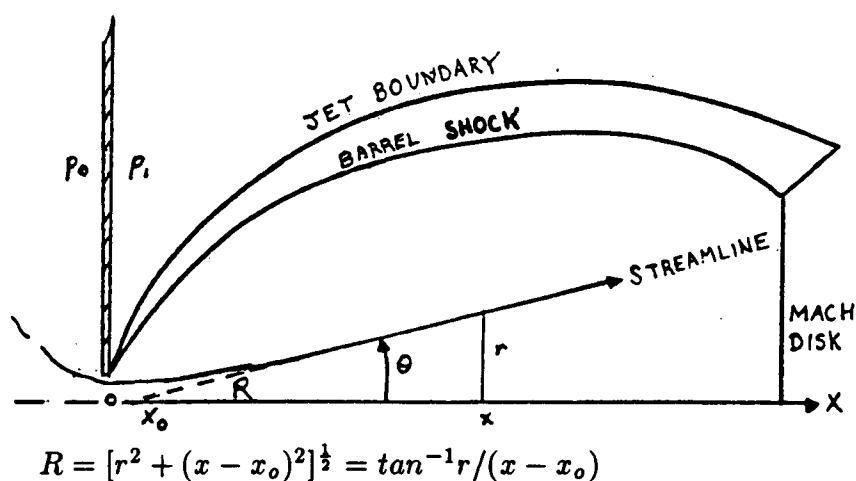


Figure III-2. Radial Flow Geometry (from Reference [2]).

Using the isentropic expansion equations in conjunction with the Ashkenas and Sherman results, the other features of the flowfield can be deduced. For example, the temperature profile is given by

$$\frac{T_o}{T} = 1 + \frac{\gamma - 1}{2} M^2, \quad (3.4)$$

where T_o is the reservoir temperature. The rest of the relevant equations are given in Appendix C. The resulting axial variation of ratioed pressure, $\frac{P}{P_o}$, temperature, $\frac{T}{T_o}$ and Mach number are shown in Figures III-3 through III-5. The radial variations of the pressure and flux, which are pertinent to these experiments, are presented in Figures III-6 through III-8.

The prediction and location of the continuum flow Mach disk is very useful when setting up a free jet expansion experiment. The presence of a Mach disk, which is a normal shock, can present problems which can be avoided by taking such simple measures as decreasing the chamber pressure slightly or changing the incoming pressure. By plotting the Mach disk location as a function of the source pressure, P_o , the region for Mach disk formation can be located. At this point, it is useful to note that the region of interest for this experiment, $7.6 \times 10^8 \leq \frac{P_o}{P_1} \leq 2.8 \times 10^9$, allowed for no Mach disk to present itself.

The classification of the four flow regimes is based on the Knudsen number, $Kn = \frac{\lambda}{L}$, where λ is the mean free path and L is some characteristic length. In this case, the nozzle diameter will serve as an appropriate characteristic length. The free molecule flow regime is characterized by $Kn \geq 3$. Transitional flow shows Knudsen numbers of $0.1 \leq Kn \leq 3$, whereas slip flow has $0.01 \leq Kn \leq 0.1$. Lastly, continuum flow is classified to have $Kn \leq 0.01$. Occasionally, continuum and slip flow regimes are considered to be part of the continuum flow regime. Using the

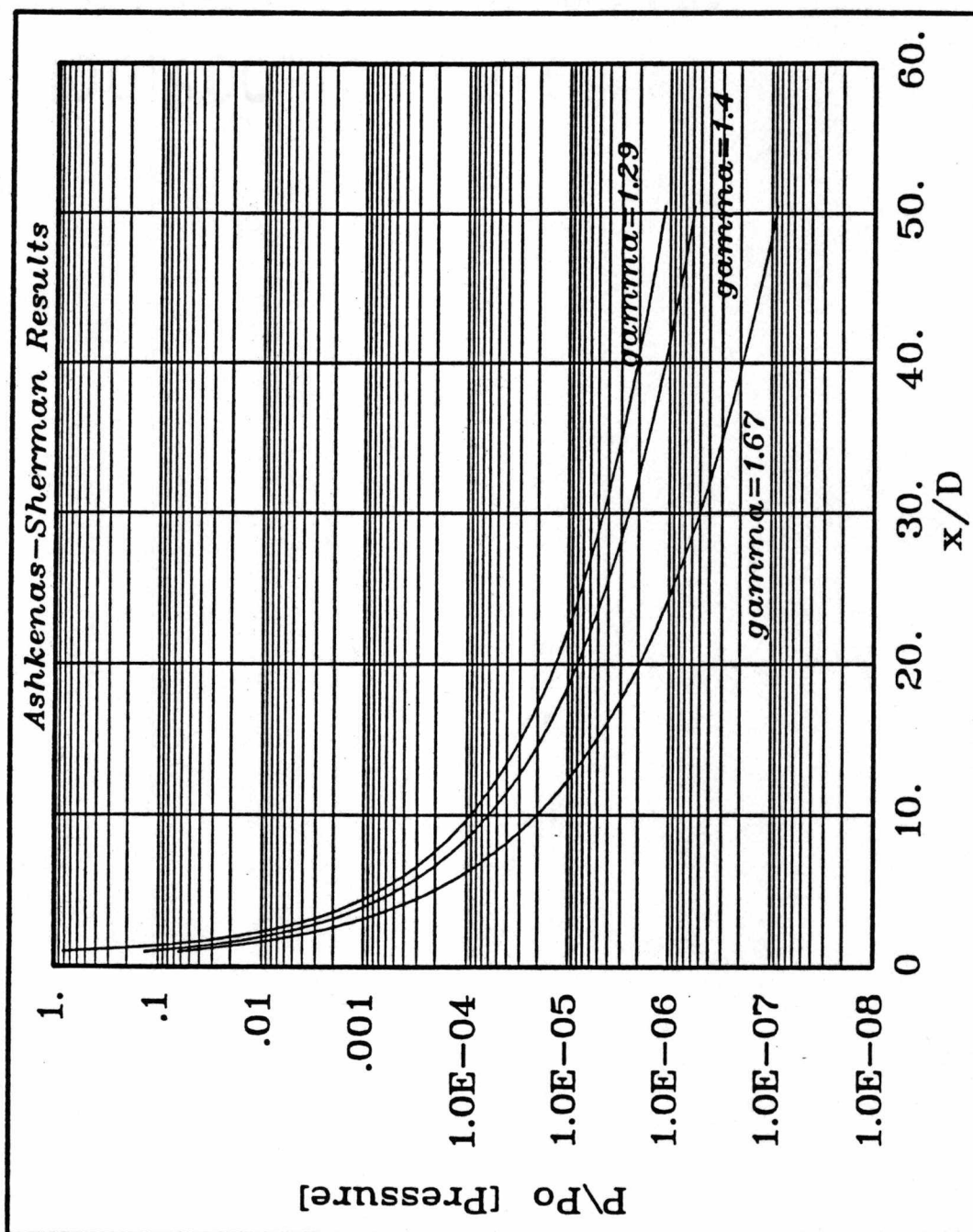


Figure III-3. $\frac{P}{P_0}$: axial variation.

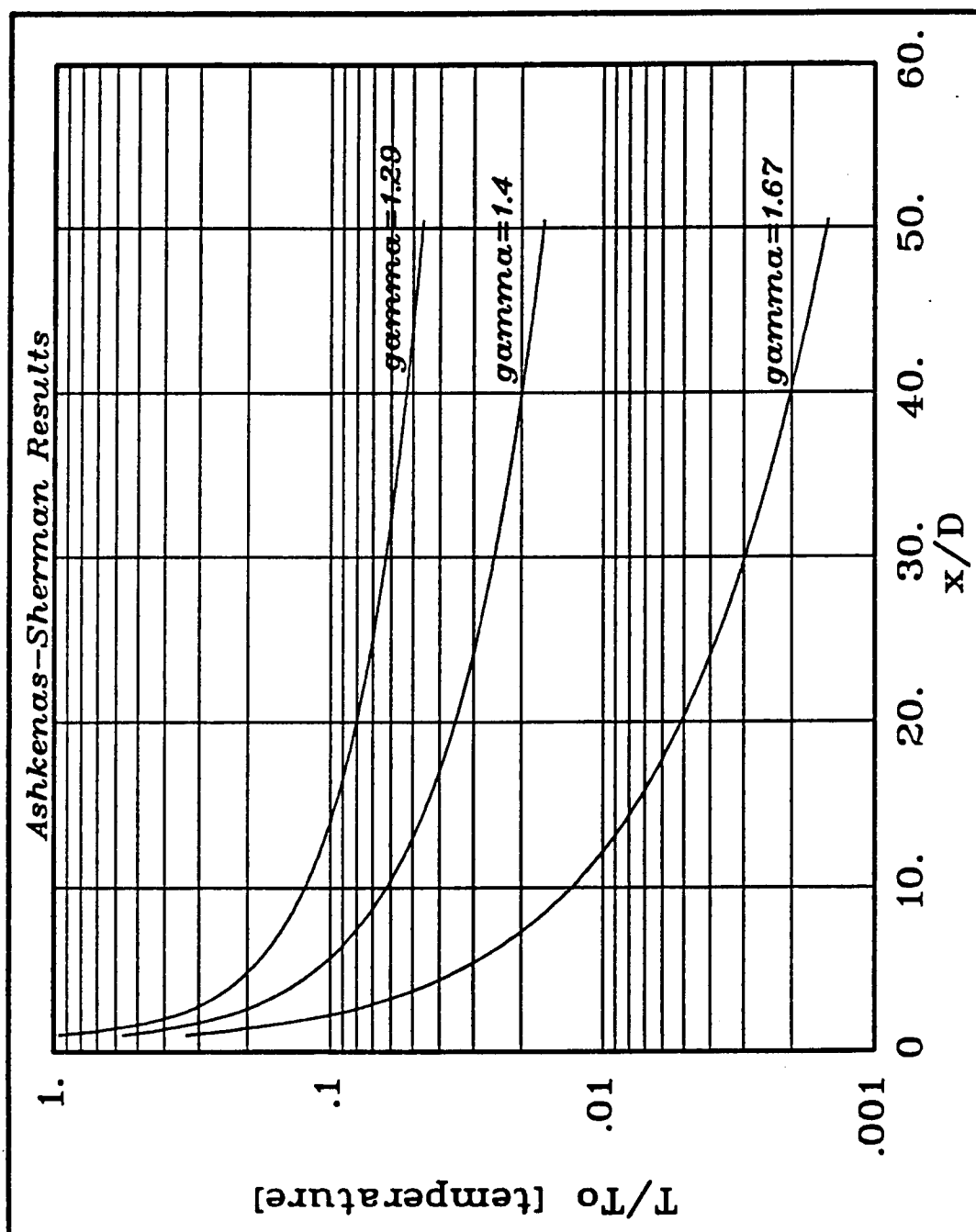


Figure III-4. $\frac{T}{T_0}$: axial variation.

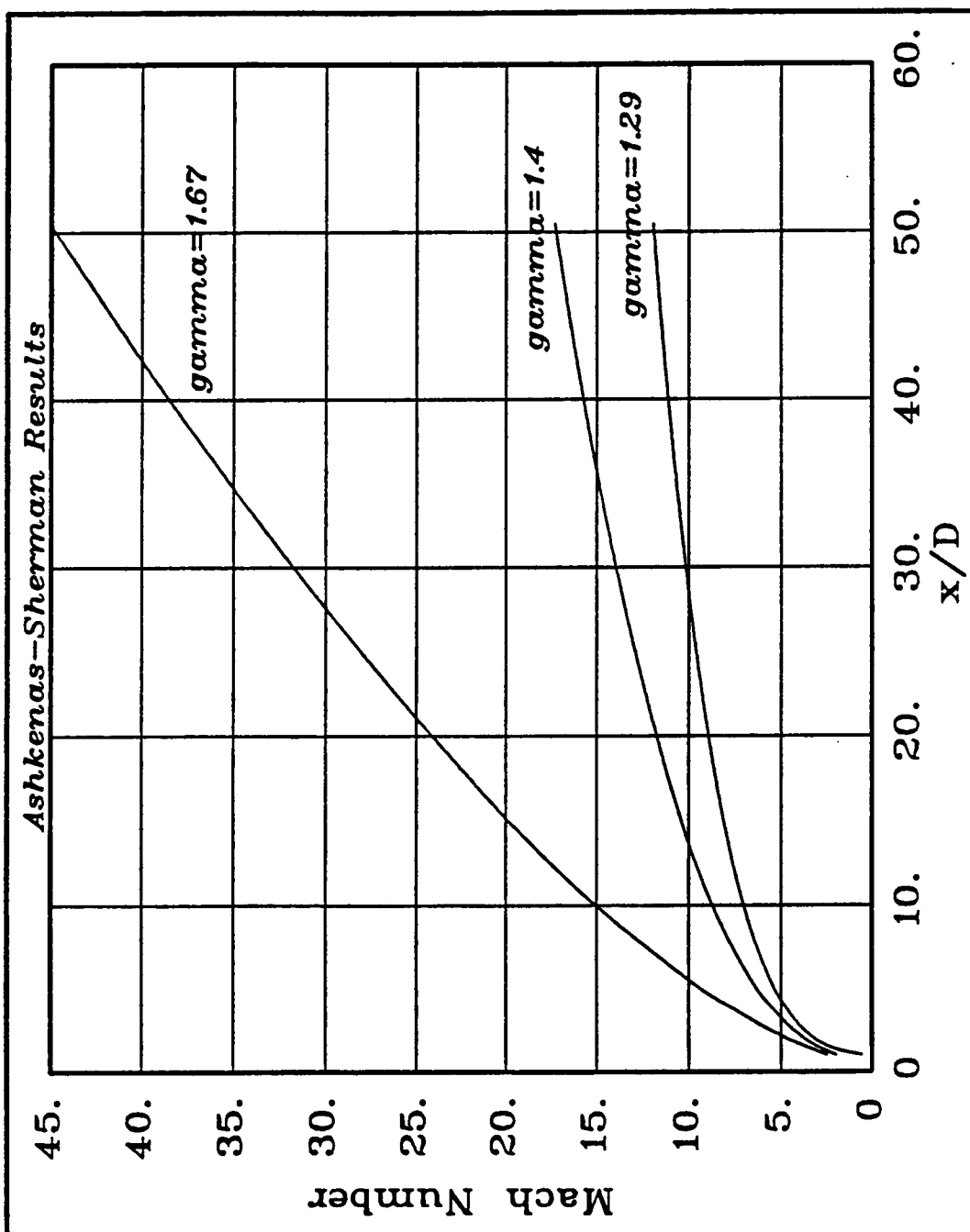


Figure III-5. Mach number: axial variation.

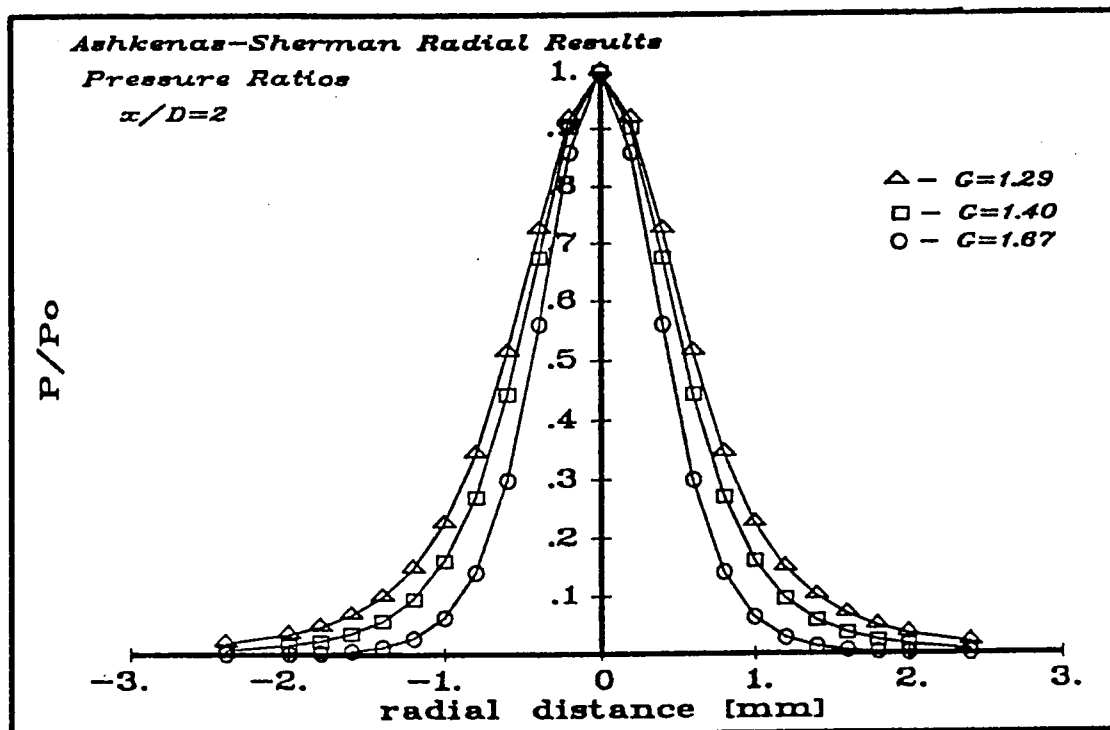


Figure III-6. $\frac{P}{P_o}$: radial variation ($\frac{x}{D} = 2$).

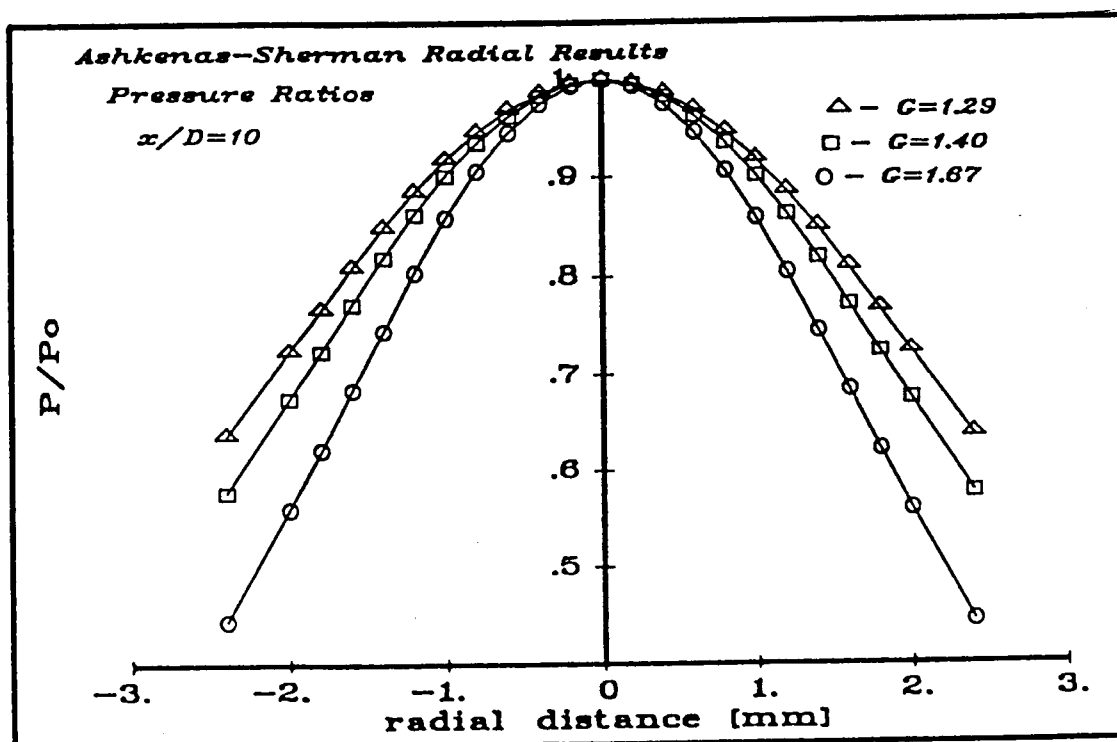


Figure III-7. $\frac{P}{P_o}$: radial variation ($\frac{x}{D} = 10$).

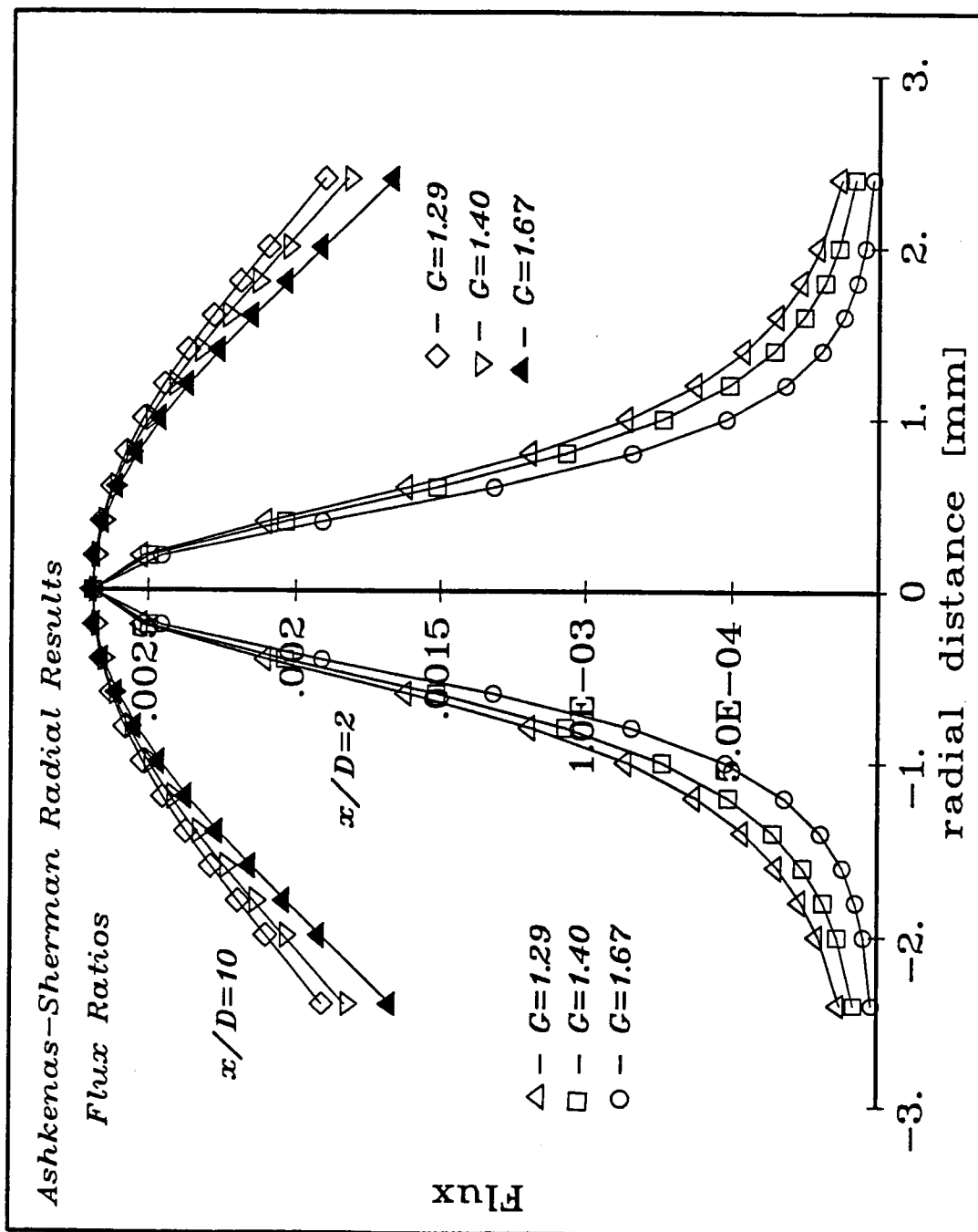


Figure III-8. Flux: radial variation.

approximation for the mean free path,

$$\lambda = \frac{1}{\sqrt{2}(n\pi d^2)}, \quad (3.5)$$

where n is the number density and d is the molecular diameter. Approximating the cross-sectional area (πd^2) as 45 Angstroms^2 and substituting $P = nkT$ leads to the following equation as an order of magnitude approximation:

$$\lambda(\text{cm}) \approx \frac{4.4}{P(\text{mTorr})}, \quad (3.6)$$

for $T = 300K$, for N_2 and CO_2 . Using this relationship and the Ashkenas and Sherman predictions for pressure variation with $\frac{x}{D}$ provides a mean free path variation with axial distance from the source, which is shown in Figure III-9. This approximation leads to a relationship between the Knudsen number and pressure or axial distance (Figure III-10). The main conclusion to be derived from these graphs is that this experiment lies in the continuum flow regime for $\frac{x}{D} = 2$ to about 6, but in the transitional regime for $6 \leq \frac{x}{D} \leq 10$. Thus, the possibility for boundary layer interference is unlikely for the lower axial distances, but is possible at higher axial locations.

Translational freezing occurs when the collisional frequency becomes so low as to prevent the conversion of energy into translational motion. From this point on, the gas continues to expand with the density decreasing in proportion to the inverse square of the distance but with a constant velocity and Mach number. The translational freezing surface has been shown to occur at a Mach number given by:

$$M_\infty \approx 78 \left(\frac{P_o D}{T_o} \right)^{0.4}. \quad (3.7)$$

In Figure III-11, this relationship is plotted with $T_o = 300K$ and $D = 0.05\text{cm}$, which is the diameter of the nozzle used in this experiment. As shown in Figure

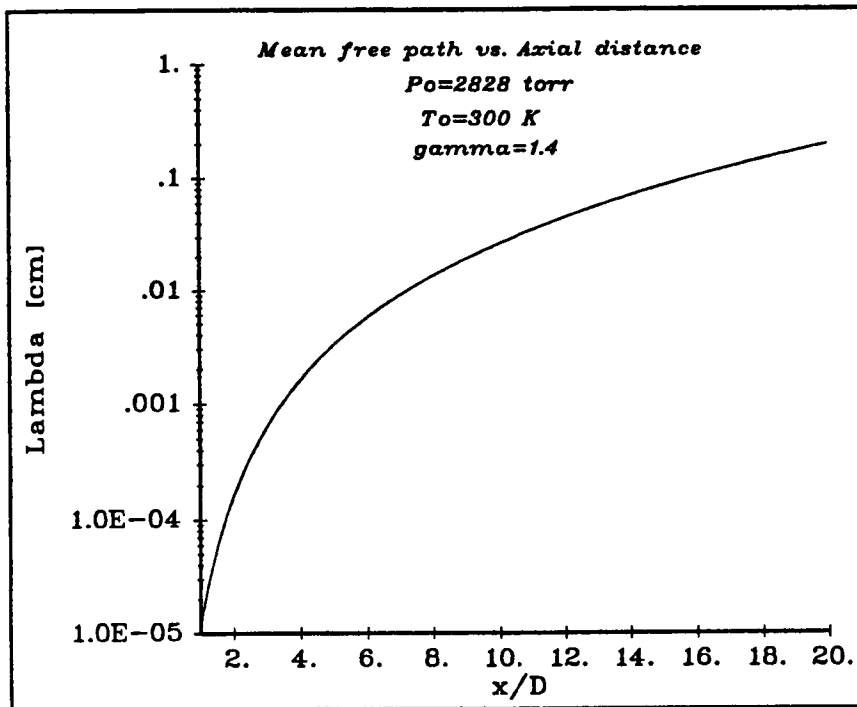


Figure III-9. Mean free path: axial variation

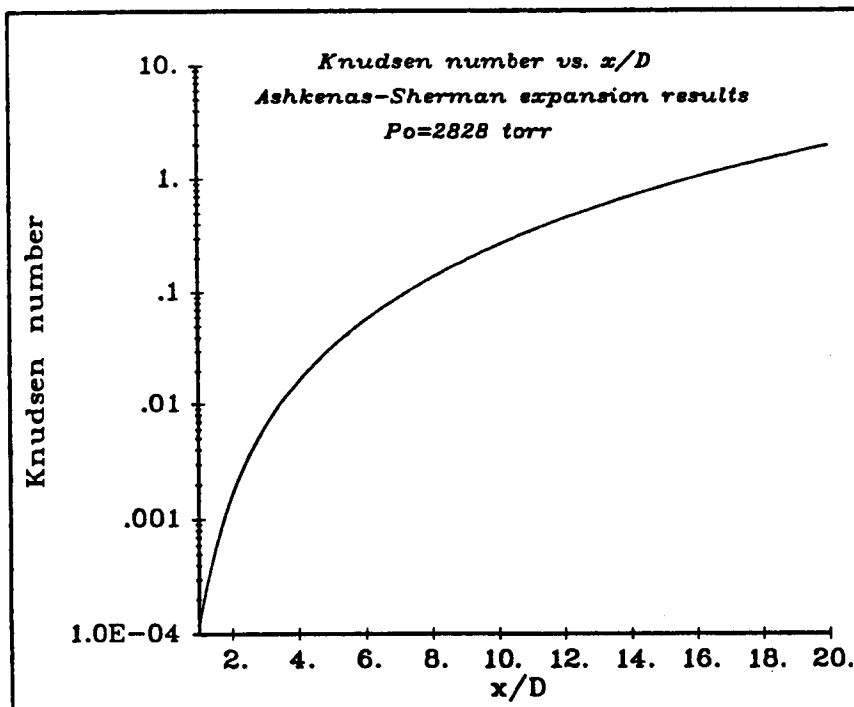


Figure III-10. Knudsen number: axial variation

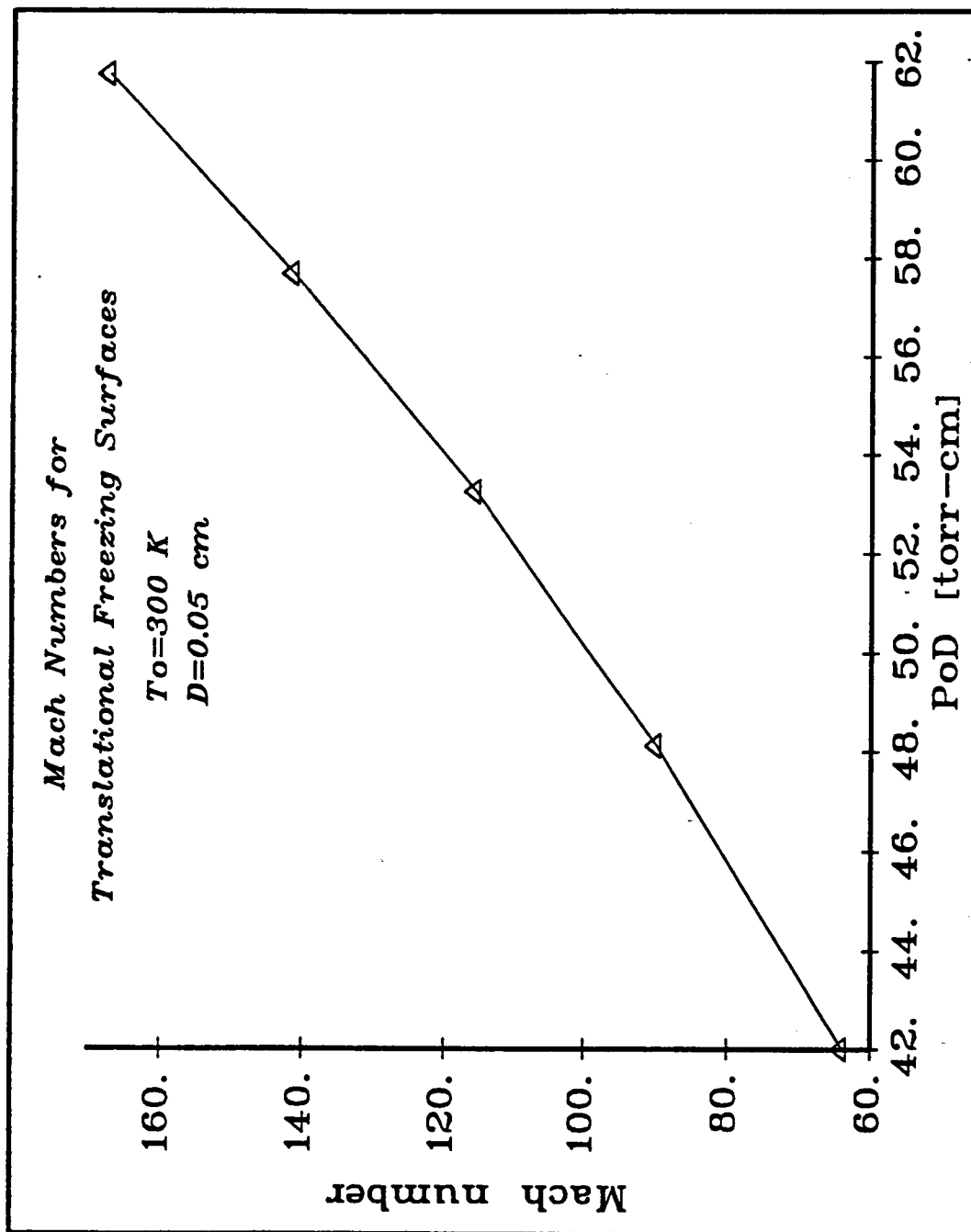


Figure III-11. Translational freezing surface location.

III-11, the translational freezing surface occurs at Mach numbers between 42 and 58. According to Ashkenas and Sherman, these Mach numbers would be reached for a 0.05 cm orifice at axial distances of $\frac{x}{D} > 20$, which is outside the region studied in this experiment ($2 \leq \frac{x}{D} \leq 10$). Thus, the presence of a translational freezing surface is unlikely for the range of values of P_o used in this experiment, which is $1277 \leq P_o \leq 2828$ torr.

Flowfield Prediction for Chamber

The performance of the chamber can be predicted using the above results. The mass flowrate, $\dot{m}_i$, given by the Ashkenas-Sherman equations can be inserted into the generalized pumping equations. The resulting axial dependence of the chamber pressure on the gas pulsewidth and pulse rate is given by:

$$\frac{dP}{dt} = \frac{\dot{m}_i RT}{MV_c} + \frac{a_c A_c}{V_c} - \frac{SP}{V_c}, \quad (3.8)$$

where $\dot{m}_i$ is now given by the Ashkenas-Sherman result:

$$\left(\frac{\dot{m}_i}{A} \right)_{source} = \frac{\rho_o a_o M}{(1 + (\frac{\gamma-1}{2})M^2)^{\frac{\gamma-1}{2(\gamma+1)}}}, \quad (3.9)$$

where the subscript o denotes reservoir quantities and ρ_o =mass density and a_o =speed of sound. Figure III-12 shows the resulting time dependence of the chamber pressure for the axial locations of $\frac{x}{D} = 2$ and 10.

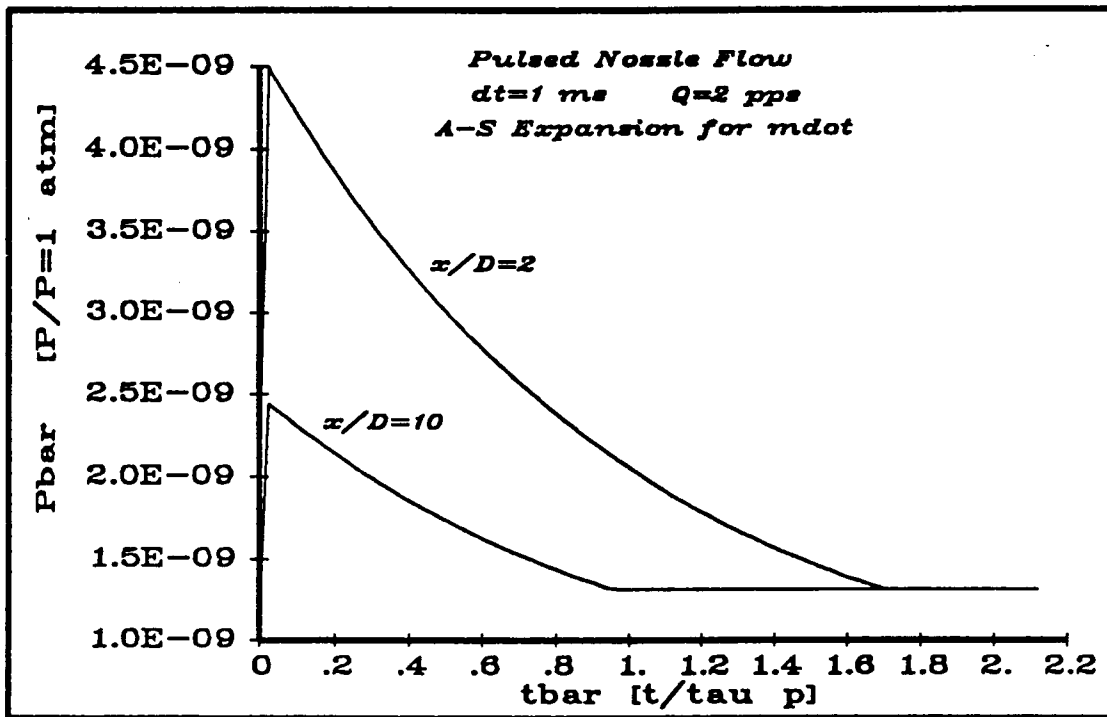


Figure III-12. Pumping equation with Ashkenas and Sherman value for $\dot{m}_i$.

SECTION IV

DESCRIPTION OF PENTODE GAUGE STUDIES

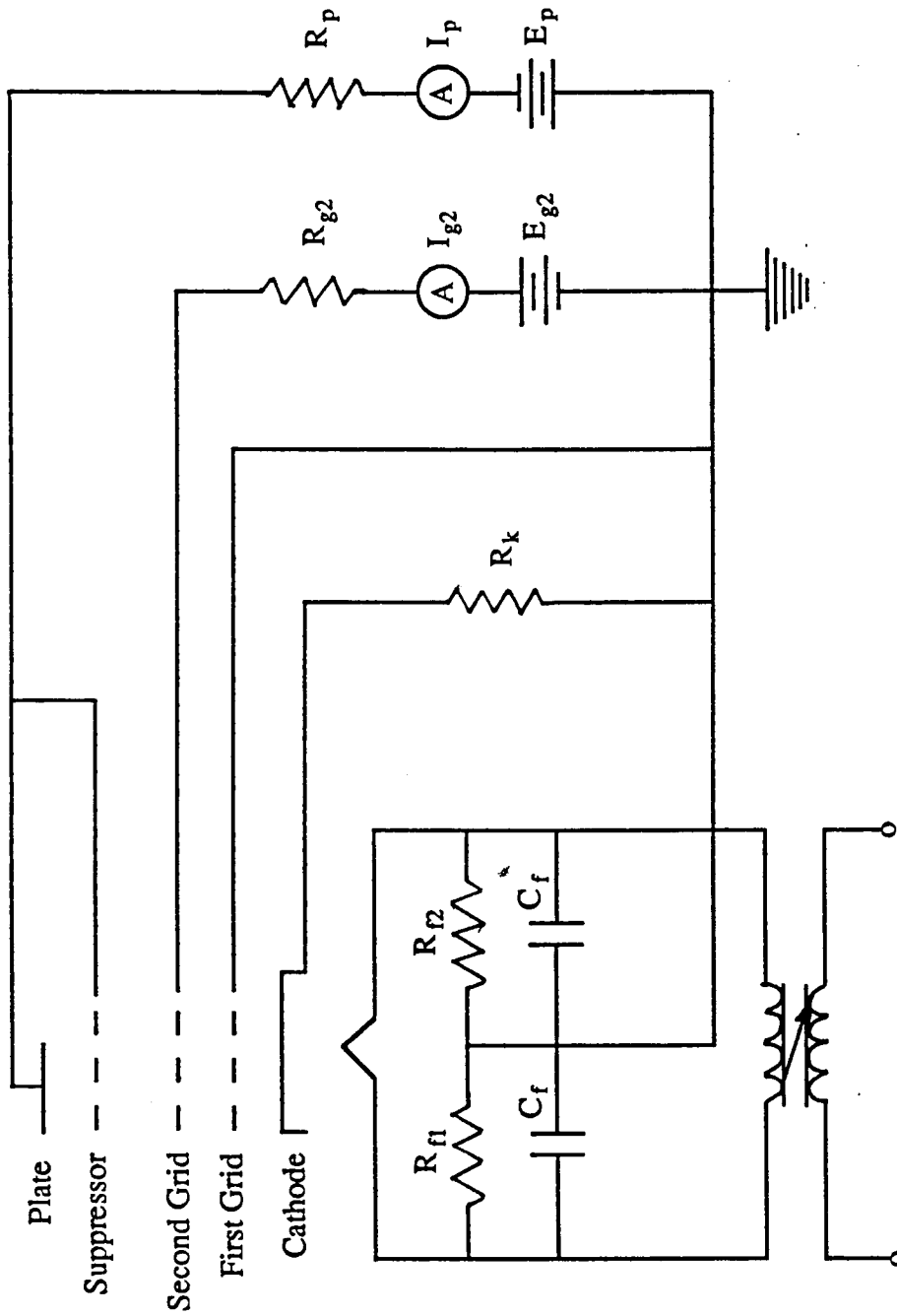
Gauge Choice

The pressure gauge used for the flowfield study was a subminiature, pentode vacuum tube, a CK-5702, which is at present only made by Raytheon. The glass envelope was removed to expose the tube elements. The small size of the tube lessens interference with the flowfield and makes it more suitable for gas profile measurements because the pressures are averaged over smaller volumes. The constant sensitivity and fast time resolution of the pentode also made it a good choice. Valsamakis determined the CK-5702 to have a risetime better than $20\mu\text{sec}$.

The electrical schematic of the system, modeled after the work of Valsamakis [16], is shown in Figure IV-1. Electrons are emitted at the cathode and are accelerated by the second grid to perform ionizing collisions with neutral gas atoms in the region between the second grid and the plate. The ion current collected at the plate is related to the gas pressure in the following way,

$$\frac{i_c}{i_a} = Kp^n, \quad (4.1)$$

where i_c is ion current, i_a is electron emission current, K is sensitivity, p is gas pressure, and n is a constant. The gauge can be made to behave linearly by removing the pressure dependence of the emission current, if the sensitivity of the gauge is also pressure independent. The circuit shown in Figure IV-1 provides this pressure independence through the resistors R_{g_2} and R_k . Acting as negative current feedback elements, the values chosen for R_{g_2} and R_k provide constant emission current and eliminate steady state drift. The ion collection depends on the potential distribution between the second grid and the suppressor grid. The



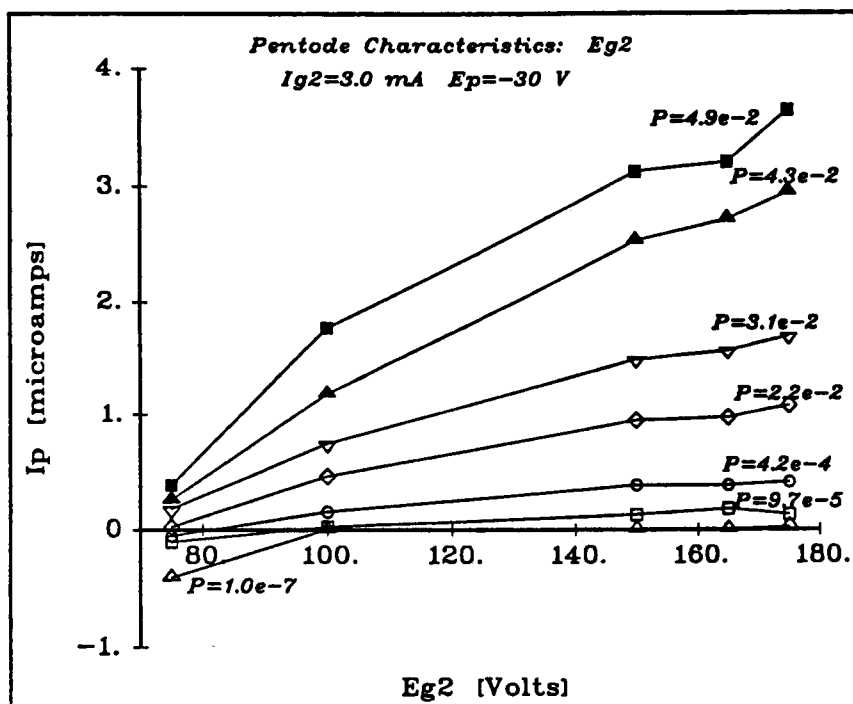
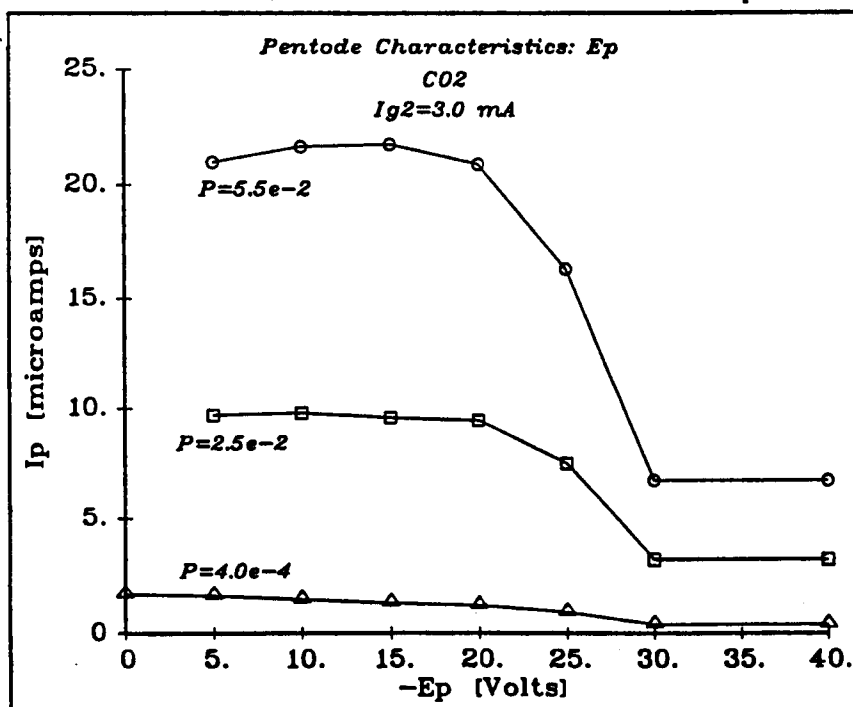
$R_k = 100\Omega$, $R_{g2} = 27k\Omega$, $R_p = 3.9k\Omega$,
 $R_{f1} = 100\Omega$, $R_{f2} = 200\Omega$, $C_f = 0.02\mu F$.

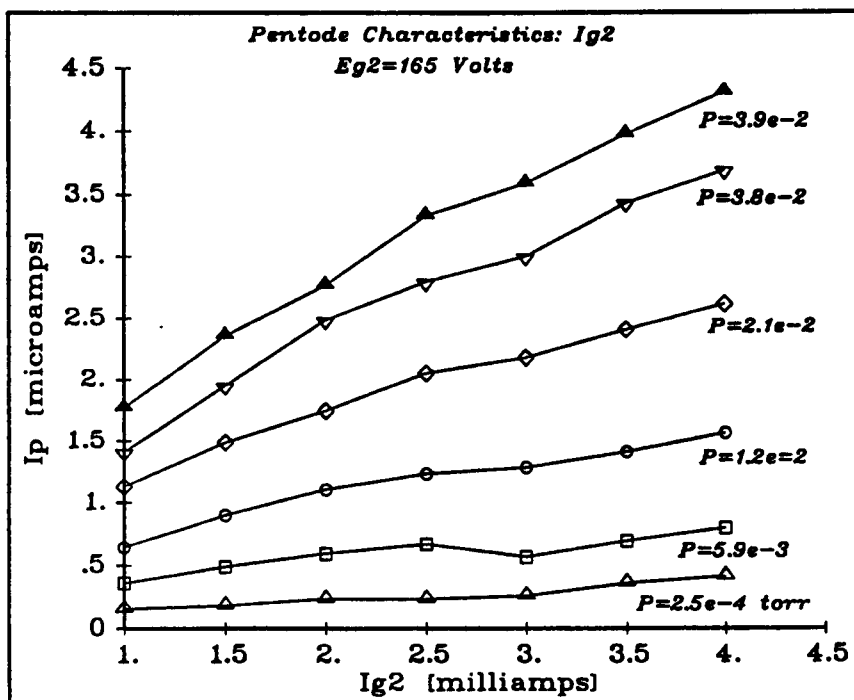
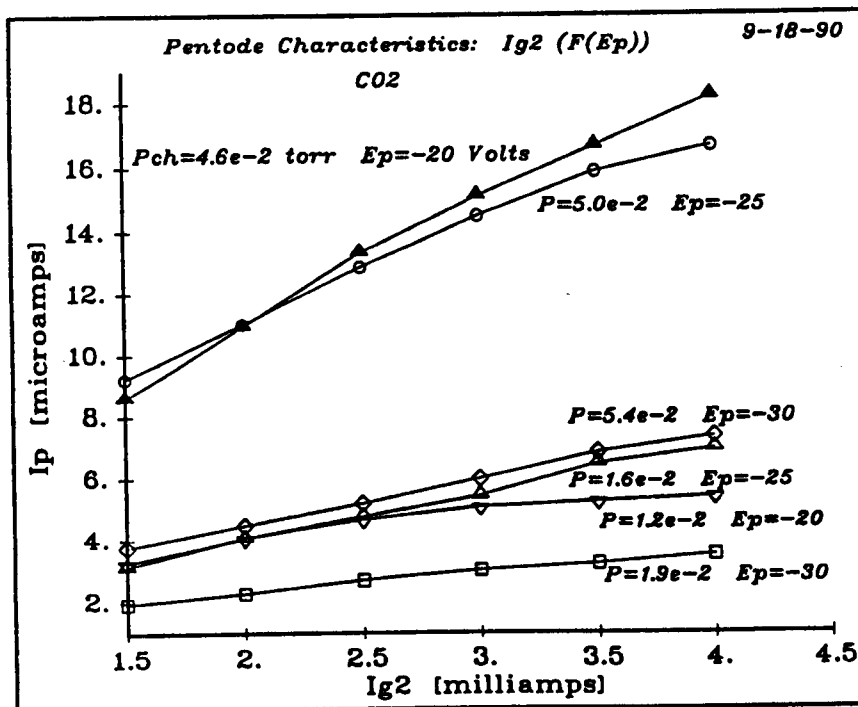
Figure IV-1. Electrical schematic for pentode circuit.

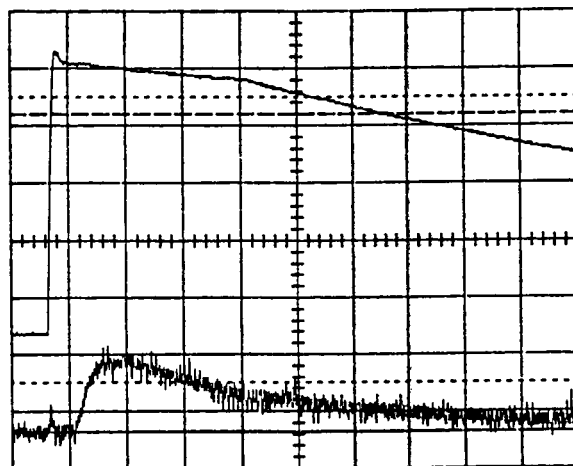
plate resistance, R_p is kept low in order to avoid changing of the plate voltage, which would affect the ion collection. The ionization efficiency by electron impact for most gases has a maximum for electrons of about 100eV , as stated by von Engel [17]. Therefore, the value of E_{g_2} must be larger than 100 volts. In Figure IV-2, the gauge response appears to level off between $E_{g_2} = 150$ and 165V . Since Valsamakis [16] claimed that $E_{g_2} = 165\text{V}$ proved effective in his pentode studies, the value of E_{g_2} was set at 165V . Figure IV-3 shows the plate current, I_p , as a function of plate power supply voltage for various pressures and indicates that a value of -30V be used for E_p in order to maintain linear response of the gauge. Figure IV-4 shows that the plate current rises with I_{g_2} as pressure rises, however, steady operation appears possible at a value of $I_{g_2} = 3.0\text{mA}$, as lower values of I_{g_2} allowed circuit drifts. Valsamakis showed that the optimum emission current was about 2.5mA , but this value resulted in non-linear gauge response. Figure IV-5 indicates that optimal operation of the gauge may be achieved with $I_{g_2} = 3.0\text{mA}$ and $E_p = -30\text{V}$.

The pulses from the nozzle source were observed on a Lecroy 9400 digital oscilloscope. As shown in Figure IV-6, the pulses were not very clean. The operational amplifier, shown in Figure IV-7 was constructed in order to obtain better resolution on the pulses. Figure IV-6 shows the resulting pulse with the operational amplifier for N_2 .

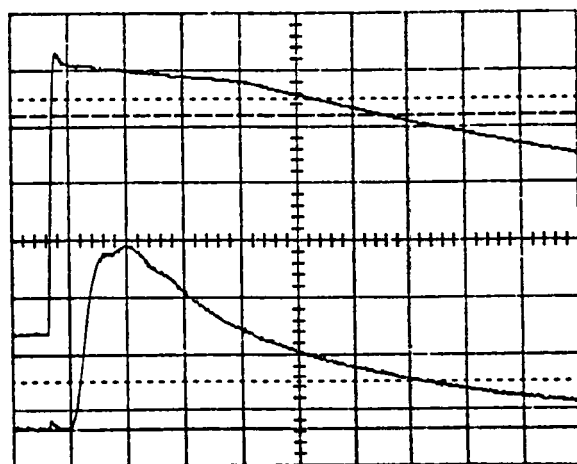
The filaments were necessarily raised to higher-than-normal voltages, between 8V and 18V , in order to maintain gauge linearity as the chamber pressure was increased. The short lifetime of the pentode, averaging about 6 weeks, can be attributed to the higher filament voltages and to the unavoidable deterioration of

Figure IV-2. Pentode characteristics: E_{g2} .Figure IV-3. Pentode characteristics: E_p .

Figure IV-4. Pentode characteristics: I_{g2} .Figure IV-5. Pentode characteristics: $I_{g2}(E_p)$.



x-axis: 0.5 ms/division; y-axis: 5 mV/division
Pentode signal without operational amplifier.



x-axis: 0.5 ms/division; y-axis: 50 mV/division
Pentode signal with operational amplifier.

Figure IV-6. Pentode signal with and without operational amplifier.

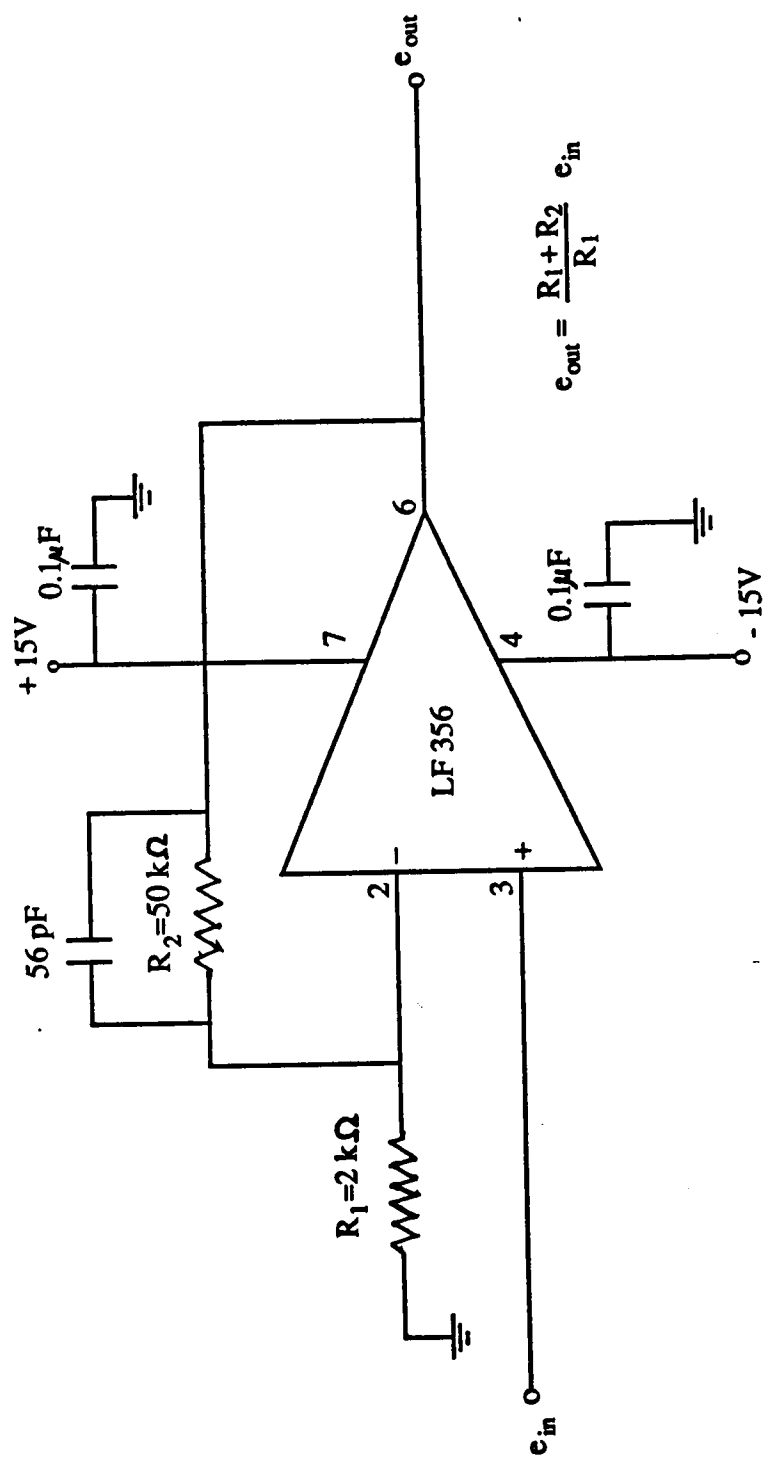


Figure IV-7. Electrical schematic of operational amplifier.

the oxide coating on the tube cathode with age. Kelly [7] discussed a method for extending the life of oxide coated filaments, but this information was not utilized in these experiments.

Degassing of the tube played an important part in achieving accurate results. The degassing procedure consisted of removing the accelerating grid potential, I_{g2} , and keeping the filament at working temperatures. By systematic repetition of the degassing procedure, gas clean-up effects are avoided and the linearity of the gauge can be maintained with lower filament voltages.

Static Calibration

In order to gain information on the local pressure and density profiles within the vacuum chamber, the pentode was calibrated first under static conditions. The method of calibration consisted of four steps. First, the pentode was placed in a static pressure environment. Second, the chamber pressure was steadily increased by admitting gas through the sonic orifice in its continuous mode. Third, the chamber pressure was read using the IGD or TC pressure detectors. The plate voltage of the pentode was read from a digital voltmeter to within ± 1 millivolts. In order to operate in the optimum conditions for the pentode, some parameters were necessarily fixed. The emission grid current (I_{g2}) was maintained at 3.0 milliamps in order to maintain a stable plate current, and, as stated previously, the plate power supply voltage, E_p , was fixed at -30 volts, and E_{g2} was set at 165 volts. Fourth, the plate voltage was plotted against the pressure. (The degassing procedure was also performed at this point.) Figures IV-8 through IV-13 show the data for N_2 and CO_2 , respectively. The data show the consistency of the pentode for pressures greater than 1×10^{-4} torr, but, as pointed out by Valsamakis [16], the pentode proved unreliable at lower pressures. Upon plotting all of the N_2 data

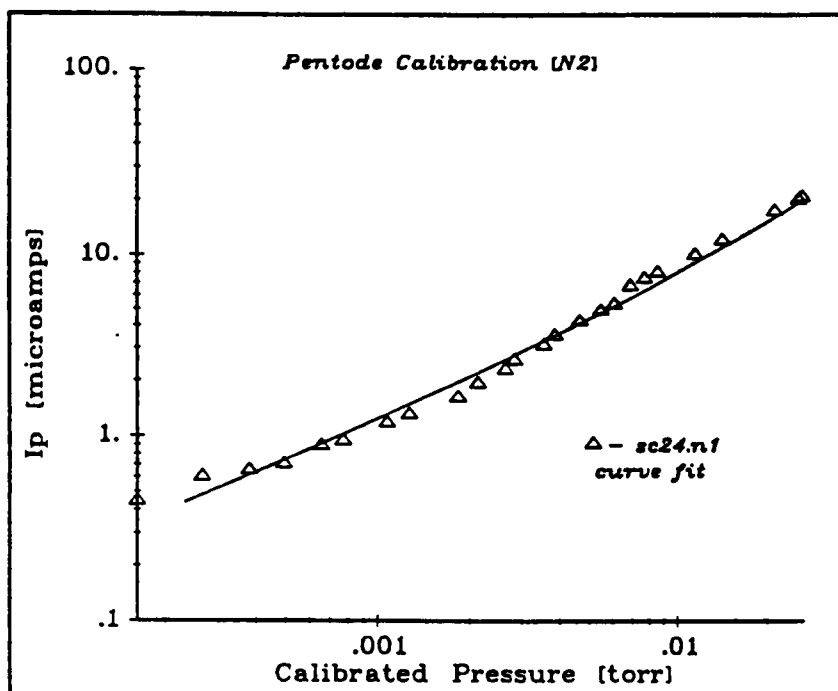


Figure IV-8. Pentode calibration: N_2 pentode 24 set 1.

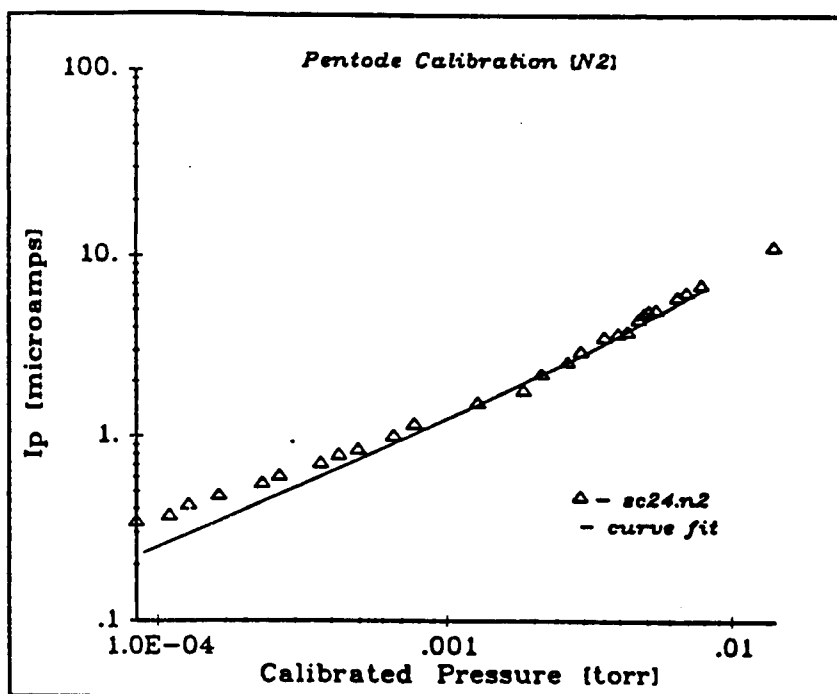


Figure IV-9. Pentode calibration: N_2 pentode 24 set 2.

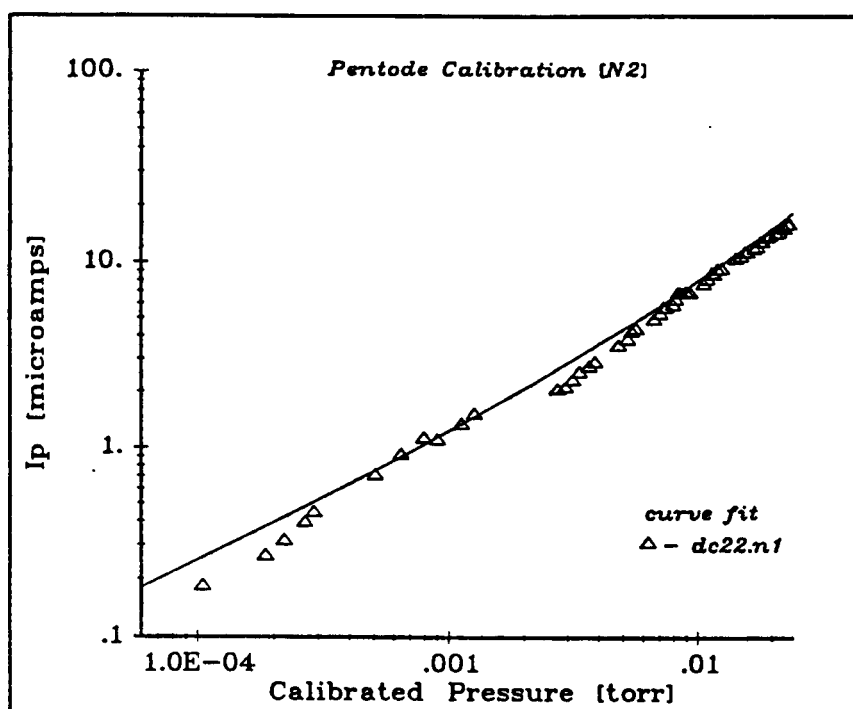


Figure IV-10. Pentode calibration: N_2 pentode 22 set 1.

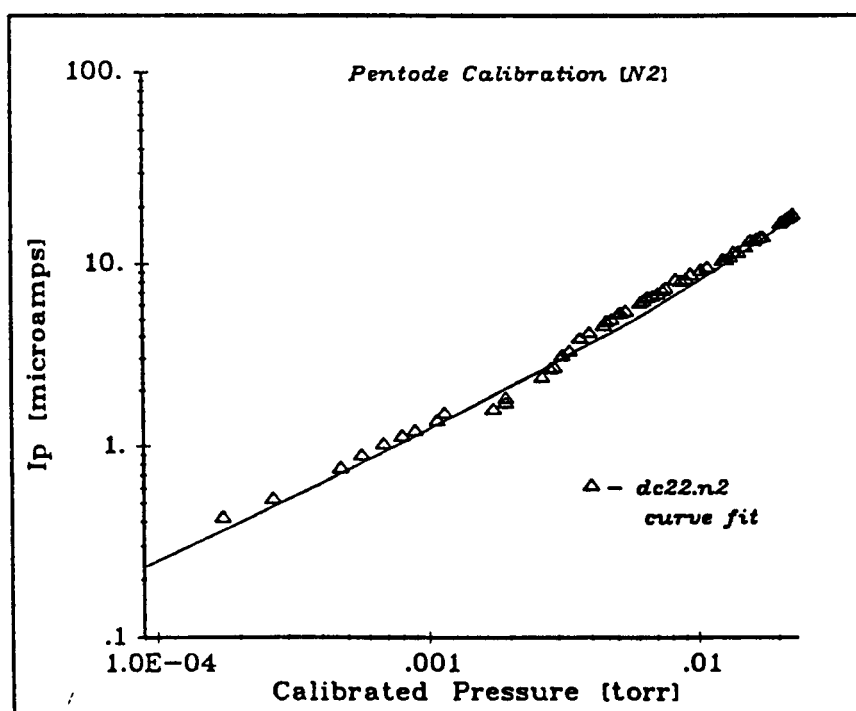


Figure IV-11. Pentode calibration: N_2 pentode 22 set 2.

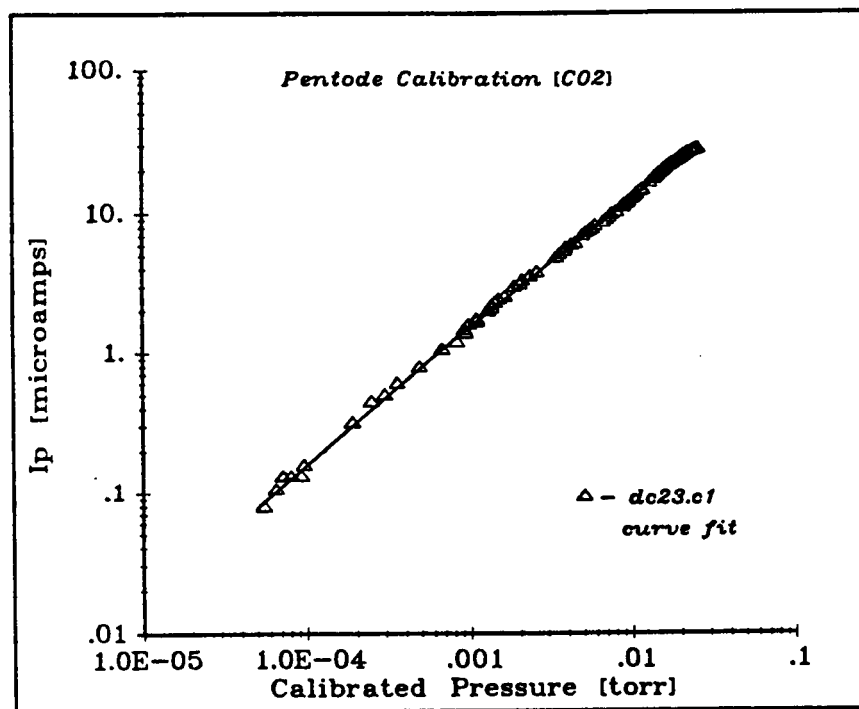


Figure IV-12. Pentode calibration: CO₂ pentode 23 set 1.

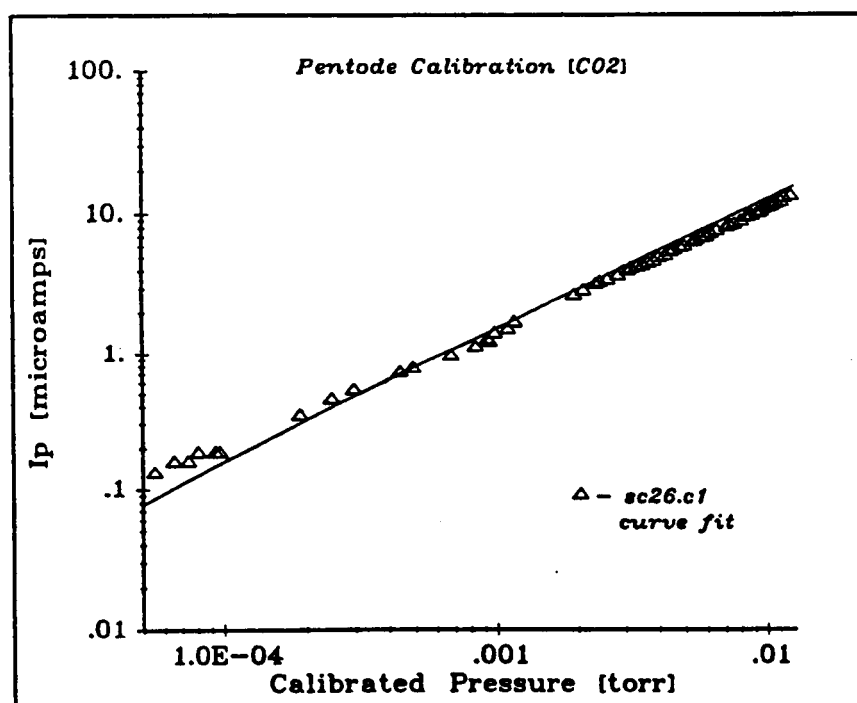


Figure IV-13. Pentode calibration: CO₂ pentode 26 set 1.

sets, the first data set from pentode 24 appeared to be a good representation of the average results. Using least-squares curve fitting methods, a curve was fitted to these data (Figure IV-8). The same curve fit was, then, compared to other data sets; set 2 from pentode 24, and sets 1 and 2 from pentode 22. Figures IV-9 through IV-11 show the comparisons gave good results. A similar procedure was followed with the CO_2 data, where the curve was fitted to data set 1 of pentode 23, and then, compared to data set 1 from pentode 26. The results, shown in Figures IV-12 and IV-13, were satisfactory. The fitted equations provided in Appendix B give pressures correct to within 2% of the value.

Dynamic Calibration

For the purpose of better interpretation of the dynamic calibration results, a conical skimmer was placed between the sonic orifice and the pentode. The function of the skimmer was to allow specification of the plume region to be observed by the pentode, as illustrated in Figure IV-14. By keeping the entrance diameter small, the portion of the flow being detected by the pentode is decreased. The radial Ashkenas-Sherman equations give results for the mass density variance along the radial streamlines. Narrowing the portion of the plume observed by the pentode allows comparison between the resulting pressures and the Ashkenas-Sherman predictions. However, Zapata, Parker and Bodine [19] showed in their study of the effects of skimmer geometry, it is necessary to keep the entrance diameter large compared to the mean free path, and to provide a sharp skimmer edge in order to maintain supersonic flow through the skimmer. As shown earlier (Figure III-9, page 26), the mean free paths predicted by the Ashkenas and Sherman results are on the order of 0.1 mm and the nozzle diameter was 0.5 mm. Thus, a satisfactory skimmer diameter of 1.0 mm was chosen.

In order to avoid shock formation before, or within the skimmer entrance, the cone half angle, θ_c , was optimized. According to Liepmann and Roshko, a cone, when placed in a supersonic flowfield, will acquire an oblique attached shock with a range of angles that vary with the Mach number as $\sin^{-1}(\frac{1}{M}) \leq \beta \leq \frac{\pi}{2}$. This shock, as shown in Figure IV-15, will cause minimal disturbance to the flow provided it does not become detached. Prevention of a detached shock can be accomplished by satisfying the above inequality for β , as follows. Using the Ashkenas-Sherman predictions for the Mach number, it was determined that the lowest Mach number achieved in this experiment would be 1.5. Thus, the skimmer

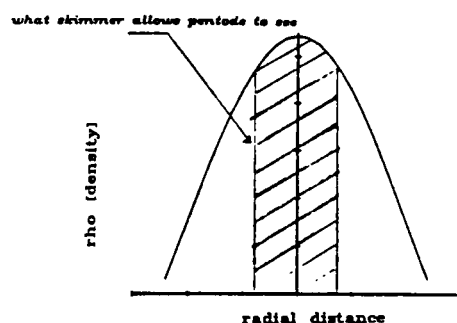


Figure IV-14. Plume portion viewed with skimmer.

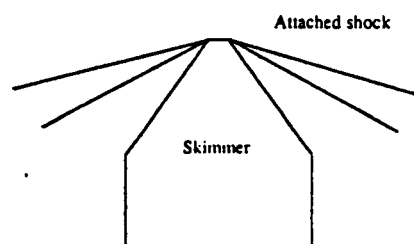


Figure IV-15. Illustration of an attached shock.

One other restriction on the skimmer was that the exit be such as to allow for rapid pumping of the pentode, in order to avoid a gas buildup or shock formation within the pentode or skimmer. Therefore, the exit of the skimmer needed to be kept as open as possible. With all of these requirements in mind, a conical skimmer

was designed using .005 inch thick brass shimstock. The resulting skimmer had a 1.0 mm entrance diameter, a cone half-angle of 41° , a height of 1.0 cm and an exit diameter of 1.74 cm. The pentode was placed 6.0 mm from the skimmer entrance with three straps, which extended from the skimmer cone exit to the pentode tube, and served to maintain the pentode location (see Figure IV-16).

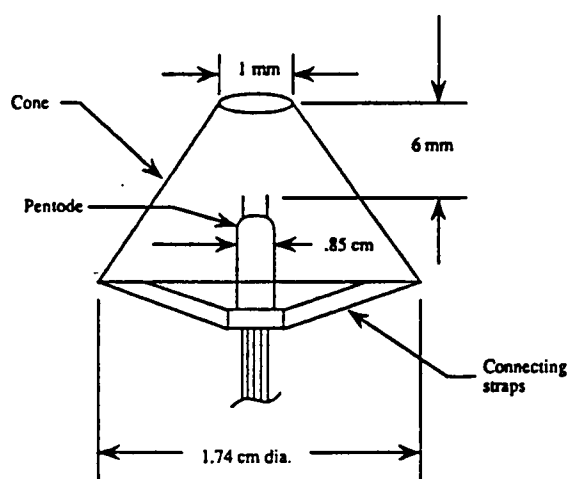


Figure IV-16. Diagram of pentode-skimmer apparatus.

The location of the skimmer-pentode apparatus was changed two ways. The apparatus was placed at the end of an aluminum arm extending from the wall of the vacuum chamber. Using this arm, the skimmer-pentode could be placed in a variety of radial locations. Initially, the skimmer exit was placed just beneath the nozzle orifice. This point was the zero-zero point, that is, $(\frac{x}{D} = 0, r = 0)$. The nozzle was located orifice-side down, towards the skimmer, such that the plume was directed into the cryopump. This also aided in the attempt to satisfy the requirement for rapid pumping on the skimmer exit. The three-dimensional motion of the nozzle was accomplished using a traversing mechanism (Oriol Encoder Mike

Controller Model 18011). The traversing mechanism had a range of motion of two inches in each of the three directions and a digital readout to ± 0.1 microns. However, calibration of the mechanism showed it to be accurate only to ± 10 microns.

The operating procedure for the dynamic calibration of the pentode required a more rigorous measurement of the skimmer-pentode apparatus location. As stated previously, the apparatus was, first, placed directly beneath the nozzle orifice, such that the skimmer entrance was aligned with the orifice. This was done with the vacuum chamber open to atmosphere and consisted of moving the radial arm to the proper position and then traversing the nozzle into the approximate centered location. The chamber was closed and pumped down to 1×10^{-6} torr. Once the lowest pressure was reached, the nozzle was traversed 1 mm in the positive z-direction, where the z-axis is positive in the up direction and negative in the down direction. With the skimmer now located at $\frac{x}{D} = 2$, the nozzle was pulsed with a reservoir pressure of 10psi. Traversing the nozzle in the x and y directions, and observing the pentode pulse on a digital oscilloscope (Lecroy 9400), the nozzle was centered on the skimmer entrance. The oscilloscope showed a rise and fall of pulse height as the nozzle moved toward, through and away from the center of the skimmer entrance. Once the center position was known, the subsequent data from other positions could be referenced to this center.

The main objective of the dynamic calibration was to collect data that could be compared to the expected, time-dependent pressure results. Referenced to the center location, the nozzle was traversed radially, collecting data every 0.2 mm in the x-direction and then, the y-direction. The radial pulse profile was completed when the pulse reached a minimum, which usually occurred at a distance of less than 2.4 mm, depending on the $\frac{x}{D}$ location. Upon completion of the radial

scan, the nozzle was traversed to the next $\frac{x}{D}$ value, where the radial scan was repeated. Using two scope probes across the plate resistor, the plate voltage of the pentode was fed into the data acquisition system. The time-dependent pentode pulse (mV) was collected and stored in the digital storage oscilloscope (Lecroy 9400), which was programmed for this task by Dr. Christian Parigger. The resolution of the scope, which was triggered by the valve driver for the nozzle, was 4 microseconds/point and 125 points/division.

SECTION V

RESULTS

Dynamic Calibration

Using the procedure outlined previously, the pentode was calibrated in the dynamic pressure environment of the pulsed sonic orifice. The basic problem encountered with the pentode was determining how the pentode signal was related to the pressure. Assuming that the flowfield was defined by the Ashkenas-Sherman equations and using ratioed values, a systematic procedure produced a way of obtaining pressure values that corresponded to the millivolt signal given by the pentode. The axial CO_2 data will serve as an example of the process used to obtain the pressure from the signal.

The axial data gave a set of signal peak values corresponding to an axial position, $\frac{x}{D}$, where those observed included $\frac{x}{D} = 2, 3, 4, 5, 6, 7, 8, 10$. Each of the signal peaks of the raw data from various axial positions (Figures V-1 through V-5) were ratioed to the peak from $\frac{x}{D} = 6$. In this way, the $\frac{x}{D} = 6$ data served as the means for normalization. These ratioed values were compared with the Ashkenas and Sherman results obtained from ratioing, as well. Recall that the Ashkenas and Sherman equations for $\gamma = 1.4$ do not give accurate results for the region $\frac{x}{D} < 4$. However, extrapolation techniques, such as those used by Sharma, et. al. [12], allow application of the Ashkenas and Sherman results to axial distances in the region $\frac{x}{D} < 4$. The Ashkenas and Sherman paper presented results for the variation of Mach number, and thus, pressure, with axial distance. Ratioing the Ashkenas and Sherman axial $\frac{P}{P_o}$ values to the $\frac{P}{P_o}$ value at $\frac{x}{D} = 6$, served to compare with the experimental results.

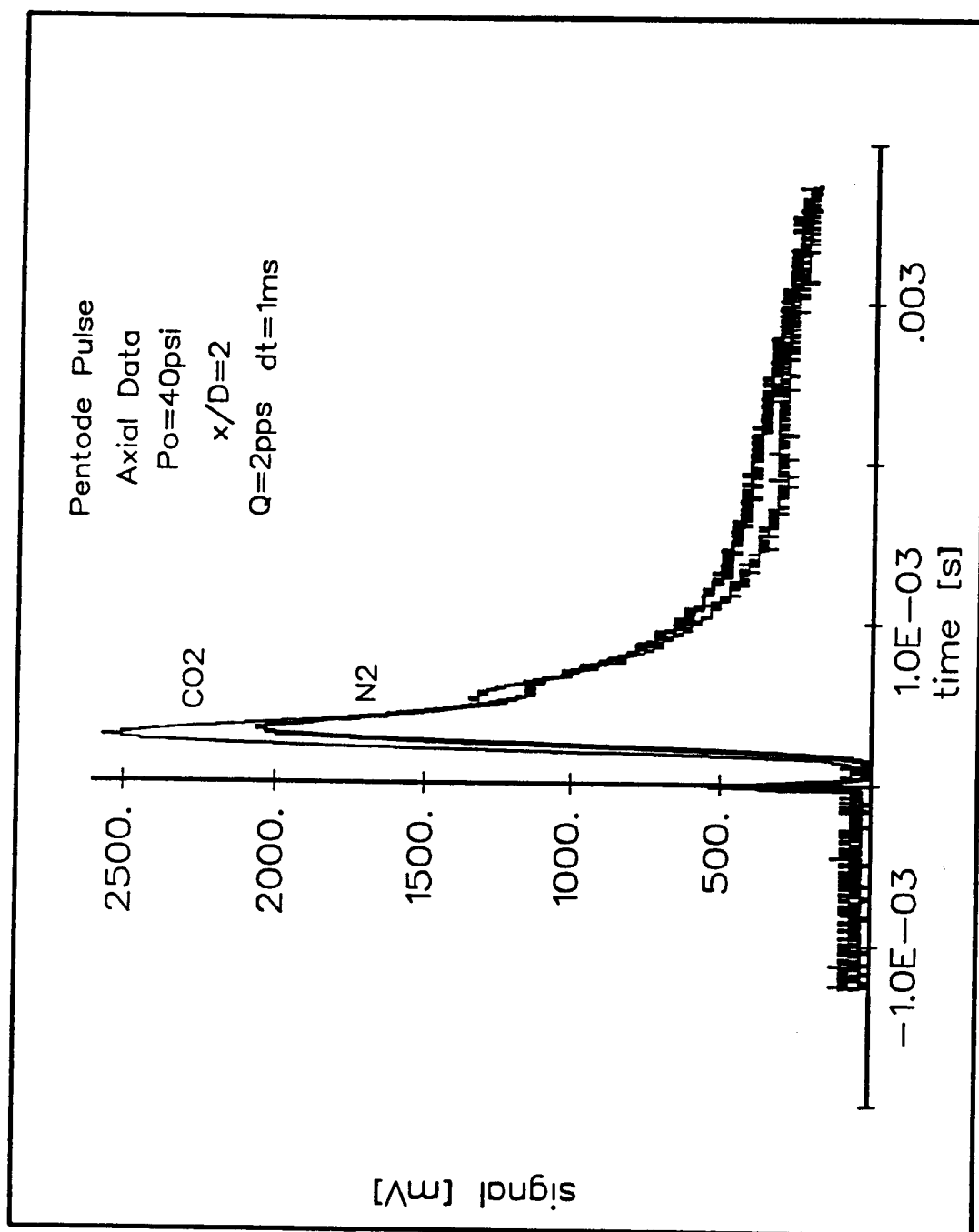


Figure V-1. Raw axial data CO_2 and N_2 ($\frac{x}{D} = 2$).

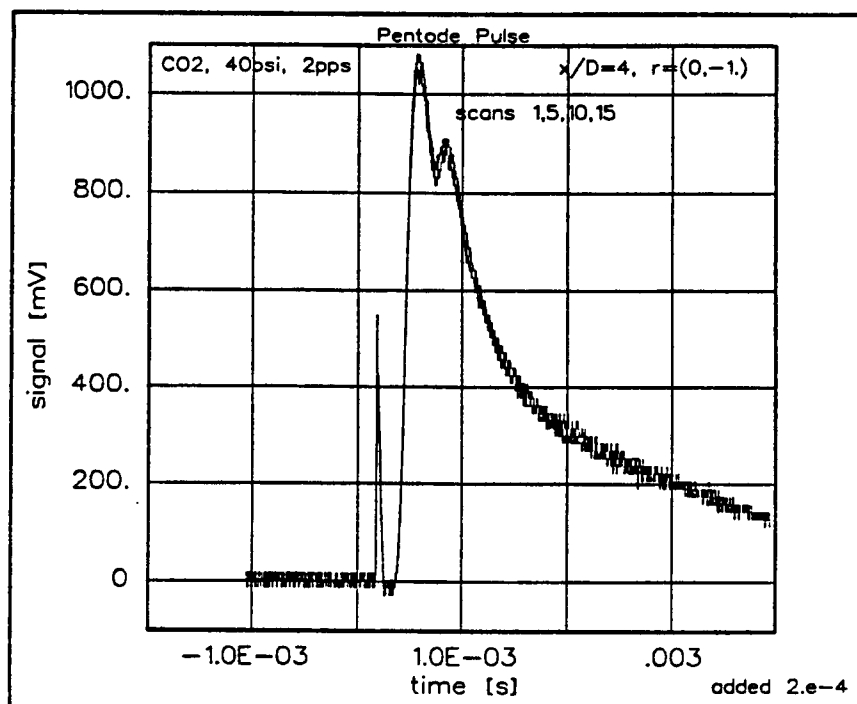


Figure V-2. Raw axial data CO_2 ($\frac{x}{D} = 4$).

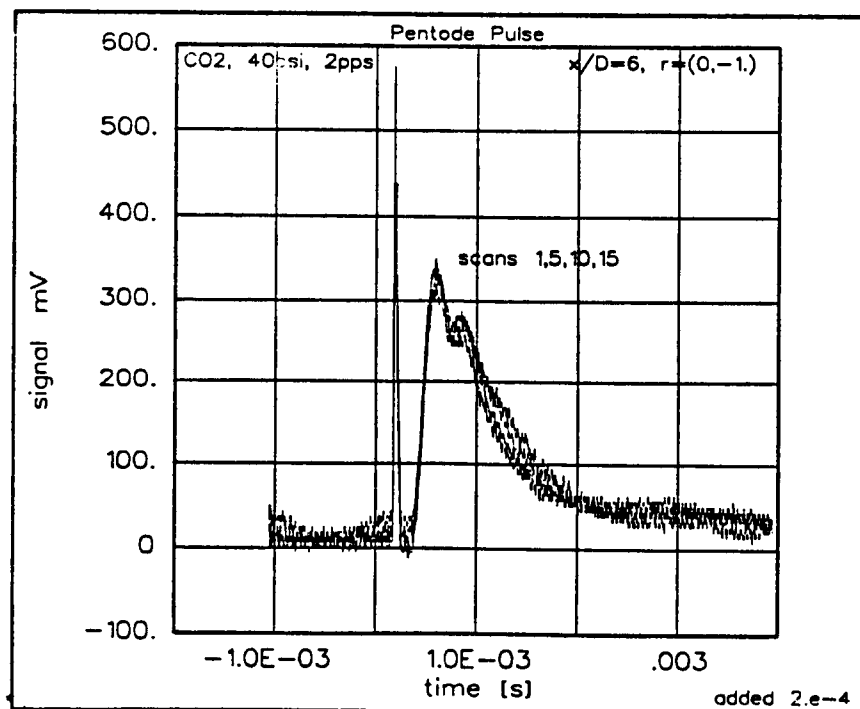


Figure V-3. Raw axial data CO_2 ($\frac{x}{D} = 6$).

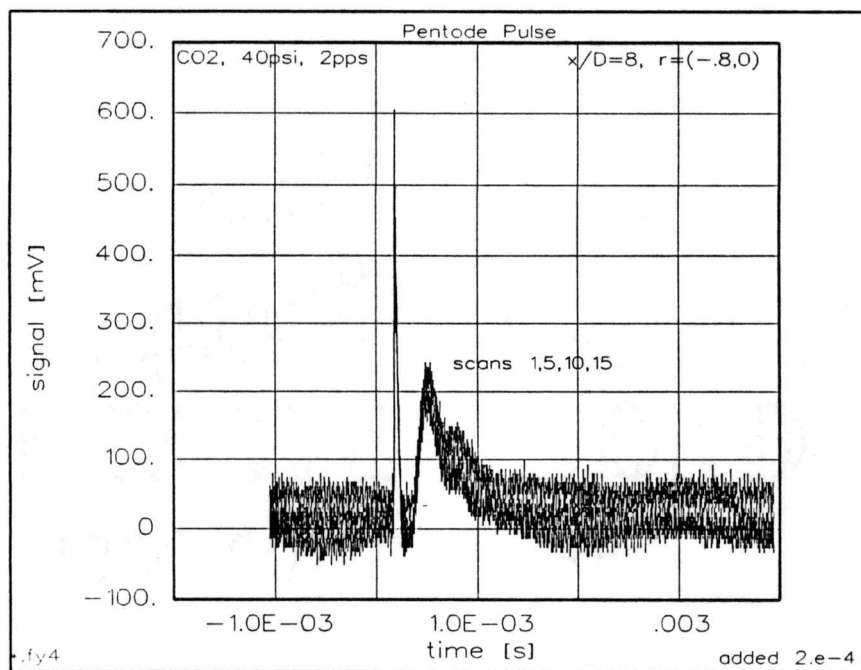


Figure V-4. Raw axial data CO_2 ($\frac{x}{D} = 8$).

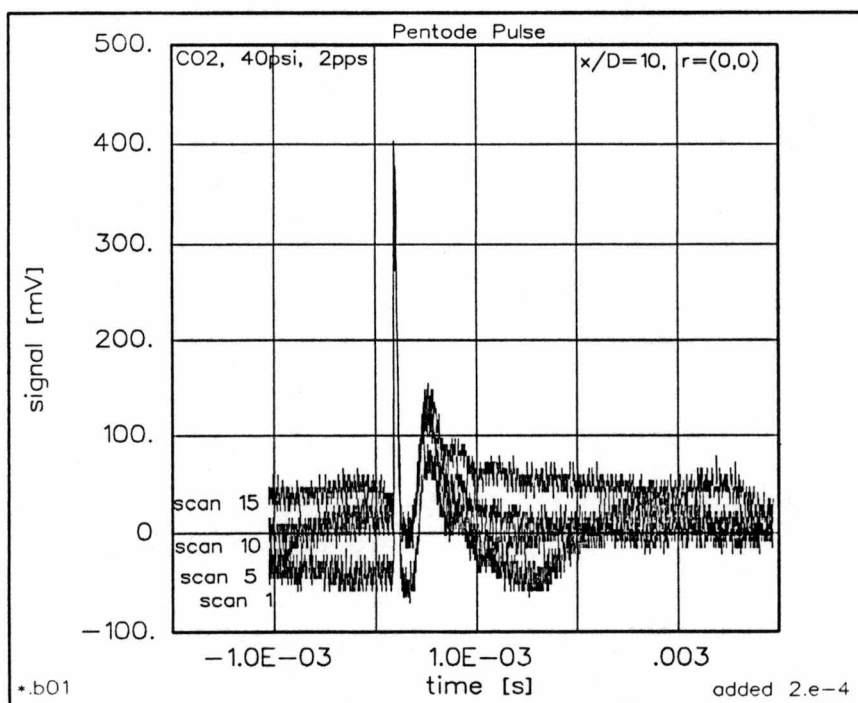


Figure V-5. Raw axial data CO_2 ($\frac{x}{D} = 10$).

Axial Data

The CO_2 axial data were reduced using the above procedure and compared with the Ashkenas and Sherman results with $\gamma = 1.4$, for reasons which will be explained later. Results shown in Figure V-6 are from two sets of axial data obtained with the same pentode under the same dynamic conditions. The represented conditions are: the reservoir pressure, $P_o = 40$ psi, the pulse rate, $Q = 2$ pps, and the pulse width $dt = 1$ ms. At $\frac{x}{D} = 2$, the extrapolated Ashkenas and Sherman results predict a ratio of 35. However, the experimental results gave a much lower ratio of about 8. The reason for this discrepancy will be discussed below; however, as the experimental error bars show, the pentode results agreed well with the Ashkenas and Sherman predictions for $\frac{x}{D} \geq 4$.

It is possible to proceed still further using these normalized data sets. Figure V-6 shows the results of the following relationship:

$$\frac{S}{S^*} = \frac{\frac{P}{P_o}}{\left(\frac{P}{P_o}\right)_{\frac{x}{D}=6}}, \quad (5.1)$$

where S is the pentode signal at some $\frac{x}{D}$, S^* is the signal at $\frac{x}{D} = 6$, and the $\frac{P}{P_o}$ values are the corresponding Ashkenas and Sherman pressure ratios. Solving this equation for $\frac{P}{P_o}$, results in:

$$\frac{P}{P_o} = \frac{S}{S^*} \left(\frac{P}{P_o}\right)_{\frac{x}{D}=6}, \quad (5.2)$$

which gives the pressure ratio for the pentode in terms of the pentode signal. Figures V-7 and V-8 show the results of this procedure, given the data presented above, where Figure V-7 shows results for reservoir pressures of 10 and 20 psi and Figure V-8 shows the results for 30 and 40 psi. Once again, there appears to be

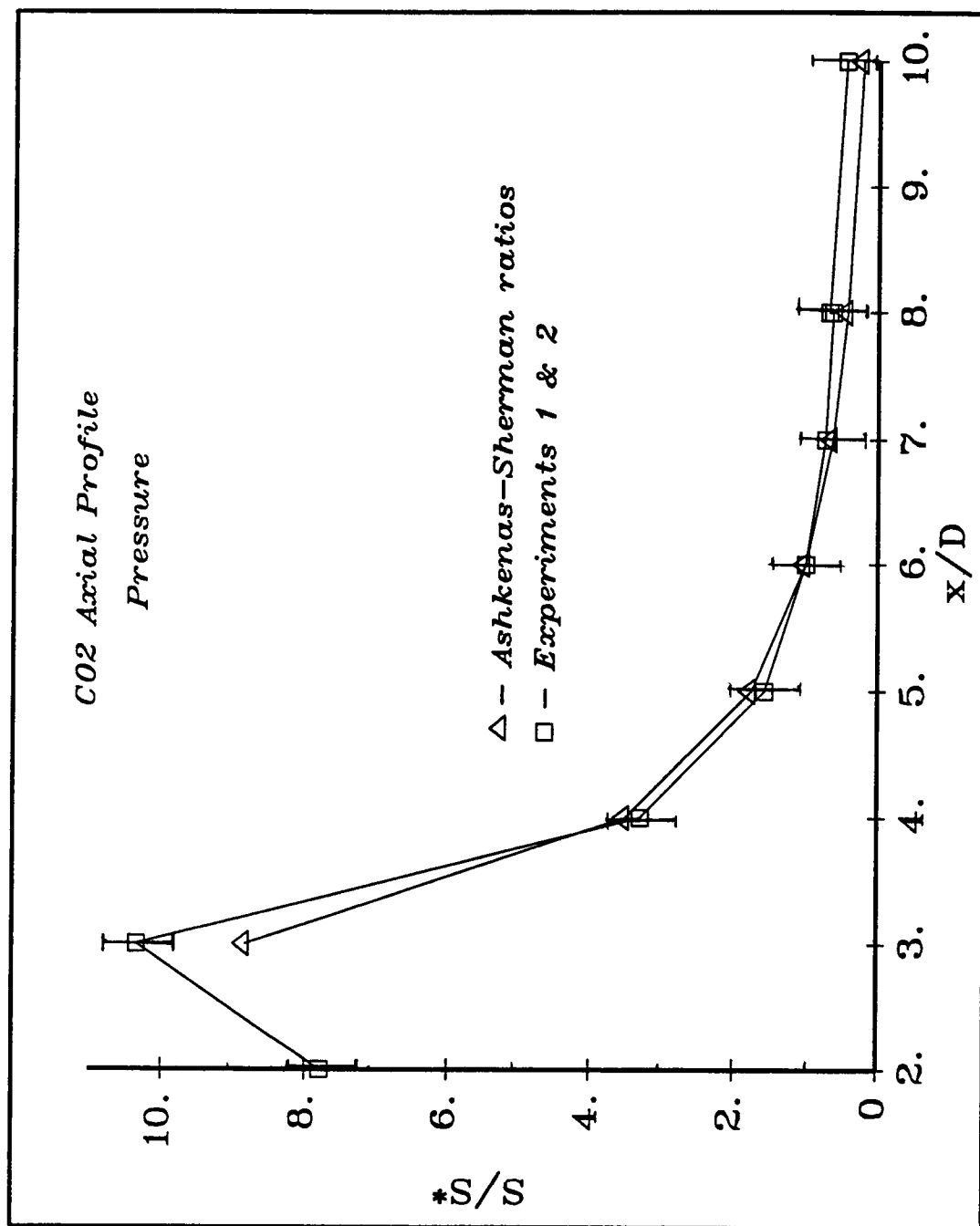


Figure V-6. CO_2 axial profile: signal ratios.

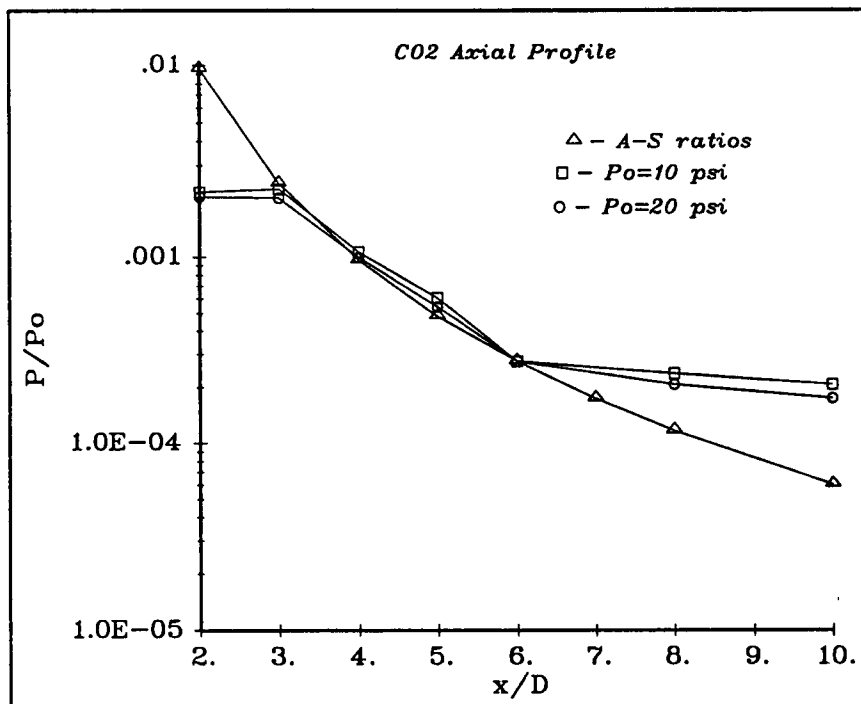


Figure V-7. CO_2 axial profile: pressure ratios ($P_o=10$ psi, $P_o=20$ psi).

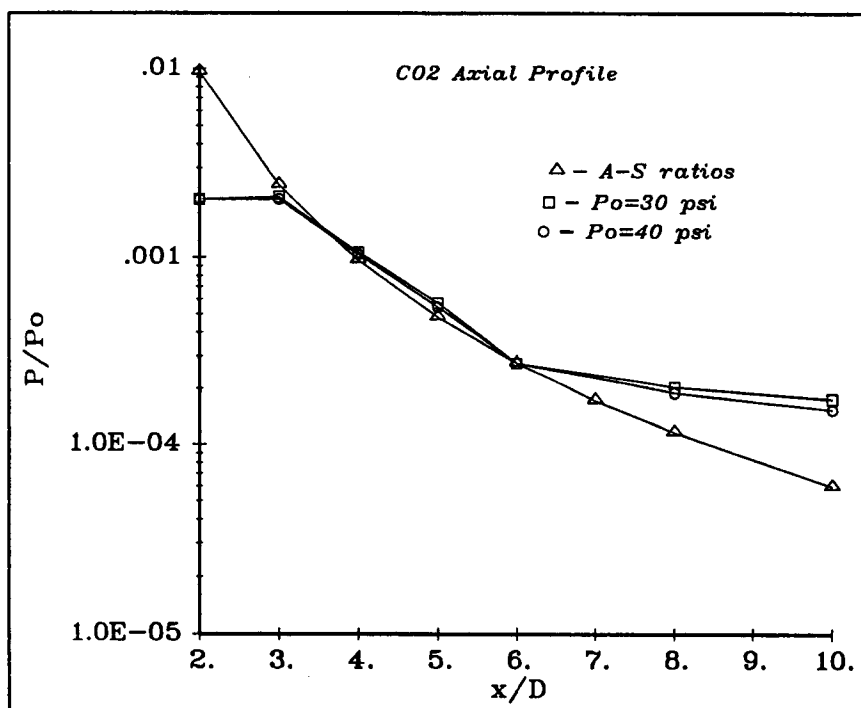


Figure V-7. CO_2 axial profile: pressure ratios ($P_o=30$ psi, $P_o=40$ psi).

good agreement between the experimental data and the Ashkenas and Sherman predictions.

The final step is to obtain the pressure values associated with the pentode signals. Multiplying the above equation by P_o , the pressure value can be related to the signal as:

$$P = \frac{S}{S^*} \left(\frac{P}{P_o} \right)_{\frac{x}{D}=6} P_o. \quad (5.3)$$

The agreement with the Ashkenas and Sherman results is still good with the exception of the difference at $\frac{x}{D} = 2$. This may be due to a shock forming when the skimmer is brought in this close to the nozzle. The presence and exact location of such a shock, however, is open to speculation and would require more data. Perhaps, a visualization of the flowfield would better resolve this question.

The raw, N_2 axial data, were also ratioed to the $\frac{x}{D} = 6$ results. A sample of the N_2 data is shown in Figure V-1, page 47. It is apparent from the normalized data shown in Figure V-9 that the N_2 data follow a trend similar to the CO_2 data and appear to agree well with the Ashkenas and Sherman predictions. The N_2 data also show a lower ratio at $\frac{x}{D} = 2$; however, unlike the CO_2 data, the N_2 data do not show an increase in peak in the region from $\frac{x}{D} = 2$ to $\frac{x}{D} = 3$. The reason for this may be that N_2 did not experience shock formation but that CO_2 did. More experiments would, perhaps, provide an answer.

Following the same procedure with the N_2 data that was used to reduce the CO_2 data, the pressure ratio variation with the axial position was determined. The resulting data compared well with the Ashkenas and Sherman prediction. Like the CO_2 data, the N_2 data were reduced further to give the pressure change with axial distance, which, again, agreed well with the predicted values.

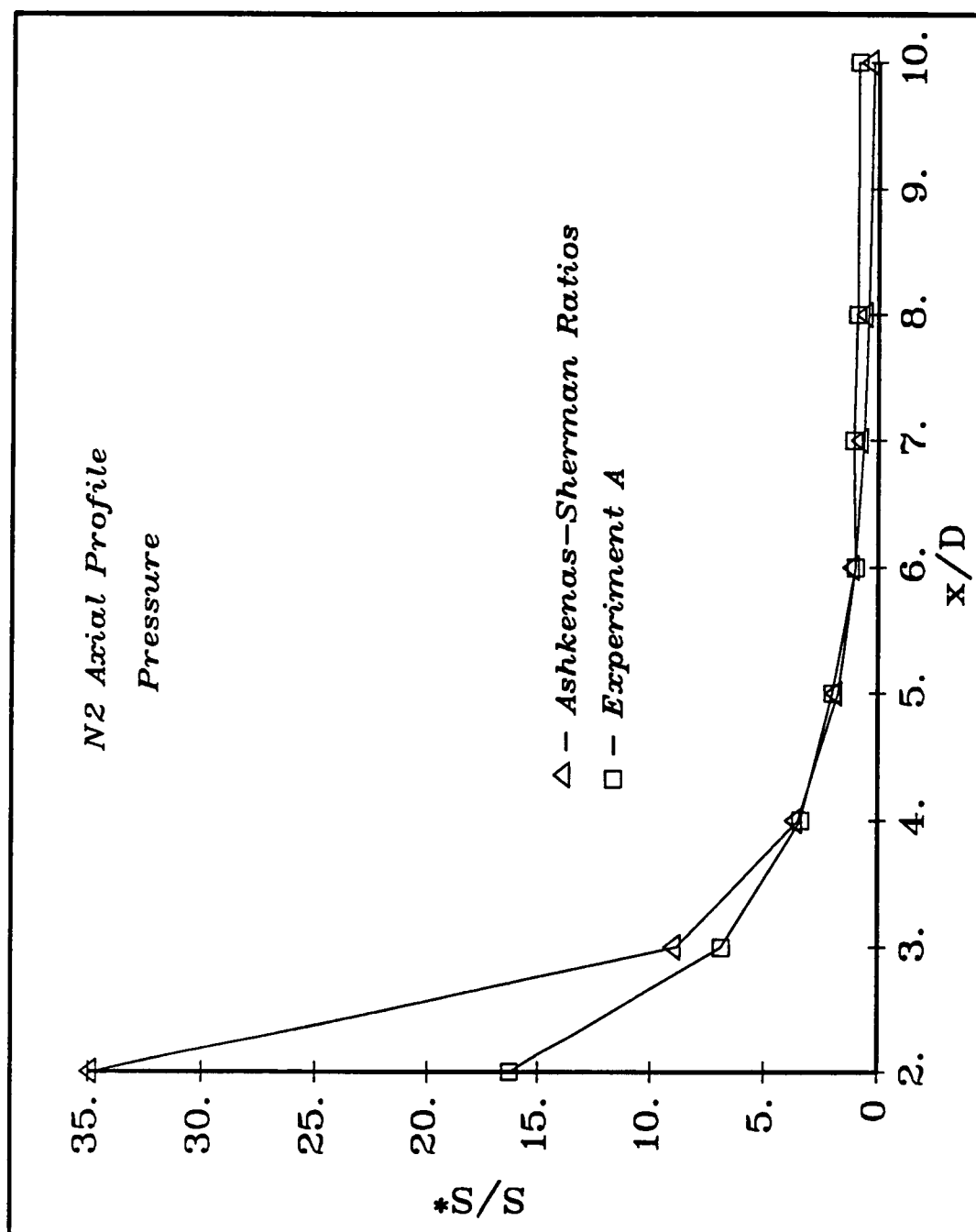


Figure V-9. N_2 axial profile: signal ratios.

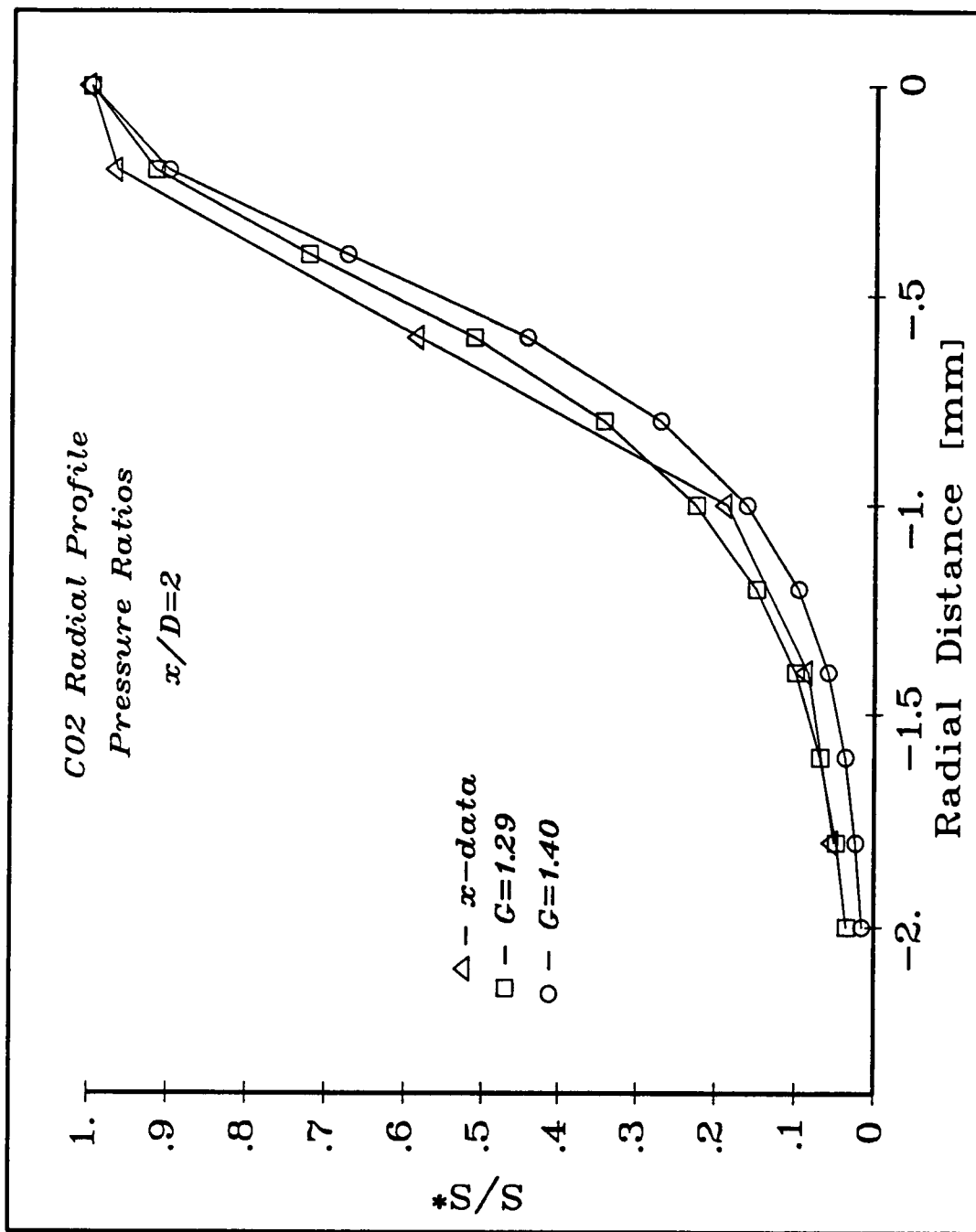


Figure V-10. CO_2 radial profile: pressure ratios ($\frac{x}{D} = 2$).

Radial Data

A radial scan was done for a pulsed, CO_2 flow. The raw data from this portion of the experiment are extensive, so only the resulting peaks, normalized to the $\frac{x}{D} = 6$ data, from the scan are presented. Figure V-10 shows the radial variation of the plume, traversing in the negative x direction, at the axial position of $\frac{x}{D} = 2$. Similar results for $\frac{x}{D} = 5$, and 10 are given in Figures V-11 and V-12. Also shown in Figures V-10 through V-12 are the Ashkenas and Sherman predictions for three γ values. The reason for this ambiguity will be discussed shortly. It should be noted that the x-axis shows the relative distance, which is just the distance traversed as related to the center of the plume located as stated previously. As expected, the radial variation of the plume varies greatly with the axial position. The plume is quite narrow at $\frac{x}{D} = 2$, approximately 2 mm, but it broadens appreciably to about 5 mm at $\frac{x}{D} = 10$. The agreement with the Ashkenas and Sherman predictions for a $\gamma = 1.4$ is reasonably good at the axial positions of $\frac{x}{D} = 5$ and 10. The $\frac{x}{D} = 2$ data show better agreement with the $\gamma = 1.29$ prediction. This apparent discrepancy will be resolved in the discussion to follow.

Time of Flight

An attempt was made to determine the time of flight for the molecules to travel from the nozzle to the pentode. Raw data for CO_2 at $\frac{x}{D} = 2, 5$, and 10 (Figures V-2 through V-5, pages 48 and 49) show an initial, very small peak at about 20 microseconds, which was produced by the source trigger. The electrical pulse, sent by the valve driver to open the nozzle, triggered the digital oscilloscope

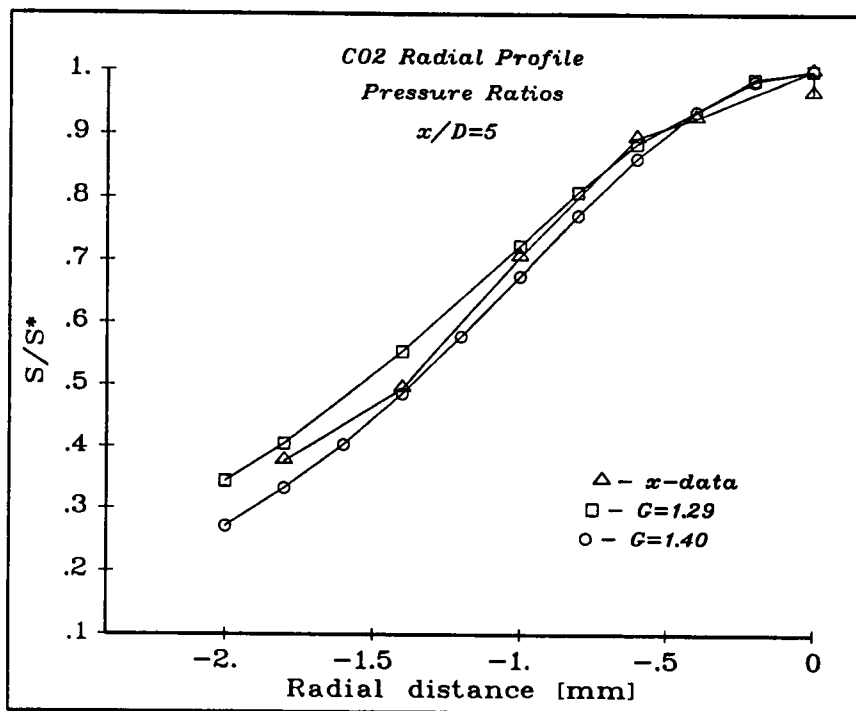


Figure V-11. CO_2 radial profile: pressure ratios ($\frac{x}{D} = 5$).

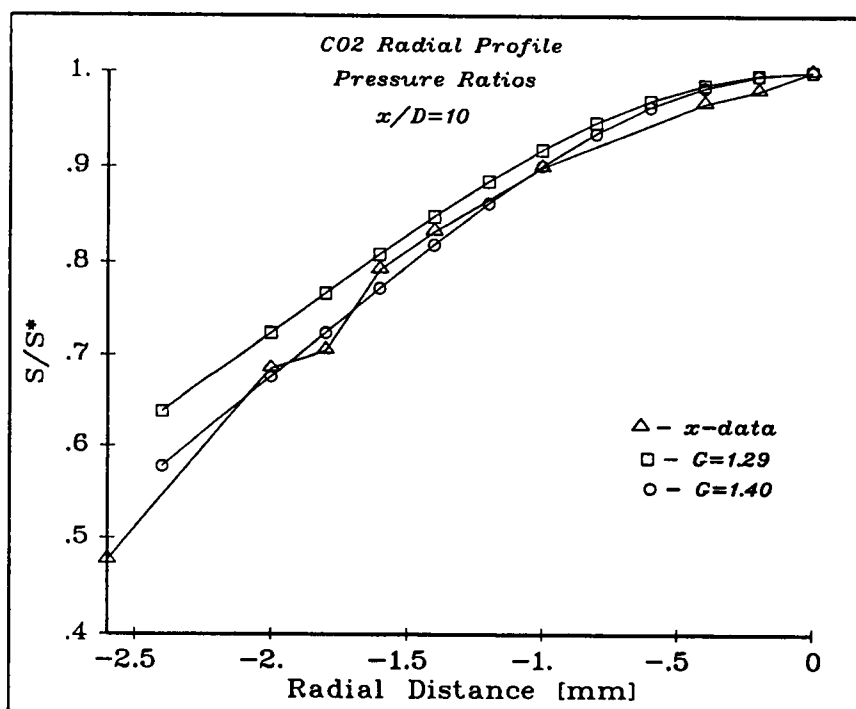


Figure V-12. CO_2 radial profile: pressure ratios ($\frac{x}{D} = 10$).

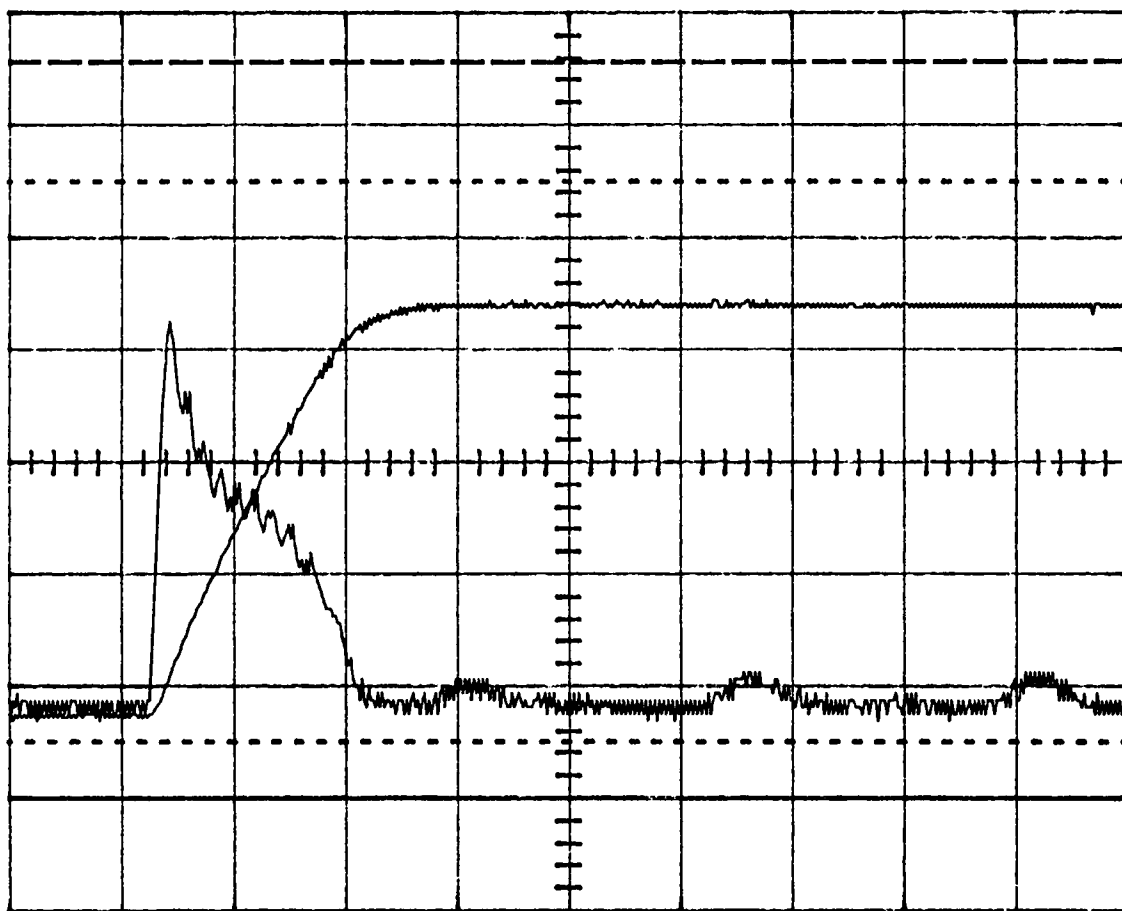


Figure V-13. Trigger signal.

for data taking. Figure V-13 shows that the pentode picked up the trigger signal as well. The top curve is the pulse produced by the nozzle. The bottom curve is the signal given by the pentode, when the pentode was still intact, that is, the glass envelope was left on. The correlation between the rise time of the nozzle pulse and the width of the initial small pulse, or electronic signal, observed by the pentode seems to indicate that the electronic pulse was synchronous with the opening of the nozzle. Initially, it was believed that the trigger pulse provided a time zero point for a time of flight determination. Several unsuccessful attempts were made to relate the trigger pulse to the time of flight, such as, taking the difference between the end time of the trigger pulse and the start of the rise in the pentode pulse, or the peak in the gauge pulse. Then, a comparison for these values at various $\frac{x}{D}$ positions was done. Of course, the expectation was that as the axial distance was increased, the time of flight, and thus, the distance between peaks, would increase. No such trend was observed. Therefore, the time of flight question requires more data and perhaps, modification to the experimental system.

SECTION VI

ANALYSIS OF RESULTS

Comparison with Predictions

The determination of the value of the specific heat ratio, γ , was necessary for the evaluation of the CO_2 data. The calculation of γ for CO_2 , while it is in the reservoir, can be performed using the methods described by McQuarrie [9], which yields a value of 1.287. However, this steady-state value of γ is only correct assuming that CO_2 does not experience relaxation of any of its modes. Experimentally, it has been shown that CO_2 does, indeed, undergo a freezing of its vibrational mode as it is expanded. Sharma, et. al. [12] have used experimental results to create a ‘sudden freezing’ model of this relaxation process. Using this model, freezing of the vibrational mode of CO_2 was predicted to occur at an axial distance $\frac{x}{D} < 2.75$. Therefore, experimental results might show CO_2 starting with a $\gamma = 1.29$ and, as the expansion progresses, γ should increase to $\gamma = 1.4$ due to the freezing of the vibrational mode. Figures V-11 and V-12, page 57, seem to indicate that $\gamma = 1.4$ is a reputable value for the expanding CO_2 . Figure V-10, page 56, which shows the radial variation of pressure ratios at $\frac{x}{D} = 2$, draws good agreement between the experimental data and the Ashkenas and Sherman predictions extrapolated for this region for $\gamma = 1.29$.

Throughout this paper the assumption has been made that the pentode is measuring pressure as opposed to number density or flux. Perhaps, from the theoretical basis of the pentode, that is, the fact that it basically measures the number of ions produced, one would conclude that the pentode actually measures number density rather than pressure. In Figure VI-1, the Ashkenas and Sherman

pressure, number density and flux ratios are compared to the experimental data for CO_2 and N_2 with a reservoir pressure of 40 psi. At $\frac{x}{D} \geq 6$, the difference between the pressure, number density and flux theoretical values is negligible. Thus, while the data do agree with the theoretical values for pressure, this provides no evidence to support the pentode-as-pressure gauge theory. For smaller $\frac{x}{D}$ values, there appears to be better agreement between the data and the pressure curve, rather than the number density or flux curves. However, at $\frac{x}{D} = 2$ and 3, there is considerable uncertainty in the data due to the high pressures being measured and the possibility of shock formation. The $\frac{x}{D} = 4$ data point, which is, perhaps, the only reliable point, shows good agreement with the pressure curve. This data point is reliable because it is probably unmarred by shocks or condensation effects. As will be shown, condensation appeared in the flow at $\frac{x}{D} = 4.5$. Thus, higher $\frac{x}{D}$ values may be showing the effects of condensation. Therefore, the only conclusion to be derived from Figure VI-1 is that the data are in agreement with the pressure measurement theory, but they do not conclusively prove the theory. Perhaps, better support for the pentode-as-pressure gauge theory can be found in the explanation of how the ionization gauge measures pressure.

The behavior of the pentode can be compared with the ionization gauge theory arrived at by Smetana and Daggerhart [15]. The small, compact size of the pentode, which is in essence an ion gauge, allows a temperature increase of the entire gauge when the filament is heated to a working temperature. A majority of the gas particles entering the gauge at higher pressures and smaller mean free path lengths strike the pentode structure before becoming ionized and being collected. They, therefore come into equilibrium with the gauge structure temperature, which is independent of their original temperature. Thus, the particles collected by the pentode represent a portion of those at pressure equilibrium with the surrounding

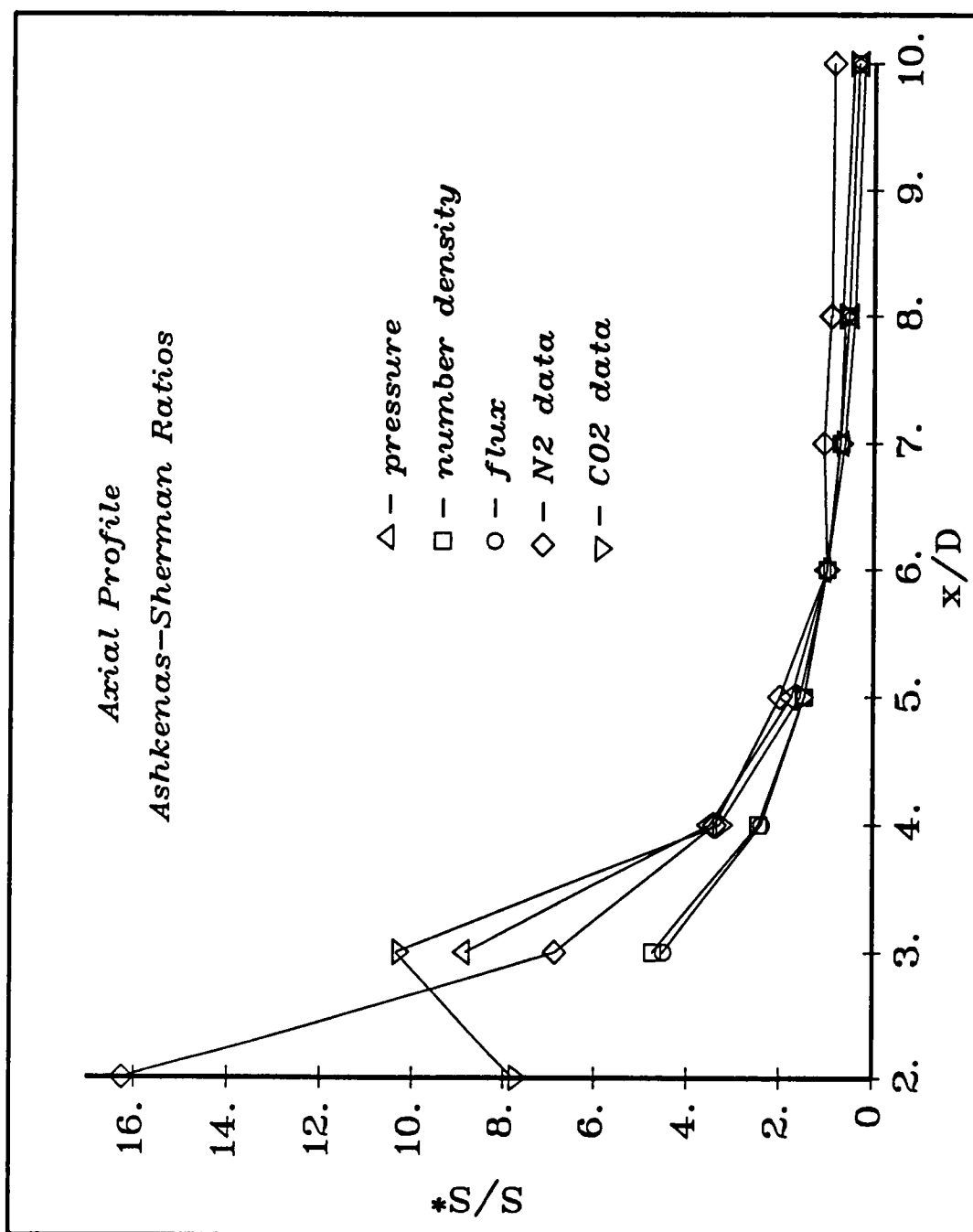


Figure VI-1. Axial profile: comparison of pressure, number density and flux ratios with CO_2 and N_2 data.

gas and having constant temperatures. Thus, the pentode should continue to behave as a pressure gauge until a pressure or density is reached such that the mean free path becomes larger than the filament dimensions. The dimensions of the filament may be approximated to be less than 0.01 mm, indicating proper pentode performance as a pressure gauge up to a pressure of about 44 torr. As shown in Figure III-3, page 20, this pressure was not reached in these experiments. Thus, the pentode gauge was, indeed, reading pressure as desired.

The presence of the skimmer in the flowfield introduced a number of new parameters. The purpose of the skimmer was discussed previously. However, the concerns caused by its presence were not approached until now. As discussed earlier, the design of the skimmer was based partially on the mean free path of the gas. Using the Ashkenas and Sherman equations, along with a couple of approximations, the variation of the mean free path with axial distance was obtained (Figure III-9, page 26), which lead to the skimmer diameter of 1 mm. A previous discussion showed that the best skimmer half-angle was 41° . Liepmann and Roshko predicted the presence of an attached shock when a cone with a half-angle less than the oblique shock angle is placed in a supersonic flowfield. Thus, it was believed that an attached shock existed throughout these experiments. The data imply that this was the case. More accurately, the data indicate neither the presence of a detached shock, nor, as will be shown, conclusive existence of a shock within the skimmer.

Returning to the pumping equations that gave the pressure versus time relationship for the experimental setup provides a theoretical comparison for the data. The equation:

$$\frac{dP}{dt} = \frac{\dot{m}_i RT}{MV_c} + \frac{a_c A_c}{V_c} - \frac{SP}{V_c} \quad (6.1)$$

can be modified to consider the time response of the skimmer system. The new

$\dot{m}_i(skimmer)$ is given by

$$\dot{m}_i(skimmer) = \left(\frac{\dot{m}_i}{A} \right)_{source} A_{skimmer} \quad (6.2)$$

and the values of a_c , A_c , and V_c are now the skimmer quantities. The pumping speed, S , must also be changed to a pumping speed that corrects for the smaller area of the skimmer exit being pumped, rather than the large area of the chamber. The resulting pumping speed is

$$S = \bar{S} A_{exit_{skimmer}}, \quad (6.3)$$

where $\bar{S}$ is the standard pumping speed for air (or N_2) of 10 *liters/sec* – cm^2 and $A_{exit_{skimmer}}$ is the area of the skimmer exit, 2.38 cm^2 . Initially, the above relationship was used to obtain a theoretical pressure response for the skimmer system. However, another consideration was added in order to improve the validity of the predicted response. The $\dot{m}_i$ value being used above provides a value for the mass flow rate but only at the radial center point. This neglects the fact that there is, in reality, a radially dependent flux rather than a streamline $\dot{m}_i$. More realistic $\dot{m}_i$ values were obtained by integrating the Ashkenas and Sherman predictions for the radial variation of the flux over the area of the skimmer entrance. This provided a larger and, in fact, more representative mass flow rate. The results of the theoretical predictions were then compared with the pulses obtained from the experiments, as shown in Figures VI-2 through VI-6. The experimental pulses were recorded in millivolts, the peaks of which were converted to pressure in torr, using the static calibration equation. The pulses were, then, scaled, accordingly. The N_2 data showed consistently lower peaks than theory predicted (Figure VI-7), whereas, CO_2 showed larger peaks than the theory (Figures VI-2 through VI-6). As mentioned earlier, the pentode sensitivity deteriorates with age, resulting in a

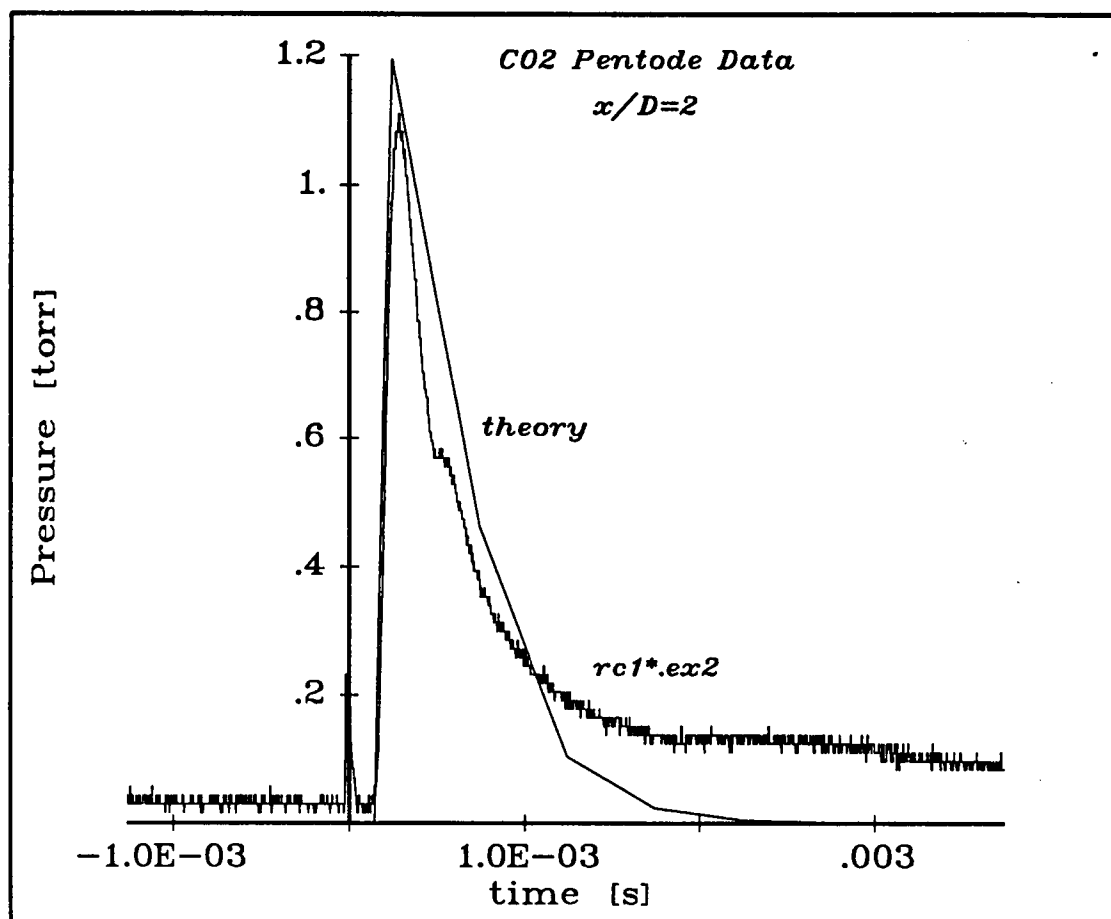


Figure VI-2. CO₂ pentode pulse compared with theory ($\frac{x}{D} = 2$).

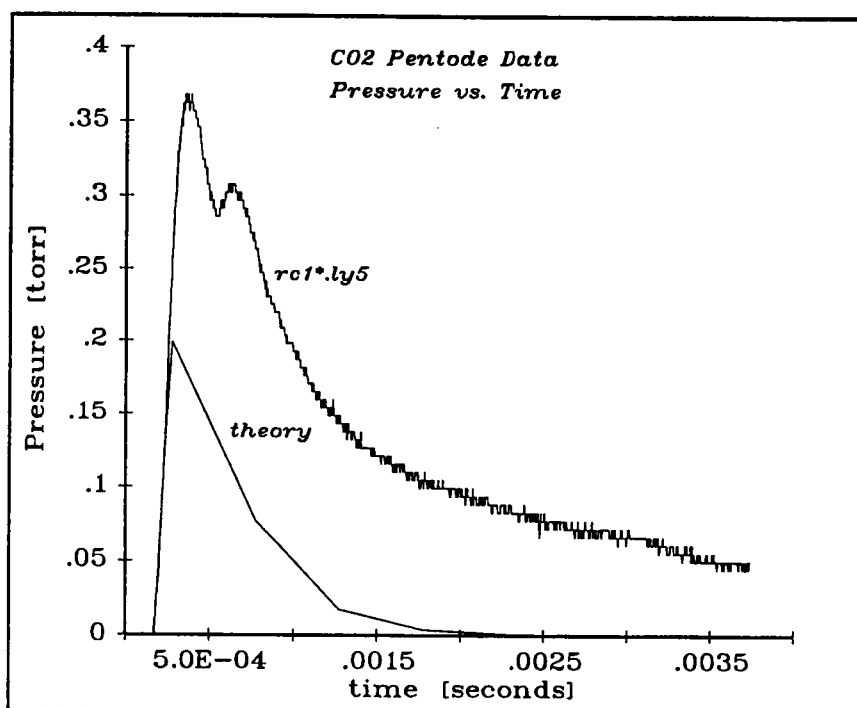


Figure VI-3. CO₂ pentode pulse compared with theory ($\frac{x}{D} = 4$).

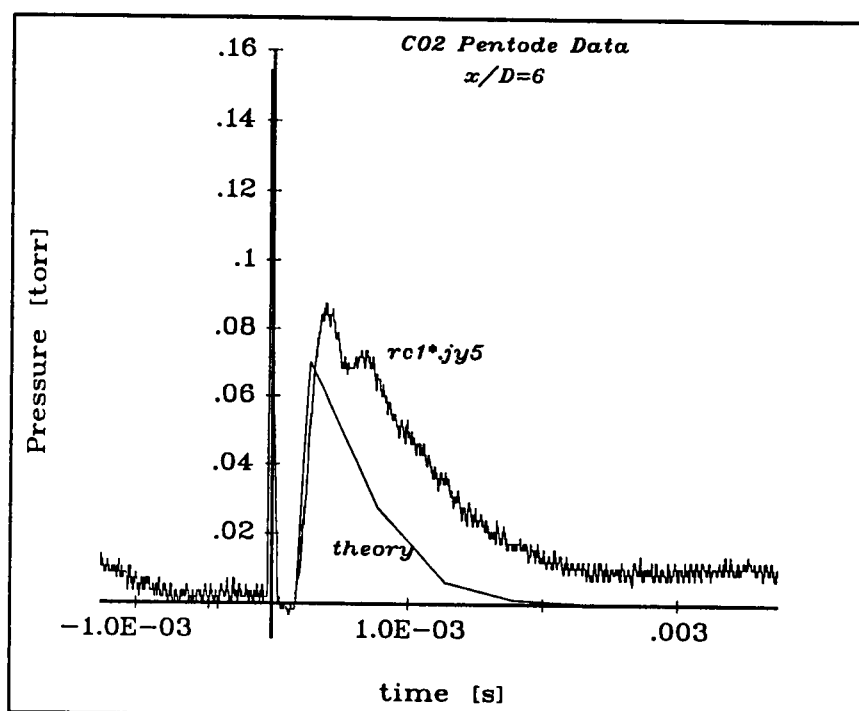


Figure VI-4. CO₂ pentode pulse compared with theory ($\frac{x}{D} = 6$).

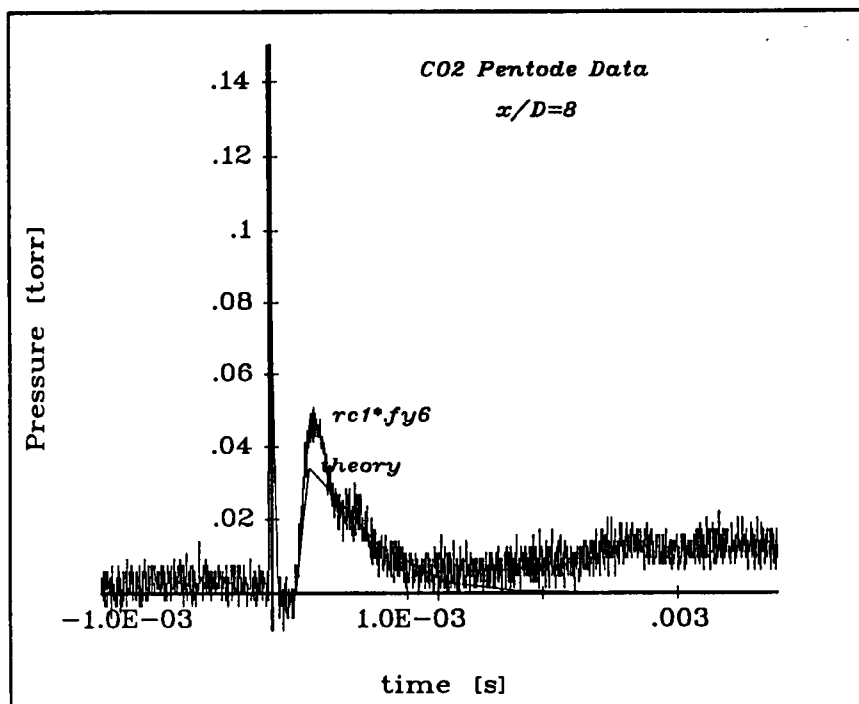


Figure VI-5. CO_2 pentode pulse compared with theory ($\frac{x}{D} = 8$).

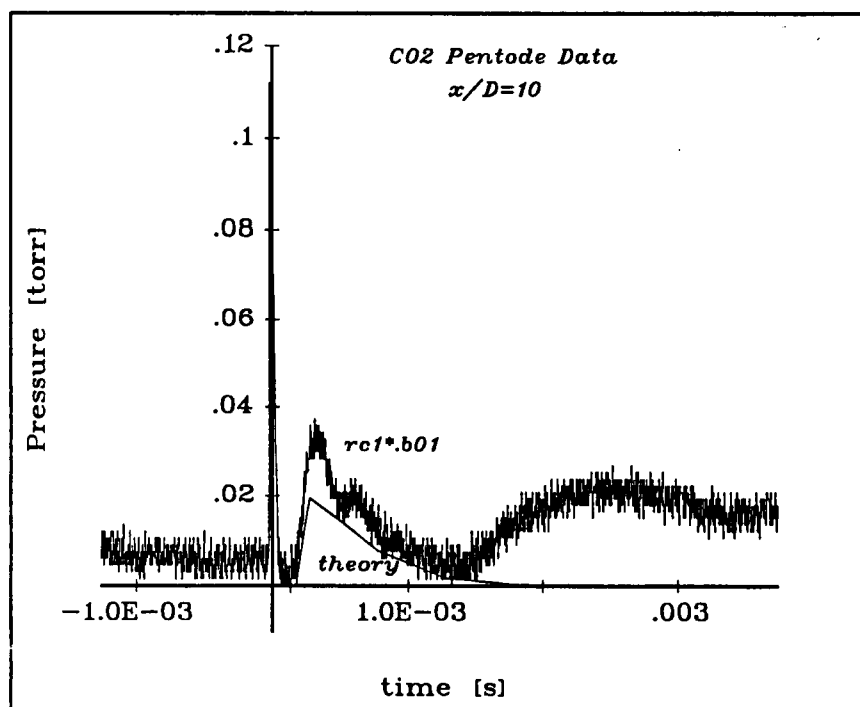


Figure VI-6. CO_2 pentode pulse compared with theory ($\frac{x}{D} = 10$).

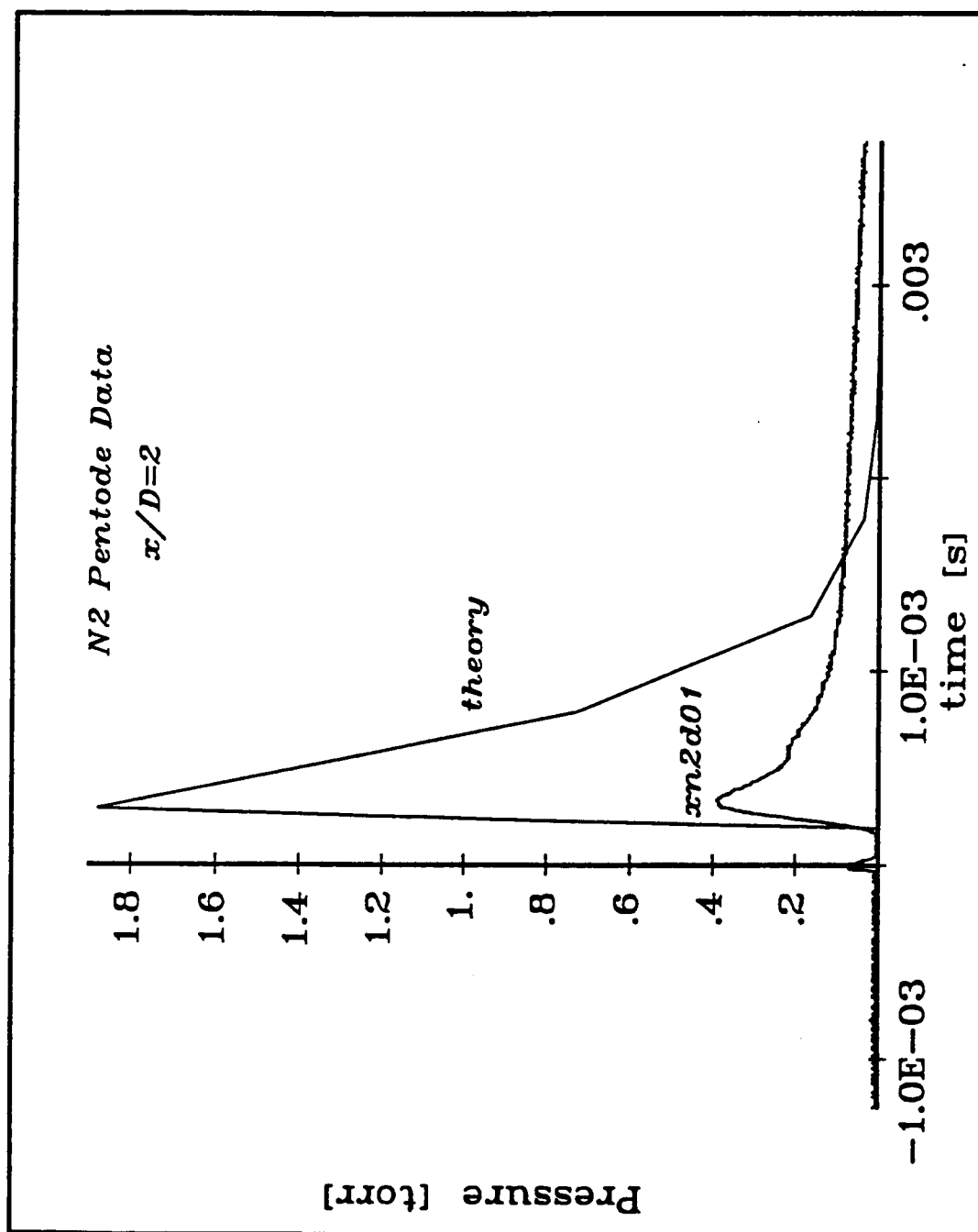


Figure VI-7. N_2 pentode pulse compared with theory ($\frac{x}{D} = 2$).

decrease in pulse size, which was more pronounced at lower $\frac{x}{D}$ values (see Figures VI-8 and VI-9). For example, at $\frac{x}{D} = 3$, the pulse decreased from about 3200 to 1000 mV over about 60 days, whereas, for $\frac{x}{D} = 5$ the pulse height went from about 500 to 240 mV in the same period of time. Thus, over 60 days, the pentode peaks decreased by a factor of 3.2 for $\frac{x}{D} = 3$ and by a factor of 2.1 for $\frac{x}{D} = 5$. The N_2 data shown were taken when the pentode was approximately 60 days old. The CO_2 data, however, were taken with a 7-day-old pentode. Therefore, the N_2 data are misleading and discussing it further, in this regard, is not necessary.

The experimental pulses for CO_2 are larger in all cases, with the exception of $\frac{x}{D} = 2$. Small [13] noted similar effects, when comparing static with dynamic results, stating "allowances must be made for the fact that this pentode does not allow the gas to freely flow through its sensing region." The large experimental pulses for the rest of the CO_2 data may, then, be explained by the fact that the desired infinite pumping on the skimmer exit was not truly attained, which resulted in a minor pressure buildup within the gauge. However, recalling the Knudsen number variation with axial distance (Figure III-10, page 26) may, also, provide a clue to the reasons for the elevated experimental pressures. At $\frac{x}{D} = 2$, the Knudsen number is about .004, which is well into the continuum flow regime. However, at $\frac{x}{D} = 4$, the Knudsen number increases to about 0.06, which is in the slip flow region. The Knudsen number continues to increase into the transitional flow regime, to about .6 at $\frac{x}{D} = 10$. As stated earlier, boundary layer effects increase with increasing Knudsen number. Thus, at $\frac{x}{D} = 2$ such effects are probably negligible, whereas, increasing axial distance increases the likelihood of such interference. Experimentally, the larger axial distances gave consistently higher pressures than theory predicted, which points toward boundary layer interferences. Although the effect is noticeable at $\frac{x}{D} = 4$ and 6, it appears

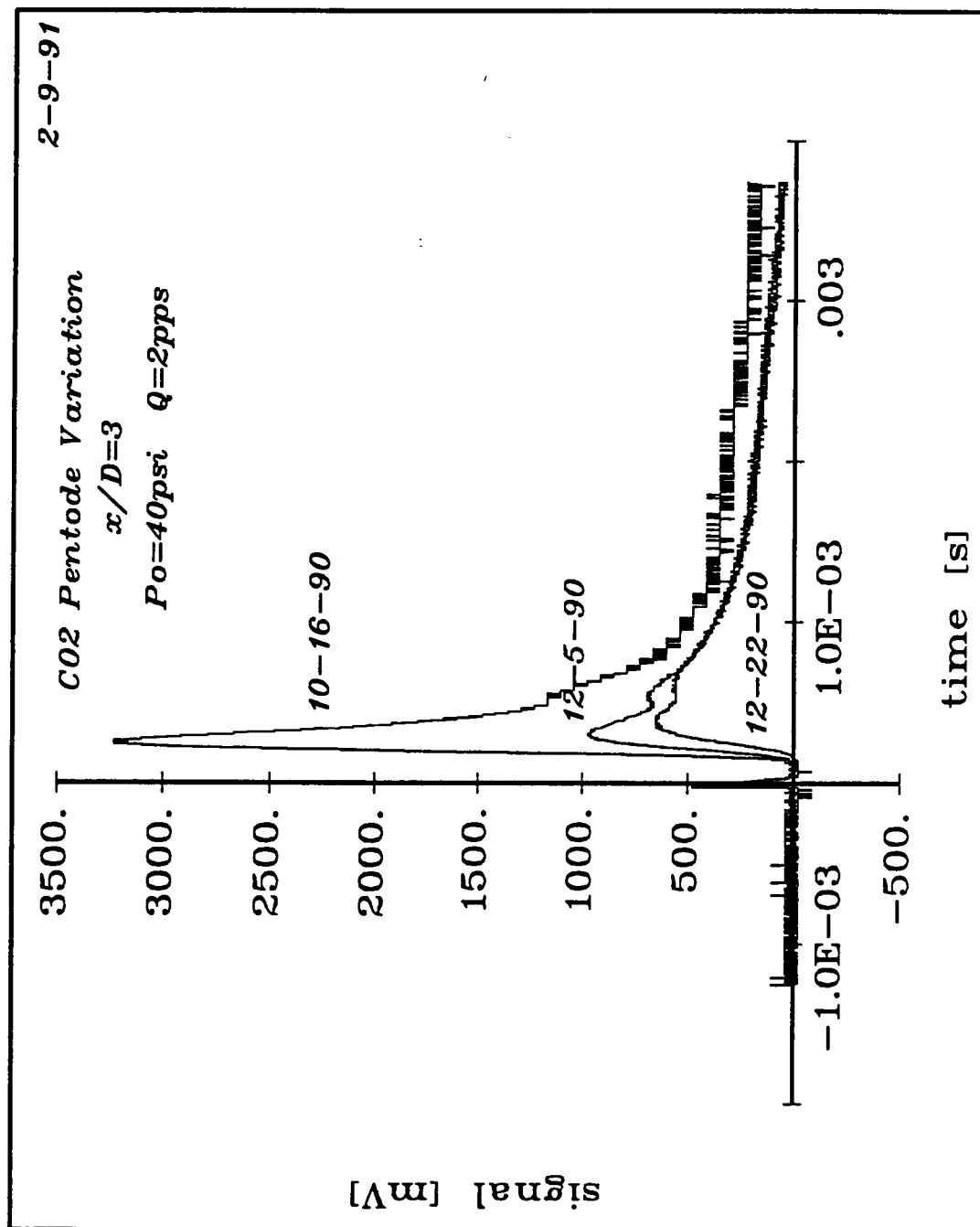


Figure VI-8. CO_2 pentode variation with age ($\frac{x}{D} = 3$).

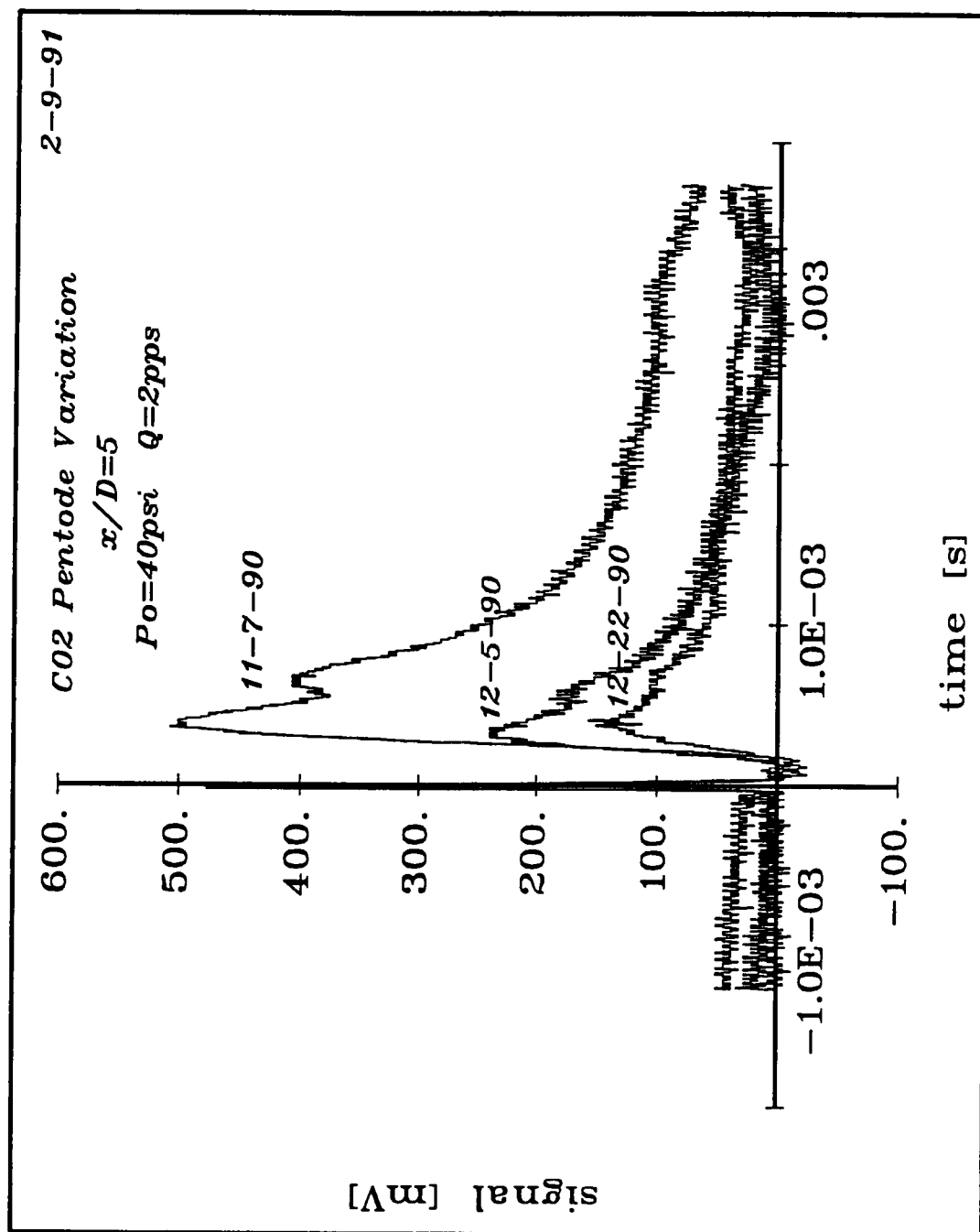


Figure VI-9. CO₂ pentode variation with age ($\frac{x}{D} = 5$).

to decrease with $\frac{x}{D} = 8$ and 10. At these distances, free molecular flow is approached and the pentode is operating in almost static conditions, thus, giving readings in agreement with theory. The graphs do, however, indicate that the pumping was adequate enough to 'pump the shock', or eliminate the shock. Thus, the assumption that no shock existed in front of the skimmer appears appropriate; however, another comparison gives more adequate proof.

With the skimmer in the flowfield three possible flows may exist. The first flow is straight through the skimmer, where the gas expands as predicted by Ashkenas and Sherman from the nozzle to the pentode. The resulting pressure ratio as a function of Mach number, along with the CO_2 data, is shown in Figure VI-10. The theory shows poor agreement with the data, which leads to the conclusion that this flow is not that of the experiment. The second possibility is for a shock to form in front of the skimmer. A normal shock in front of the skimmer would cause the supersonic Mach number, M_1 , to be shocked down to a subsonic Mach number, M_2 . After the shock, there is a new stagnation or reservoir pressure, p_{02} . The flow then, re-expands into the skimmer but with p_{02} as the new reservoir pressure. Thus, the pressure within the skimmer would reach a higher value than if no normal shock had existed. The equations relating the pressures before and after the shock in this case are given by:

$$\frac{p_{02}}{p_{01}} = F_1 F_2, \quad (6.4)$$

where

$$F_1 = \left(\left(1 + \frac{2\gamma}{\gamma+1} \right) (M_1^2 - 1) \right)^{\frac{-1}{\gamma-1}} \quad (6.5)$$

and

$$F_2 = \left(\frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2 + 2} \right)^{\frac{\gamma}{\gamma-1}}. \quad (6.6)$$

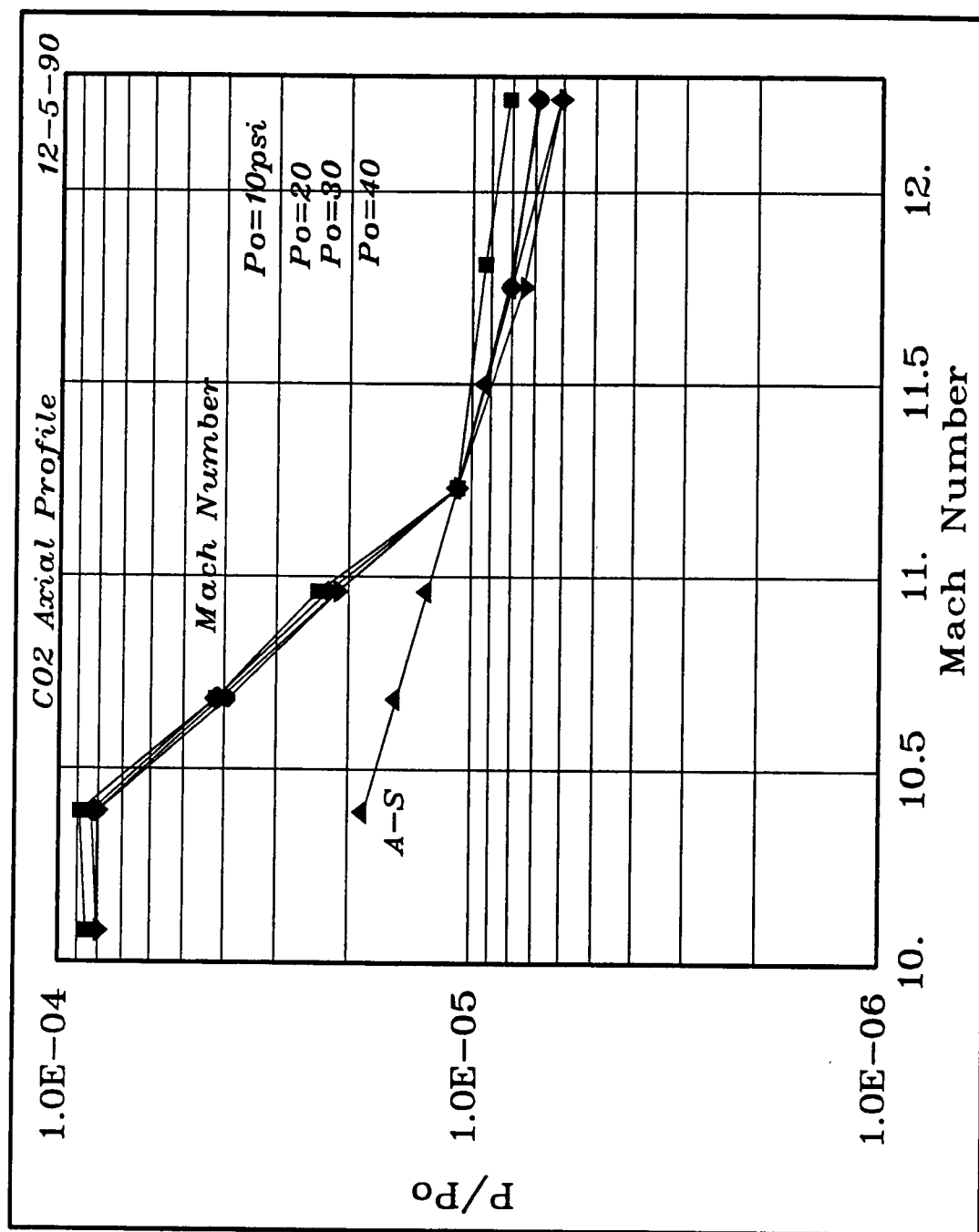


Figure VI-10. CO_2 axial profile: Ashkenas-Sherman flow through expansion.

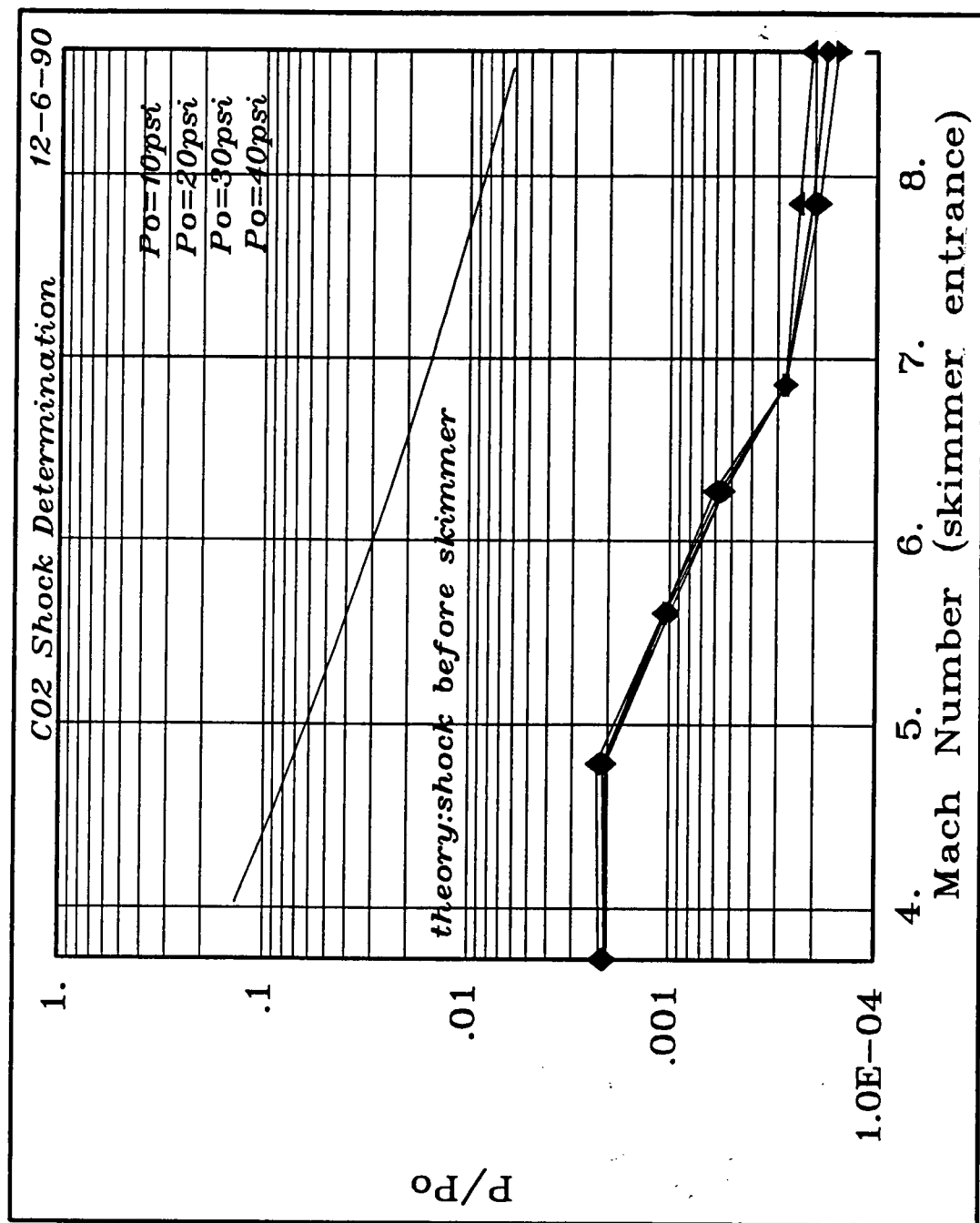
The pressure observed by the gauge is proportional to the pressure after the shock and therefore is proportional to the initial pressure, p_{01} . The resulting pressure in the gauge would then show a Mach number, M_1 , and $\frac{x}{D}$ dependence that did not agree with Ashkenas and Sherman predictions. Figure VI-11 shows the CO_2 data for various P_o values as compared to this theory. The data differ from the theory by a factor of about 100, implying that there was no normal shock present during these experiments. The third possibility is that a shock existed within the skimmer. The presence of this type of shock is not calculable, but would result in an increase in the pressure obtained by the pentode. Based on the fact that higher experimental pressures were observed by the pentode than theory predicted the existence of such a shock appears possible, if not likely. However, the higher pressures observed may also be due to the presence of condensation, which will be discussed below.

Analysis of Flowfield

Due to the higher-than-predicted pressures observed, some consideration was given to the possibility that condensation existed within the flow. The two points to be determined were the axial distance where saturation was expected and the point where condensation occurred. Using the isentropic expansion equation:

$$\frac{P}{P_o} = \left(\frac{T}{T_o} \right)^{\frac{\gamma}{\gamma-1}}, \quad (6.7)$$

the pressure versus temperature was plotted on a log-log scale. The points of intersection with the vapor pressure curve provide the pressure and temperature values for saturation onset. Figure VI-12 shows the curves for CO_2 with $\gamma = 1.4$. Using the pressure ratioed to the reservoir pressure, the $\frac{x}{D}$ location for saturation onset was determined through the Ashkenas and Sherman equations. Determining

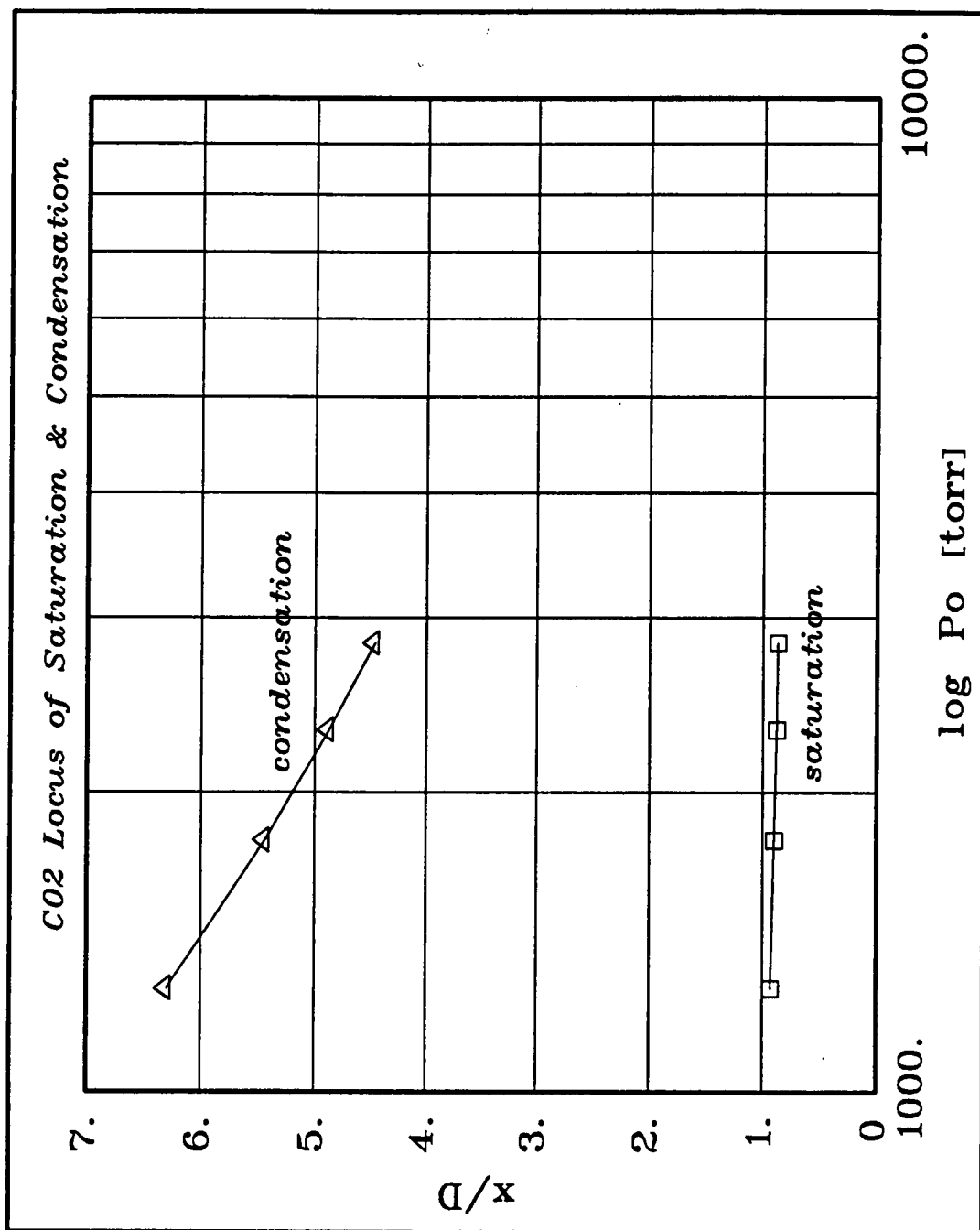
Figure VI-11. CO₂ shock determination.

the condensation onset location required the experimental results of Williams and Lewis [18]. They presented a set of equations that predict the location of condensation onset for expanding flows. The following proportionality was arrived at through the fitting of their data:

$$\hat{x}_\theta \propto \left(P_o^{m_2} D_{eq} \right)^{-m_3} T_o^{m_4}, \quad (6.8)$$

where $\hat{x}_\theta$ is the axial location of condensation onset, P_o is the backing pressure, T_o is the reservoir temperature, D_{eq} is the equivalent orifice diameter, and m_2 , m_3 , and m_4 are experimental, gas specific constants. The equivalent, orifice diameter is a concept initially, presented by Hagena in [5], which uses the physical size of the molecule and another constant derived by Hagena to relate all types of nozzles to a standard equivalent diameter. The equivalent diameter was not of significance in this case, however, since the values used in the present experiment were ratioed to the data of Williams and Lewis. This equation provided the axial distances for the condensation onset in the present experiment for both CO_2 and N_2 . Clearly, Figure VI-12 shows that the onset of saturation occurs very early, at $\frac{x}{D} \leq 1$ (where extrapolation techniques have been used to obtain Ashkenas and Sherman results in this region), for CO_2 , while the onset of saturation was calculated to occur at $\frac{x}{D} = 7.6$ for N_2 . Saturation indicates that condensation is possible, but does not conclusively prove that condensation exists. The condensation onset, as predicted from the use of the Williams and Lewis data, occurs at $\frac{x}{D} \approx 4.5$ for CO_2 and at $\frac{x}{D} \approx 75$ for N_2 . Thus, the presence of condensation in the CO_2 flow is indicated to occur for $\frac{x}{D} \geq 4.5$. The calculations show that the N_2 flows observed in these experiments do not contain condensates.

Condensation in the flow would cause increased pressures after the point of condensation onset. This effect was observed, as shown in Figures VI-2 through VI-6. Figure VI-2 shows that the data agree well with predicted pressure for

Figure VI-12. CO_2 locus of saturation and condensation.

$\frac{x}{D} = 2$, which was a pre-condensation distance. At $\frac{x}{D} = 4$, saturation occurred indicating condensation was possible. Figure VI-3 shows higher-than-predicted pressures, which may indicate condensation occurred as early as $\frac{x}{D} = 4$. Higher axial distances (Figures VI-4 through VI-6) show higher-than-predicted pressures giving further evidence for the presence of condensation.

SECTION VII

CONCLUSION

In summary, these experiments demonstrate the usefulness of the pentode as a fast response, non-optical pressure gauge. The subminiature CK-5702 has a $20\mu\text{sec}$ risetime and is small in size so that interference effects are minimized. Observations made with the skimmer-pentode apparatus placed in the pulsed flowfield of a sonic orifice lead to the following conclusions:

- 1 . Placement of a skimmer between the pentode and nozzle allowed better interpretation of the flowfield region under observation, as well as, closer placement of the pentode to the pulsed source.
- 2 . The problems associated with the aging of the pentode can be avoided with real-time calibration of each pentode.
- 3 . The pentode provides a qualitative monitor for comparison of various source and flowfield parameters. With real-time calibration, the pentode becomes a gauge for quantitative measurements.
- 4 . The pentode is capable of spanning a pressure range of 1×10^{-4} to 5 torr, while maintaining a $20 \mu\text{sec}$ response time.
- 5 . Although the data do not conclusively show the pentode is a pressure gauge, they do agree with this theory.
- 6 . Theoretical pressure variation with time predictions compared well with the actual pentode pulses, especially considering that the possibility for shock or boundary layer interference, and condensation were not included in the theoretical model.
- 7 . Condensation occurred at $\frac{P}{D} \geq 4.5$ for CO_2 , while N_2 showed no condensation. However, the pentode data did not, conclusively, represent the presence or absence of condensation.

SECTION VIII

RECOMMENDATIONS FOR FUTURE WORK

During the experiments presented here, a number of questions arose about the pentode results, leading to the following suggestions for future research.

- 1 . A visualization of the flowfield would provide a good comparison for the pentode results, and perhaps, give conclusive evidence for or against the presence of attached or detached shocks.
- 2 . Modification of the experimental apparatus, in order to do time of flight measurements, is desirable so that a risetime for the pentode may be obtained experimentally.
- 3 . Both of the above suggestions would also provide a better indication of the presence and extent of condensation in the flowfield.

LIST OF REFERENCES

LIST OF REFERENCES

1. Anderson, J. and J.B. Fenn, 'Background and Sampling effects in free jet studies by molecular beam measurements', *Rarefied Gas Dynamics*, Fourth Symposium, Vol. II, edited by J.H. deLeeuw, Academic Press, New York, (1966), pp. 311-330.
2. Ashkenas, H. and F. S. Sherman, 'The Structure and Utilization of Supersonic Free Jets in Low Density Wind Tunnels,' *Rarefied Gas Dynamics*, Fourth Symposium, Vol. II, edited by J.H. deLeeuw, Academic Press, New York, (1966) pp. 84-105.
3. Buckley, O.E., 'An Ionization Manometer,' *Proceedings of the National Academy of Science of the United States*, Vol. 2 (1916) pp. 683-685.
4. French, J. Barry, 'Continuum-Source Molecular Beams,' *AIAA Journal*, Vol 3 (June, 1965) pp. 993-1000.
5. Hagena, Otto, 'Condensation in Supersonic Free Jets,' *Rarefied Gas Dynamics*, edited by L. Trilling and H.Y. Wachman, Academic Press, New York, Vol. II (1969) pp. 1465-1468.
6. Inutake, M. and K. Kyoichi, 'Fast Ionization Gauge Studies of Quasisteady Gas Injection in Vacuum,' *The Review of Scientific Instruments*, Vol. 43 No 11 (November, 1972) pp.1670-1674.
7. Kelly, J.W., 'A method for extending the life of oxide-coated gauges,' *Journal of Scientific Instruments*, Vol. 39 (1962) pp. 473-474.
8. Liepmann, H.W. and A. Roshko, *Elements of Gasdynamics*. John Wiley and Sons, Inc., New York, 1957.
9. McQuarrie, Donald A., *Statistical Mechanics*, Harper and Row, New York, 1976.
10. Marshall, J., 'Hydromagnetic Plasma Guns,' *Plasma Acceleration*, S.W. Kash, editor, Stanford University Press, Stanford, California, (1960) pp. 60-72.
11. Schulz, G.J. and A.V. Phelps, 'Ionization Gauges for Measuring Pressures up to the Millitorr Range,' *The Review of Scientific Instruments*, Vol. 28 No. 12 (December, 1957) pp. 1051-1054.
12. Sharma, P.K., Young, W.S., Rodgers, W.E. and E.L. Knuth, 'Freezing of vibrational degrees of freedom in free-jet flows with application to jets containing CO_2 ,' *The Journal of Chemical Physics*, Vol. 62 No. 2 (January 15, 1975) pp. 341-349.

13. Small, R.L., "Measurements of Gas Pulses in the 1 Torr Range," *The Review of Scientific Instruments*, Vol. 39 No. 2 (February, 1968) pp. 256-257.
14. Small, R., Lind, A., Connell, G., and E.A. Valsamakis, "A Nonadiabatic Electrodeless Accelerator for Use in Hypervelocity Research," *Third Hypervelocity Techniques Symposium Proceedings*, Denver, Colorado, (March, 1964).
15. Smetana, F.O. and J.A. Daggerhart, Jr., "Pressure Sensitivity in Ionization Gauges," *Journal of Vacuum Science and Technology*, Vol. 5 (1968) pp. 62- 65.
16. Valsamakis, E.A., "Ionization Gauge for Transient Gas Pressure Measurements," *The Review of Scientific Instruments*, Vol. 37 No. 10 (October, 1966) pp. 1318-1320.
17. von Engel, A., "Ionization in Gases by Electrons in Electric Fields," *Handbuch der Physik*, Vol. XXI, Gas Discharges I, S. Flügge, Editor, Springer-Verlag, Berlin, (1956) p. 508.
18. Williams, W.D. and J.W.L. Lewis, "Summary Report for the CONSET Program at AEDC," AEDC-TR-80-16 (September, 1966).
19. Zapata, R.N., Parker, H.M. and J.H. Bodine, "Performance of a Supersonic Molecular Beam," *Rarefied Gas Dynamics*, edited by L. Talbot, Academic Press, New York, (1961) pp. 67-81.

APPENDIXES

APPENDIX A

GENERAL PUMPING EQUATIONS

The time variance of the chamber pressure simply depends on the inflow minus the outflow. Using the parameters of this experiment, the chamber pressure satisfies the following equation:

$$\frac{dP}{dt} = \frac{\dot{m}_i RT}{MV_c} + \frac{a_c A_c}{V_c} - \frac{SP}{V_c}. \quad (\text{A.1})$$

The first and second terms are inflow terms, resulting from the nozzle flow, as well as, the outgassing of the chamber. The pressure increase due to the nozzle, given by the first term, includes $\dot{m}_i$, the mass inflow, R , the universal gas constant, T , the temperature, M , the molecular mass, and V_c , the chamber volume. The outgassing term relies on a_c , the outgassing coefficient, and A_c , which is the inside surface area of the chamber. The last term is the outflow due to the pump and contains the pumping speed, S , and P , the pressure.

Dividing by $P_a = 1$ atmosphere, non-dimensionalizes the equation with respect to pressure. Letting $\hat{P} = \frac{P}{P_a}$ gives the result:

$$\frac{d\hat{P}}{dt} = \frac{\dot{m}_i RT}{MV_c P_a} + \frac{a_c A_c}{V_c P_a} - \frac{S\hat{P}}{V_c}. \quad (\text{A.2})$$

Defining the characteristic times as:

$$\text{pumping time} \equiv \tau_p = \frac{V_c}{S}, \quad (\text{A.3})$$

$$\text{fill time} \equiv \tau_i = \frac{MV_c P_a}{\dot{m}_i RT}, \quad (\text{A.4})$$

$$\text{outgassing time} \equiv \tau_o = \frac{V_c P_a}{a_c A_c}, \quad (\text{A.5})$$

results in the following equation:

$$\frac{d\hat{P}}{dt} = \frac{1}{\tau_i} + \frac{1}{\tau_o} - \frac{\hat{P}}{\tau_p}. \quad (\text{A.6})$$

Dividing by τ_p and, defining

$$\hat{\tau}_\alpha = \frac{\tau_\alpha}{\tau_p}, \quad (\text{A.7})$$

gives the following equation,

$$\frac{d\hat{P}}{d\hat{t}} = \frac{1}{\hat{\tau}_i} + \frac{1}{\hat{\tau}_o} - \frac{\hat{P}}{\hat{\tau}_p}, \quad (\text{A.8})$$

which is non-dimensional with respect to time.

The solution to this equation is obtained with the integration technique:

$$\frac{d(Pe^{Bt})}{dt} = Ae^{Bt}. \quad (\text{A.9})$$

The solution follows easily and has the form:

$$P(t) = P(0)e^{-Bt} + \frac{A}{B}(1 - e^{-Bt}), \quad (\text{A.10})$$

where $A = \frac{1}{\hat{\tau}_i} + \frac{1}{\hat{\tau}_o}$, and $B = \frac{1}{\hat{\tau}_p}$. The properties of this solution are shown in the text in Figure II-5, page 12.

APPENDIX B

PRESSURE CURVE FIT EQUATIONS

I. Thermo-gauge voltage to torr conversion

The thermocouple pressures were read from a digital voltmeter, in order to obtain better accuracy. The manual specifies a voltage reading of 1.1 volts as equivalent to pressures less than or equal to 1×10^{-3} torr. Observations showed that the gauge voltage was off by 0.048 volts, which was considered the zero point offset during subsequent calculations. The thermo-gauge manual provides a figure showing the gauge output voltage versus pressure in torr for various gases. Least-squares curve fits to the manual figure resulted in two equations, one for the region from 1.1 to 1.1788 volts and another for voltages from 1.1788 up to 2.4, as that was the maximum used in these experiments.

The zero offset was subtracted from the voltage reading first

$$V' = V - offset, \quad (B.1)$$

where V is the voltage read and offset is the zero point offset. For voltages less than 1.1788, the N_2 and Ar curves are similar. Thus, the following equation is applicable for both N_2 and Ar :

$$P = 0.113900V' - 0.124254, \quad (B.2)$$

where P is the log of the pressure in torr. In the higher voltage region from 1.1788 to 2.4 volts, separate equations, for N_2 and Ar , were necessary. For N_2 , the resulting expression was:

$$P = -0.1684837 + 0.1780276V - 0.401456 \times 10^{-1}V^2 + 0.1490173 \times 10^{-1}V^3, \quad (B.3)$$

where P is again the log of the pressure in torr. The curve fit for Ar gave the equation:

$$P = -0.1020924 + 0.362604 \times 10^{-1}V - 0.4435804 \times 10^{-1}V^2 + 0.4706886 \times 10^{-2}V^3. \quad (B.4)$$

The carbon dioxide voltages were evaluated with the argon equations, due to the similar molecular weights of carbon dioxide, $M_{CO_2} = 44$, and argon, $M_{Ar} = 40$.

II. Pressure gauge calibration

Using the results from calibration experiments as described in the text, data sets were obtained for nitrogen (N_2) and carbon dioxide (CO_2). Least-squares curve fits to the ionization gauge detector data resulted in equations of the following form.

$$P_{calib} = a0 + a1P_{gauge} + a2P_{gauge}^2, \quad (B.5)$$

where

$$P_{gauge} = \log(P_{gauge}) - offset \quad (B.6)$$

and P_{calib} is the log of the calibrated, correct pressure in torr. The constants, $a0$, $a1$, and $a2$ are dependent on the gas as shown in Table B-1.

A similar set of equations was obtained in the thermo-gauge calibration. However, the least-squares curve fit required a fourth order equation, which gave correct values to 2%. The constants are shown in Table B-2.

Table B-1
Ionization Gauge Calibration Constants

	$a0$	$a1$	$a2$	$offset$
N_2	-3.1623	1.0074	1.57×10^{-2}	-3.2240
CO_2	-3.1902	1.0120	3.86×10^{-2}	-3.2240

Table B-2
Thermo-Gauge Calibration Constants

	<i>a0</i>	<i>a1</i>	<i>a2</i>	<i>a3</i>	<i>a4</i>	<i>offset</i>
<i>N</i> ₂	-1.9788	1.0127	-0.20669	0.45472	8.42×10^{-2}	-1.9031
<i>CO</i> ₂	-2.2200	1.0611	-0.69624	0.15524	0.95429	-2.0068

III. Pentode Calibration

The static pentode calibration, performed as indicated in the text, gave CO_2 and N_2 data, in the form of a pentode reading in microamps versus a pressure reading (from IGD or TC) in torr. The pentode reading was taken across a plate resistance, $R_p = 3.9k\Omega$, with a digital voltmeter. This voltage was converted to microamps with $I_p = \frac{V}{R_p}$. The data was, then, fitted, using least-squares curve-fitting techniques, with an equation of the form:

$$P = a0 + a1I_p + a2I_p^2, \quad (B.7)$$

where P is the resulting log of the pressure in torr and I_p is the log of the pentode reading in microamps. The a terms are gas specific constants and are shown in Table B-3. The offset shown in the table represents the point where the curve fit begins. Results from these equations were in agreement with the data to within 2%.

Table B-3
Pentode Gauge Calibration Constants

	$a0$	$a1$	$a2$	<i>offset</i>
N_2	-2.4533	1.12189	-0.28255	0.48813
CO_2	-2.0284	1.1227	3.81×10^{-2}	1.7045

APPENDIX C

ISENTROPIC EXPANSION EQUATIONS

The Ashkenas and Sherman results can be used in conjunction with the isentropic expansion equations, listed below, to obtain a full set of equations that characterize the flowfield. In an isentropic expansion, the relationship of the pressure to the mass density is expressed by the equation

$$\frac{P}{P_o} = \left(\frac{\rho}{\rho_o} \right)^\gamma, \quad (C.1)$$

where the subscript o denotes reservoir quantities and γ is the specific heat ratio.

The other pertinent equations include:

$$\frac{n_o}{n} = \left(\frac{T_o}{T} \right)^{\frac{1}{(\gamma-1)}}, \quad (C.2)$$

which relates number density to temperature and

$$\frac{P_o}{P} = \left(\frac{T_o}{T} \right)^{\frac{\gamma}{(\gamma-1)}}, \quad (C.3)$$

which gives the pressure as a function of temperature. From these expressions, the flux and mass flowrates can be derived, using $M = \frac{u}{a}$, where u is the gas speed, a is the speed of sound in the gas and M is the Mach number. For sonic flow, the mass flow rate, $\dot{m}_i$, is just $\rho u A$, which is equivalent to the same quantities at the nozzle throat, $\hat{\rho} \hat{u} \hat{A}$, where $\hat{A}$ is the area at the throat, or, in this case, the area of the sonic orifice exit. Then, the mass flowrate per unit area can be written as:

$$\frac{\dot{m}_i}{A} = \left(\frac{2}{\gamma+1} \right) \left(\frac{\hat{T}}{T_o} \right)^{\frac{1}{2}} \frac{\hat{A}}{A} \rho_o a_o, \quad (C.4)$$

where hatted quantities refer to those at the throat. The flux is expressed as

$$F = \frac{n u}{(n u)_o}, \quad (C.5)$$

which is easily put into any desirable form, given the above equations.

Full characterization of any isentropically expanding flowfield can be achieved with these equations as described in the text.

VITA

Lisa Michelle McGee was born in Chicago, Illinois on March 22, 1966. She graduated from Alan B. Shepard High School in 1984. She received a Bachelor of Arts in Physics from The University of Chicago in June 1988. In the fall of 1988, she accepted a graduate research assistantship at The University of Tennessee Space Institute and began study toward a Master's degree, which she received in May 1991. The author is a member of American Institute of Aeronautics and Astronautics, as well as, American Association for the Advancement of Science. She will pursue a doctoral degree in Physics at The University of Tennessee Space Institute.

While at The University of Tennessee Space Institute, she married her husband Terry. They have a son Jacob Ryan.