(2)

AL-TR-90-043 AD:

AD-A231 342

Phase IV
Final Report
for the period
July 1986 to
February 1990

Boundary Layer Study Experimental Validation Test Plan

November 1990

Authors:
H. Kehtarnavaz
D.E. Coats

Software & Engineering Associates, Inc.
1000 E. William Street, Suite 200
Carson City NV 89701

F04611-86-C-0055

Approved for Public Release

Distribution is unlimited. The AL Technical Services Office has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

Prepared for the: **Astronautics Laboratory (AFSC)**
Air Force Space Technology Center
Space Systems Division
Air Force Systems Command
Edwards AFB CA 93523-5000

NOTICE

FOREWORD

This Phase IV final report was submitted by Software and Engineering Associates, Inc., Carson City NV on completion of contract F04611-86-C-0055 with the Astronautics Laboratory (AFSC), Edwards AFB CA 93523-5000. AL Project Manager was Jay Levine.

This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the DD Form 1473.

Jay N. Levine

JAY N. LEVINE
Project Manager

Lawrence P. Quinn

LAWRENCE P. QUINN
Chief, Aerothermochemistry Branch

FOR THE DIRECTOR

Michael L. Heil

MICHAEL. L. HEIL, Lt Col, USAF
Deputy Director
Astronautical Sciences Division

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for Public Release; Distribution is unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AL-TR-90-043
6a. NAME OF PERFORMING ORGANIZATION Software and Engineering Associates, Inc. 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Astronautics Laboratory (AFSC)
6c. ADDRESS (City, State, and ZIP Code) 100 E. William St., Suite 200 Carson City NV 89701	7b. ADDRESS (City, State, and ZIP Code) AL/LSCF Edwards AFB CA 93523-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F04611-86-C-0055
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
62302F	5730	00VH	340830

11. TITLE (Include Security Classification)
Boundary Layer Study. Experimental Validation Test Plan. (U)

12. PERSONAL AUTHOR(S)
Kehtarnavaz, H.; Coats, D.E.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Phase IV Final	FROM 8607 TO 9002	9011	158

16. SUPPLEMENTARY NOTATION AL-TR-90-040 is the final report for this contract. AL-TR-90-041 is the Phase II report. AL-TR-90-042 is the Viscous Interaction Performance Evaluation Routine (VIPER) report.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
21	08	
20	04	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
boundary layer measurements; thick boundary layer test; rocket nozzle boundary layers

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

(cont'd on p i)

This report presents an experimental plan which if executed would validate computational techniques used in evaluating propulsion performance losses due to boundary layers in rocket nozzles. The importance of the loss and the basis for the experimental work are established. Experimental techniques are also reviewed. Visits to ~~Visitations~~ with numerous experimental facilities are described along with recommendations from these facilities. Finally, recommendations as to the diagnostic techniques of choice are made.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL JAY N. LEVINE	22b. TELEPHONE (Include Area Code) 805-275-5366 22c. OFFICE SYMBOL AL/LSCF

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

I. INTRODUCTION

The trend towards very large area ratio nozzles, which result in performance gains for space propulsion applications, has increased the need for detailed knowledge of the momentum losses due to nozzle viscous effects (i.e., boundary layer). These losses degrade overall system performance, such as increasing system weight, decreasing useful payload weight, and/or decreasing effective system range. Another important factor in the designing of propulsive nozzles is the detailed knowledge of heat transfer at the wall for regeneratively cooled walls and/or material performance.

Because of the importance to rocket propulsion, the AL sponsored the Boundary Layer Study Contract to improve the understanding and computational predictive capabilities for boundary layers in rocket nozzles with very high area ratios. The contract consists of five phases with Phase 5 being documentation of the work done in the four phases described below.

The first phase extends current boundary layer computational technology and is independent of Phases 2 and 3. Phases 2 and 3 attack the problem of thick shear layers with Phase 2 being an assessment of the methods available for mapping out the effects of thick shear layers on performance prediction and calculations of their impact on performance. Phase 3 is aimed at producing new tools to analyze nozzle performance and will result in a new generation computer program.

Phase 4, consists of preparing an experimental test plan, which, if executed, would supply the necessary experimental data to validate the analytical efforts of Phases 1 to 3. This report details the experimental test plan developed during Phase 4.

Some time ago, the experimental facilities for measurements of high speed flows were limited to supersonic/hypersonic wind tunnels, shock tunnels, and shock tubes. The instrumentation included pressure transducers, heat transfer gauges, Schlieren and interferometry. These diagnostic instrumentations were able to provide limited data. With the development of computers and laser technologies, the activity in Experimental Fluid Dynamics (EFD) with sophisticated instrumentation has been accelerated(1). However, detailed and reliable measurements of complex flow phenomena, such as vortex interactions, boundary layer parameters, as well as transition and chemistry, are not yet available.

The various performance losses are currently evaluated by computer programs, such as TDK, BLM, BLIMPJ, etc. The JANNAF thrust chamber evaluation procedures are based upon a physical model that accounts for the processes occurring in the thrust chamber, losses associated with these processes and interactions among the processes[2].

In the model, propellants enter the combustion chamber through the injector, are mixed, vaporized and combusted. Deviation from complete and homogeneous mixing vaporization or combustion to equilibrium are referred to as energy release losses or injector losses. Theoretically, these losses are modeled by Coaxial Injection Combustion Model (CICM) and the Standard Distributed Energy Release Model (SDER) codes[2]. Experimentally, the energy release loss can be estimated from the characteristic exhaust velocity efficiency, η_{C*}.

The products of the chemical reactions are then expanded in the nozzle. The reactions continue during the expansion. Deviation from the local chemical equilibrium are referred to as the kinetic losses. There are no direct methods of measuring the kinetic losses.

The losses due to non-uniform expansion of the available momentum in the direction of thrust are referred to as two-dimensional or divergent losses[2]. Theoretically, these losses are evaluated from the difference between the ODK (One-Dimensional Kinetics) and MOC (Method of Characteristics) modules of the TDK code.

Viscous effects are significant in the region near the nozzle wall. The losses due to the momentum decrement at the wall, because of momentum and heat transfer in the wall region, are referred to as boundary layer losses. In theory, these losses are evaluated by codes such as BLM and BLIMPJ. In real rocket engines, the boundary layer losses are estimated from global measurements of the heat transfer.

Graphically, all of the above described losses are shown in Figure 1a[2]. The ideal performance is based on ODE calculations.

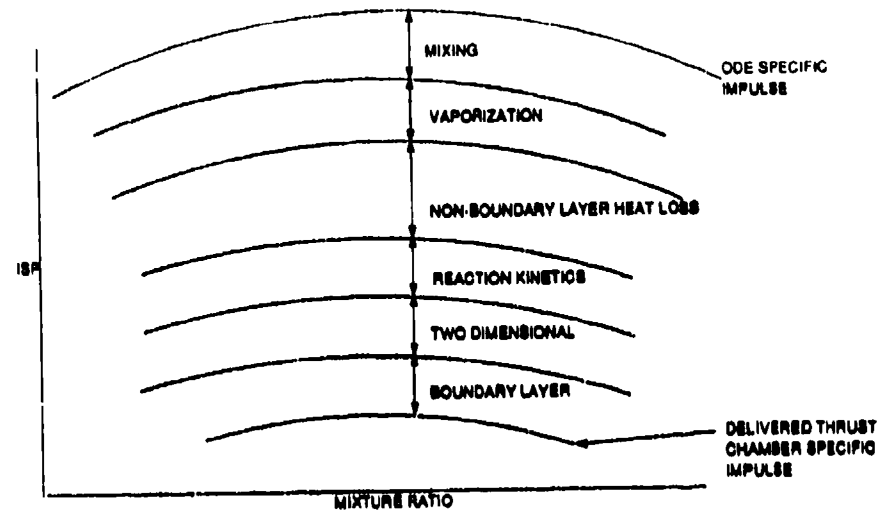


Figure 1a. Illustration of thrust chamber losses from ideal performance

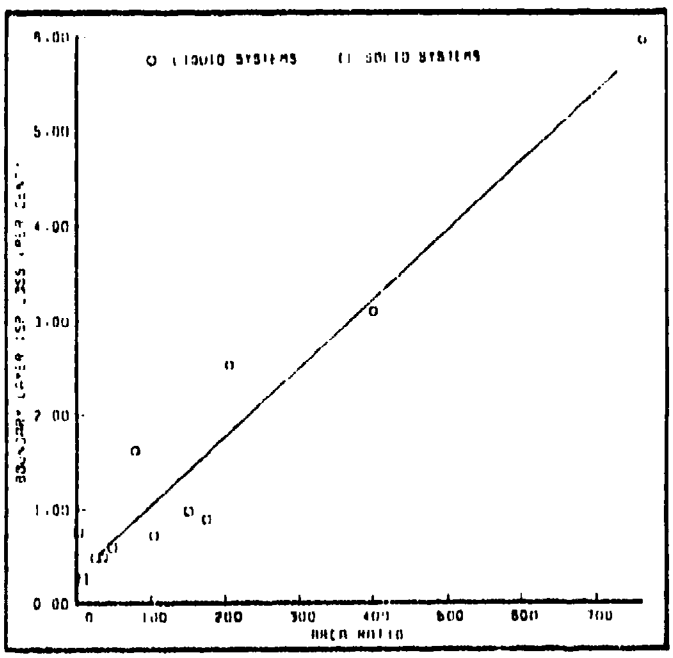


Figure 1b. Boundary Layer Isp Losses.

Systematic measurements to verify the predicted magnitude of the aforementioned losses are sparse, and a high degree of uncertainty is associated with the available data. For both the kinetic and boundary layer losses, experimental validation of the predictive techniques for real engines are not available. For low area ratio nozzles, the boundary layer loss has been considered small enough that any errors associated with the predictions were acceptable. The magnitude of the boundary layer loss as a percent of total performance increases with area ratio. Figure 1b shows the boundary layer losses as calculated by the SPP and TDK codes for a variety of motors as a function of area ratio. The dependency of these results on the particular turbulence model used in the calculation are on the order of ± 30–40%. That is, a predicted 10 second loss could actually be only 7 seconds or could be as high as 13 seconds. Since a 1% change in Isp can result in approximately a 4% change in payload, the accurate knowledge of the boundary layer loss is very important. Hence, the boundary layer calculations must be validated directly using experimental data.

In order to validate or extend analytical methods, the planned experimental effort must include techniques to measure boundary layer parameters that will produce high quality data. Quality data on nozzle wall boundary layers it very limited at present. Perhaps, the best work in this area is that of Back, et al, at JPL[3–6], which was for cold flow.

This report is an attempt to prepare an experimental validation test plan. Numerous testing facilities were contacted and visited. After the discussion of available experimental methods and facility and test requirements, recommendations are made to the Astronautics Laboratory, based on the facts that SEA, Inc. has received from the facilities (documented in this report), for a test plan to validate the analytical methods for the boundary layer study.

Certain ground rules were used in preparing this test plan. The first ground rule was that we wanted a program which would measure the desired data, we did not want to embark upon a research program to develop improved boundary layer diagnostic techniques. Secondly, we wanted the test environment to simulate as close as feasible the conditions in a real propulsive nozzle. The minimum requirements for this condition are shown in Table 1, below. Last, and most important, we wanted accurate data.

Table 1. Miminum Test Environment Criteria

- o The flow in the boundary layer must be turbulent from before the throat.

- o The boundary layer should encompass between 10% to 40% of the flow at the exit plane.

- o The heat transfer to the wall should be high enough to simulate conditions in a real rocket nozzle.

- o The expansion process should maintain, as realistic as possible, the conditions in a real rocket nozzle. For example, axisymmetric instead of 2D nozzles, ratio of specific heats ≤ 1.4.

Some of the ground rules were found to be mutually exclusive. For example, accurate data taking precluded using a real engine as a test bed. The environment in real engines is too severe for many diagnostic techniques. We also found that off the shelf techniques were not sufficiently accurate for all of the data measurements desired. With this in mind, the following outline has been documented in this report.

1. Experimental Methods
2. Test Environment & Facilities Requirements
3. Contacting the Testing Facilities
4. Visiting the Testing Facilities
5. Recommendations for Experimental Validation Test Plan

1.0 Experimental Methods

1.1 Parameters to be Measured

The primary interest is computing the boundary layer parameters in propulsive nozzles is in determining the viscous thrust loss and wall heat transfer rate. The most fundamental property in the thrust loss is the wall shear stress. The heat transfer to the wall is determined by the temperature (enthalpy for reacting flows) gradient at the wall. While both the shear stress and temperature gradient can be deduced from other quantities, a direct measurement of these items is definitely preferred. In the absence of direct measurements, diagnostics which require the least amount of assumptions are preferential.

Average velocity and temperature throughout the boundary layer and Reynolds stress terms, u', v', are other parameters to be measured. Although the last two are less important, their correct evaluation yields valuable data for validation of turbulent models. Briefly the following measurements are to be made:

1. Local wall shear;
2. Local heat flux at the wall;
3. Average velocity and temperature in the boundary layer; and
4. Reynolds stress terms.

1.2 Methodologies:

There are basically seven principal methods of measuring the local wall shear stress[1]:

1. The Stanton tube
2. Direct measurement
3. Thermal method
4. The Preston tube
5. The electro–chemical techniques
6. Extrapolation of direct velocity measurement

1.2.1 The Stanton Tube

The schematic of the Stanton tube is shown in Figure 2 (Ref. 1). The method consists of measuring the static pressure in the static hole with and without the blade. Then the difference between these two pressures will be calibrated against the wall shear. The value of ΔP can be quite small such that a micromanometer with an accuracy of $\pm$ 0.01mm should be used. The results of this calibration for turbulent flow of air over a flat plate can be found in Reference 1.

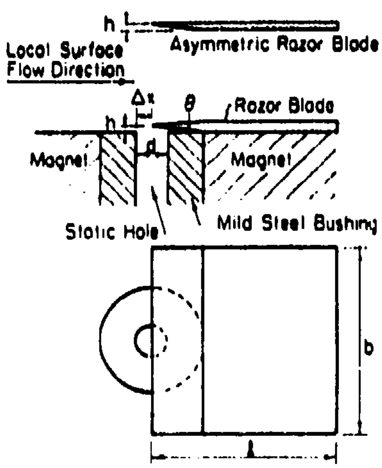


Figure 2. Design of Stanton Gauge [1]

1.2.2 Direct Measurements

The need for measuring the local wall shear stress has led towards the development of instrumentation for measuring small forces or deflections. These methods are referred to as direct measurements. One of these instruments is Kistler gauge shown in Figure 3. Maybey and Gaudet[7] describe the use of this gauge in skin friction measurements.

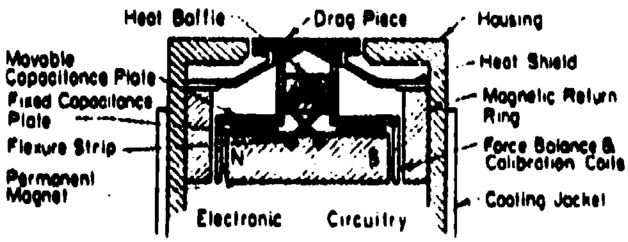


Figure 3. Construction of Kistler Skin–Friction Gauge as Presented in Literature from the Kistler Instrument Co.

1.2.3 Thermal Method

The relationship between the local wall shear stress and the rate of heat transfer from small thermal elements mounted flush with the surface has been studied by Fage and Falkner[8]. This method uses Reynolds analogy to obtain the wall shear from the Nusselt number. The main difficulty in using these heat transfer probes is that the heat is lost to the substrate, as well as to the fluid, so that the effective length of the probe can be much larger than that of the heating element. Works by Rubesin, et al[9], and Sandborn[10,11] offer methods to reduce this effect.

1.2.4 The Preston Tube

Theoretically, the Preston method relates the local wall shear stress to the velocity variation as[1]:

$$U = \left[\frac{\tau_w}{\rho}\right]^{1/2} f\left[\frac{y\rho(\tau_w/\rho)^{1/2}}{\mu}\right] \tag{1}$$

and for distances close to the wall:

$$f\left[\frac{y\rho(\tau_w/\rho)^{1/2}}{\mu}\right] = \frac{y\rho(\tau_w/\rho)^{1/2}}{\mu} \tag{2}$$

Details about the method and the most convenient system to calibrate the Preston tube are given in Reference 1. However, the application of the Preston tube and its calibration to turbulent boundary layer flows depends on the accuracy of the law of the wall model.

1.2.5 The Electro–Chemical Techniques

The electro–chemical probes[12,13] are based upon the mass transfer analog of the heated surface film. An electro–chemical reaction takes place on the surface of an electrode mounted flush with the wall. The basis of this method is that the current flowing through the electrode circuit, which is proportional to the rate of mass transfer at the electrode surface, can be related to the velocity gradient at the surface. This method has been used in liquid flows and has not yet been applied to the gas flows.

1.2.6 Extrapolation of Direct Velocity Measurements

Extrapolation of direct velocity measurements to obtain the velocity gradient is another widely used method. The accuracy depends on basically two factors:

1. How close to the wall the measurements can be made; and
2. The accuracy of the velocity measurements.

The methods of measuring the velocities in the boundary layer fall into two categories. They are:

a) intrusive probes (e.g. pitot static probes)
b) non or minimally intrusive probes (e.g. laser induced fluorescence)

The most widely used intrusive method of measuring flow velocities is the pitot static tube. The Mach number of the flow is deduced from the ratio of the pressures measured at two stations (nose point and side location). The static temperature and flow composition are then required to determine the local flow velocity. The main advantage to this method is that it is a widely available and understood method. For boundary layer measurements, the major drawbacks are the size of probes required and the frequency response of the measurements. The probe size limits how close to the wall the measurements can be taken and also influences the values to be measured by obstructing the flow. The response time associated with pitot measurements is often significantly longer than the turbulent flow fluctuations, and hence it is not a good vehicle for measuring Reynolds stresses.

The static temperature measurements are usually performed by reading the output signal of a thermometer when the fluid stagnates against the sensor surface and reaches to thermal equilibrium with the sensor's surface. A variety of temperature probes have been developed which are capable of determining the temperature profile in the boundary layer (see Section 2.2.2 and Appendix C). However, the temperature being measured is the stagnation temperature and must be correlated to the static temperature. In hypersonic flow, the determination of the local static temperature can be a significant source of error.

With the advent of fast computers and powerful lasers, a tremendous amount of laser–based experimental research activities in the field of fluid dynamics and combustion have been investigated to allow measurements of properties without disturbing the local flow environment. These activities include flow visualization and 2–D planar imaging of velocity, temperature, pressure and species concentrations[14–17].

A non–intrusive method of two–wave Laser Induced Fluorescence Spectroscopy (LIFS) seems to be promising in temperature profile measurements. The advantage of this method is in the fact that it measures the static rather than total temperature directly, and the need for use of pitot pressure and total temperature sensors are eliminated. This method consists of the selective excitation of a chemical species of interest and detection of the resulting fluorescence signal normal to the incident laser beam. Then the Boltzmann ratio can be used to correlate the temperature to the ratio of number of ground state to excited state transitions.

Mean velocity measurements, as well as higher order fluctuation terms, have received a lot of attention lately. Non-intrusive laser-based velocimeter techniques are generally divided into two groups: 1) those who measure the Doppler Shift of light scattering particles assumed to be traveling with the flow; and 2) those who directly measure the Doppler Shift related to the collective molecular motion. Laser Doppler Anemometry (LDA), Laser Transit Anemometry (LTA), and Laser Doppler Spectrometry (LDS) are among the first group, and Laser Induced Fluorescence (LIF) and Coherent Raman Spectroscopy (CRS) fall into the second group.

Laser Doppler Anemometry (LDA) uses dual beams, one of which is a reference beam. A sample volume will be produced by crossing two focused laser beams at the measurement location and forming a well defined set of interference fringes in the seeded flow. The scattered light beam is modulated by a frequency which is proportional to velocity. References 18-20 can be consulted for more details.

Laser Transit Anemometry (LTA) is based on the generation of two or more spatial markers at the measurement points. The time of transit of the scatter centers through the markers defines the instantaneous velocity[21]. LTA, which is usually applied in a backscatter mode, is self-contained, does not require coherence (and, therefore, is more tolerant to phase distortions along its optical paths), and can cope with smaller particles for equivalent laser power. Its superiority close to walls and surfaces has been established.

A more promising method for gas velocity measurements in high speed flows is Laser Doppler Spectrometry (LDS). The technique that was originally employed for velocity measurements in highly transient and short duration flows[22-24] can also be applied to non-transient flows[25]. Monochromatic light is concentrated at the measuring point. Doppler shifted light scattered by the tracer particles at this point is collected and transmitted to the spectrometer. The Doppler shift in terms of the relative wavelength change, $d\lambda/\lambda$, depends on the velocity components U of the particles. This method is able to continuously monitor the change in the velocity[22,25].

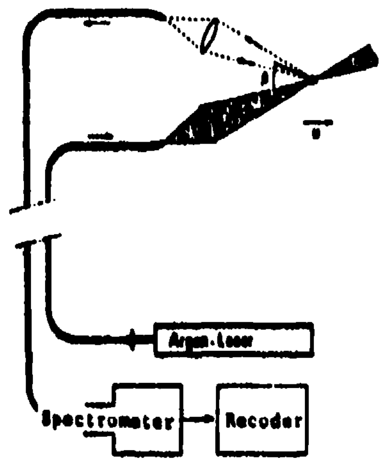


Figure 4. Laser Doppler Spectrometer (Ref. 22)

Spectroscopic methods are based on measuring the Doppler shift in either the absorption line frequency or the fluorescence emission or scattering spectra of an agent specie in the flowfield, upon interaction with a laser source. These methods extract the velocity directly from molecular motion, and therefore, avoid the slip velocity ambiguity. These methods provide favorable tools for high speed flow velocity measurements.

Laser Induced Fluorescence (LIF) methods have been successfully applied for supersonic and subsonic flow measurements[26]. Measurements of the Doppler shifted absorption is the basis for velocity measurements using LIF. The Doppler shift of an absorption line, Δv_D is proportional to the velocity component u, in the direction of laser beam propagation, such that

$$\frac{\Delta v_D}{v_o} = \frac{u}{c} \tag{3}$$

where v_o is the center of the laser frequency. There are two schemes to measure the velocity using LIF: 1) narrow band excitation scan of the absorption line, together with broad band fluorescence detection; and 2) narrow band wing excitation with counter–propagating beams and broad band fluorescence detection.

The first scheme uses a tunable narrow–band laser beam to scan a resonant transition of the agent species. The resulting broadband fluorescence signal is then detected. The Doppler shift is determined by comparing the center of the fluorescence signals of moving molecules to that of molecules in a stationary cell. The velocity is then obtained from equation (3). This scheme can measure velocity to within 5 m/sec, depending on the energy levels of the agent species. It requires tuning the laser beam over the entire absorption line, which prohibits the use of this method in unsteady flows. This technique also requires the acquisition of a large number of data frames and, therefore, a large buffer space for storage.

The second scheme fixes a narrow–band laser at the frequency of the wing of the absorption line near the point of maximum slope, where the line shape is approximately linear for small Doppler shifts. The fluorescence intensity, I_F, is proportional to the amount of absorption. At high speed, the Doppler shift causes the center of the absorption line to shift away from the laser frequency, resulting in a change in fluorescence intensity. In this case, the frequent shift, Equation (3), can be expressed in terms of the difference in I_F, fluorescence and the slope of the line shape function, g(v), such that

$$u = \frac{c}{v_o} \cdot \frac{\Delta I_F}{I_o} \left[\frac{\partial g(v)}{\partial v} v_0\right]^{-1} \tag{4}$$

where I_o is the fluorescence at the center of the line. However, if the flow is monitored with two beams in such a way that one beam is upward Doppler shifted and the other downward shifted as schematically illustrated in Figure 5, both the difference, and center fluorescence intensity, I_o are easily determined using equation (5), and as shown in Figure 6.

$$u = \frac{c}{v_o} \cdot \frac{I_u - I_d}{I_u + I_d} g(v) \left[\frac{\partial g(v)}{\partial v} v_o\right]^{-1} \tag{5}$$

This technique requires two successive laser pulses to measure one velocity component. This scheme is capable of determining the mean velocity particularly in high speed situations. The accuracy range is similar to the former scheme. In order to measure the velocity vector in a two–dimensional flow, two additional beams are required[29]. This method requires four successive laser shots and subsequent measurements of the fluorescence signal. Present development in detector technology does not allow signal recording in less than 50 msec, and therefore hinders the ability of performing two–dimensional velocity measurements in highly turbulent or transient flows. For more details, the reader should consult with References 26–29.

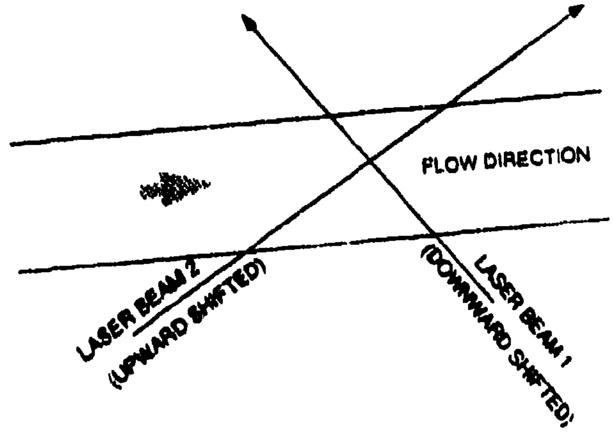


Figure 5. Illustration of counter beam configuration

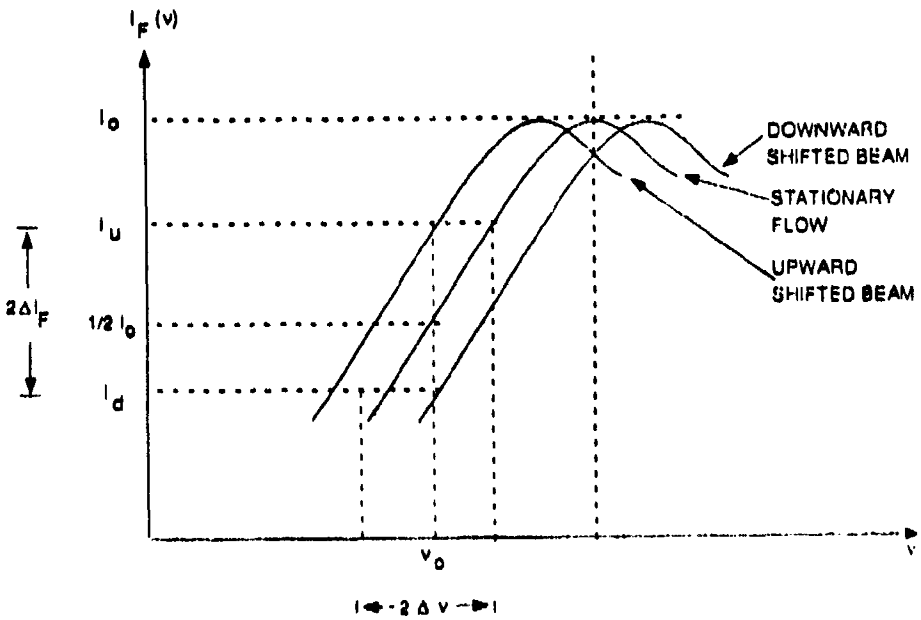


Figure 6. Schematic of fluorescence intensity vs. frequency [ref. 28]

She, et al[30] was the first to propose the application of Coherent Raman Spectroscopy (CRS) for velocity measurements in high speed flows. CRS includes Coherent Anti-Stokes Raman Spectroscopy (CARS)[31], Inverse Raman Spectroscopy (IRS)[32], and Simulated Raman Gain Spectroscopy (SRGS)[33]. Similar to LIF methods, these techniques measure the velocity from the Doppler shift of the spectrum of the scattered signal. Coherent Raman have scattering cross sections several orders of magnitude higher than spontaneous Raman, and therefore, higher signal-to-noise ratio. This method has been successfully used to measure supersonic velocities up to 1010 m/sec, with a velocity resolution of 34m/sec, using methane as the agent species[31].

1.3 Test Environment and Facilities Requirements

The primary interest of experimental studies for nozzle boundary layers is focused on high area ratio nozzles. It is known that the boundary layer growth increases with area ratio. Table 2 indicates the calculated boundary layer thickness ($\delta_{0.995}$) at the exit plane for four different nozzles.

Table 2. Boundary Layer Thickness at the Exit Plane for Four Nozzles. Cooled Wall $T_w = 1000^0R$.

Nozzle	Area Ratio	Transverse Radius at the Exit Plane r exit,inches	Boundary Layer Thickness $\delta_{0.995}$ inches	$\delta_{0.995}/r$
ASE	400:1	25.10	3.25	13%
RL-10	204:1	36.80	4.40	12%
XLR-134	767:1	10.97	2.08	19%
Hughes 300:1	300:1	1.61	0.45	28%

It can be seen that for higher area ratio nozzles the boundary layer occupies up to 20% of the nozzle. The flow is turbulent in the first three of the above engines. For smaller engines with lower chamber pressures and comparable area ratios, the flow is laminar and the boundary layer occupies an even larger portion of the nozzle. Some of the high area ratio station keeping engines fall into this category. However, turbulent flows in high area ratio nozzles are the primary concern for this experimental program. To assure the turbulent nature of the flow, one should compute the boundary layer parameters for the experimental set up and make sure that these values fall in the turbulent flow regime. One generally used criteria is that the boundary layer becomes turbulent when the Reynolds number based on momentum thickness becomes greater than 360, i.e., $\rho_e u_e \theta / \mu_e > 360$.

For internal flows, the Reynolds number is a function of the mass flow rate and is inversely proportional to the local radius, i.e.

$$Re_r = \dot{m} / (\pi r \mu) \tag{6}$$

In order to relate the throat Reynolds number, Re_{r*}, to the onset of turbulence, boundary layer calculations were made for a variety of conditions using combustion gases ($\gamma = 1.2$) so that the Reynolds number based on momentum thickness was equal to 360 at the throat plane. These results are shown in Figure 7. Cross plotted results of throat radius versus mass flow rate for the $Re_{\theta*} = 360$ line are shown in Figure 8. Finally, the results from Figure 7 are superimposed in Figure 9 on a plot of mass flow versus throat radius. Hence, the transition point from laminar to turbulent flow can be estimated from knowing the value of Re_{r*}. From the information on Figure 8, it appears that values of $Re_{r*} > 1X10^4$ are required for turbulent flow. The experiment test facility should be designed to operate well within the turbulent regime.

To be able to measure the heat flux at the wall, hot or at least warm flow is required. The higher the flow temperature, the easier it is to measure a significant amount of heat flux at the wall. However, if the hot gas is diluted with injection of a cold gas to control the temperature, complete mixing of both gases is of concern in order to assure uniform stagnation enthalpy of the gas. The above consideration is important since it is very desirable that the only significant source of vorticity be generated by the wall shear layer. If other strong sources of vorticity are present, the validity of the data for a wide range of conditions will be opened to question. According to Crocco's theorem, the vorticity is given by

$$\zeta = (T\, ds/dn - dh_T/dn)/u \tag{7}$$

where s = entropy
h_T = total enthalpy
n = direction normal to streamlines

which shows the dependency of vorticity on stagnation enthalpy

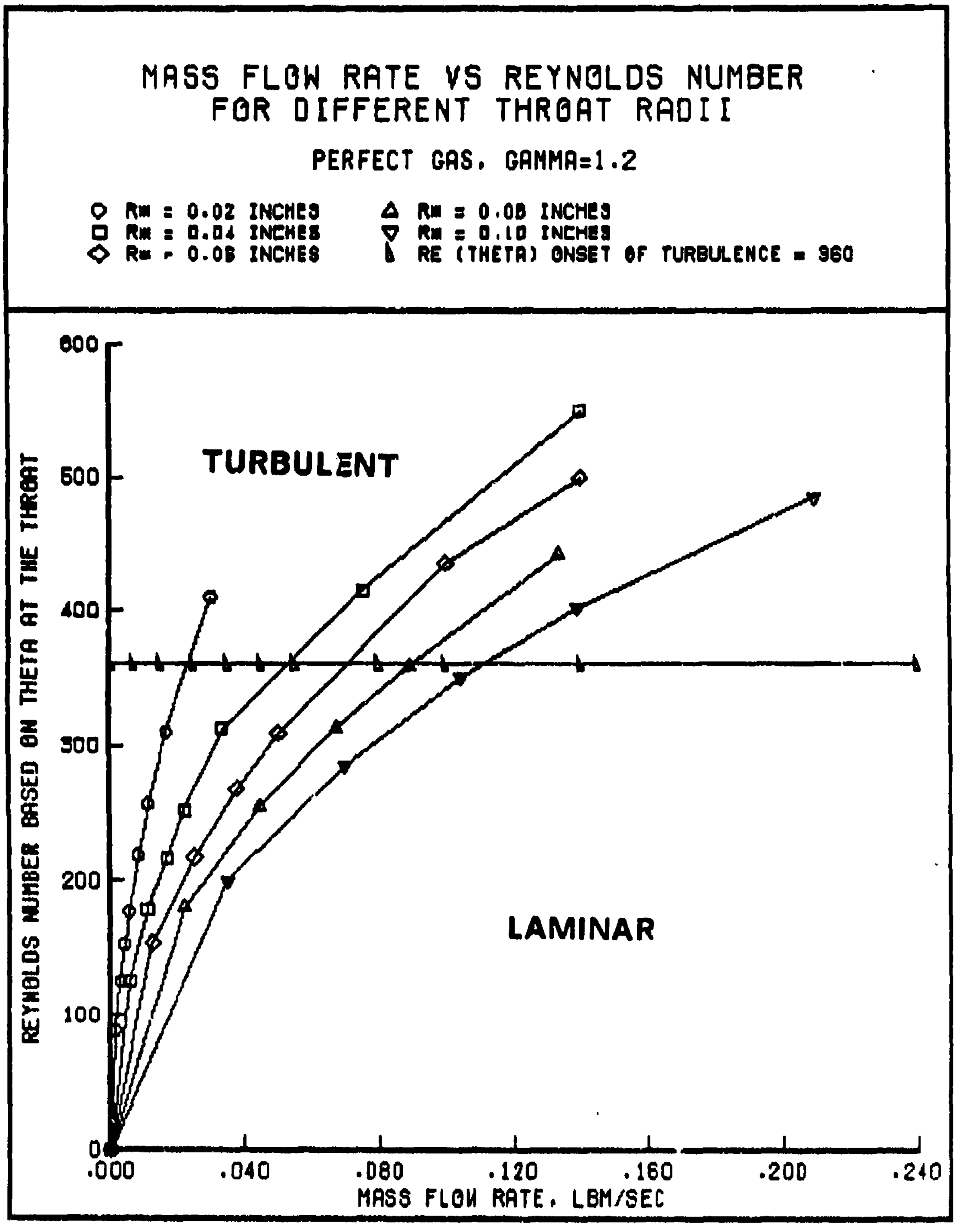


Figure 7. Onset of Turbulence for Different Throat Radii

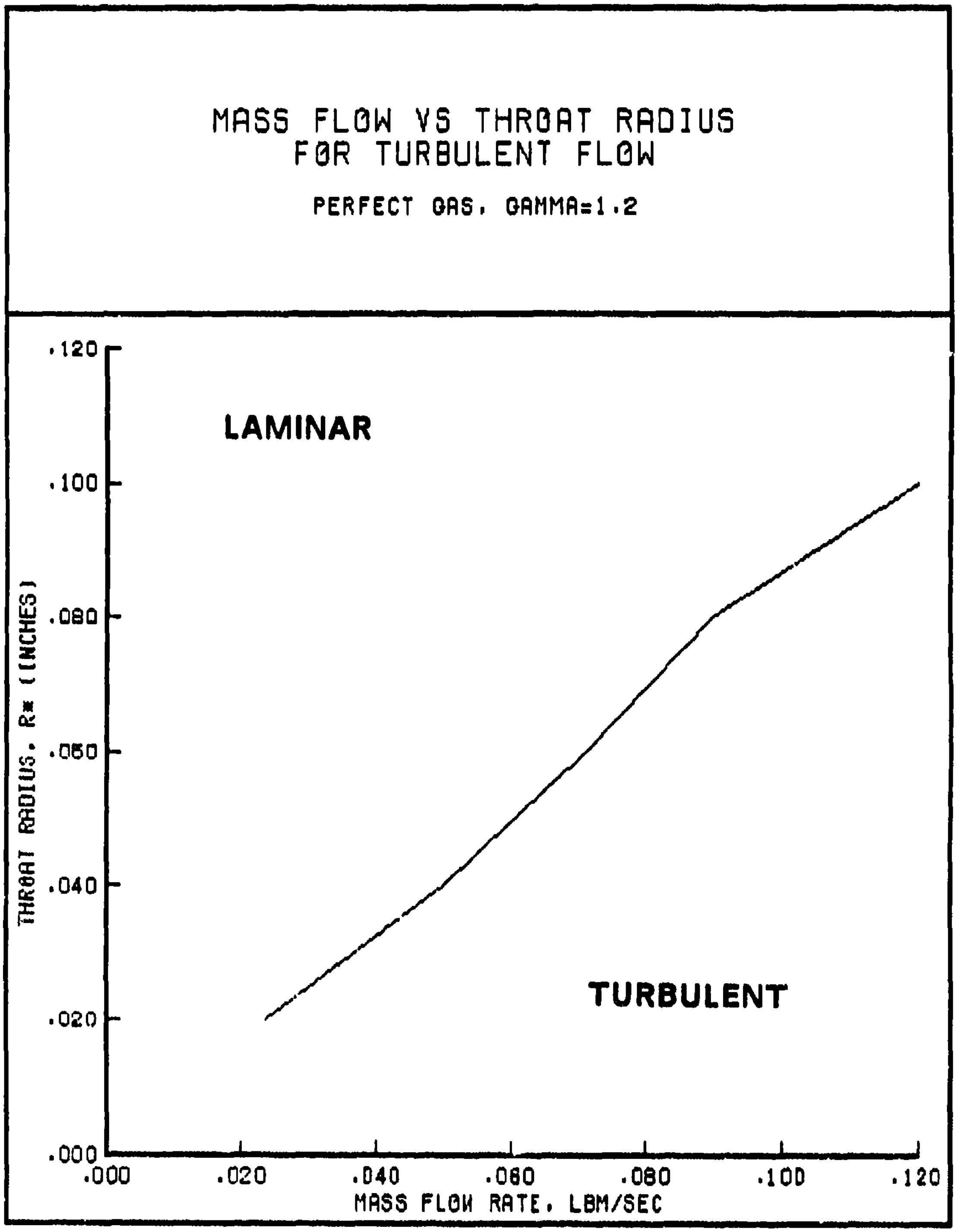


Figure 8. Mass Flow vs. Throat Radius for Turbulent Flow

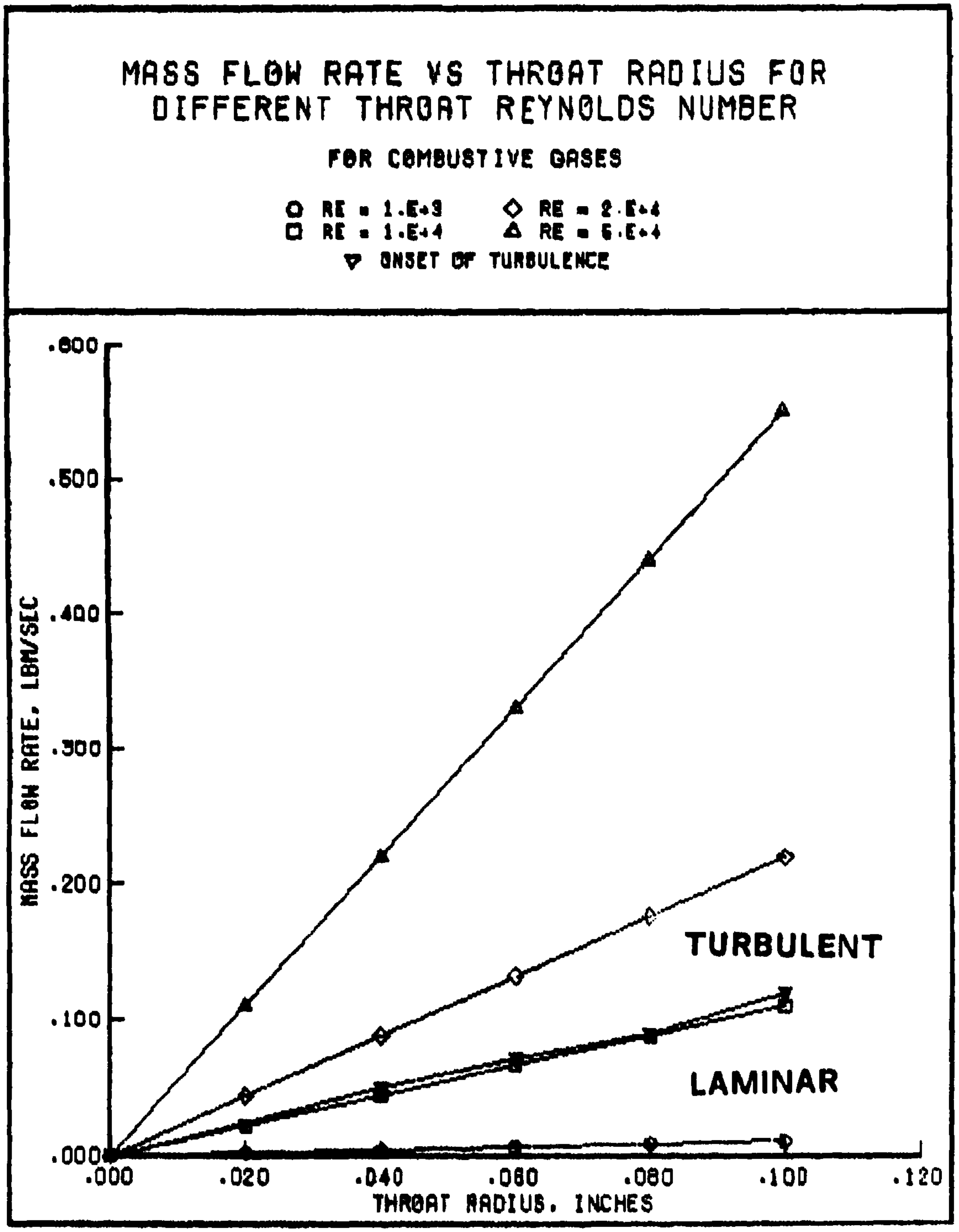


Figure 9. Mass Flow Rate vs. Throat Radius for Different Throat Reynolds Number

For LDV type of measurements, the flow should be seeded properly. The proper seeding of the flow is a crucial problem in LDV techniques[34,36]. The seeded particles have to be small enough to follow the flow fluctuations and at the same time large enough to scatter detectable laser light. Moreover, the dynamics of particles should be known analytically for better velocity measurements and particles should be chosen to have almost the same size to avoid artificial turbulence in the flow. In general, the required particle sizes are determined by the flow acceleration and the level of turbulence. However, the problem of particle response lag cannot be totally eliminated, and even particles as small as 0.5 micron have a finite relaxation time[37,38]. For Stoke's flow, i.e. particles and gas velocities in near equilibrium, the characteristic velocity and temperature relaxation times for the particles are:

$$\tau_v = \rho_m d_p^2 / 18\mu \tag{8}$$

$$\tau_T = \rho_m d_p^2 P_r / 24\mu \tag{9}$$

For aluminum oxide particles in air at room temperature, the characteristic times are

$\tau_v = 12.5 \; d_p^2$; with d_p in microns

$\tau_T = 6.56 \; d_p^2$ and τ in microsecond

The errors for submicron particles (0.1 - 0.5 micron) for free stream velocity measurements in the presence of large velocity gradients without shock waves are within few percent which are acceptable[25]. However, production of submicron particles is not a trivial problem and should be tailored to the specific situation in hand. Particles such as polystyrene latex with good uniformity and small sizes are available, but they cannot be used in combustion application because they burn, or in supersonic flows because the carrier volatile fluid condenses and generates polydisperse particles. Therefore, polydisperse solid particles, such as aluminum oxide, silicon carbide, or silicon dioxide[39,40], are commonly used in flows with combustion; and liquid particles, such as silicon oil or dioctyl-phthalate, are candidates in supersonic flows[41-43].

1.4 Summary

Two families of techniques are suitable for hypersonic flow velocity measurements: particle scattering and molecular scattering. Particle scattering techniques which include real fringe laser Doppler velocimetry, laser transit anemometry, and Doppler spectrometry, are well developed and velocity measurements in supersonic and hypersonic flow regimes have been demonstrated. However, particle scattering techniques share the same concerns and difficulties when applied to hypersonic wind tunnels: The requirement of seeding the flow, and the ambiguity due to particle lag in accelerated or decelerated flows. The question of particle lag has been addressed and it is concluded that the measurement uncertainties are small when the particles used are less than 0.3 µm in shock–free expansion flows.

The uncertainty of the fluctuating components of the velocity within the boundary layer will depend on the density of the flow and the frequency response of the particles.

Molecular techniques which encompass laser induced fluorescence (LIF), inverse Raman scattering (IRS) and coherent Anti–stokes Raman scattering CARS, are being developed. These techniques have the potential of yielding more accurate results than particle–based techniques. However, several practical aspects hinder their application to hypersonic flow measurements. LIF of alkalis, which is more accurate than LIF of 0_2, requires seeding the wind tunnel with highly corrosive materials such as sodium. Seed molecules condense under the low pressure and temperature conditions characteristic to hypersonic wind tunnels. LIF of 0_2 is still under investigation and preliminary analysis shows that the velocity error is about 500 m/sec. IRS and CARS measure the velocity from the spectrum of the coherent Raman scattered signal, and therefore, pressure broadening due to a shock wave can result in large errors. Velocity measurement using IRS is on axis, and hence the spatial resolution is poor. IRS and CARS, however, have the advantage of yielding the temperature and pressure simultaneously with the velocity, giving a unified approach to the flow field.

Table 3 is a summary of velocity measurement techniques. The table shows the demonstrated velocity range, accuracy, SNR and other relevant parameters of techniques.

TABLE 3: SUMMARY OF VELOCITY TECHNIQUES, REFERENCE 25

TECHNIQUE	PARAMETERS MEASURED	TURBULENCE LEVEL	SNR LIMIT	ACCURACY	MEASURED VELOCITY RANGE	FREQUENCY RESPONSE, HZ	SPECIAL RESOLUTION	COST	STATUS	CONCERNS IN HYPERSONIC FLOW
Real Fringe (LDV)	$\bar{u}_i, \bar{u}_j$		-10 dB	0.1 to 10%	1000 m/sec	10^4	100 µm	Medium	Well Developed	Seeding, Flow Density
	$u'_i, u'_j, \overline{u_i u_j}$	30% & higher	0 to 10 dB	10 and up		10^2				
Laser Transit Anemometry	$\bar{u}_i, \bar{u}_j$		10 dB	0.1 to 10%	1200 m/sec	Steady State	100 µm	Medium	Well Developed	Seeding, Flow Density
	$u'_i, u'_j, \overline{u_i u_j}$	15%	10 dB	3 to 15%						
Doppler Spectrometry	$\bar{u}_i, u'_i$	15%	20 dB	2%	1700 m/sec	10^6	100 µm	Medium	Used in shock tubes	Seeding, Flow density S/R
Laser Induced Flourescence	$\bar{u}_i, u'_i$	Experimental	20 dB	1 to 10% Depending on the particles	500 m/sec using Iodine (29) Mach 11 using Sodium (30)	10^5	100 µm	High	Demonstrated under Laboratory Conditions	Agent Species, S/R
Inverse Raman	$\bar{u}_i, u'_i$	Have not been demonstrated	20 dB	5 to 10%	Mach 4.6 (33)	Steady State	Few cm	High	Demonstrated in wind tunnels	S/R, complexity
CARS	$\bar{u}_i, u'_i$	Experimental	20 dB	not established	1000 m/sec (31)	Steady State	Few cm	High	Demonstrated under laboratory conditions	S/R, complexity

2.0 Contacting, Visiting and Screening the Test Facilities

2.1 Contacting the Testing Facilities

As part of the Phase IV effort for the boundary layer study, the experimental sites were identified and contacted. An outline of the work to be done was provided and sent to investigators at CALSPAN, AEDC, Stanford University, UC San Diego, PRI, Rocketdyne, Aerojet, California Institute of Technology, NASA Lewis and Los Alamos National Laboratories for their further insight into the problem (See Appendix A).

The responses from the above organizations were mixed. The people/organizations who declined to support the effort were:

Dr. Tom Bowman at Stanford University;
Dr. Ron Hansen at Stanford University;
Dr. William Reynolds at Stanford University;
Dr. Gene Broadwell at Cal Tech; and
Dr. Anatol Roshko at Cal Tech.

The main reasons given were that they were either not equipped to do these types of experiments or that they were engaged in doing some other work and they do not have the resources to support our effort.

2.2 Visiting the Testing Facilities

All of the organizations contacted, except Cal Tech and Stanford University, expressed interest in performing the experimental study. Some of these organizations provided us with a white paper which is included in Appendices B thru F.

The interested people/organizations were visited. A brief report of each visit will be followed and our final conclusion will be discussed in the next section.

2.2.1 Visiting PRI

In response to our inquiry for experimental validation of the Boundary Layer Code, Physical Research, Inc. (PRI) was one of the companies who showed interest. A brief write-up was prepared by PRI about their approach to this study. After reviewing this write-up, SEA, Inc. visited the company; which is located in Torrance, CA.

The meeting was held on September 28, 1987, at Physical Research, Inc. A presentation about the company background was given by the president of the company, Dr. William Shih, which was followed by a technical presentation given by Dr. Reza Toossi. The list of people who attended this meeting are as follows:

Attendees	Organization	Telephone Number
Douglas E. Coats	SEA, Inc.	(702) 882–1966
Homayun Kehtarnavaz	SEA, Inc.	(702) 882–1966
Farro Kaveh	self/PRI	(614) 442–1016
Bill Shih	PRI	(213) 378–0056
Reza Toossi	PRI	(213) 378–0056
Bill McDermott	PRI	(213) 378–0056
Daruish Modarres	PRI	(213) 378–0056

The purpose of the meeting was to evaluate the capability of this group in performing the experiments and, moreover, the techniques they proposed to utilize to do the work and how reliable those techniques are. In their preliminary studies the following approach has been proposed:

0 Flow Visualization: Gross Observation of Flow Structure:

1. B. L. separation, possible reattachment, shock formation, and laminar–turbulent transition

0 Surface Measurements:

1. Properties along the nozzle wall
2. Derive heat transfer coefficient and skin friction

0 Flow Diagnostics in the Boundary Layer:

1. Evaluate flow diagnostic techniques
2. Measure Boundary Layer temperature and velocity profiles

Utilization of LDV has been proposed by PRI for mean and fluctuating velocity measurements. For temperature profile measurements, the (LIFS) method was recommended.

For more detailed discussion of PRI's approach, their proposed instrumentation, and list of concerns, refer to Appendix B.

2.2.2 Visiting CALSPAN

ARVIN CALSPAN Corporation located in Buffalo, New York was one of the facilities that responded to our inquiry calling for experimental validation of the Boundary Layer Code. CALSPAN was visited on October 23, 1987. The list of people who attended this meeting is:

Attendees	Organization	Telephone Number
Mike Dunn	CALSPAN	(716) 631–6747
John Lordi	CALSPAN	(716) 631–6805
Douglas Coats	SEA, Inc.	(702) 882–1966
John Grace	CALSPAN	(716) 631–6714
Don Boyer	CALSPAN	(716) 631–6817
George Skinner	CALSPAN	(716) 631–7500
Blake Pearce	CALSPAN	(716) 631–6789
Walter Wurster	CALSPAN	(716) 631–6846
Ron Drzewiecki	CALSPAN	(716) 631–6805
Homayun Kehtarnavaz	SEA, Inc.	(702) 882–1966

A presentation about the CALSPAN facilities and their experimental work in the area of nozzle flowfield measurements, and staging was given by Ron Drzewiecki of CALSPAN. Then the requirements for the boundary layer measurements for high area ratio nozzles was discussed. A tour of CALSPAN facilities was conducted in the afternoon.

The CALSPAN facilities consist of:

- o High Altitude Chamber: 13 foot diameter x 40 foot long and 10 foot diameter x 20 foot long; 400,000 foot equivalent altitude.
- o Ludwieg Tube Supersonic Wind Tunnel: ~ 5 foot diameter test section, M_∞ = 2–4.5.
- o 48 inch and 96 inch Hypersonic Shock Tunnels = ~ 4 foot diameter test sections; M_∞ = 8–18.

A high–speed 128 channel digital data aquisition system, capable of 20,000 HZ recording rate (50μm sampling interval/channel), serves these facilities.

CALSPAN can accomplish the heating of the flow by preheating gas reservoirs which is limited to temperatures of about 1000° F or by shock heating techniques if higher temperatures are desired. Another approach that has been suggested by CALSPAN is one in which the reaction products of liquid propellants can be duplicated by the combustion of gaseous mixtures (Reference 44). This gaseous equivalent approach has been used to duplicate liquid NTO/MMH and NTO/UDMH propellant rocket flows. Example of such an application is shown in exhibit A, Appendix C.

With respect to instrumentation, a variety of sensors and probes have been developed by CALSPAN to measure the gasdynamic and thermodynamic state properties of high–speed compressible flows.

A number of probes and sensors to measure the heat transfer and skin friction are indicated in exhibit B, Appendix C.

CALSPAN has also offered to consider nonintrusive diagnostics methods for boundary layer measurements.

2.2.3 NASA Lewis Research Center

NASA Lewis Research Center was visited on October 22, 1987. The list of people who attended this meeting are:

Attendees	Organization	Telephone Number
Douglas E. Coats	SEA, Inc.	(702) 882–1966
Homayun Kehtarnavaz	SEA, Inc.	(702) 882–1966
Al Pavli	LeRC	(216) 433–2470
Ken Kacynski	LeRC	(216) 433–2469
Paul Penko	LeRC	(216) 433–2404
Diane Galecki	LeRC	(216) 433–2410
Tamara Smith	LeRC	(216) 433–2467
Ken Davidian	LeRC	(216) 433–2602

First, a presentation was given by SEA, Inc. about the TDK/BLM thick boundary layer version program and the effect of a thick boundary layer on performance was discussed. Later on, the purpose of High Area Ratio Nozzle Boundary Layer Test program was discussed and then a tour of the NASA Lewis Research testing facilities was conducted by Al Pavli.

The purpose of this meeting was to evaluate the capability of this group in performing the experiments for the boundary layer contract in obtaining "accurate" results.

The schematics of the NASA Lewis Rocket Engine Test Facilities (RETF) is shown in Figure 10. Connecting the test capsule to the spray cooler is the water-jacketed second throat diffuser. The kinetic energy of the rocket exhaust gases is used in this diffuser to accomplish some of the altitude pumping of the test capsule. The diffuser was able to provide a pressure from 0.03 to 0.05 psi in the test capsule while exhausting into the spray cooler, which was at 0.3 to 0.6 psi.

The test capsule (Figure 11) is constructed in two parts. One part is the fixed end onto which the research hardware was mounted. The other part is the movable cam, which could be rolled back to provide access to the experiment. The nozzle shown in Figure 11 is a 1030:1 area ratio nozzle. More details about the experiment can be found in References 49 and 50.

The nozzle shown in Figure 11 is a 1030:1 area ratio nozzle with a flanged joint at the 428-area ratio station.

Mounted above the nozzle are the pressure tranducers and valves to measure nozzle static pressure. Visible alongside the nozzle are some of the wall temperature thermocouples. The instrumentation provided analog millivolt signals that are calibrated to be proportional to the magnitudes of the parameters to be measured. These analog signals are measured and converted to a digital signal by an automatic data digitizer at a rate of 50 readings per second per parameter and then sent to an IBM 370 computer. Once in the computer the millivolt values are converted to the engineering units of the measured parameters and arranged in groups of five readings. This will provide data output at 1/10 sec. intervals.

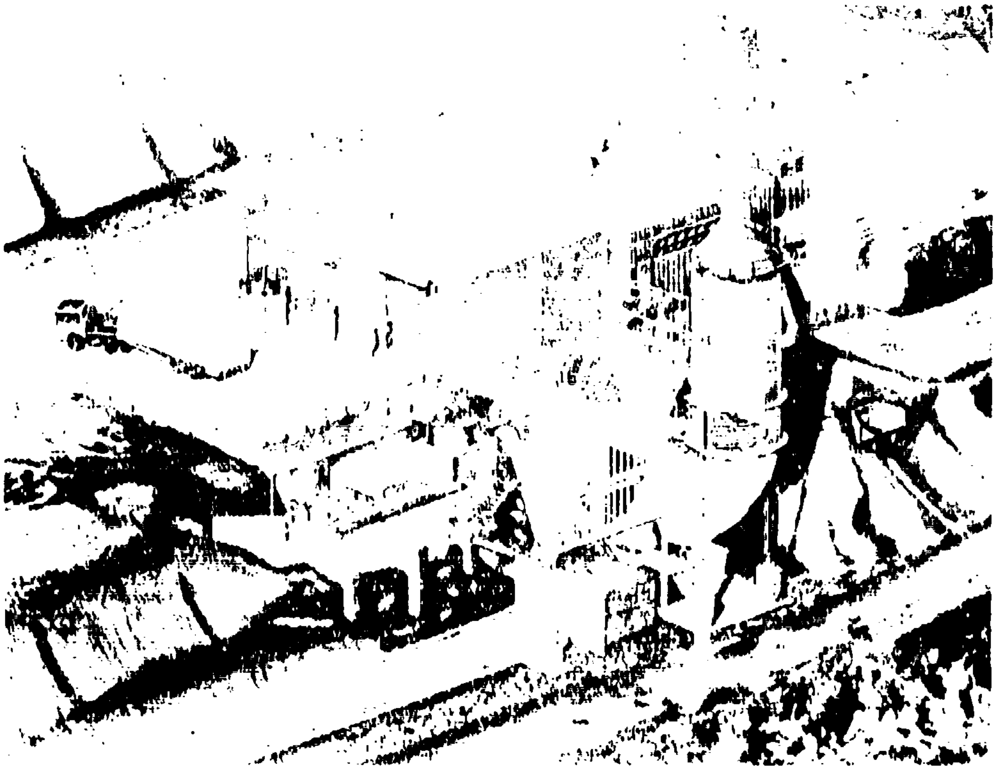
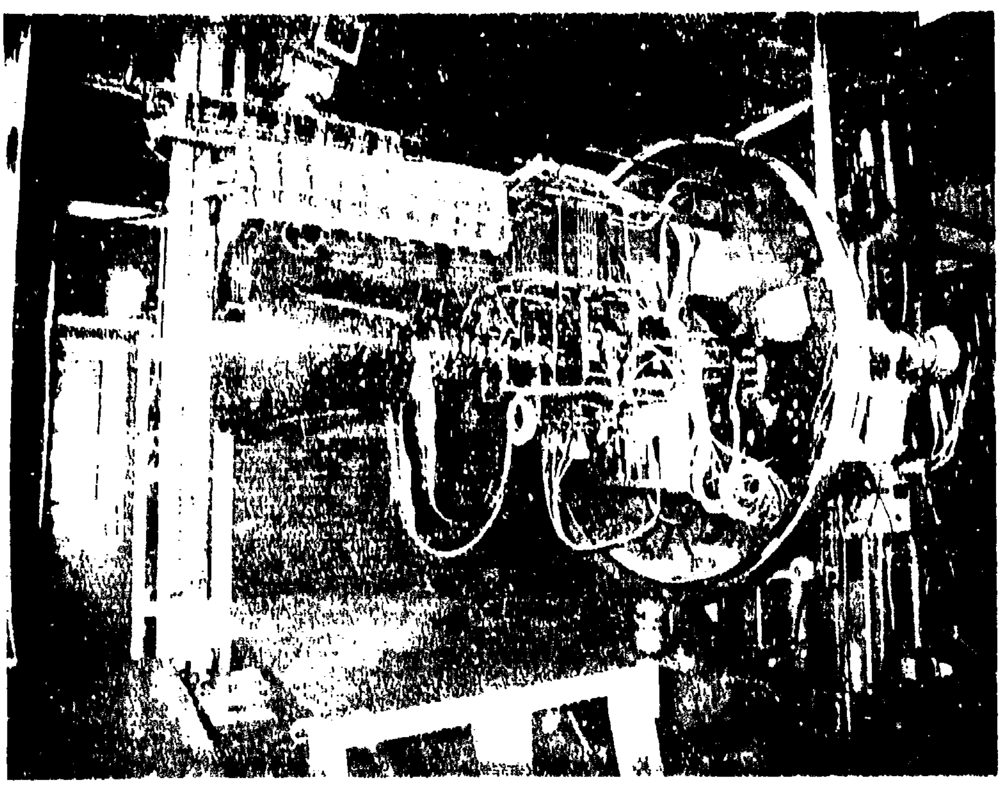


Figure [illegible]. NASA Lewis Rocket Engine Test Facility



[illegible]

2.2.4 Aerojet Tactical Systems

Following SEA's inquiry calling for experimental validation of the Boundary Layer code, Aerojet Tactical Systems, located in Sacramento, California, expressed some interest. A meeting was held on December 10th, 1987, at Aerojet. The names of people who attended this meeting are:

Attendees	Organization	Telephone Number
Homayun Kehtarnavaz	SEA, Inc.	(702) 882–1966
Jack Hyde	ATC	(916) 355–4839
Thong Nguyen	ATC	(916) 355–3664
Cherie Cotton	ATC	(916) 355–6751
Dick Ewen	ATC	(916) 355–3421
Dick Walker	ATC	(916) 355–2694

A presentation of the problem and parameters to be measured was given by Homayun Kehtarnavaz of SEA, Inc. In response, Aerojet indicated that they are not equipped to measure the Reynolds stress terms. However, they showed interest in making measurements of the heat flux and wall shear by using hot wire probes. For more details see Appendix D.

2.2.5 Visiting AEDC

AEDC was visited on May 18, 1987, by Douglas Coats of Software and Engineering Associates, Inc. Personnel contacted at AEDC were Wheeler McGregor, Chad Limbaugh, and John Jordan. The J4 and J5 facilities were visited. John Jordan suggested that the older steam facility be renovated for the boundary layer measurement tests. However, the cost of fixing up the facility was deemed excessive for these tests. A write–up on the proposed AEDC approach was supplied by Chad Limbaugh and appears in Appendix E.

2.2.6 Rockwell International, Rocketdyne Division

Dr. Lalit K. Sharma, from Rocketdyne in Canoga Park, California, responded to SEA's inquiry for an experimental validation test plan. Rocketdyne was visited on November 4, 1987. The names of people who were present at this meeting are:

Attendees	Organization	Telephone Number
Lalit K. Sharma	Rocketdyne	(818) 710-3472
Homayun Kehtarnavaz	SEA, Inc.	(702) 882-1966

An explanation of the boundary layer code and the purpose of the experimental validation program was given by Homayun Kehtarnavaz of SEA, Inc.

Laser-based velocimetry was proposed by Dr. Sharma to measure the exit plane velocity. Laser doppler velocimeter (LDV) was proposed to measure Reynolds shear stress and laser-two-focus (L2F) technique will be used to measure mean and turbulence intensity velocity profiles. Rocketdyne expressed concern about the issue of seeding. More details are given in Appendix F.

2.2.7 Visiting Los Alamos National Laboratory

Several meetings were held at Los Alamos Scientific Laboratory on January 25, 1988, to discuss boundary layer measurement techniques. The people who attended the various meetings were:

Attendees	Organization	Telephone Number
Douglas E. Coats	SEA, Inc.	(702) 882–1966
Harry Watanabe	LASL	(505) 667–6686
Wayne Danen	LASL	(505) 667–7121
Richard Oldenborg	LASL	(505) 667–2096
Ralph Castain	LASL	(505) 667–3283
David Taylor	LASL	(505) 667–7886
Mike Cline	LASL	(505) 667–9093
William Wadt	LASL	(505) 667–8680

The morning discussions centered mostly on elaborating the measurement requirements as outlined in the SEA, Inc. requirement document (Appendix A). As an adjunct, the following were listed as requirements.

- The flow in the boundary layer must be turbulent from before the throat.
- The boundary layer should encompass between 10% to 40% of the flow at the exit plane.
- The heat transfer to the wall should be high enough to simulate conditions in a real rocket nozzle.
- The expansion process should maintain, as realistic as possible, the conditions in a real rocket nozzle. For example, axisymmetric instead of 2D nozzles, ratio of specific heats ≤ 1.4.

In the afternoon, Douglas Coats toured the CARS facility with David Taylor. Taylor explained the use of the CARS equipment in his lab and indicated how it would be used in the nozzle flows and how the data could be spatially resolved. The method would require two windows in the nozzle. The major disadvantage of the windows is that it would restrict the flow environment to conditions that the window material could tolerate. The major advantage would be in avoiding taking data so near the nozzle lip that the back pressure would have a significant effect. It was also pointed out that to get the gas translational temperature using CARS would require its inference from the rotational spectra. This is a practical, not a theoretical, limitation on the method.

Rich Oldenborg explained his current work effort using Laser Induced Fluorescence (LIF), which is the measurement of Boron reaction rate data.

The main concern which was voiced about using LIF was getting an adequate amount of induced florescence from the seed gas to measure. A continuous flow device was recommended. However, at very low pressure, the measurement times could be large (~ several seconds per point). A white paper was received from Los Alamos National Laboratory which is documented in Appendix G.

3.0 Recommendation

The primary objective of developing an experimental plan for boundary layer measurements is to obtain accurate and high quality data to compare against the present and future analytical models. During the course of our investigations, no single or set of diagnostic techniques, experimental facilities, or approaches were found to be compelling as a single approach to achieving this objective. As a result, it was necessary to relax some of the ground rules which we had originally laid out in order to meet the primary goal of obtaining accurate data. As mentioned in the introduction, we concluded that hot engine firings were not compatible with accurate mapping of the boundary layer. This conclusion was based on considerations of available experimental techniques, test times, facility requirements, and cost. We also discovered that there were no diagnostic techniques which were "off the shelf" ready for boundary layer measurements of the required accuracy in simulated rocket nozzles. In addition, facility capabilities for different organizations varied tremendously. Calspan has excellent short duration test facilities, while AEDC has good large scale longer duration capability. However, the selected diagnostic techniques must be mated with the correct facility to insure adequate data acquisition. Because of the developmental nature of the diagnostic techniques and the mating of these techniques with the facilities, the following recommendations are conditional rather than absolute. First, we will cover the recommended diagnostic methods and then discuss recommendations for test facilities.

Diagnostic Methods Recommendations Velocity Profiles

LDV must be considered the primary candidate for taking velocity measurements in the boundary layer. This conclusion is based on the fact that this method is well developed in comparison to other laser techniques. Alternates and/or backup methods should include LIF and CARS. We strongly recommend that optical techniques should be the cornerstone of these measurements.

We view both LIF and CARS as potentially superior methods of velocity measurement. The trade off between LDV and LIF/CARS is the development time and difficulties associated with particulate seeding for LDV versus moving LIF/CARS from the lab into a test environment. Should the latter be accomplished, then LIF/CARS would be the recommended technique.

Static Pressure Measurements

Pressure transducers on the wall are the recommended diagnostic technique for measuring static pressure at the wall. If the selected test conditions are benign enough, pitot measurements can also be used as a backup and to verify calibration of both the wall static pressure and velocity profile.

Temperature Profiles

Laser based non–intrusive techniques are recommended. LIF seems to have a slight edge on CARS based techniques, but both methods should perform well theoretically. The final choice should be decided by the selected contractor based on cost and risk factors. Both LIF and CARS are also capable of determining the density profiles in the flow. Information about the chemical composition would thus supply enough information to compute the static pressure profile. The redundancy in pressure data will supply a useful accuracy check of the measurements. Total temperature probes are also readily available (see Appendix C), and should be used as a calibration backup if pitot measurements are also taken.

Wall Heat Transfer Measurement

There are any number of adequate methods to measure the wall heat transfer rate. However, most of these methods depend on the temperature range of the flow (total and static) and of the wall. The final selection must be based on the test environment selected. However, we do not recommend that the heat transfer rate be deduced solely from backwall temperature measurements. Such methods require operation to steady state to supply the desired accuracy.

Wall Shear Stress

Direct measurements of the wall shear stress are definitely preferred. If the test environment permits, some sort of the floating element method should be used (see Appendix C and also the description of the Kistler Skin Friction Gauge). Extrapolation of the velocity profile to the wall can also be used if floating elements are not practical. Under no circumstances should the Reynolds Analogy be used as the primary method of determining skin friction. The use of the law of the wall also presupposes the form of the results and hence its use is discouraged.

Test Facilities

The ideal facilities for these tests would be space based so that practical considerations such as pumping requirements, total pressures, and total temperatures would not be of concern. However, since we are lacking permanent space stations or lunar facilities, we must make due with earth based testing. It is always preferred that the test environment closely simulate the environment to which the data is to be applied. However, in this case, we recommend against real engine firings. Too many of the recommended diagnostic techniques are not well enough established to allow for their extension to such a hostile environment. In fact, some of the test methods suggested would best be done with windows cut into the nozzle wall. Many of the problems associated with facility requirements disappear if the diagnostic techniques can be made to work for short duration test. Calspan has an excellant short duration test capability which would allow good simulation of high area ratio nozzles. However, it is not clear if either LIF or CARS methods can be made to work with test durations in the 50 millisecond range. The Accurex arc tunnel suggested by one of the experimental test plan contributors would only be acceptable if the total enthalpy gradient across the nozzle could be eliminated.

In order to simulate a real nozzle as closely as possible, we make the following recommendations.

1) The test nozzle should be axisymmetric and have at least an area ratio of 300:1.

2) The flow should be fully turbulent before the throat plane.

3) The flow should be as hot as is compatible with the diagnostic techniques. Flows in the range of 1500°R are recommended. These types of temperatures will allow for adequate heat transfer rates, density variations, and avoid condensation problems.

4) The gas supply system should supply nearly uniform property flow.

In order to assure that the experiments achieve their goal of supplying data to validate analytical models, we also recommend that an organization such as Software and Engineering Associates, Inc. be assigned to monitor the experimental work effort.

NOMENCLATURE

c	speed of light
d_p	droplet radius
$g(\nu)$	line shape function
h	enthalpy
I	intensity
M	Mach number
n	normal direction
P	pressure
Pr	Prandtl number
r	radius
r^*	throat radius
Re	Reynold's number
s	entropy
T	temperature
u	velocity
U	velocity
v	velocity
V	velocity (total)
y	distance

Greek

θ	boundary layer momentum thickness
ξ	vorticity
ρ	density
δ	boundary layer thickness
Δ	difference
τ	shear stress, characteristic time
μ	coefficient of viscosity
ν	frequency

Abbreviations

AL	Astronautics Laboratory
ASE	Rocketdyne Advance Space Engine, area ratio 400:1
BC4515 BC1010	Experimental Nozzles by JPL, cone shaped
BLM	Boundary Layer Module of TDK computer code
CARS	Coherent Anti-Stokes Raman Spectroscopy
CRC	Coherent Raman Spectroscopy
IRS	Inverse Raman Spectroscopy
IUS	Inertial Upper Stage, Space motor, OTV
JANNAF	Joint Army Navy NASA Air Force
LDA	Laser Doppler Anemonetry
LDS	Laser Doppler Spectrometry
LDV	Laser Doppler Velocimetry
LIF	Laser Induced Fluorescence
LOX/GH_2	Liquid Oxygen and Gaseous Hydrogen
LTA	Laser Transit Anemonetry
RL-10	Pratt & Whitney Space Engine, area ratio 205:1
SEA	Software and Engineering Associates, Inc.
SRGS	Simulated Raman Spectroscopy
SSME	Space Shuttle Main Engine, area ratio 76:1
TDK	Two Dimensional Kinetic Computer Code
XDELTA	Extended Delta (Solid Propellant Space motor)
XLR134	OTV Engine, Space Storable, area ratio 767:1

REFERENCES

1. Goldstein, R. J., Fluid Mechanics Measurements, Hemisphere Publishing Corp., 1983.

2. Praharaj, S. C., and Palko, R. L., "Measurements for Rocket Engine Performance Code Verification," REMTECH, Inc. Report No. RTR–157–01, October 1986.

3. Back, L. H., Cuffel, R. F., and Massier, P. F., "Laminarization of a Turbulent Boundary Layer in Nozzle Flow–Boundary Layer and Heat Transfer Measurements with Wall Cooling," Journal of Heat Transfer, Trans. ASME, Series C, Vol. 92, No. 3, Aug. 1970, pp. 333–344.

4. Back, L. H., and Cuffel, R. F., "Turbulent Boundary Layer and Heat Transfer Measurements Along a Convergent–Divergent Nozzle," Journal of Heat Transfer, Nov. 1971.

5. Back, L. H., and Cuffel, R. F., "Turbulent Boundary Layer Measurements Along a Supersonic Nozzle with and without Wall Cooling," Transactions of the ASME, May 1972.

6. Cuffel, R. F., Back, L. H., and Massier, P. F., "The Transonic Flowfield in a Supersonic Nozzle with Small Throat Radius of Curvature," AIAA Journal, Vol. 7, No. 7, July 1969, pp. 1364–1366.

7. Mabey, D. G., and Gaudet, L., "Some Performance of Small Skin Friction Balances at Supersonic Speeds," Journal of Aircrafts, Vol. 12, 1975, pp. 819–825.

8. Fage, A., and Falkner, V. M., "On the Relation between Heat Transfer and Surface Friction for Laminar Flow," Aerospace Research Council, London, R & M No. 1408, 1931.

9. Rubesin, M. W., Okuno, A. F., Mateer, G. G., and Brosh, A., "A Hot–Wire Surface Gage for Skin Friction and Separation Detection Measurements," NASA TM X-62, 1975, p. 465.

10. Sandborn, V. A., "Surface Shear Stress Fluctuations in Turbulent Boundary Layers," Second Symposium on Turbulent Shear Flows, London, 1979.

11. Sandborn, V. A., "Evaluation of the Time Dependent Surface Shear Stress in Turbulent Flows," ASME Preprint 79–WA/FE–17, 1979.

12. Reiss, L. P., and Hanratty, T. J., "Measurement of Instantaneous Rates of Mass Transfer to a Small Sink on a Wall," AIChE Journal, Vol. 8, 1962, pp. 245–247.

13. Reiss, L. P., and Hanratty, T. J., "An Experimental Study of the Unsteady Nature of the Viscous Sublayer," AIChE Journal, Vol. 9, 1963, pp. 154–160.

14. Adrian, R. J., "New Advances in Optical Measurement of Fluid Velocity," International Symposium on Laser Anemometry, ASME FED Vol. 33, 1985.

15. Koochesfahani, M. M., and Dimotakis, P. E., "Laser Induced Fluorescence Measurements of Mixed Fluid Concentration in Liquid Plane Shear Layer," AIAA J., Vol. 23, No. 11, 1985, pp. 1700–1707.

16. Hanson, R. K., "Combustion Diagnostics: Planar Imaging Techniques," Proc. of 21st Symposium (International) on Combustion, 1986.

17. Roquemore, W. M., et al., "Development of Laser Diagnostics for Combustion Research," Proc. of the Central States Section, The Combustion Institute, May 1986.

18. Durst, F., Melling, A., and Whitelaw, J. H., "Principles and Practices of Laser Doppler Anemometry," 2nd Edition, Academic Press, 1981.

19. Drain, L. E., "The Laser-Doppler Technique," John Wiley, 1980.

20. Modarress, D., and Hoeft, T., "Dust Particle Velocity Measurement in Dusty Flows," DNA Final Report, SDL Report No. 87-2420-40F.

21. Smart, A. E., and Mayo, W. T., Jr., "A Tutorial: Laser Transit Anemometry," Proc. 4th International Conference on Photon Correlation Techniques in Fluid Mechanics, Stanford University, Stanford, 1980.

22. Smeets, G., and George, A., "Instantaneous Laser Doppler Velocimeter Using a Fast Wavelength Tracking Michelson Interferometer," Rev. Sci. Instrum., Vol. 49, 1978, pp. 1589.

23. Smeets, G., and George, A., "Novel Laser Doppler Velocimeter Enabling Fast Instantaneous Registrations," Proc. 12th International Symposium on Shock Tubes and Waves, Jerusalem, 1979, pp. 579.

24. Smeets, G., and George, A., "Michelson Spectrometer for Instantaneous Doppler Velocity Measurements," Journal of Phys. E.: Sci. Instrum., Vol. 14, 1981, pp. 838.

25. Modarress, D., and Azzazy, M., "Modern Experimental Techniques for High Speed Flow Measurements," AIAA-88-0420.

26. McDaniel, J. C., Hiller, B., and Hanson, R. K., "Simultaneous Multiple-Point Velocity Measurement Using Laser-Induced Iodine Fluorescence," Optics Letters 8, No. 1, 1983.

27. Zimmerman, M., and Miles, R. B., "Hypersonic-Helium Flow Field Measurements with the Resonant Doppler Velocimeter," Appl. Phys. Lett., Vol. 37, No. 10, 1980, pp. 885.

28. Hiller, B., and Hanson, R. K., "Two-Frequency Laser-Induced Fluorescence Technique for Rapid Velocity-Filed Measurements in Gas Flows," Optics Letters 10, No. 5, 1985.

29. Hiller, B., Cohen, L. M., and Hanson, R. K., "Simultaneous Measurements of Velocity and Pressure Fields in Subsonic and Supersonic Flows through Image-Intensified Detection of Laser-Induces Fluorescence," AIAA 24th Aerospace Sciences Meeting, AIAA Paper No. 86-0161, 1986.

30. She, C. Y., Fairbank, W. M., Jr., and Exton, R., J., "Measuring Molecular Flows with High-Resolution Stimulated Raman Spectroscopy," IEEE Journal of Quantum Electronics, Vol. QE-17, No. 2, 1981.

31. Gustafson, E. K., McDaniel, J. C., and Byer, R. L., "CARS Measurement of Velocity in a Supersonic Jet," IEEE Journal of Quantum Electronics, Vol. QE-17, No. 12, 1981, pp. 2258.

32. Moosmuller, H., Herring, G. C., and She, C. Y., "Two-Component Velocity Measurements in a Supersonic Nitrogen Jet with Spatially Resolved Inverse Raman Spectroscopy," Opt. Letter 9,536, 1984.

33. Exton, R. J., and Hillard, M. E., "Raman Doppler Velocimetry: A Unified Approach for Measuring Molecular Flow Velocity, Temperature, and Pressure," Applied Optics, Vol. 25, No. 1, 1986, pp. 14.

34. VomStein, H. D., and Pfeifer, H. J., "Investigation of the Velocity Relaxation of Micron-Sized Particles in Shock Waves Using Laser Radiation," Applied Optics, Vol. 11, No. 2, Feb. 1972.

35. Rudinger, G., "Effective Drag Coefficiency for Gas-Particle Glow in Shock Tubes," Journal of Basic Engineering, March 1970, pp. 165-171.

36. Hunter, W. W., Jr., and Nichols, C. E., Editors, "Wind Tunnel Seeding Systems for Laser Velocimeters," NASA Conference Publication 2393, March 1985.

37. Proceeding of a Workshop on "Wind Tunnel Seeding Systems for Laser Velocimeters," NASA Conference Publication 2393.

38. Heltsley, F. L., "Recent Experience in Seeding Transonic/Supersonic Flows at AEDC," pp. 121-140, Ref. 44.

39. Gouldin, F. C., Depsky, J. S., and Lee, S. L., "Velocity Field Characteristics of a Swirling Flow Combustor," AIAA Journal, Vol. 23, No. 1, 1985, pp. 95-102.

40. Samimy, M., Nejad, A. S., Lasngenfeld, C. A., Craig, R. R., and Vanka, S. P., "Isothermal Swirling Flow in a Dump Combustor," AIA . Paper 87-1352, 1987; also AIAA Journal (in press).

41. Samimy, M., Petrie, H. L., and Addy, A. L., "A Study of Compressible Turbulent Reattaching Free Shear Layers," AIAA Journal, Volume 24, No. 2, 1986, pp. 261-267.

42. Samimy, M., and Addy, A. L., "Interaction Between Two Compressible Turbulent Free Shear Layers," AIAA Journal, Volume 24, No. 12, 1986, pp. 1918-1923.

43. Samimy, M., Abu-Hijleh, B. A./K., and Bhattacharyya, S., "Performance of Laser Doppler Velocimeter with Polydisperse Seed Particles in High Speed Flows," AIAA Paper No. 88-0425, 1988.

44. Sheeran, W. J., and Hendershot, K. C., "Simulation of Earth-Storable Liquid Bipropellant with Gaseous Reactants," Journal of Applied Mechanics, June 1969, pp. 347-348.

45. Pavli, A. J., Kacynski, K. J., and Smith, T. A., "Experimental Thrust Performance of a High-Area-Ratio Rocket Nozzle," NASA Technical Paper No. 2720, April 1987.

46. Kacynski, K. J., Pavli, A. J., and Smith, T. A., "Experimental Evaluation of Heat Transfer on a 1030:1 Area Ratio Rocket Nozzle," AIAA Paper No. AIAA-87-2070, 23rd Joint Propulsion Conference, San Diego, CA, 1987.

APPENDIX A

OUTLINE OF THE EXPERIMENTAL WORK FOR THE BOUNDARY LAYER STUDY

EXPERIMENTAL EFFORTS IN BOUNDARY LAYER MEASUREMENTS

ABSTRACT

Experimental efforts should be done for accurate measurements of the flow field variables and boundary layer parameters in a rocket engine nozzle environment. Data for two different nozzles are included in this report for better understanding of an exhaust nozzle environment.

INTRODUCTION

The efforts in experimental work must include techniques to measure parameters in the boundary layer that will produce results of high quality. Quality data on nozzle wall boundary layer is very limited at the present. The data that is most pertinent for checking the analytical models are direct measurements of local wall skin friction and/or shear (τ_w) and heat transfer as well as velocity, temperature, and Reynold's stress profiles throughout the boundary layer. A generic nozzle geometry is shown in Figure 1, and the geometry of nozzles under consideration is shown in Figures 2 and 3. EPS is the expansion or area ratio at the exit plane.

Pressure and temperature at the wall for ASE and RL-10 nozzles are indicated in Figures 4 and 5 and related heat transfer fluxes at the wall for these cases are given in Figure 6.

Variation of δ^* (displacement thickness) and θ (momentum thickness) for the two engines are given in Figures 7 and 8. The temperature, velocity, and pressure boundary layer profiles for these nozzles are given in Figures 9 and 10. Pressure, temperature, and velocity at the edge of boundary layer as a function of axial location are given in Figures 11-a through 11-c for ASE nozzle and Figures 12-a through 12-c for RL-10 nozzle.

Table I and II represents the Mach number, density, and concentration of four species as a function of expansion ratio. Figure 13 represents the nozzle wall heat flux for a cold wall and Figure 14 is a plot of the adiabatic wall temperature.

These results are obtained by using TDK/BLM Computer Code.

GOAL

Experimental efforts should be done to verify the analytical results. The following parameters should be measured and accurately determined by experiment:

1. u', v' terms in turbulent model or the so called Reynold's stress terms.

2. Profiles of T/T_e, U/U_e, and possibly P/P_e comparable to those of Figures 9 and 10.

3. Profiles of δ (boundary layer thickness), δ^* (displacement thickness) and θ (momentum thickness) as a function of axial location identical to Figures 7 and 8.

4. Local wall shear (τ_w) and skin friction (C_f).

5. Local heat flux at the wall for a cold wall case, (similiar to Figure 13), and temperature at the wall for adiabatic wall comparable to Figure 14.

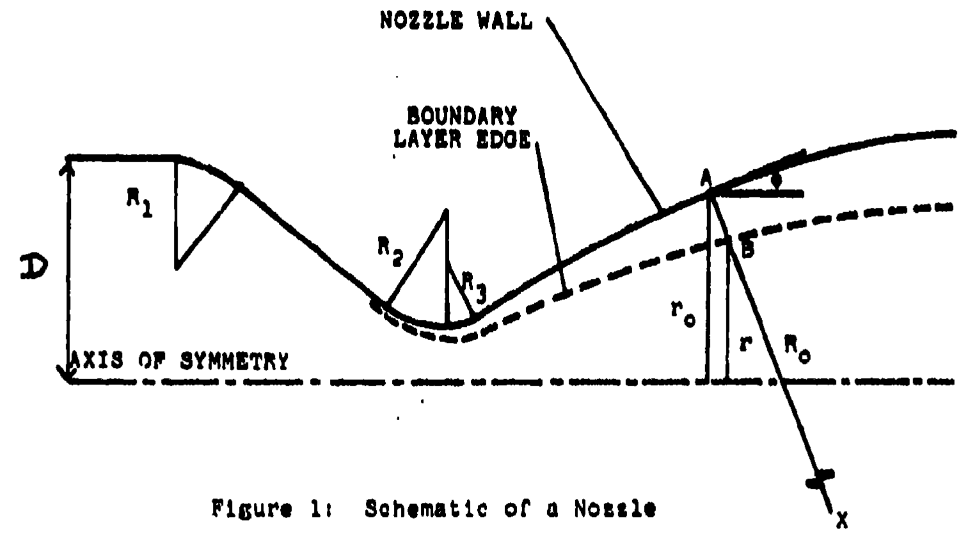


Figure 1: Schematic of a Nozzle

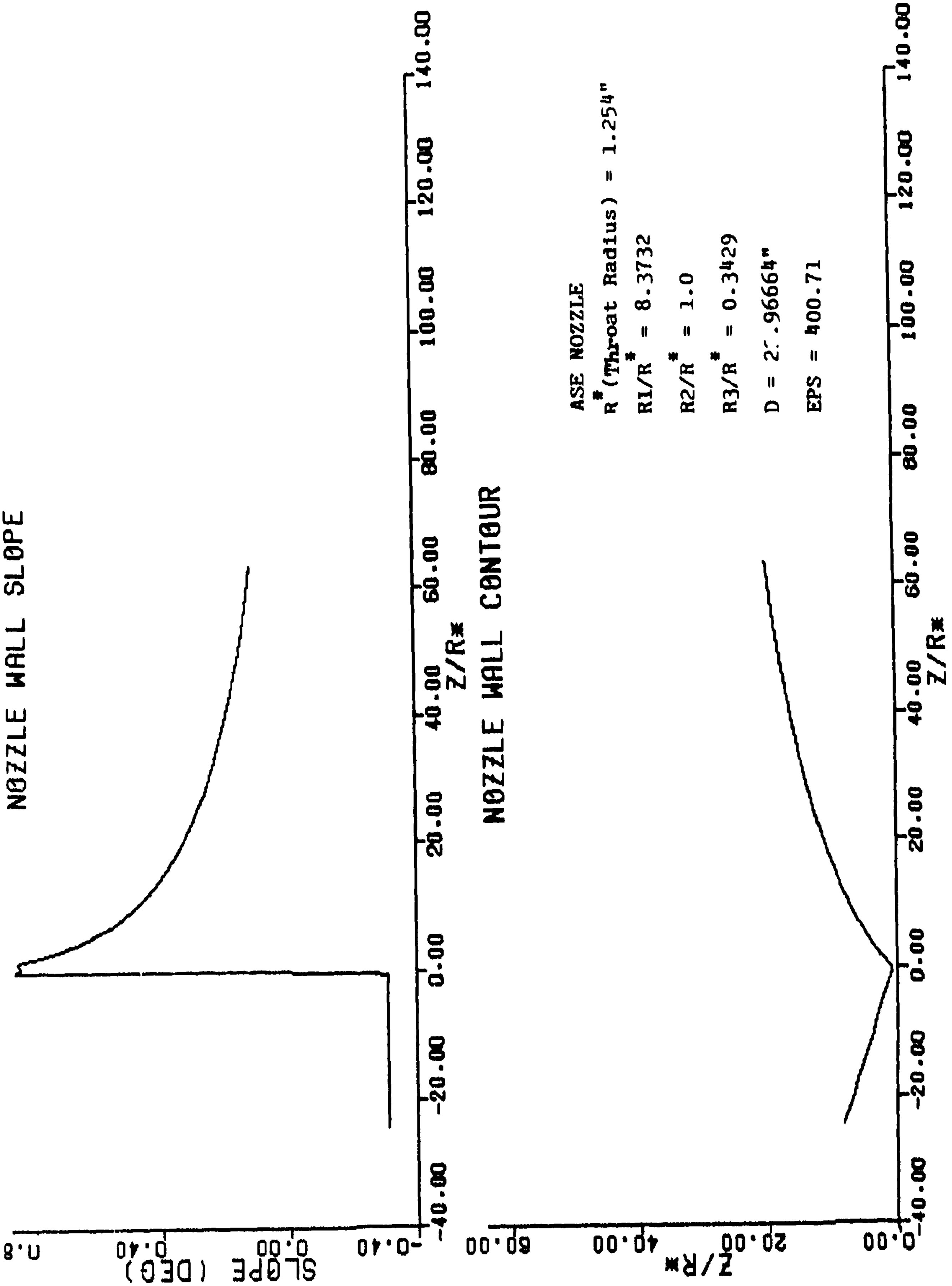


Figure 2. Nozzle Wall Slope

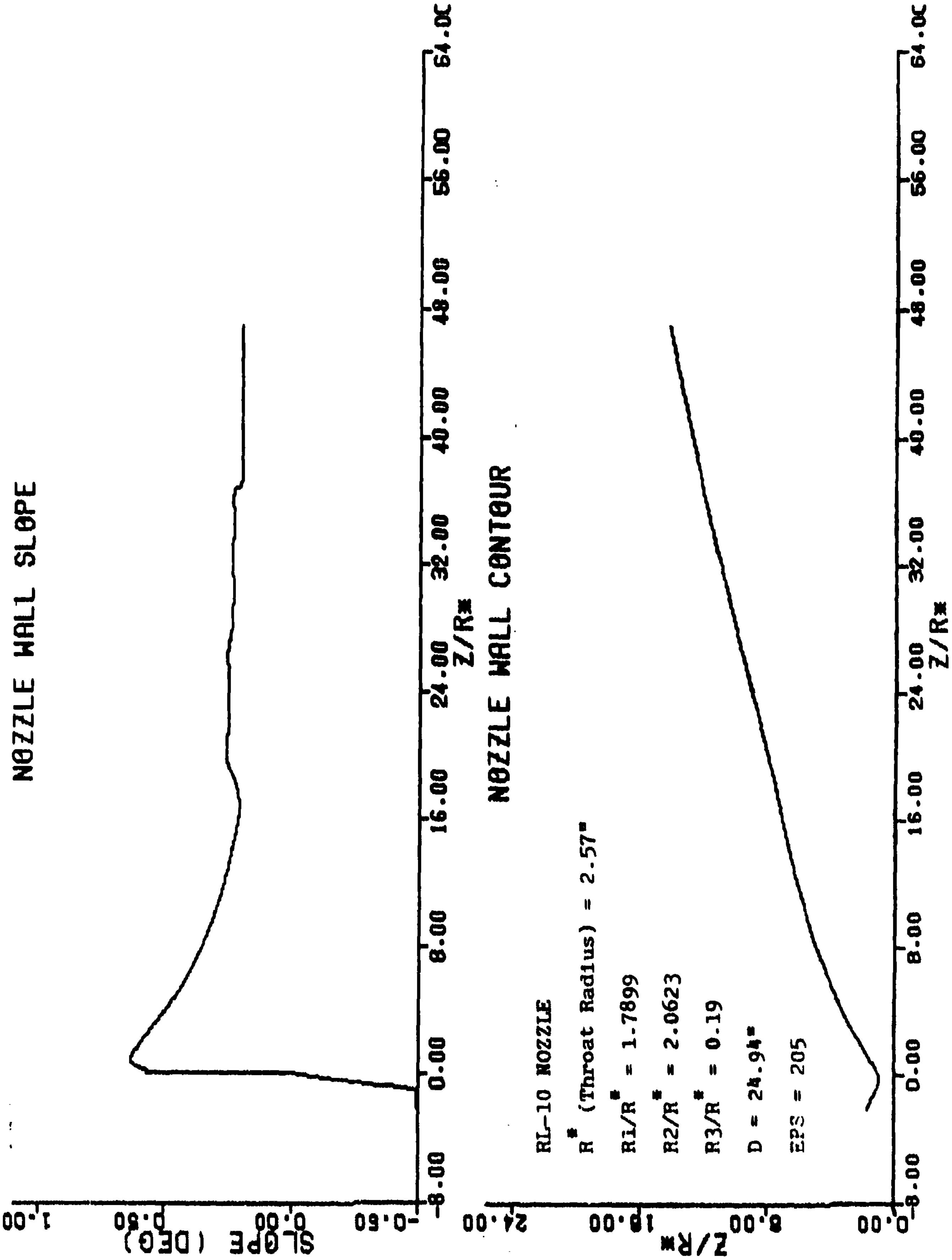


Figure 3. Nozzle Wall and Wall Slope

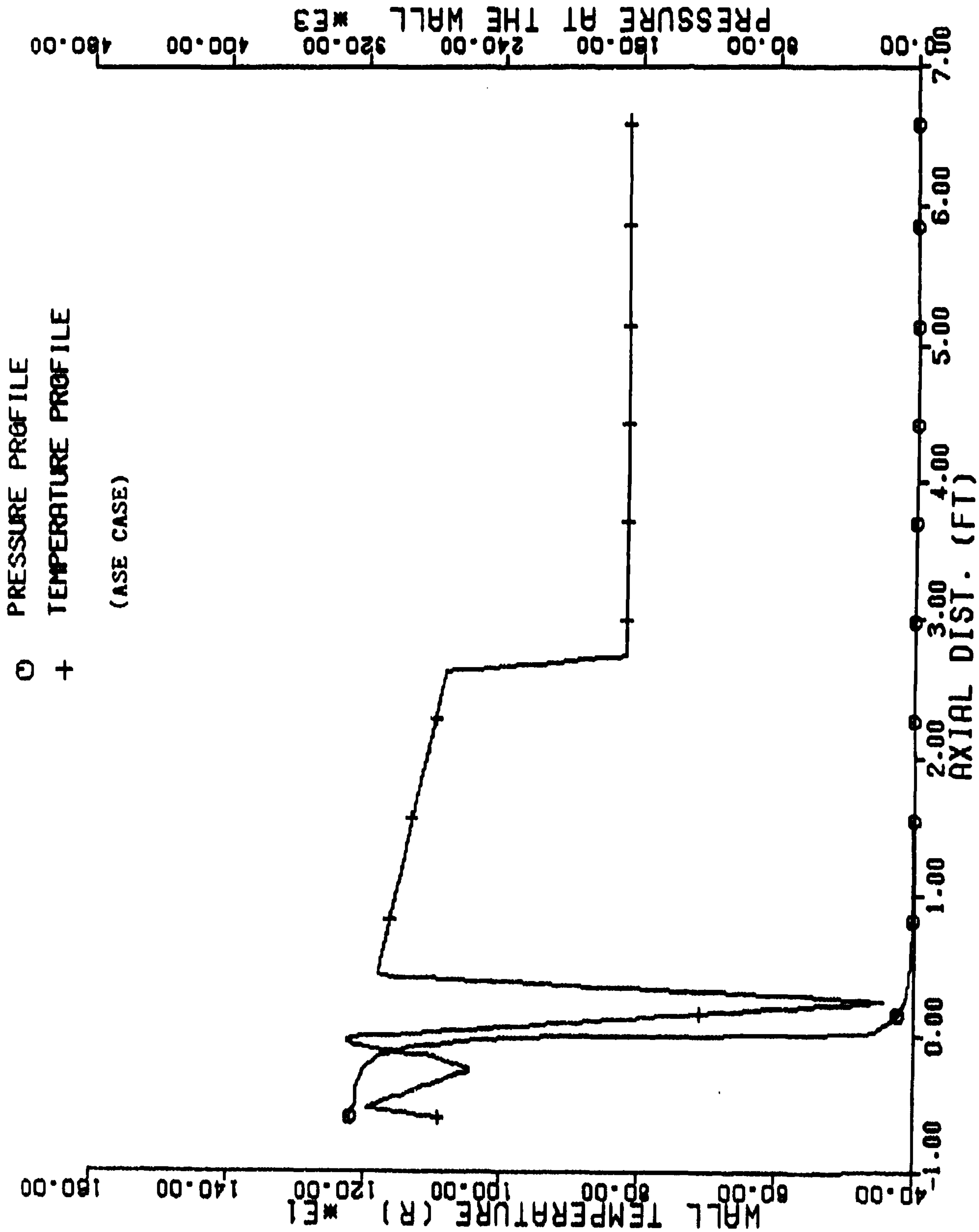


Figure 4. ASE Wall Temperature and Pressure

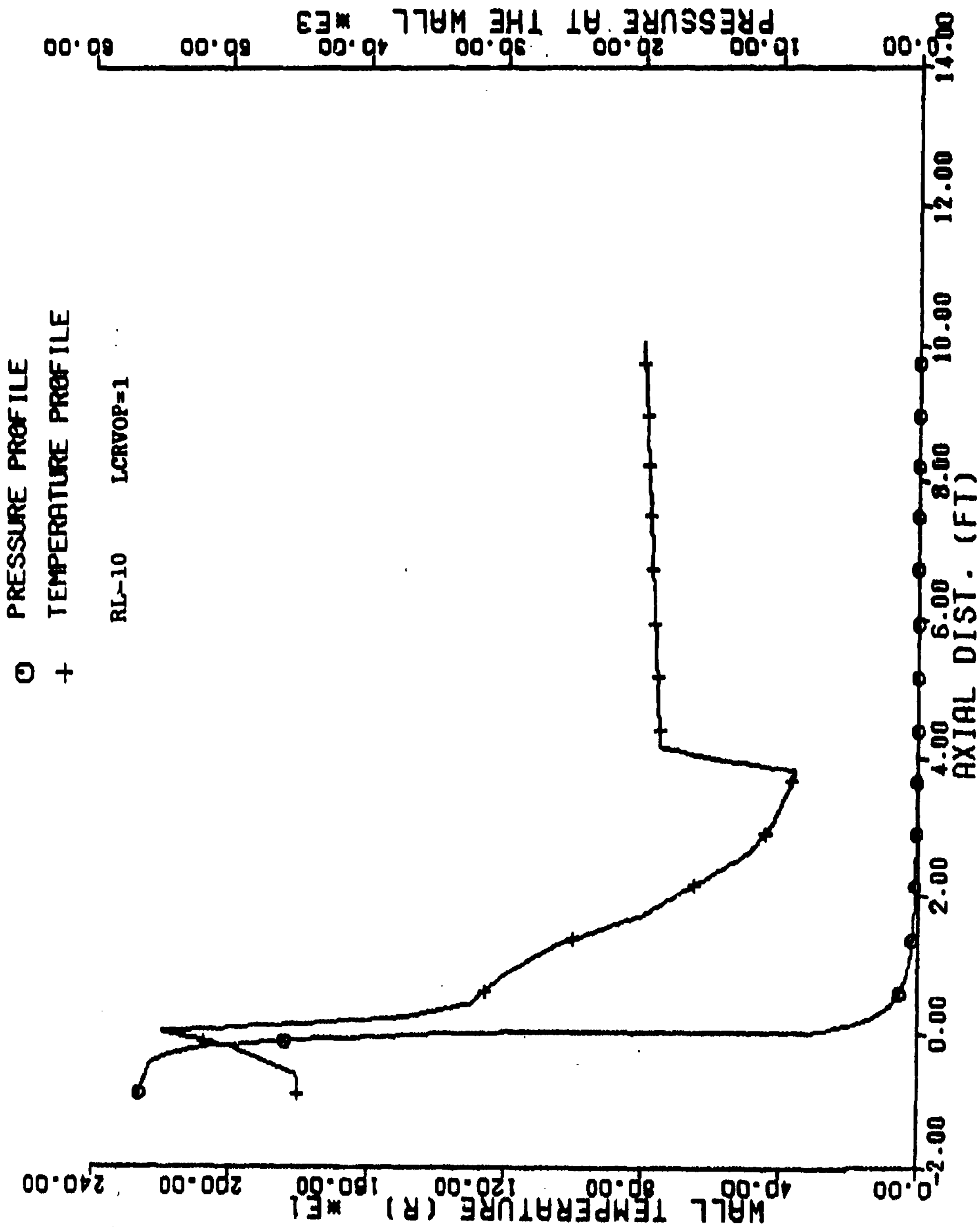
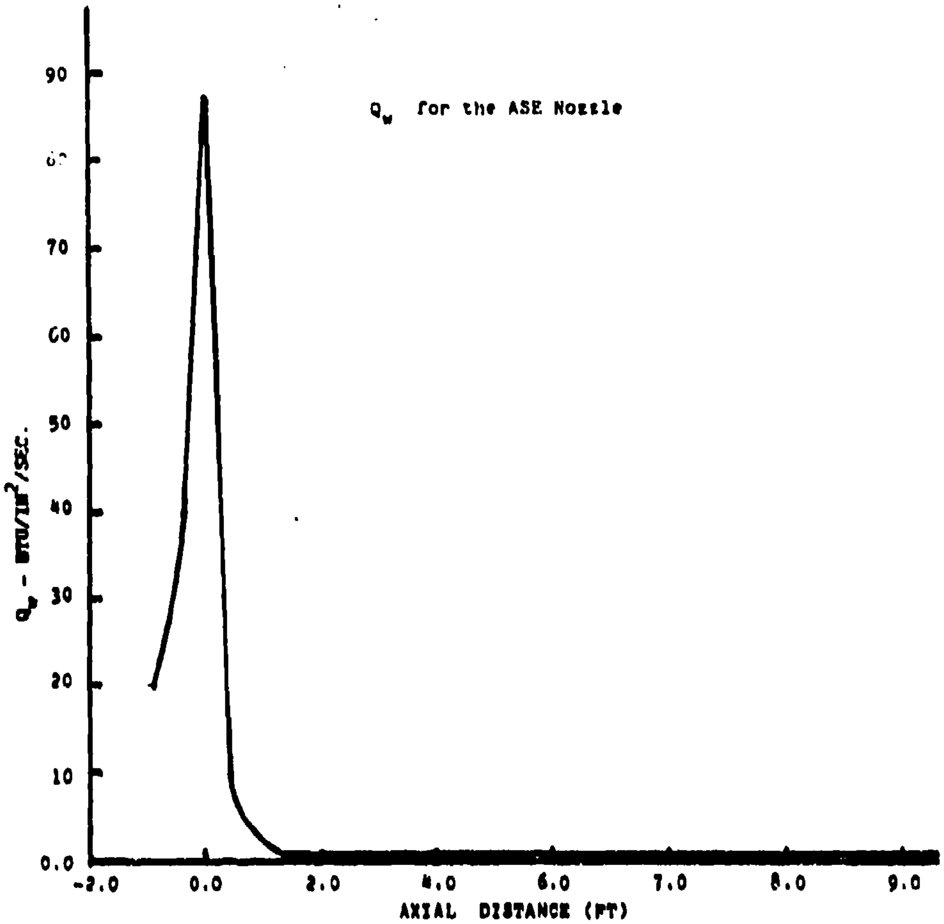


Figure 5. RL-10 Wall Temperature and Pressures



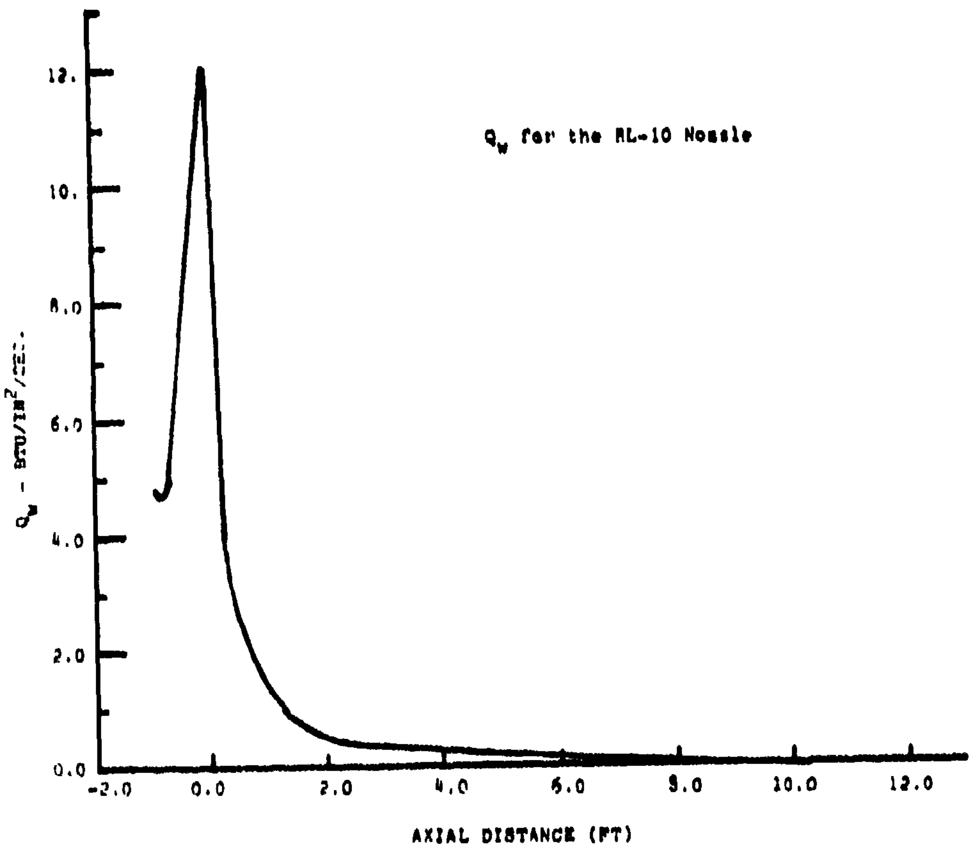


Figure 6. Nozzle Wall Heat Fluxes

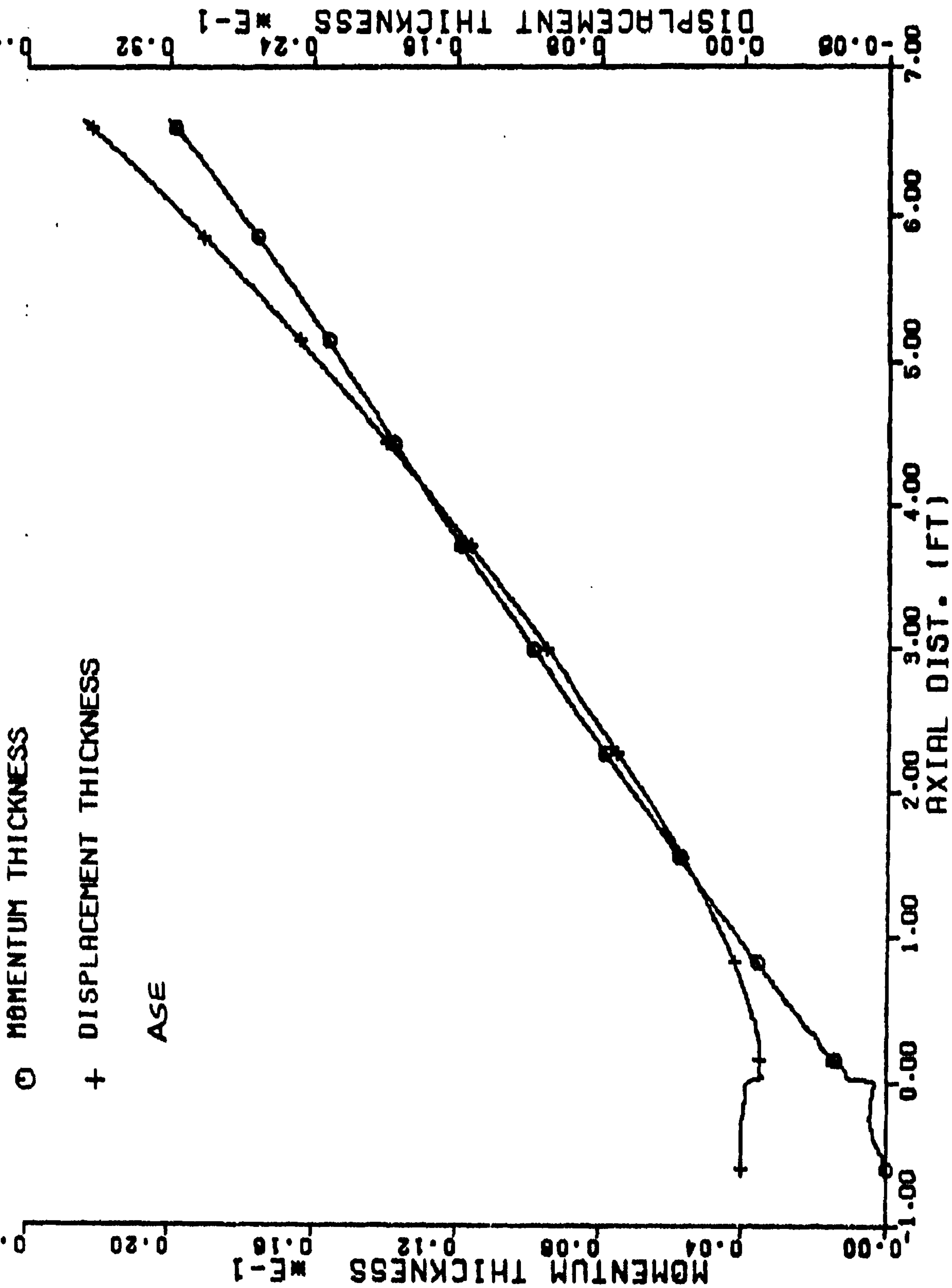


Figure 7. ASE Boundary Layer Thicknesses

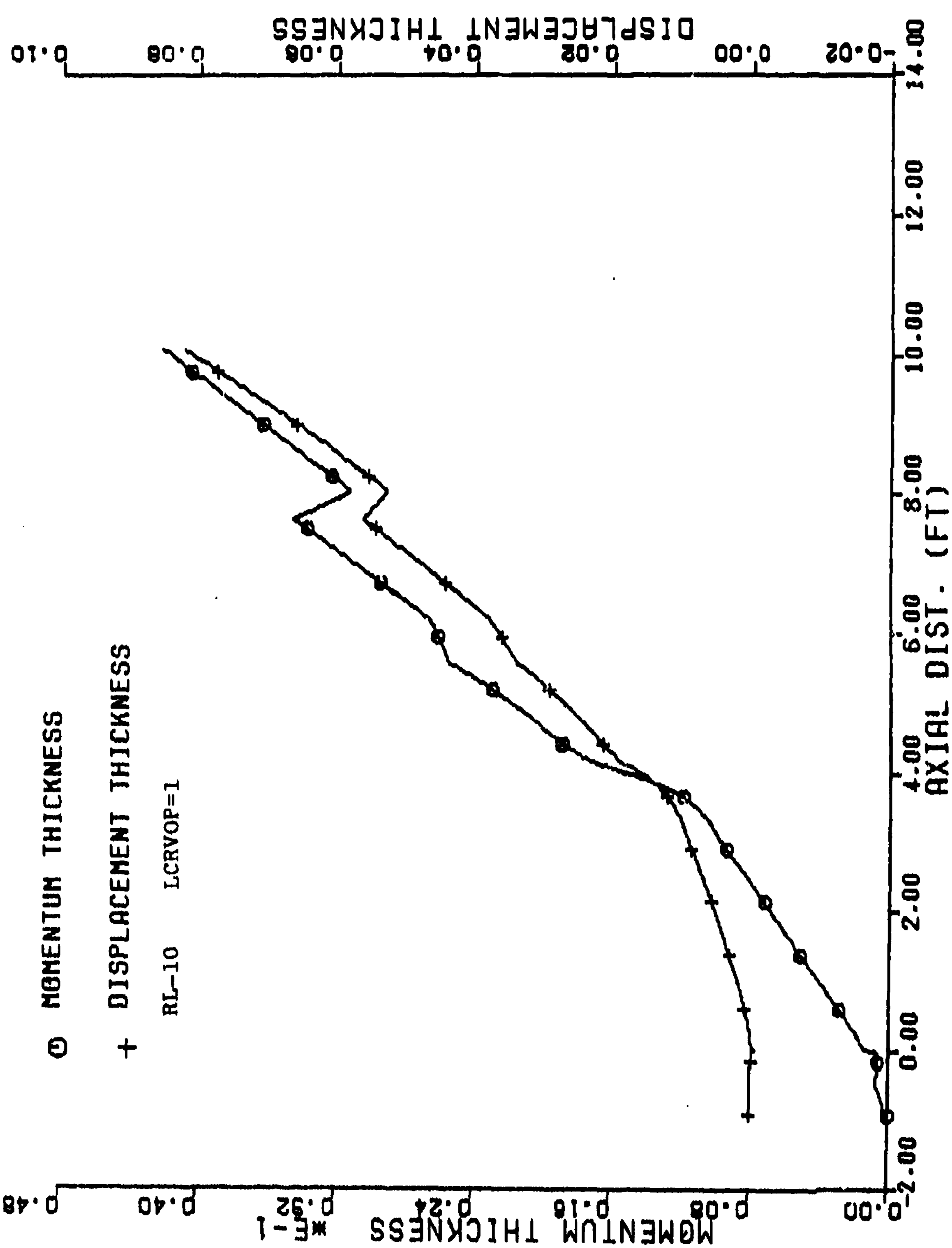


Figure 8. RL-10 Boundary Layer Thicknesses

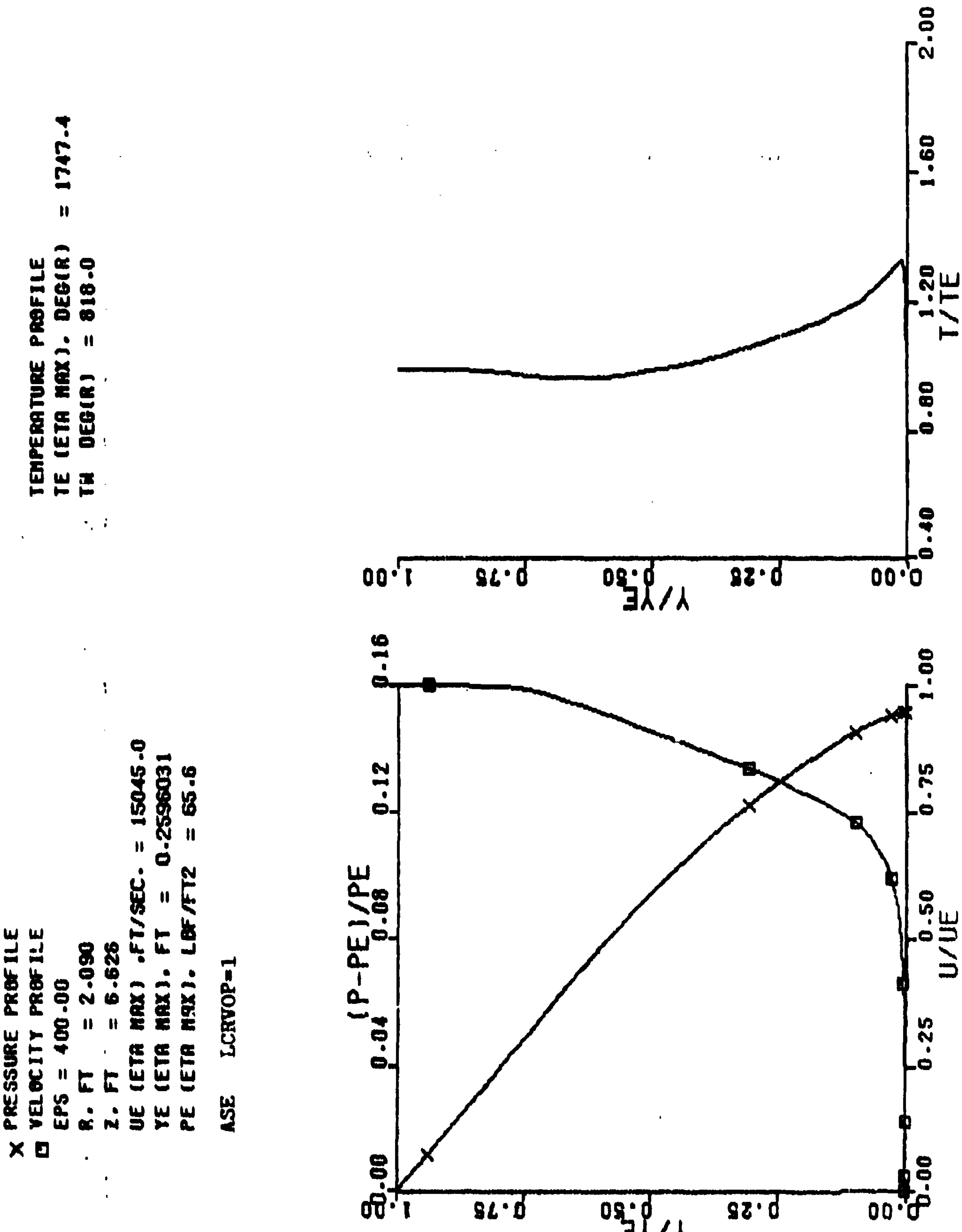


Figure 9. ASE Boundary Layer Profiles

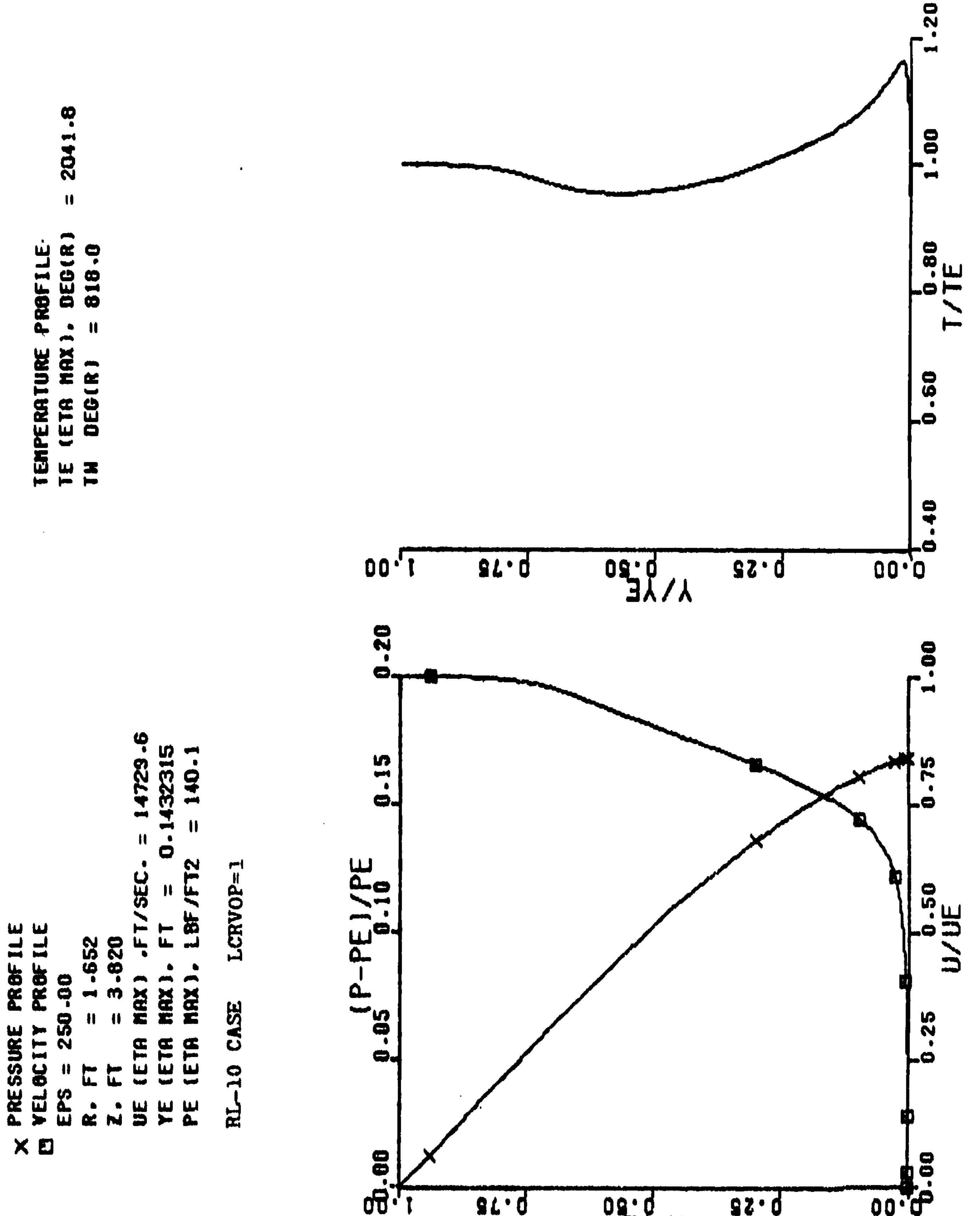


Figure 10. RL-10 Boundary Layer Profiles

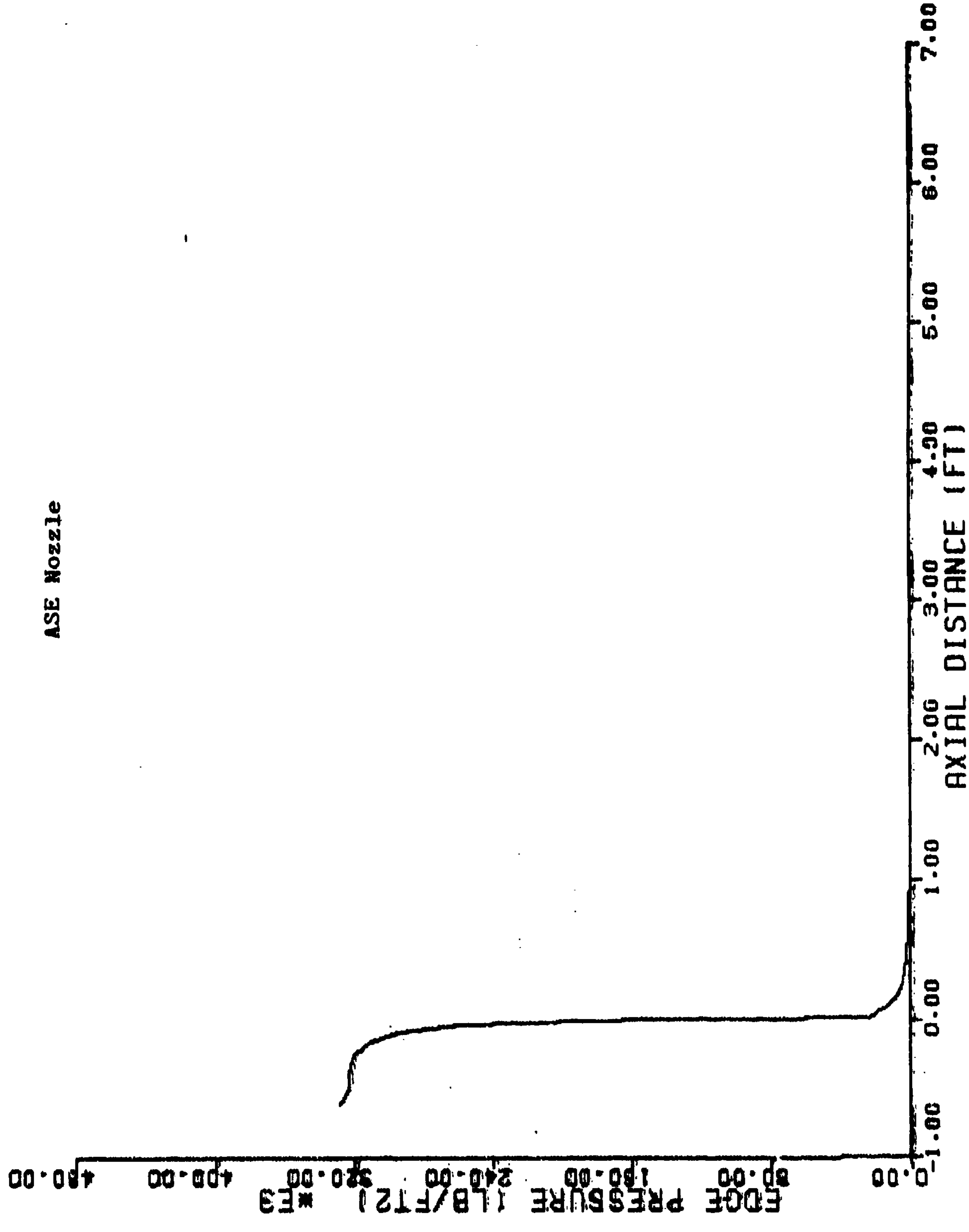


Figure 11a. ASE Boundary Layer Edge Pressure

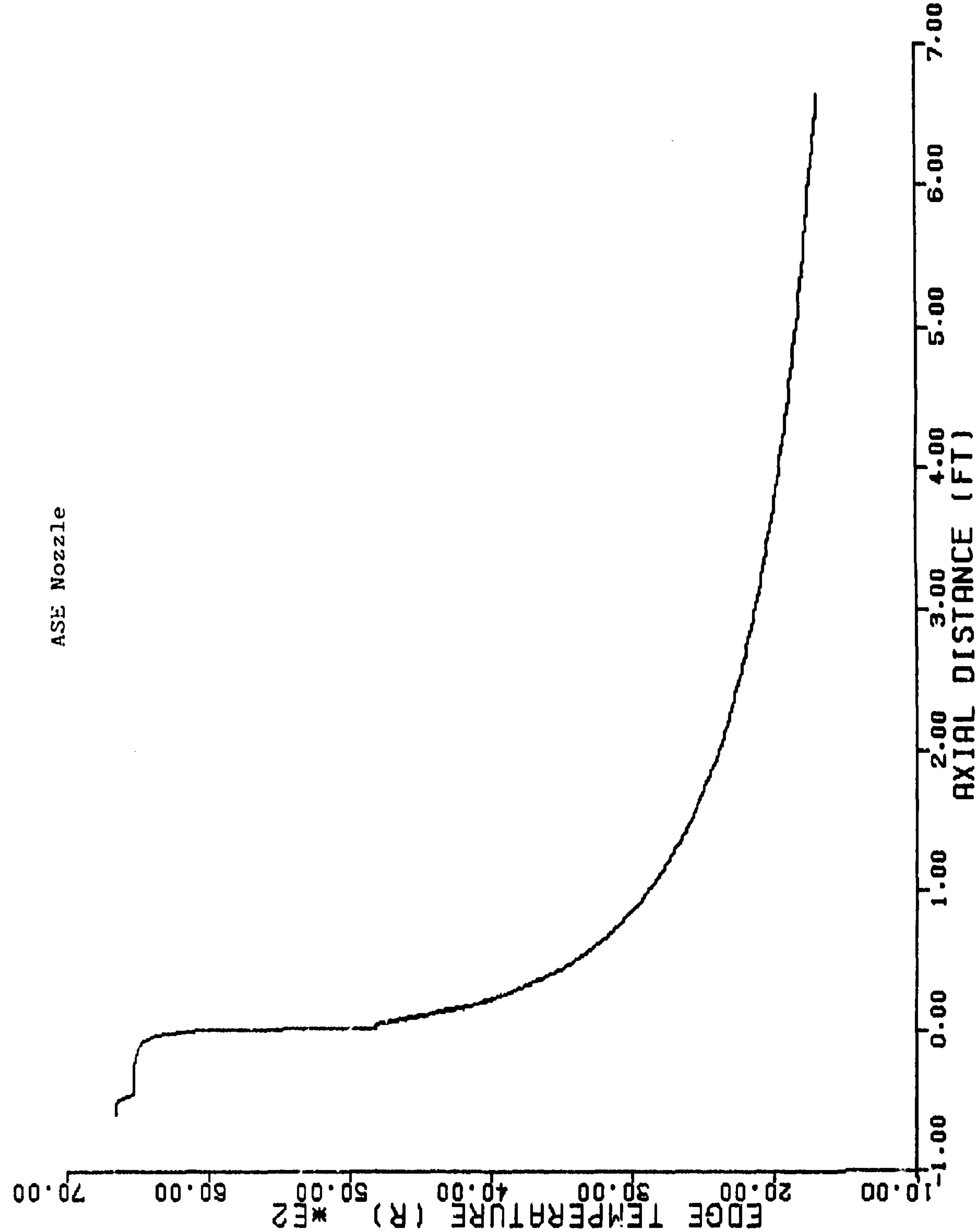


Figure 11b. ASE Boundary Layer Edge Temperature

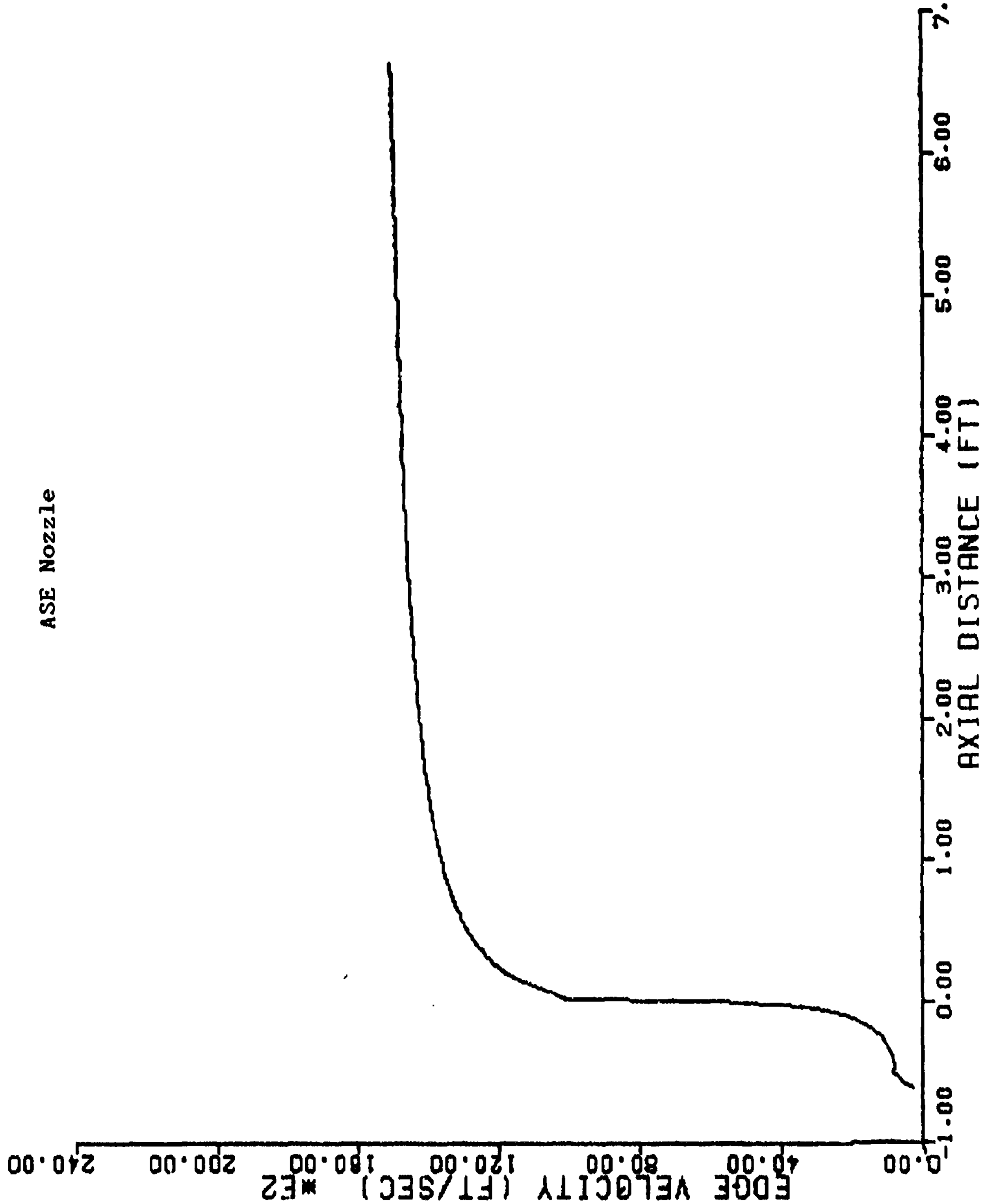


Figure 11c. ASE Boundary Layer Edge Velocity

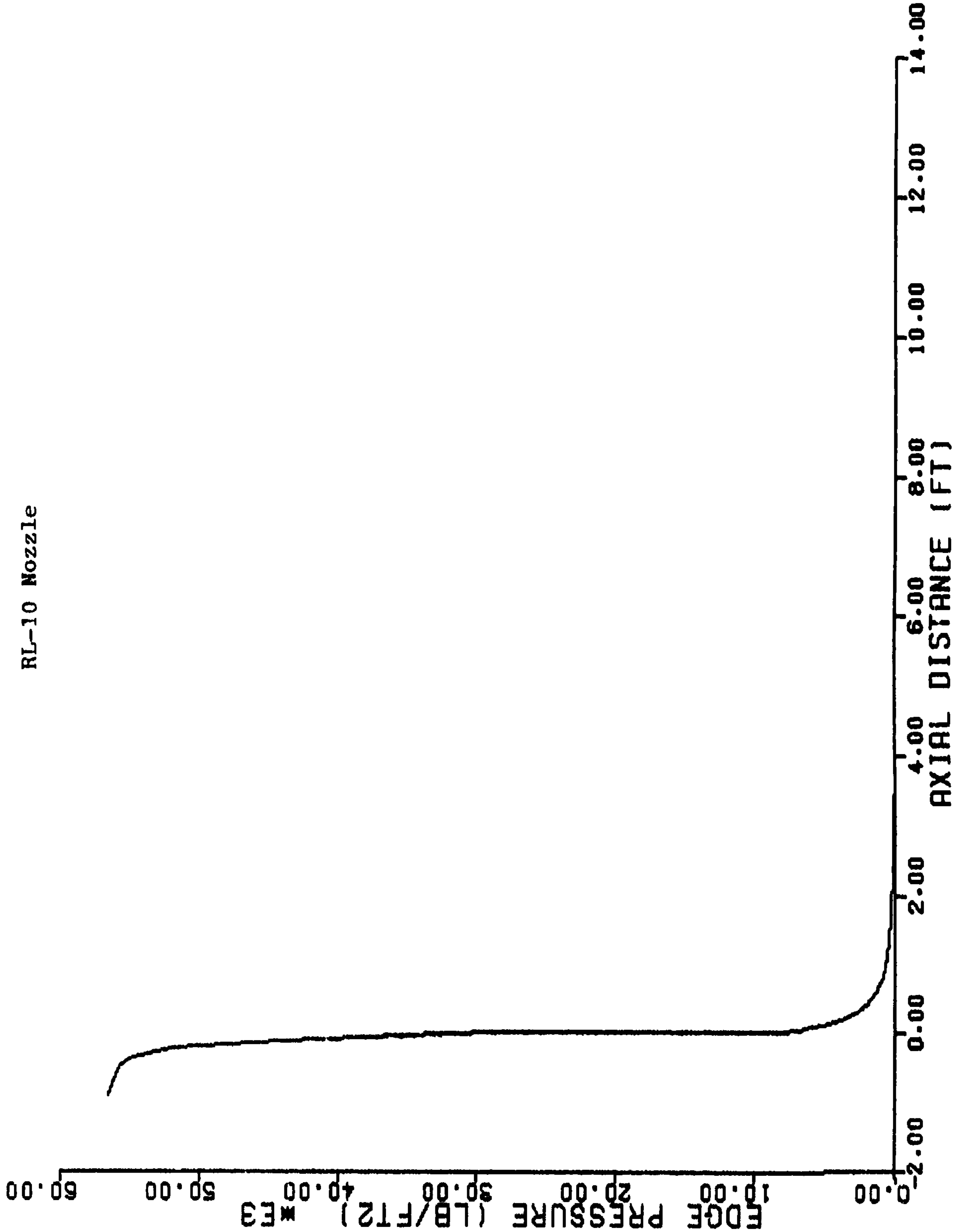


Figure 12a. RL-10 Boundary Layer Edge Pressure

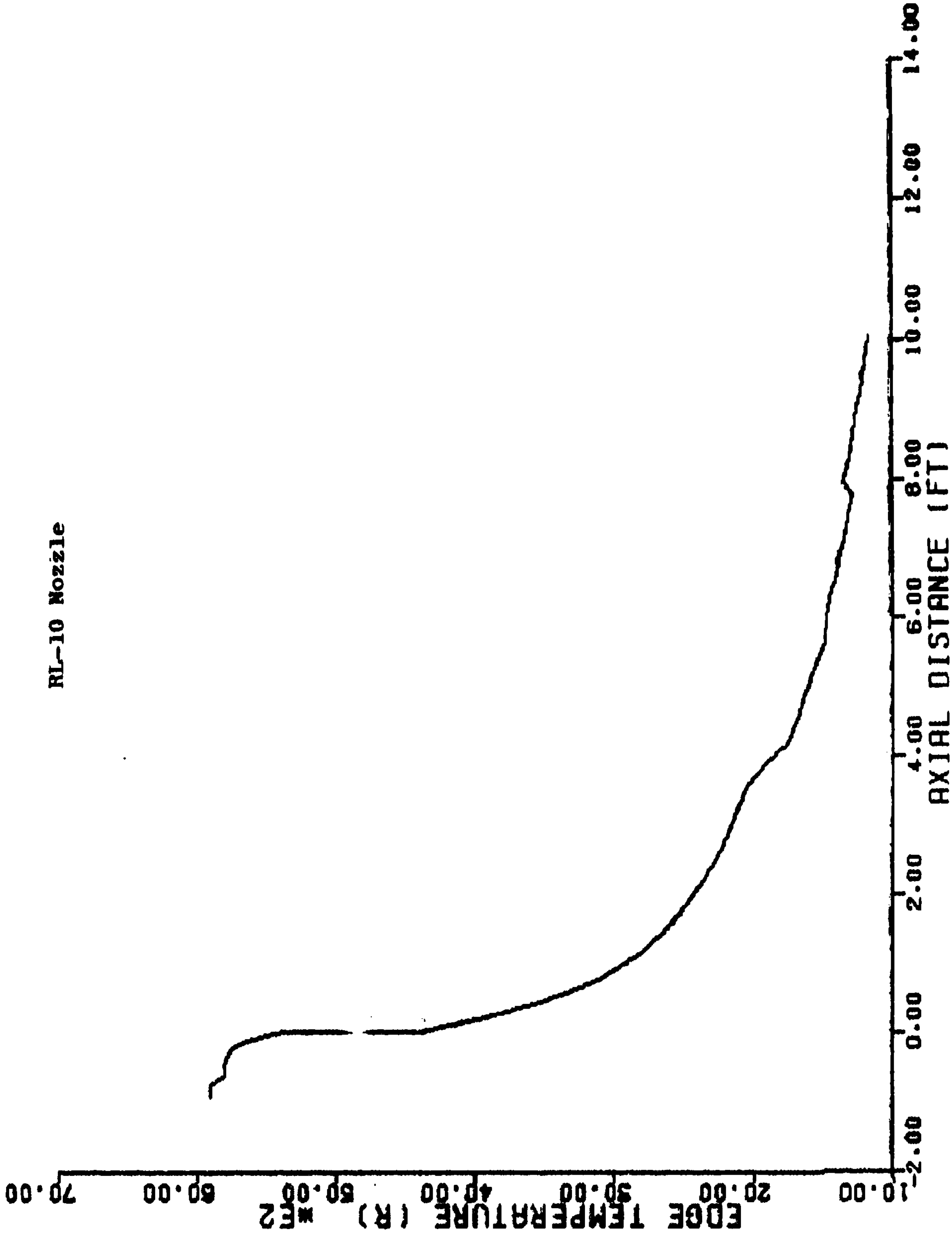


Figure 12b. RL-10 Boundary Layer Edge Temperature

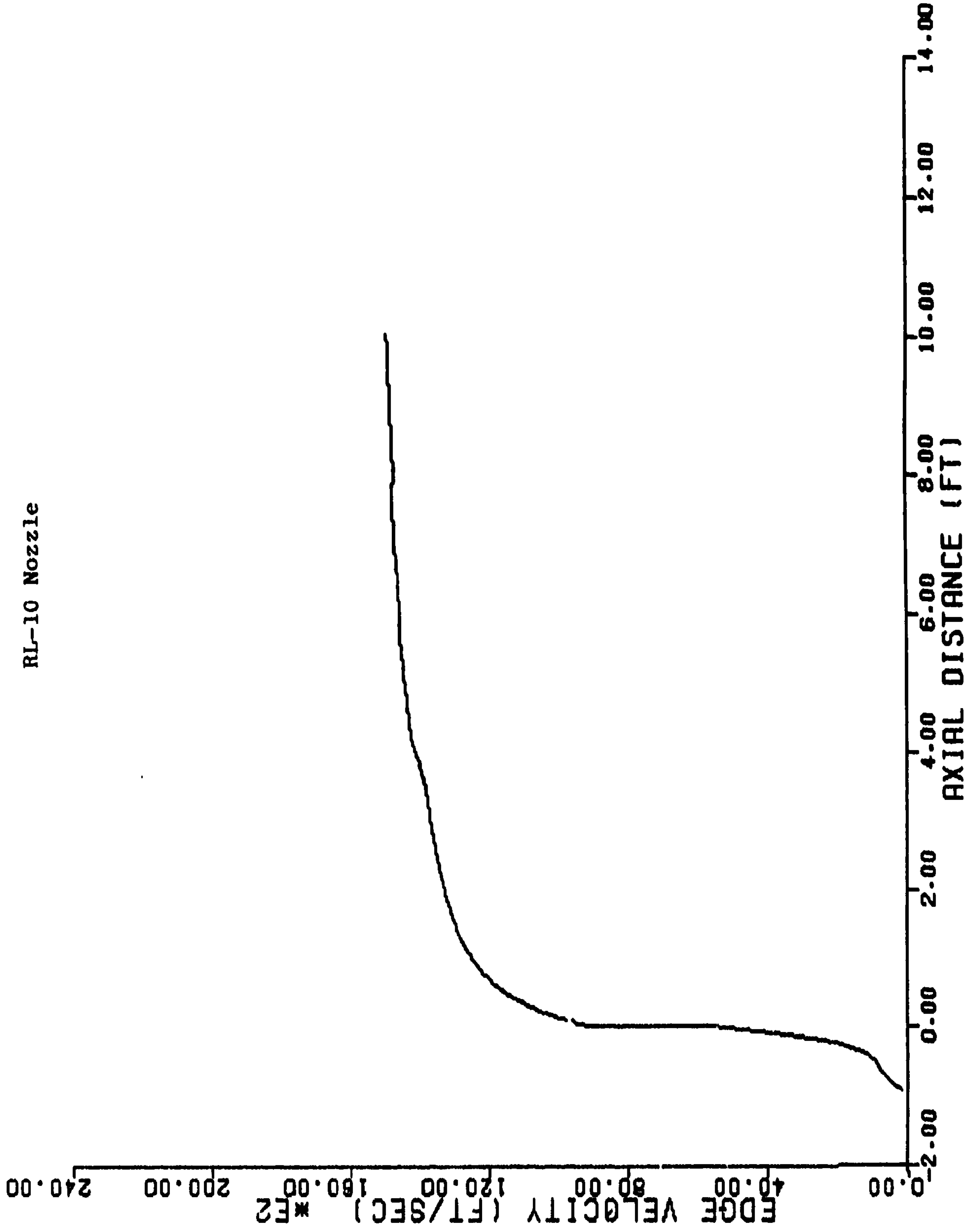


Figure 12c. RL-10 Boundary Layer Edge Velocity

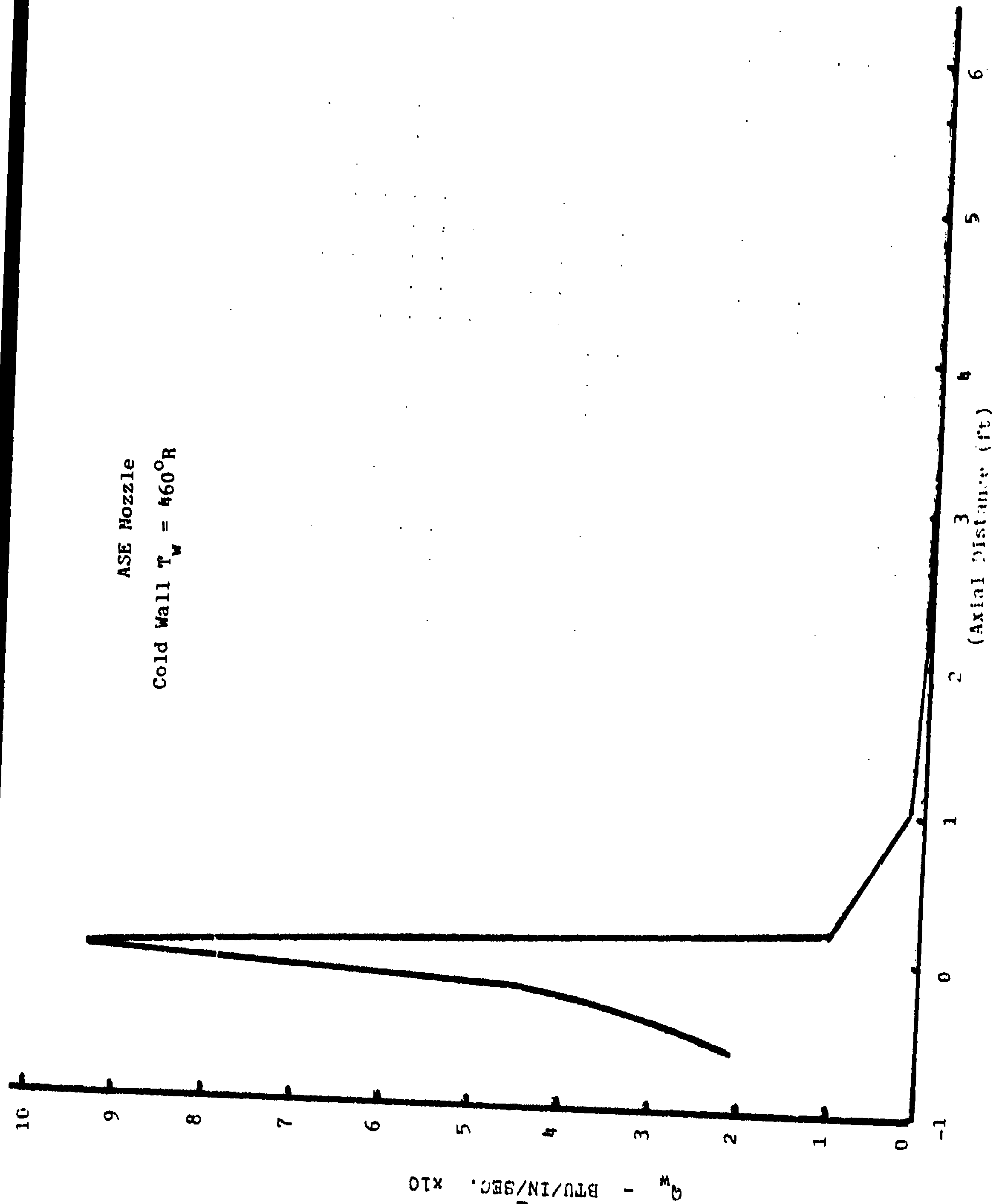


Figure 13. ASE Cold Wall Heat Flux

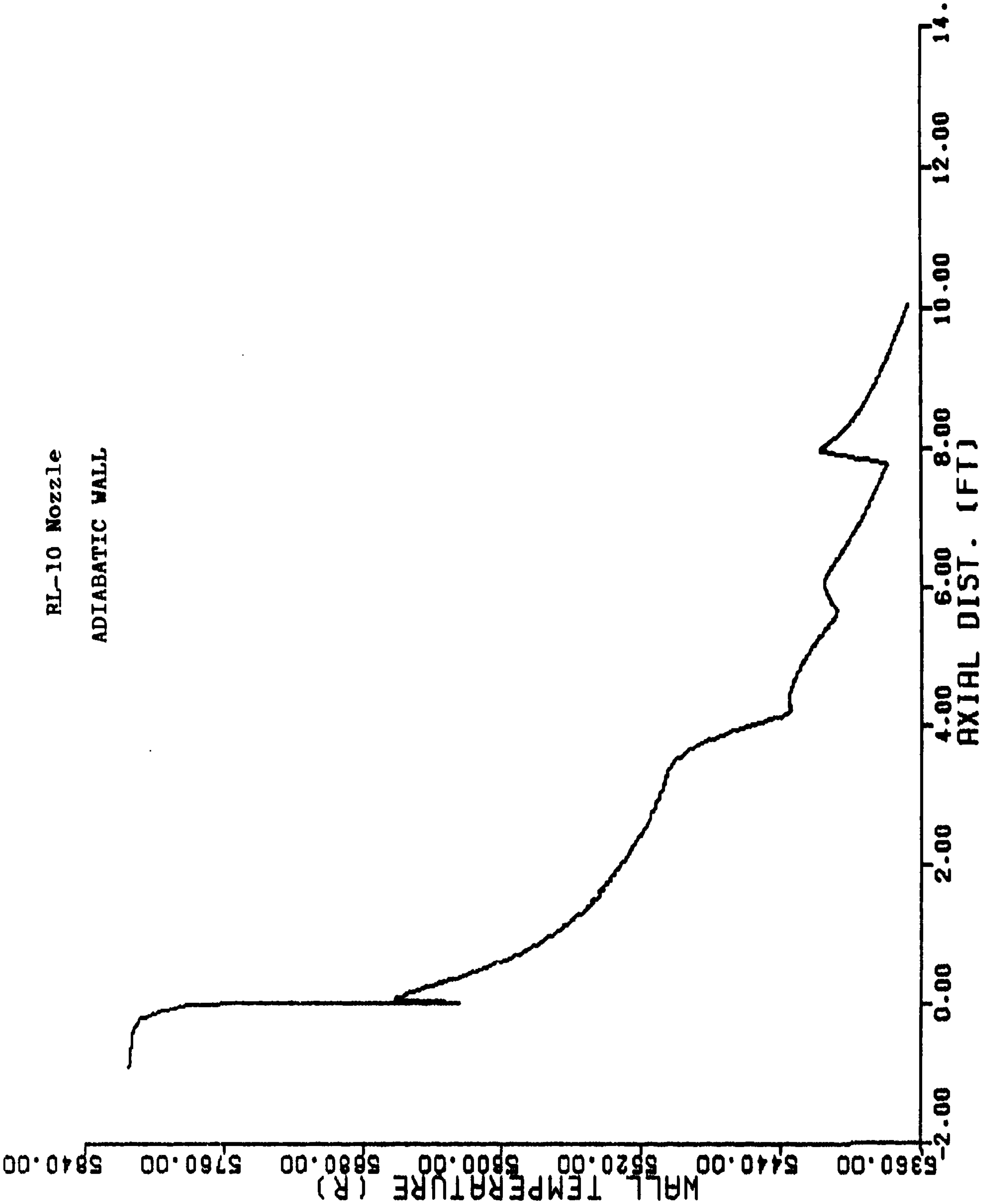


Figure 14. RL-10 Adiabatic Wall Temperature

TABLE – I. Mach number, density and concentration of some species for variety of expansion ratios for RL-10 Nozzle.

[ ] Mole fraction

EPS	INITIAL	THROAT	40	56.9	100	197.8	205
DENSITY lbm/ft^3	.0736248	.045570	.0004216	.0002910	.0001616	$.7981 \times 10^{-4}$	$.7691 \times 10^{-4}$
MACH No.	.1471146	.985947	4.3452	4.6470	5.1692	5.8750	5.9147
$[H_2]$	.3515531	.353717	.358046	.358015	.357995	.357995	.357995
[H]	.0245368	.0262330	.0110736	.011097	.0111124	.011108	.011108
[O]	.0013600	.0007021	$.2414 \times 10^{-5}$	$.1981 \times 10^{-5}$	$.1083 \times 10^{-5}$	$.7731 \times 10^{-6}$	$.7673 \times 10^{-6}$
$[O_2]$	.0009124	[illegible]	$.1491 \times 10^{-4}$	$.1457 \times 10^{-4}$	$.1444 \times 10^{-4}$	$.1443 \times 10^{-4}$	$.1443 \times 10^{-4}$

TABLE - II. Mach number, density and concentration of some species for variety of expansion ratios for ASE Nozzle.

[ ] Mole Fraction

EPS	INITIAL	THROAT	50	100	200	300	400
DENSITY lbm/ft^3	.453606	.283300	.002554	.0009679	.0004707	.0003963	.0002302
MACH No.	.16146	.97888	4.2831	4.8177	5.4028	5.7784	6.6062
$[H_2]$	.211188	.206373	.193000	.192656	.192503	.192469	.1924592
$[H]$	.029373	.024517	.006224	.006530	.006668	.006698	.006705
$[O]$	.0039977	.0027414	$.1791 \times 10^{-4}$	$.9030 \times 10^{-5}$	$.4081 \times 10^{-5}$	$.2603 \times 10^{-5}$	$.1921 \times 10^{-5}$
$[O_2]$	.005247	.0038248	$.6255 \times 10^{-4}$	$.5716 \times 10^{-4}$	$.5527 \times 10^{-4}$	$.5491 \times 10^{-4}$	$.5478 \times 10^{-4}$

APPENDIX B

PRI RESPONSE - EXPERIMENTAL VALIDATION STUDIES FOR LARGE AREA-RATIO NOZZLES

EXPERIMENTAL VALIDATION TEST STUDIES FOR LARGE AREA-RATIO NOZZLES

SUMMARY

Design of propulsion nozzles with very large area ratio is of interest to the Air Force. Software and Engineering Associates, Inc. (SEAI) is presently under contract from the Air Force Astronautics Laboratory to develop improved analytical methods of computing the thrust loss in space engines due to nozzle boundary layers. Validation of the method requires appropriate experimental data which is not available in the open literature. This document discusses a test methodology which would generate the necessary data base for support and validation of the analytical efforts. The experiment concerns the study of the boundary layer flow developed in propulsion nozzles with very large area ratios.

Critical to the success of the program is the choice of the flow facility and the measurement diagnostics. A test facility for analysis of scaled models of nozzles with large area ratios such as RL-10 and ASE nozzles has been identified. A preliminary evaluation of the nozzle scale and performance, and a test plan is presented. The flow diagnostics include the measurement of mean velocity, turbulence intensity, shear stress component, and temperature profile across the boundary layer. Also included are the measurement of surface properties including pressure, temperature, heat transfer rate, and shear stress. The proposed experimental program will provide a complete data-base. This includes data identified by SEAI and required as the initial conditions for their computations. Non-intrusive techniques will be employed for the measurements where possible. The uncertainty of the measurement data will be evaluated either theoretically or experimentally.

1.0 Introduction

Software and Engineering Associates, Inc., under contract to the Air Force Astronautics Laboratory, has developed improved analytical methods for prediction of the thrust losses in space engines due to nozzle boundary layers. Validation of the analytical model requires experimental data with sufficient fidelity and completeness. Such boundary layer data for nozzles with high expansion ratios and operating at conditions of interest is not available. It is therefore necessary to develop a test where the appropriate flow conditions and the experimental data base can be obtained.

The purpose of the proposed experimental program is to generate the data base necessary for the validation and verification of the analytical codes developed for the prediction of high-expansion-ratio rocket nozzle performance. The parameters which are of interest include:

- Boundary layer velocity profiles
- Turbulence intensity profiles
- Boundary layer temperature profiles
- Surface pressure and heat transfer
- Location of laminar/turbulent transition on the wall

In this white paper, brief descriptions of potential measurement techniques and of the flow facility are given.

2.0 Test Plan

Development of a complete data-base required for validation of analytical predictions must be based on experimental facilities which can accurately simulate operating conditions of interest. It should also provide data on initial and boundary conditions necessary for analytical simulation studies. Data must also be collected at regions in the flow field where new features incorporated in the computational code can be tested. For high area ratio nozzles, these requirements call for design of an experimental test facility that can model very high expansion rates. This can be achieved by designing nozzles of large area ratios and short-to-moderate lengths. Three nozzle designs with area ratios of 77, 205 and 400 were considered in the SEAI computational simulations.

Because of prohibitive costs associated with design of full scale model test configurations, smaller scaled models of these nozzles are to be considered. Unfortunately, even these scaled experiments present some difficulties. The high area-ratio nozzles require very high pump throughputs and very low back pressures. This requirement limits the nozzle throat diameter, which in turn demands relatively small-scale nozzles thereby making detailed flow measurements inside the boundary layer extremely difficult.

The proposed experimental test plan is based on the facilities available at Acurex Corporation laboratories. The design has been a compromise between the requirements set forward by SEAI for code verification and the experimental limitations of the Acurex test facilities.

2.1 Acurex Experimental Test Facilities

The arc plasma laboratory of the Acurex Corporation is equipped with an arc plasma generator for providing reentry simulations, rocket engine simulations, and testing of ablative materials. The arc heater is generally used as a high temperature gas source. The schematic of the present plasma test facility is shown in Figure 1. Maximum input power of 1 MW can be supplied to the arc heater. Vacuum pumping limits of the steam jet ejector vacuum pumps is 0.2 torr, and maximum standard operating pressure of the arc heater is 10 atmospheres. Estimated bulk arc enthalpy is 2000 BTU/lb at a gas temperature of 6300°R. It may be possible to lower the gas enthalpy by injecting cold nitrogen into the mixing plenum upstream of the arc heater; however, vacuum pumping limits the total mass flow rate to 150 lb/hr at the lowest vacuum tank pressure levels.

2.2 Experimental Test Set Up

The available test configuration will be slightly modified for the proposed experiments. The schematic of the proposed test set up is given in Figure 2. The nozzle will be placed external to and bolted up to the forward bulkhead of the vacuum chamber. The nozzle will be water cooled, made of copper, and have a throat diameter of 1/4-inches. The length of diverging section of the nozzle is 5.8-inches, which is slightly smaller than the 6-inch length required for an area ratio of 205. This was necessary to prevent the exit temperature from dropping below the air liquification temperature. The contour of the nozzle, however, is identical to that of RL-10 (see Figure 3). The exit condition under these conditions are calculated to be

$$M_e = 8.04, \quad P_e = 2.63 \times 10^{-4} \text{ atm}, \quad T_e = 100^{\circ}K$$

The arc exit conditions are

$$P_t = 2.85 \text{ atm, and } \quad T_t = 1400^{\circ}K$$

The total mass flow rate is calculated to be the abovenoted limiting value of 150 lb/hr. The area ratio is 193, and the boundary-layer thickness at the exit is estimated to be between .5 and 1 cm, which is of sufficient thickness for profile measurement at several stations along the nozzle.

The instrumentation required for boundary-layer profile measurements will be placed outside the nozzle. In this way the problems associated with window contouring and non-uniform wall cooling will be avoided.

The following instrumentation will be employed for the proposed study.

1. Laser Doppler velocimetry for measurement of velocity profiles across the boundary layer at several stations, measurement of Reynold stresses, and location of boundary layer separation, if any.

2. Measurement of wall temperature history for estimation of total heat flux and skin friction.

3. Two-wave Laser Induced Fluorescent Spectroscopy for measurement of the boundary layer temperature profiles.

4. Measurement of the location of boundary layer transition by application of a sheet of piezoelectric material along the nozzle wall.

The details of these experiments are given below.

2.2.1 Mean and Fluctuating Velocity Measurement

Experimental data on mean velocity components, u,v, fluctuating velocity components u',v', and the shear stress component, u'v', are usually of critical importance in the understanding of the development of a flow within a given geometry. They also provide the detailed map of the flow field needed for validation of experimental data. From the velocity data, other important data such as boundary layer thickness, momentum thickness, wall shear stresses, and location of boundary layer separation may also be inferred.

Measurement of gas velocity in the environment of interest is desired. Because of the small measurement scales involved, the disturbances caused by intrusive techniques, such as pitot probes or hot wires, will result in large inaccuracies. Laser Doppler velocimetry is a reliable technique for such measurements in an accurate and nonintrusive manner.

Figure 4 illustrates the basic components of a dual scatter laser anemometer system. One can interpret the process as the production of two sets of fringes in the detection volume. For two-component measurement of velocity, two laser light wavelengths are used. Argon lasers are ideally suited for this process, since two dominant wavelengths (488 nm and 514 nm) are of nearly equal power in available lasers. In Figure 4, beams B and C are of two different colors, while beam A is a mixture of the two.

In a two-component system, the orientation of the fringes, with respect to each other and with respect to the flow direction, can be optimized for most cases. If the flow direction is approximately known, then the fringes should be oriented symmetrically about this direction. The optimum angle between the fringes is about 60 degrees. This provides the most accurate data for both components of velocity.

In any of the geometries described above, a bias frequency can be added to the Doppler signal. In terms of the fringe model, this can be described as producing a system with moving fringes, so that for a stationary scattering center in the sample volume, the scattered light will be modulated at a frequency determined by the rate at which the fringes move. Fringes that are produced by interfering beams of two different optical frequencies will move at a rate that increases with the frequency difference. Any point in the fringe pattern will vary sinusoidally at the frequency difference of the two waves. Moving fringes can be produced by several different methods. A frequency shift can be added to either or both of the two waves with a Bragg cell.

Fiber optics may be used to transmit the beam to the measurement location and transfer the collected beam back to the detectors. Figure 5 shows the sketch of a fiber-optics LDV transmitter and Figure 6 shows a fiber based complete LDV system for use in a shock tube.

2.2.1.1 Flow Seeding

The subject of proper seeding of the flow has been acknowledged as one of the most critical problem areas in LDV. Fundamental to all applications of LDV is the assumption that the flow can be characterized by the motion of the scatter centers, that either reside in the flow naturally or are introduced into it artificially. The effects of particle dynamic on LDV measurements may be summarized as follows:

1. Interpretation of LDV measurements requires the capability of analytically examining particle dynamics effects;
2. Broad particle-size distributions produce artificial turbulence and should be avoided;
3. Maximum acceptable particle size for typical mean velocity measurements are less than 0.5 microns;
4. Absolute maximum acceptable particle size is probably driven by turbulence, not mean-flow requirements;
5. Correction for mean-flow particle lag may be feasible for monodisperse seed particles.

Figure 7 illustrates the response of various size particles to a shock wave, showing that even the smallest particles required a considerable relaxation distance to attain the gas velocity after passing through the shock.

Approaches dealing with the problem experimentally include seeding with known particle distributions or preferably with monodisperse particles, and also attempting to reject data arising from particles that are too large to accurately follow the flow. In the early days of LDV, attempts were focused on making measurements without artificial seeding. Today, it is almost universally accepted that starting with a clean flow and artificially seeding with a proper material is preferred. Submicron particles of sizes between 0.1 and 0.5 microns at the rate of 1000-5000 per second are recommended for LDV measurements. Computations were made for particle concentration requirement for accurate LDV measurement over the entire flow field between the nozzle throat and exit plane. It was concluded that such requirements could be met by generation of soot particles from burning of a relatively small amount of sufficiently rich mixture of acetylene air gases.

2.2.2 Heat-Transfer Rate and Temperature Measurements

Several different sensors and/or techniques are used for the measurement of heat transfer rate. These include discrete transducers such as the Gardon gage and Schmidt-Boelter gage, surface temperature sensors such as thin-film resistance thermometers and coaxial surface thermocouples, and calorimetric devices such as thin-skin models and individual slug calorimeters. Measurements are also made by thermal mapping techniques, which include an infrared scanning camera, phase-change paint, and thermographic phosphorescent paint. Each of these sensors and/or techniques has its own merits and liabilities.

As part of this task, investigations will be made to determine the most appropriate temperature measurement devices. Due to the presence of high wall temperature and physical limitations, Gardon gages seem to provide a convenient method of measurement.

The principle of operation of a Gardon gage is based on radial heat conduction, as illustrated in Figure 8. For a constant heat flux, $\dot{q}$, at the gage surface, a constant temperature difference (T_C-T_E) is established between the center and edge of a constantan foil attached to a copper heat sink. A self-generating transducer is thus formed with an output signal directly proportional to the incident heat flux at the sensing surface. An additional thermocouple is attached to the inside wall of the heat sink for monitoring the temperature of the gage during aerodynamic testing. High temperature components can be used in the fabrication of the conventional Gardon gage to permit continuous service operation at temperatures of 1000°F.

Since the temperature levels present in the wall nozzle are higher than the maximum range permitted by these gages, surface measurements will be made during transient blow-down operation of the arc heater. The system will be operated until steady-state conditions are obtained at the nozzle. The arc heater is then shut off and temperature-time history is recorded. The heat transfer rate is given by

$$\dot{q} = \rho_w C_w \frac{dT_w}{dt}$$

where ρ_w and C_w are density and specific heat of the thermocouple junction, T_w is the wall temperature, and t is time.

2.2.2.1 Measurement of Skin Friction

In principal, determination of local skin friction requires the determination of the velocity gradients close to the wall $\tau_w = \mu \frac{du}{dy}\Big|_w$. Although these measurements are straightforward at low speeds, measurements at high Mach numbers cannot be directly made with high accuracy. Reynolds analogy hypothesis states that a constant ratio exists between heat flux and shear stresses at the wall, and therefore provides a convenient means for predicting skin friction. The skin friction coefficient, C_{f_x}, is given by

$$\frac{C_{f_x}}{2} = \frac{Nu_x}{Re_x \cdot Pr}$$

On the basis of experimental evidence Colburn expirically modified the Reynolds analogy as

$$\frac{C_{f_x}}{2} = \frac{Nu_x}{Re_x \cdot Pr^{1/3}}$$

where $Nu_x = \frac{h_x \cdot x}{k} = \frac{\dot{q} \cdot x}{(T_r - T_w)k}$ is local Nusselt number

$Re_x = \frac{\rho u_\infty x}{\mu}$ is local Reynolds number

$Pr = \frac{\mu}{\rho C_p}$ is fluid Prandtl number

x is distance along the wall, T_r is recovery temperature and ρ, C_p, μ, and k are density, specific heat, viscosity and thermal conductivity of the fluid, respectively. Other relationships that could be used for determination of skin friction are given by the Prandtl analogy and the Von Kármán analogy.

2.2.3 Measurement of Temperature Profiles

Measurement of temperature in supersonic flows usually involves determination of total temperature and Mach number at the point of interest. Mach number can be determined by means of a static-pitot pressure sensor. When flow is hypersonic, total temperature could be higher than the range measureable by most thermocouples. In the nozzle flow considered here the total temperature is 1400°K. Nozzles with higher area ratios encounter even higher total temperatures. In addition, the technique is intrusive and physical size of the thermocouple assembly limits the spatial resolution. A non-intrusive method of temperature measurement, such as two-wave Laser Induced Fluorescence Spectroscopy (LIFS), is recommended in this study. This method is highly desirable since it measures static rather than total temperature directly. The need for use of pitot pressure and total temperature sensors are eliminated altogether.

The LIFS technique involves the selective excitation of a chemical species of interest and detection of the resulting fluorescence signal normal to the incident laser beam. The fluorescent signal is proportional to the number density. The selective excitation of two absorption lines and the ratio of the fluorescence signals, which is equivalent to the ratio of number of ground state to excited state transitions, is given by the Boltzmann ratio and is used to determine the temperature. This technique has been used by many authors for determination of flame temperature using OH as the fluorescing specie (see References 1 and 2).

In the present study iodine gas will be added to the nitrogen (or air) gas. The fluorescence levels of the ground vibrational level at 5145 nm and the strong transition at 550 nm will be measured for determination of the gas temperature. A maximum of 1 part of iodine to 3720 parts of air is required.

The sampling volume is 100 μm in length by 100 μm in diameter. It is therefore concluded that a minimum of 20 measurements across the boundary layer can be made.

2.2.4 Determination of Laminar-Turbulent Transition Location

The technique involves application of a very thin (10-100 μm thick) film of high elasticity polyvinylidenfluorid (PVDF) compound. The thermo-electric polarization allows utilization of this foil as a pressure transducer. The film can be glued to the wall surface. Micro-leads on or under the surface can be used to obtain the electric signal. The signal responds to the pressure gradient rather than pressure as in conventional stress gages. With this measuring technique it is possible to utilize the pressure fluctuation in the transitional boundary layer region. This technique was successfully applied in the wind tunnel boundary layer transition testing over the wing of an Airbus model by the German aircraft industry (Reference 3).

This approach will be employed for determination of the transition point from laminar to turbulent flow in the high area-ratio nozzles. The nozzle wall will be covered by the PVDF film. Several piezo foils will be glued in the area where transition is expected (see Figure 9). The distinct increase in piezo RMS values between different sensors defines the position and also the extent of the transitional regime. The only concern in applying this approach is the temperature resistance of the foil material to the wall temperatures. These materials have been successfully used up to temperatures of 140°C. The question of whether sufficient cooling can be achieved at the wall has to be investigated.

References

1. Daily, J.W., "Laser Induced Fluorescence Spectroscopy in Flames," In Laser Probes for Combustion Chemistry, D.P. Crosley, Ed., Amer. Chem. Soc. Symp., Series 134, p. 61, 1980.

2. Chan, C. and Daily, J.W., "Measurement of Temperature in Flames Using Laser Induced Fluorescence Spectroscopy of OH," Applied Optics, Vol. 19, No. 12, p. 1963, 1980.

3. Stodrach, J., et. al., "The Role of Experimental Aerodynamics in Future Transport Aircraft Design," AIAA 19th Fluid Dynamics, Plasma Dynamics and Laser Conference, June 8-10, 1987, Honolulu, Hawaii, Report No. AIAA-87-1371.

Personnel

Physical Research, Inc. (PRi) will conduct the experimental investigation. The personnel directly charged with the performance of the investigation are:

Dr. Dariush Modarress, Director of Experimental Group

Dr. Hung Tan, Scientist

Dr. Reza Toossi, Scientist

Dr. Farro Kaveh, Scientist

Moreover, Professor M. Gharib of the University of California at San Diego will serve as a consultant to the program. Together, the above mentioned group has over fifty years of experience in the experimental investigation and measurement program. The resumes of key personnel are enclosed.

Cost Estimate and Duration

Two separate experimental programs are suggested here for the verification studies outlined in this paper.

I. An experimental program consisting of surface measurements can be carried out over a period of 12 months as the requirement for obtaining minimum data. These include pressure, temperature, and heat flux measurement at a number of axial and circumferential stations on the nozzle wall. Total cost of this plan estimated at $230K, as:

Cost of usage for Acurex arc heater facilities (2 weeks)		$ 50K
Nozzle design, manufacturing and instrumentation		$ 50K
Labor		$130K
	Total	$230K

II. Detailed test data can be obtained if the program can be extended to two years and for an additional cost of $270K. The experimental study in addition to the surface measurements include determination of velocity and temperature profiles across the boundary layer in the nozzle exit plane. The cost of this plan includes

Cost of usage for Acurex arc heater facilities (4 weeks)	$100K
Nozzle design, manufacturing and instrumentation	$ 50K
Optical instruments, monochrometer, multichannel analyser for LDV and LIFS systems	$ 70K
Labor	$280K
Total	$500K

DR. DARIUSH MODARRESS

DIRECTOR, INSTRUMENTATION GROUP

University of London, Kings College: B.Sc. (1970), Mechanical Engineering

California State University, Long Beach: M.S. (1972), Mechanical Engineering

University of California, Berkeley: Ph.D. (1974), Mechanical Engineering

NASA Ames Research Center: (1975-76), Post Doctoral Research Associate

Dr. Modarress has recently joined Physical Research, Inc. (PRi) as a principal research scientist and director of the instrumentation group. His research background has been in the areas of numerical analysis, LDV application, and two-phase flow. He has designed and conducted experiments in the strong shock wave/boundary layer interaction region and also conducted experiments concerned with the velocity biasing problem in the application of LDV to highly turbulent flows.

Dr. Modarress is also conducting experimental research at the NASA Ames Research Center under a grant to the California State University at Long Beach. In addition, he is teaching courses in gas dynamics, combustion vibration, and technical design and dynamics. Prior to this, Dr. Modarress was Assistant Professor at Tehran University of Technology where he was also in charge of the department's graduate program.

At the same time, Dr. Modarress consulted with the Department of Energy for a period of two years on a Mission Analysis program on the use of alternate sources of energy in Iran. There he initiated and directed an 18-month project on a feasibility study of wind energy utilization for rural electrification.

Dr. Modarress worked at the NASA Ames Research Center after graduation as a National Research Council Research Associate. While there he conducted experimental research on supersonic turbulent boundary layer separation using a frequency shifted laser Doppler velocimeter.

Dr. Modarress has published numerous articles.

Dr. Dariush Modarress

PUBLICATIONS

"Theoretical Investigation of Laminar Separation in a Three-Dimensional Flow," Ph.D. Thesis.

"Laser Velocimeter Supersonic and Transonic Wind Tunnel Studies," with W. Bachalo and D. Johnson. Presented at the Minnesota Symposium on Laser Anemometry, October (1975).

"Laser Velocimeter Applied to Transonic and Supersonic Aerodynamics," with W. Bachalo and D. Johnson. Presented at AGARD Symposium on Non-Intrusive Instrumentation in Fluid Flow Research, Saint Louis, France, April (1976).

"Laminar Boundary Layer Solution in Three Dimension," with M. Holt. Presented at the 5th International Conference on Numerical Methods in Fluid Dynamics, Enschede, Netherlands, July (1976).

"Investigation of Shock-Induced Separation of a Turbulent Boundary Layer Using Laser Velocimetry," with D. Johnson. Presented at AIAA 9th Fluid Plasma Dynamics Conference, San Diego, California, and published as AIAA Paper, 76-374, July (1976).

"Application of the Method of Integral Relation to Three-Dimensional Boundary Layer Flows with Separation," with M. Holt. Proceedings of the Royal Society of London, A., 353, pp. 319-347.

"Experiments on Transonic and Supersonic Turbulent Boundary Layer Separation," with W. Bachalo and D. Johnson. Presented at AIAA 15th Aerospace Science Meeting, Los Angeles, California, and published as AIAA Paper, 77-47, (1977).

"Boundary Layer Solutions of Flows Over Bodies of Revolution," Computer Methods in Applied Mechanics and Engineering, Vol. 14, No. 2, May (1978).

"Investigation of a Turbulent Boundary Layer Separation Using Laser Velocimeter," with D. Johnson. AIAA Journal, Vol. 17, No.7, July (1979).

"Two-Phase Turbulent Flow in a Round Jet," with S. Elghobashi and J. Wuerer, Accepted for publication in Chemical Engineering Communications, (1984).

"Velocity Biasing Error in the Application of LDV to Highly Turbulent Flow," with D.A. Johnson. Presented at the ASME Winter Annual Meeting, Phoenix, Arizona, November 14-19, 1982 and published in Engineering Applications of Laser Velocimetry, edited by W. Coleman and P.H. Pfund. Accepted for publication in ASME Journal (1984).

"Two-Component LDA Measurement in a Two-Phase Turbulent Jet," with H. Tan and S. Elghobashi. Accepted for publication in AIAA Journal (1984).

DR. HUNG TAN

RESEARCH SCIENTIST

Graduate Institute of Chinese Academy of Science, Beijing	Ph.D. (1966), Aeronautics
Tsing Hua University, Beijing	M.S. (1962), Engineering Physics

Dr. Tan is a Research Scientist in the Fluid Dynamic Group. His research activities have been in the areas of LDV application, two-phase flow measurements, applied optics, tomography, and holographic interferometry. He has designed and conducted a number of experiments in the above areas.

He was a post doctoral Research Associate at Arizona State University, Tempe, Arizona, where he conducted the polymer drag reduction program. He also was a consultant at the University of Houston, Department of Mechanical Engineering, where he was in charge of laser instruments for the Turbulent Group.

He was an Associate Professor at the Institute of Mechanics, Chinese Academy of Science, Beijing, where he was in charge of the turbulent research program.

Dr. Tan's publications are listed on the following pages.

Dr. Hung Tan

PUBLICATIONS

1. "A New Method for Processing the Signal of Laser Dual Focus Velocimeter," Yao Loh and Hung Tan, J. of Phys. E. p 981-984, Vol. 14, 1981.

2. "Nuclear Spin Density Wave Mapping by NMR Time Axis Zeugmatography," Hung Tan, J. of Magnetic Resonance, V. 45, p. 356-358, 1981.

3. "A Laser Method to Determine Turbulent Intensity Using Probability After Effects," Hung Tan and Neil S. Berman, J. of Phys. E. p. 906-910, V. 15, 1982.

4. "Simultaneous Eulerian and Lagragian Measurement of Turbulence Using Laser Velocimetry," Neil S. Berman and Hung Tan, AICHE Meeting on Fundamental Research in Fluid Mechanics, Los Angeles, Nov. 1982.

5. "Probability After Effects and Two Spot Laser Velocimetry in Turbulent Jets," Neil S. Berman and Hung Tan, 35th Meeting of American Physical Society Division of Fluid Dynamics, Rutgers, New Brunswick, New Jersey, Nov. 1982.

6. "Turbulent Structure of Polymer Solution Jet," Neil S. Berman and Hung Tan, AICHE Journal, Accepted.

7. "Two-Component LDA Measurement in a Two-Phase Turbulent," D. Modarress, H. Tan and S. Elghobashi, AIAA Paper, 83-0052, 1983, Accepted for Publication in AIAA J.

8. "Application of LDA to Two-Phase Flows," D. Modarress and H. Tan, J. of Experiments in Fluid Mechanics, V. 1, p. 129-134, 1983.

9. "A Laser-based System for Particle Size and Velocity Measurement in Two-Phase Flow," Hung Tan and D. Modarress, Presented at the International Conf. on Lasers, 1983, Canton, China, Sept. 6-9, 1983.

10. "The Technology of Gas Dynamic Lasers," p. 411, Ed. by Hung Tan and Z.H. Chu, National Defense Publishing House, 1977, Peking, in Chinese.

11. "Analysis of the Irreversible Process of Proton Transport in the Purple Membrane of Halobacterium Halobium," H. Tan and M.C. Tan, Scientia Sinica, V. 23, p. 502-509, 1980.

12. "Measurement of Local Convective Heat Transfer Coefficient for Plant Calorimeter by Polarization Interferometer," Hung Tan and M. Yan, Kexue Tongbao, V. 25, p. 31-36, 1980.

13. "Digital Laser Velocimeter Using Polarization," Hung Tan, Y. Wang and Y. Ho, LDV Sym., Tianjin, 1978, in Chinese.

REZA TOOSSI

University of California, Berkeley
M.S., Mechanical Engineering (1974)
Ph.D., Mechanical Engineering (1978)

WORK SUMMARY

Dr. Toossi has had several years of research experience in the areas of combustion and environmental sciences. He has worked both as a research scientist and consultant on various projects related to air pollution, flame propagation and diffusion modellings. He has authored a number of papers in both referred and nonreferred journals. He is also a member of ASME, ASEE and Sigma Xi.

PROFESSIONAL EXPERIENCE

Physical Research, Inc.

Research Scientist (present): Dr. Toossi has been involved in various code development programs since joining PRi. He is currently working on data analysis from BEAU-GESTE gas explosive simulation experiments and on the design of a smoke generator to be used in flow visualization studies. He is also the principal investigator of a program to study the infrared characteristics of a helicopter exhaust interacting with unsteady vortex wake.

California State University, Long Beach

Associate Professor (1981-present): Dr. Toossi has taught a number of courses in areas of combustion processes, thermal sciences, and fluid mechanics and supervised graduate students research activities.

Max-Planck Institute, Gottingen, West Germany

Visiting Scholar (Summer 1982): During 3 month visit, Dr. Toossi conducted experiments on laser induced photocondensation of benzene nuclei generation and coagulation. He also collaborated with University of Gottingen professors in studies of soot formation on flat flame burners at reduced pressures.

Lawrence Berkeley Laboratory, Berkeley, California

Post - Doctoral Research Scientist (1978-1981): In this position, Dr. Toossi developed mathematical model for dispersion of reactive plumes of combustion gases and investigated the effect of gaseous and particulate emissions on the air quality of a large urban area. He also conducted experimental and theoretical studies of heterogeneous SO_2 oxidations in aqueous droplets.

University of California, Berkeley

Teaching and Research Assistant (1974-1978): Dr. Toossi worked both as a Teaching Assistant and Research Assistant while continuing his studies in the Ph.D. program. Research in this period included flame propagation over a solid fuel bed, development of an improved flat flame burner, generation and characterization of soot particles, electron microscopy and x-ray photoelectron spectroscopy. He left university of California after completing his doctoral dissertation entitled "Physical and Chemical Characterization of Combustion Generation Soot Particles".

PUBLICATIONS

1. "Physical and Chemical Properties of Combustion-Generated Soot," Ph.D. Thesis.

2. "The Importance of Soot Particles and Nitrous Acid in Oxidizing SO_2 in Atmospheric Aqueous Droplets," with S.G. Chang and T. Novakov, Atmospheric Environment, 15, 7, 1287 (1981).

3. "Flat Flame Burner Analyses," with P.J. Pagni and A. Ortega, Combustion Science and Technology, in press.

4. "Lifetime of Aerosol Droplets in Ambient Air: Consideration of the Effects of Surfactants and Chemical Reaction," with T. Novakov Atmospheric Environment, 19, 1, 127 (1985).

5. "A Review of Combustion-Generated Carbon Particles," UCB-FRG-WP-75-8, Mechanical Engineering Department, University of California, 1975.

6. "Sulfur Dioxide Oxidation in a Dispersing Plume," with S.G. Chang and T. Novakov, Atmospheric Aerosol Research Annual Report, 1977-78, Lawrence Berkeley Laboratory Report LBL-9037 (1979).

7. "Catalytic Oxidation of SO_2 on Carbon in Aqueous Suspensions," with S.G. Chang, R. Brodzinsky, S.S. Markowitz and T. Novakov, Proceedings, Conference on Carbonaceous Particles in the Atmosphere, Lawrence Berkeley Laboratory Report LBL-9037 (1979).

8. "Preliminary Report on BEAU-GESTE Gas Explosive Simulation Experiment," Final Report, Physical Research, Inc., PRi-PV-86-R004 (1986).

DR. FARRO KAVEH

Ohio State University

Ph.D. (1981), Mechanical Engineering
M.S. (1977), Mechanical Engineering

Dr. Kaveh's research has involved the areas of experimental fluid mechanics, fiber technology, and control systems. During his four year activities in Owens-Corning Fiber Glass Technical Center he developed a laser-based non-contact method for measurement and control of flow of molten glass. He has made optical temperature sensors measurement in furnaces. He has recently been a principal investigator in a research program for study of dispersion characteristics of fibrous material under the influence of air drag and centrifugal forces.

Dr. Kaveh s publications include:

1. Numerical Analysis of the Interaction of an Electric Field with a Two-Dimensional Jet. With H.R. Velkoff. Bulletin of the American Physical Society 37th Annual Conference, 1984.

2. Characterization of the Flow and Temperature Fields of a Novel Fiberizing System - Owens-Corning Technical Report.

3. Direct Digital Control of the Flow Rate of an Electric Melter - Owens-Corning Technical Report.

4. Numerical Study of the Flow of a Gravity Driven Non-isothermal Liquid Jet - Owens-Corning Technical Report.

5. The Stability of the Electrohydrodynamic Two-Dimensional Jet. 6th Annual Meeting of Electrostatics, Japan, November 1982.

6. Behavior of a Liquid Jet in a Cross-flow - Owens-Corning Technical Report.

7. Experimental Study of the Effect of an Electric Field on the Stability of a Two-Dimensional Jet. With H.R. Velkoff. Bulletin of the American Physical Society, Volume 25, Number 9, 1980.

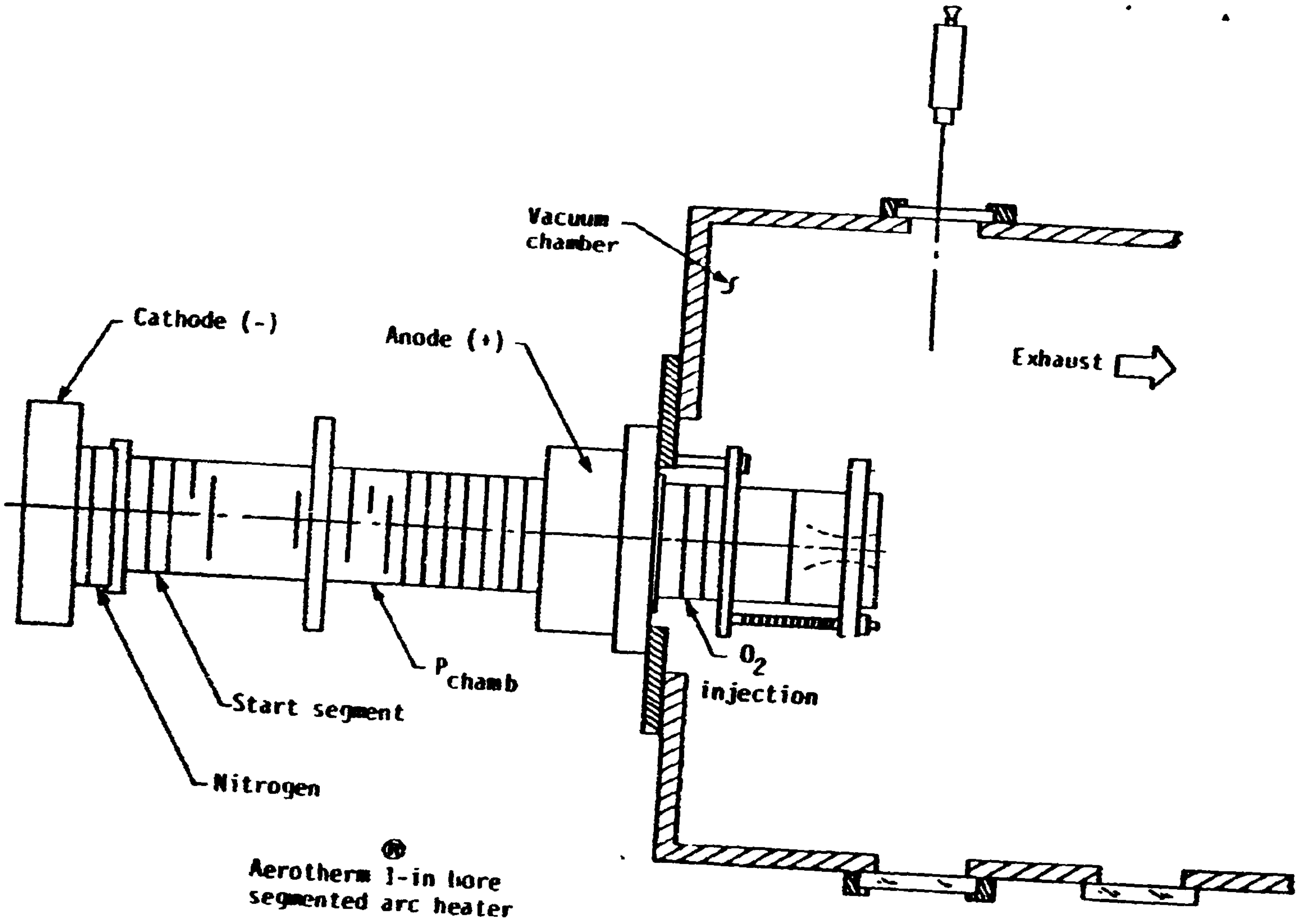


Figure 1. Existing Accurex Arc Jet Test Facilities

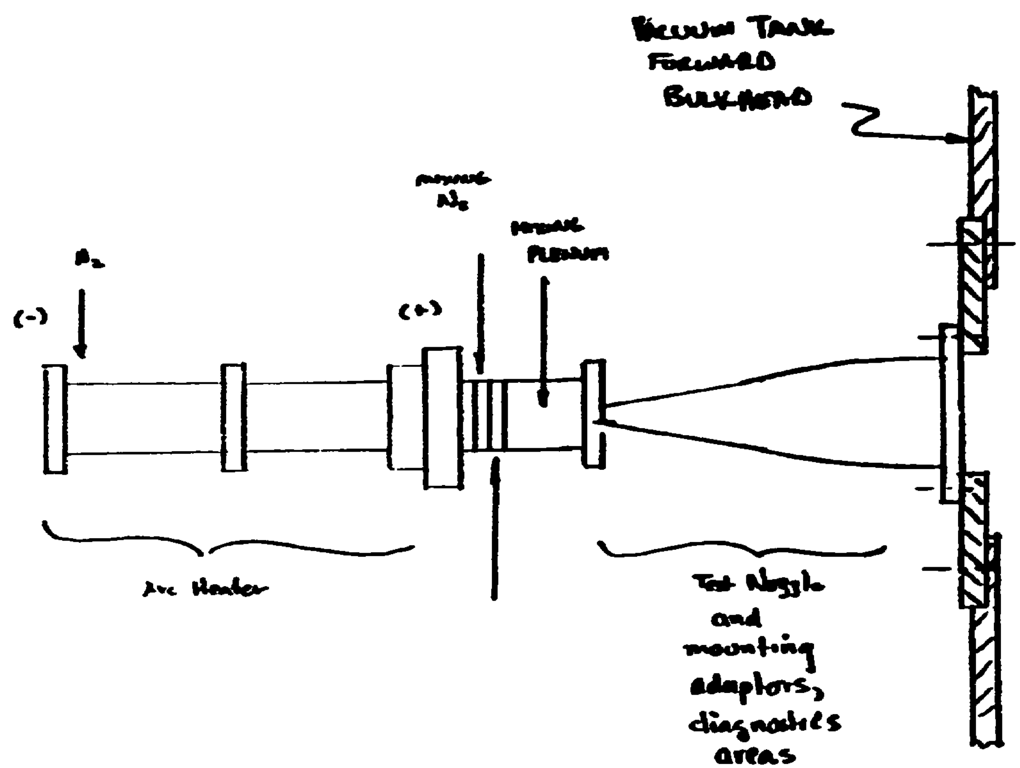


Figure 2 Proposed Modification for Nozzle Testing

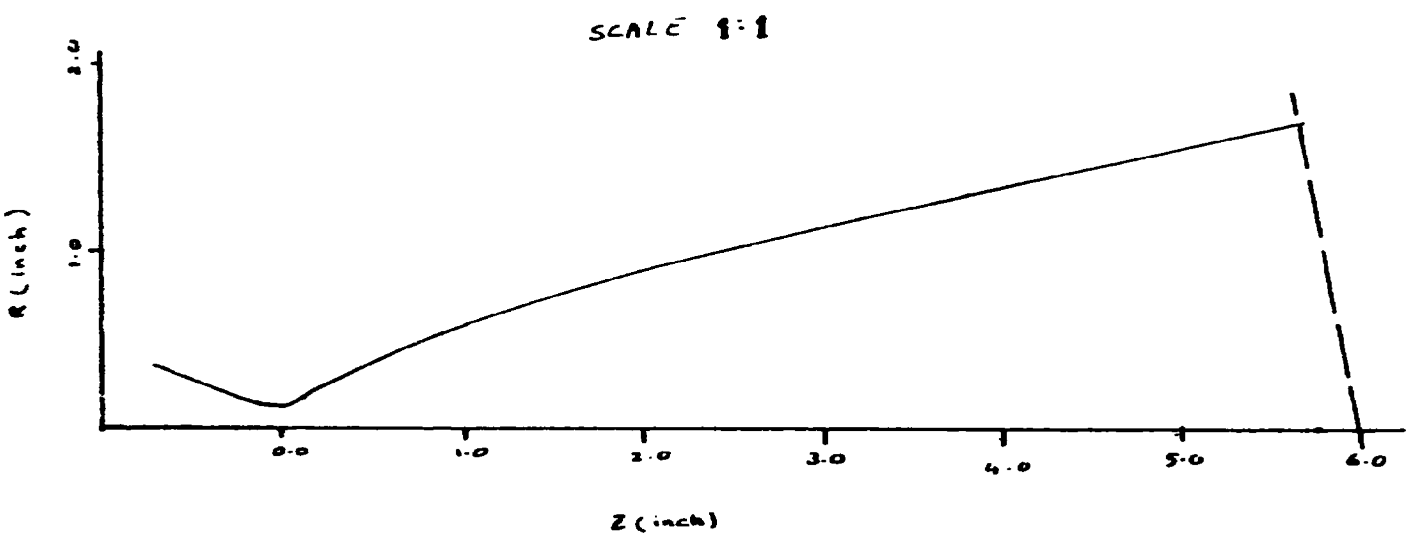


Figure 3. Contour of Prototype Model of RL-10 Nozzle

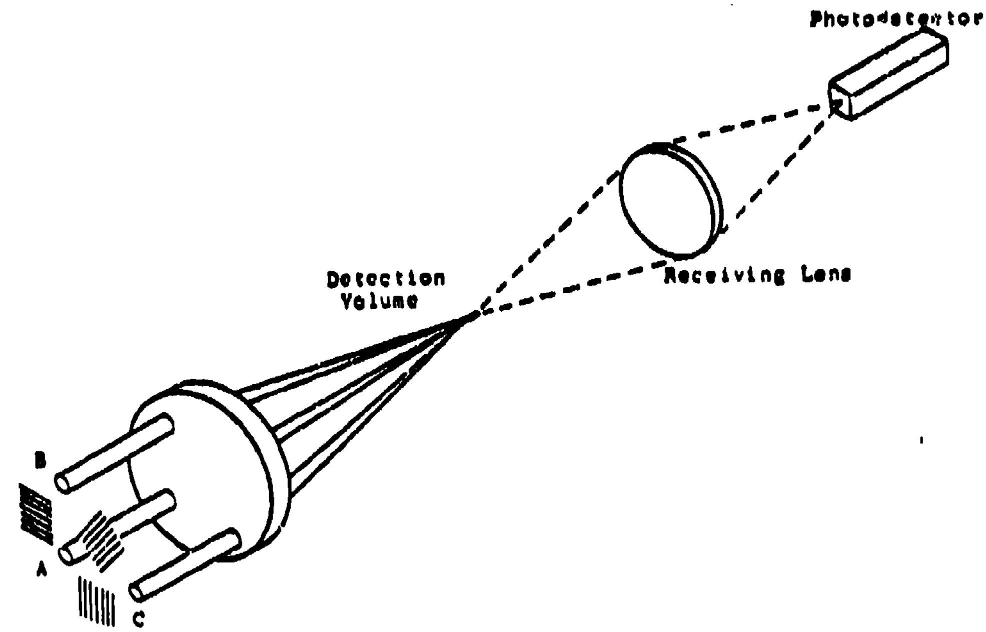


Figure 4. Two Component Dual Scatter System

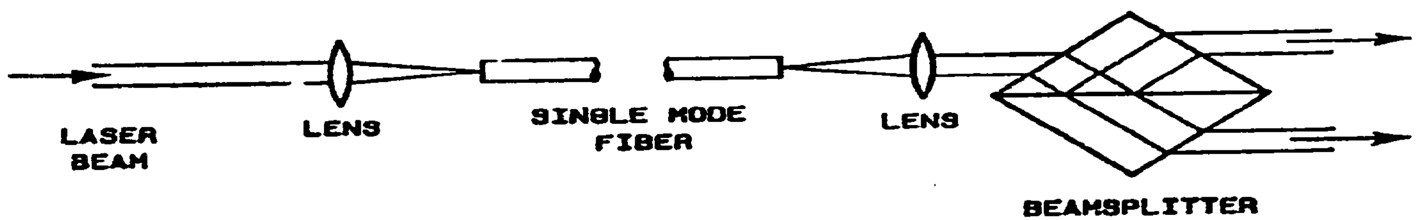


Figure 5. Fiber Optic LDV Transmitter

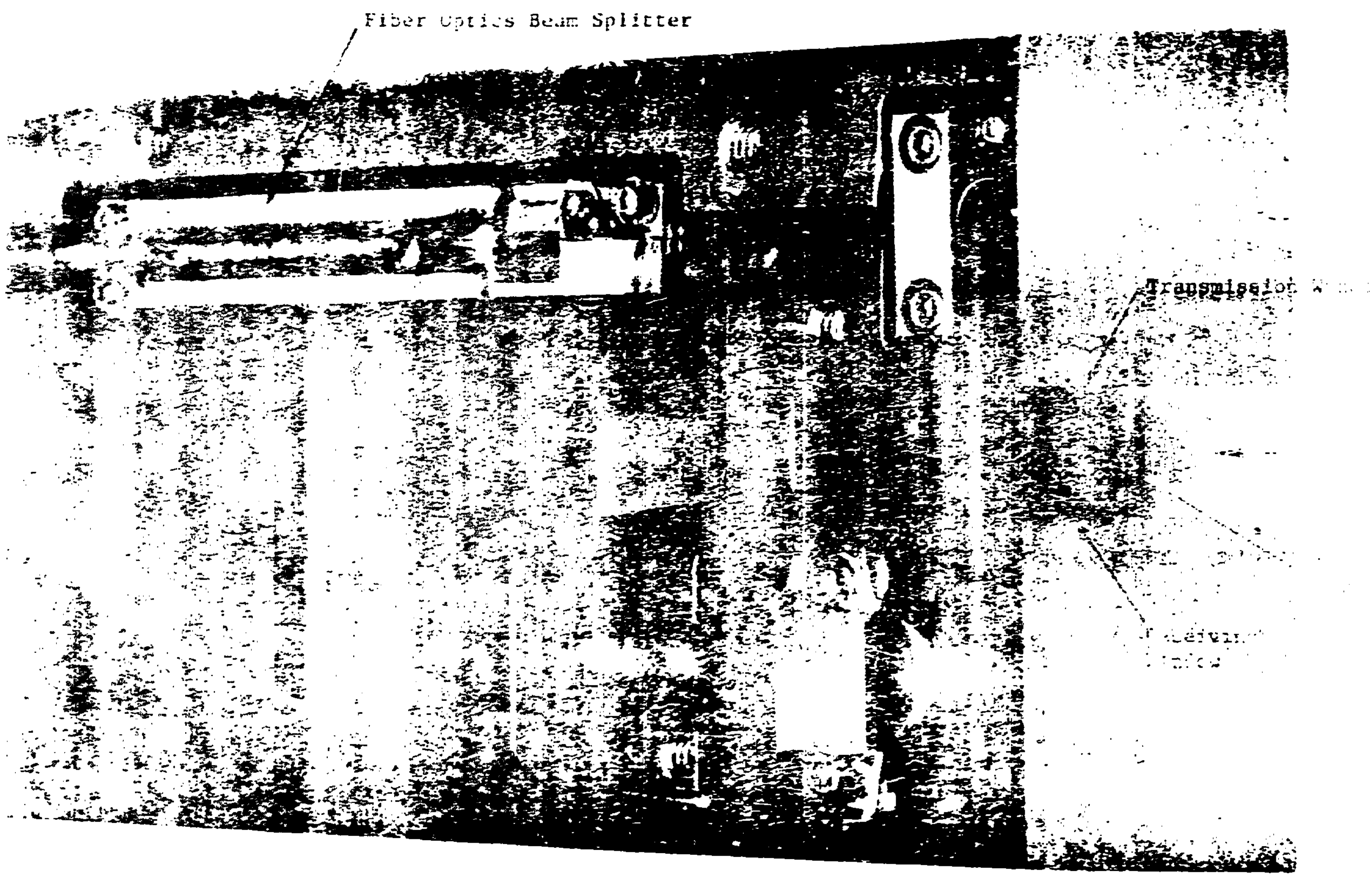


Figure 6. Fiber Optics Based LDV Probe

PARTICLE RESPONSE TO SHOCK

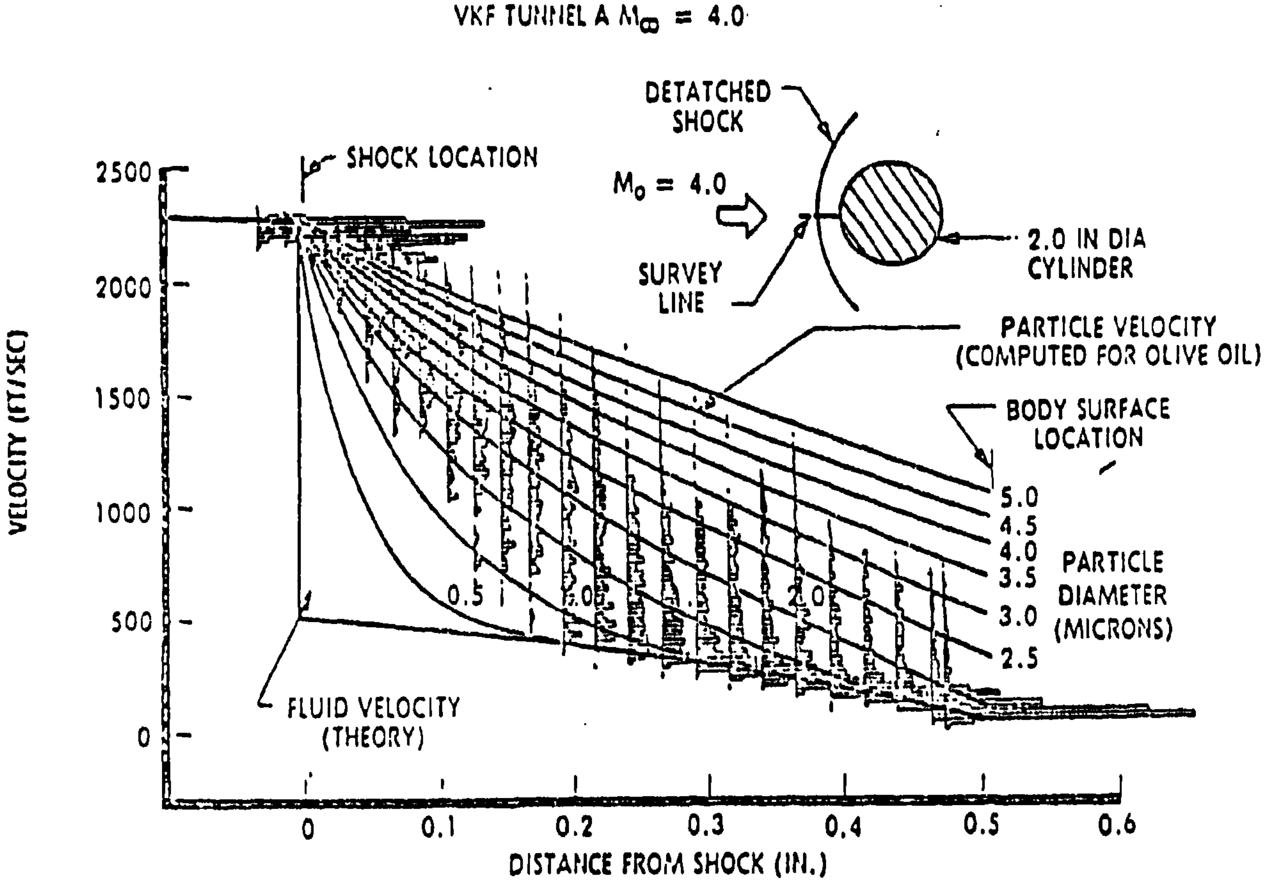


Figure 7. Seeding Particles - Use in LV

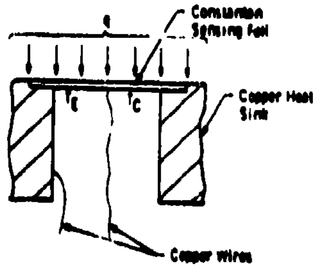


Figure 8. Gardon Gage Schematic

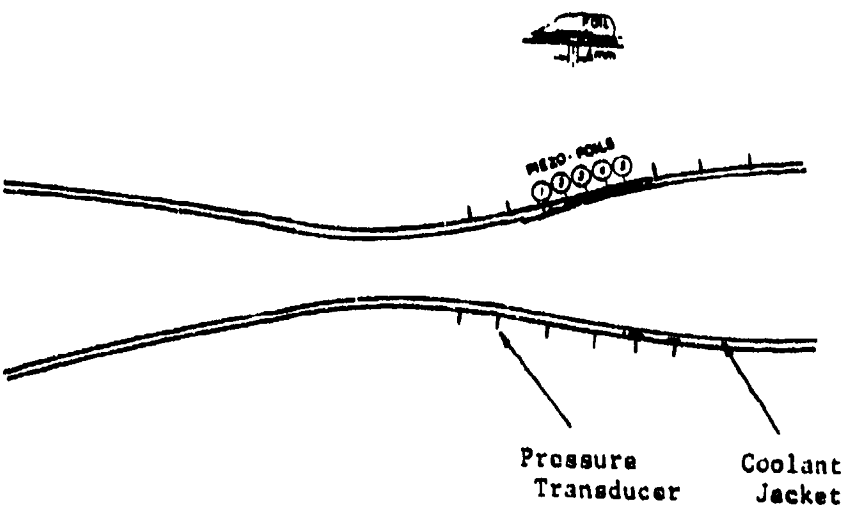


Figure 9. Setup for Measuring Temperature and Pressure and their Gradients at the Wall

APPENDIX C

CALSPAN RESPONSE - BOUNDARY LAYER MEASUREMENT CAPABILITIES

EXHIBIT A

GASEOUS - EQUIVALENT THECNIQUE
AND
REPRESENTATIVE MEASUREMENTS

4.3 GASEOUS-EQUIVALENT TECHNIQUE

The gaseous-equivalent propellant technique was developed by Calspan[26] and has been used for simulating the combustion of a wide variety of gaseous and liquid bi-propellant combinations[27–30]. Most recently, this technique was applied successfully to the simulation of a solid propellant combustion process[32,33].

As discussed in Reference 26, the combustion products and combustion conditions of an earth-storable liquid propellant combination can be exactly duplicated by the combustion of a gaseous fuel and oxidizer combination which is at the same initial temperature if (1) the elemental composition (i.e., atomic species and their proportions) of the liquid and gaseous propellants are the same and (2) the initial energies (i.e., total enthalpies) of the two propellant combinations are the same. Based upon these requirements, a liquid NTO/MMH rocket which operates at the nominal mixture ratio can be duplicated by the combustion of a gaseous oxidizer having a volumetric composition of 33.3% nitrogen and 66.7% oxygen with a gaseous fuel mixture of 28.6% nitrogen, 14.3% ethylene and 57.1% hydrogen.

A comparison of the predicted combustion conditions and products of reaction for NTO/MMH liquid and gaseous equivalent reactants is presented in Table 4. These rocket performance calculations, based on the assumptions of chemical equilibrium combustion and nozzle expansion, were made using the CEC combustion code,[34] which incorporates a library of least-square temperature coefficient fits to the JANNAF (circa 1971) species thermochemical data.

TABLE 4 THEORETICAL PERFORMANCE OF LIQUID AND GASEOUS-EQUIVALENT NTO PROPELLANTS

	Combustion Chamber		Area Ratio = 34.1	
	Liquid	Gas-Equiv.	Liquid	Gas-Equiv.
Pressure, psia	200	200	0.44	0.44
Temperature, °R	5536	5494	1840	1809
Molecular Weight (MW)	20.4	20.4	20.8	20.8
Specific Heat Ratio (γ)	1.16	1.16	1.25	1.25
Characteristic Velocity (c^*), ft/sec	5725	5693	—	—
Combustion Products, Mole Fractions				
CO	0.1321	0.1320	0.0659	0.0637
CO_2	0.0360	0.0364	0.1061	0.1082
H	0.0215	0.0201	—	—
H_2	0.1620	0.1621	0.2325	0.2346
H_2O	0.3241	0.3263	0.2833	0.2812
NO	0.0023	0.0021	—	—
N_2	0.3043	0.3050	0.3123	0.3123
O	0.0012	0.0011	—	—
OH	0.0152	0.0140	—	—
O_2	0.0010	0.0009	—	—

The gaseous-equivalent approach is shown to provide nearly identical conditions within the combustion chamber and at the exit plane of the nominal 34.1 area ratio nozzle.

The mean properties of the oxidizer and fuel gas mixtures are:

Oxidizer		Fuel	
MW	= 30.67	MW	= 13.16
R	= 50.38 lbf ft/lbm °R	R	= 117.4 lbf ft/lbm °R
C_p	= 0.228 BTU/lbm °R	C_p	= 0.562 BTU/lbm °R
γ	= 1.40	γ	= 1.368

4.4 OPERATION OF [redacted] TEST CONFIGURATION ROCKET SYSTEM

The gaseous propellant supply system employed was similar in scale and operation to systems used in previous Calspan experiments. It consists of propellant charge tubes (30-40 feet long x 0.87 inch I.D.), flow control venturis, rapid-opening solenoid valves, and an injector to which the combustion chamber and rocket nozzle are attached. The system is represented schematically in Figure 19 which also presents data records illustrative of the system operation. Upon opening the solenoid valves, a rapid equilibration of the feed system pressures upstream of the injector occurs. Steady-state flows are established through the venturis and the injector passages. Combustion is initiated by energizing a spark plug located within the rocket combustion chamber.

Coincident with the initiation of the flow from the propellant charge tubes, centered expansion waves propagate upstream in the charge tubes at acoustic velocity. During the period required for these waves to reach the upstream end of the charge tubes, reflect, and return to the venturis, the supply conditions at the venturi inlets remain constant and flow conditions are completely steady with time. Two wave transit times are in evidence during the 70-80 ms rocket firing duration. Note, however that the pressure changes

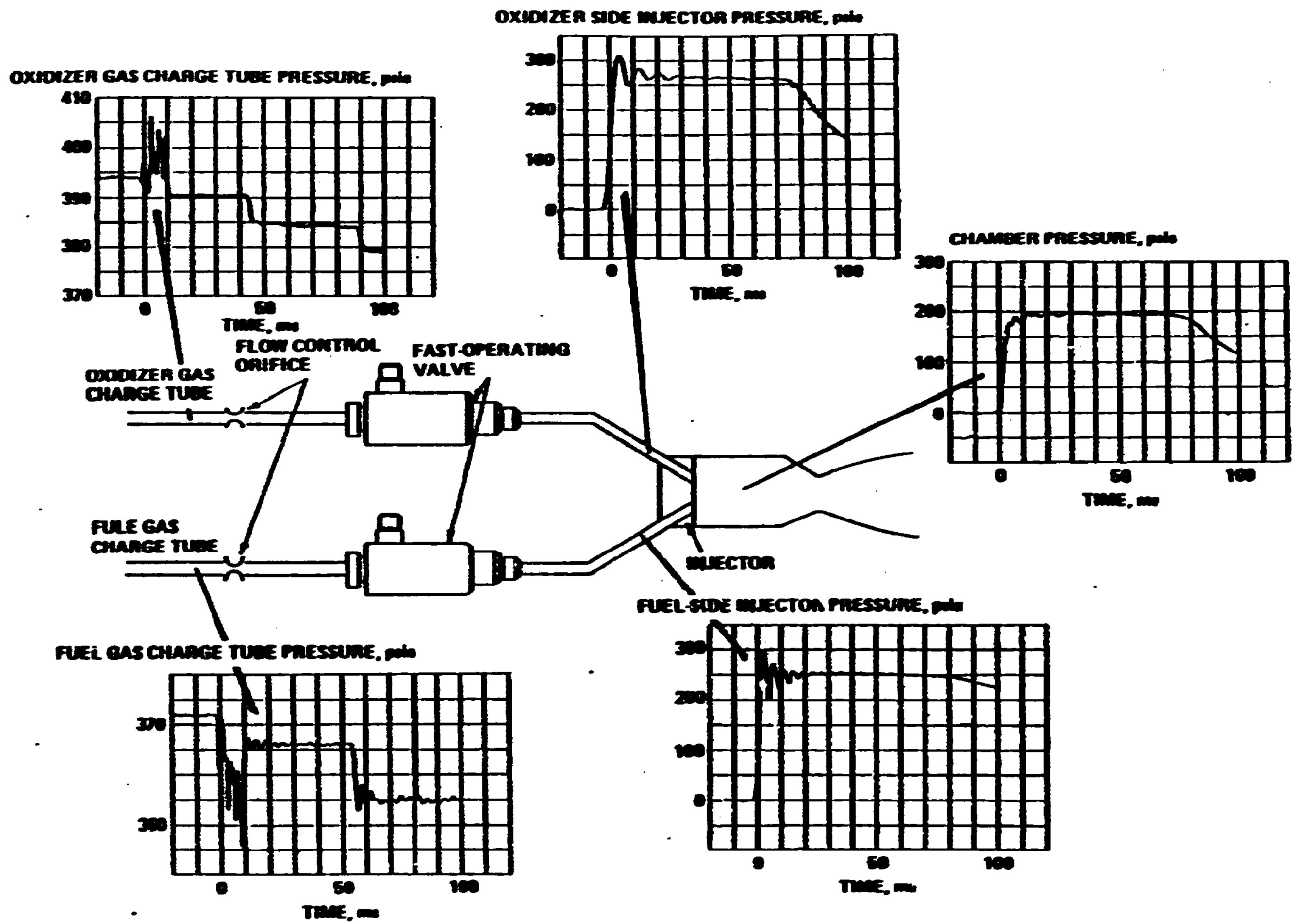


FIGURE 19 GASEOUS-EQUIVALENT PROPELLANT [redacted] ROCKET SYSTEM

resulting from the re-reflected expansion waves are very small (~ 1%). The injector inlet pressures and the chamber pressure remain constant for a duration which is much longer than required to acquire the plume stagnation pressure data.

Oxidizer and fuel flowrates were determined from the respective charge tube pressures and venturi flow calibrations conducted prior to the plume survey test series. Adjustments of these flowrates for the purpose of changing the rocket chamber pressure were thus accomplished by simply increasing or decreasing the charge tube pressures to maintain the desired nominal mixture ratio.

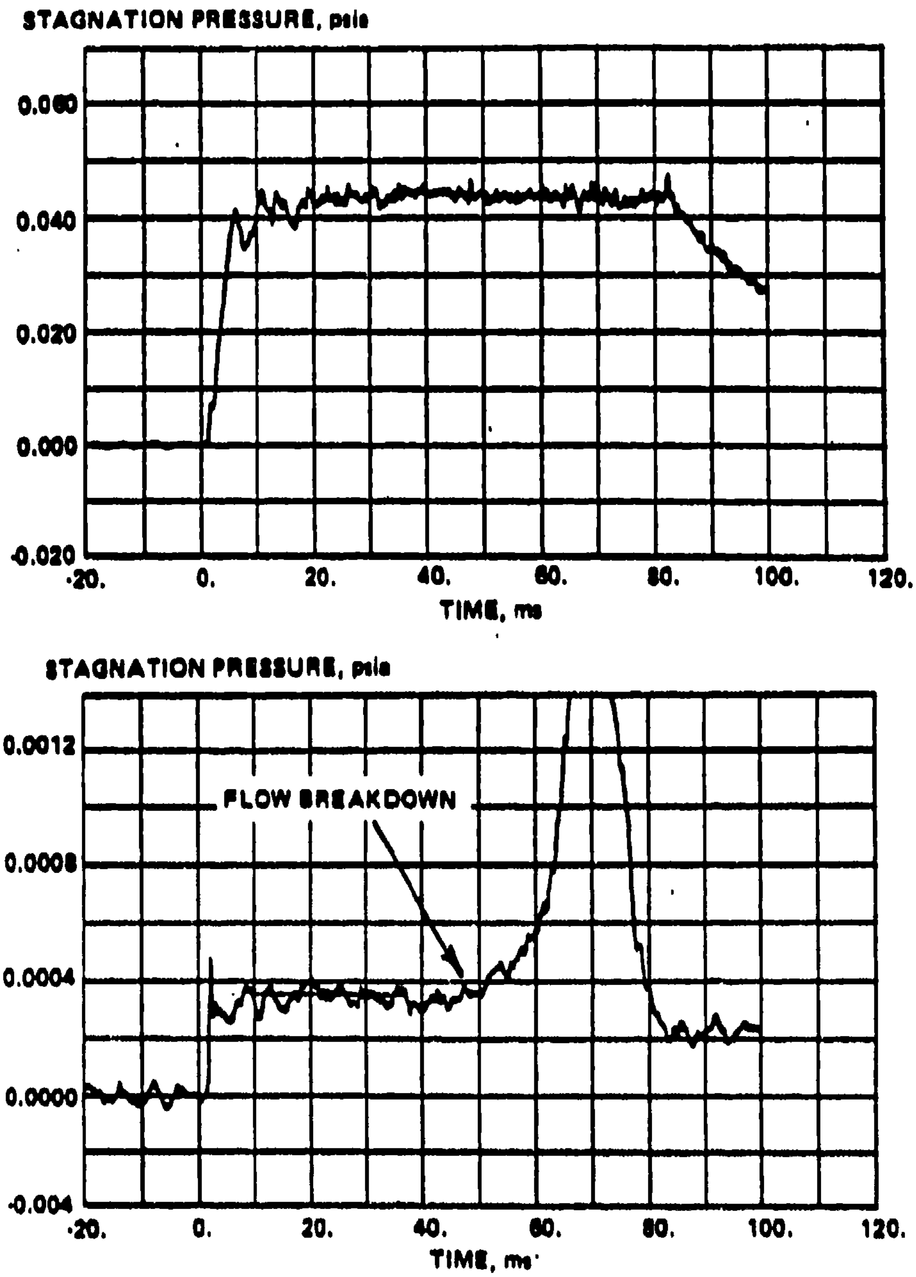


FIGURE 21 REPRESENTATIVE [redacted] PLUME STAGNATION PRESSURE MEASUREMENTS

EXAMPLES OF ROCKET NOZZLE MEASUREMENTS FROM SHORT-DURATION EXPERIMENTS

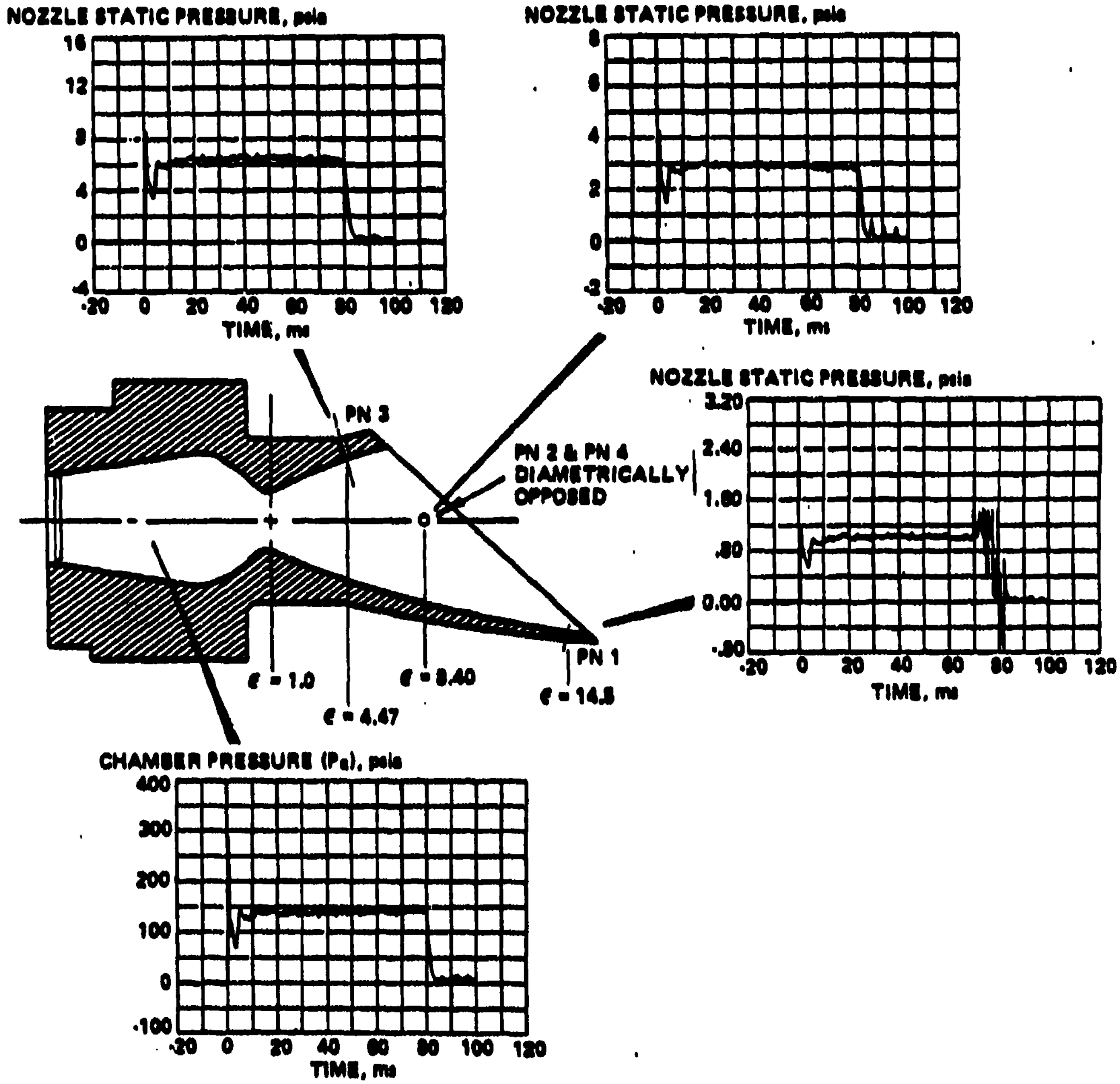


FIGURE 16 TYPICAL [redacted] NOZZLE STATIC PRESSURE MEASUREMENTS

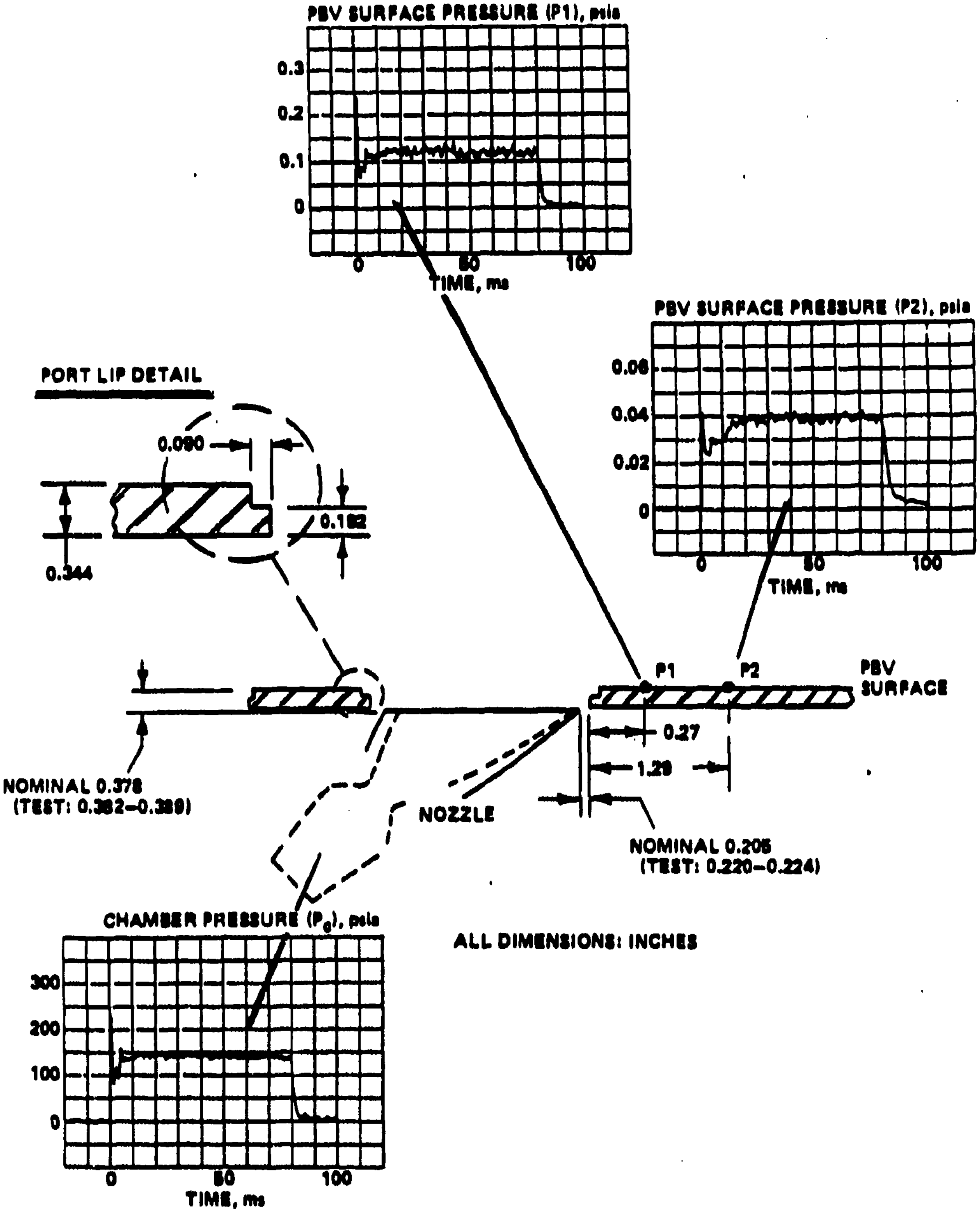


FIGURE 17 TYPICAL [redacted] SURFACE PRESSURE MEASUREMENTS

EXHIBIT B

DESCRIPTION OF SELECTED INSTRUMENTS

Resistance Thermometer Total Temperature Probe

Shielded fine-wire resistance thermometers have been developed to measure the total temperature in hypersonic flows as well as in the near-wake, reverse flow regions behind aerodynamic models. The probe sensing element is a resistance wire mounted on slender needles (Figure 1). Temperature is sensed electrically by utilizing the sensing element as a resistive component in a constant current circuit; thus the recorded voltage across the resistance wire

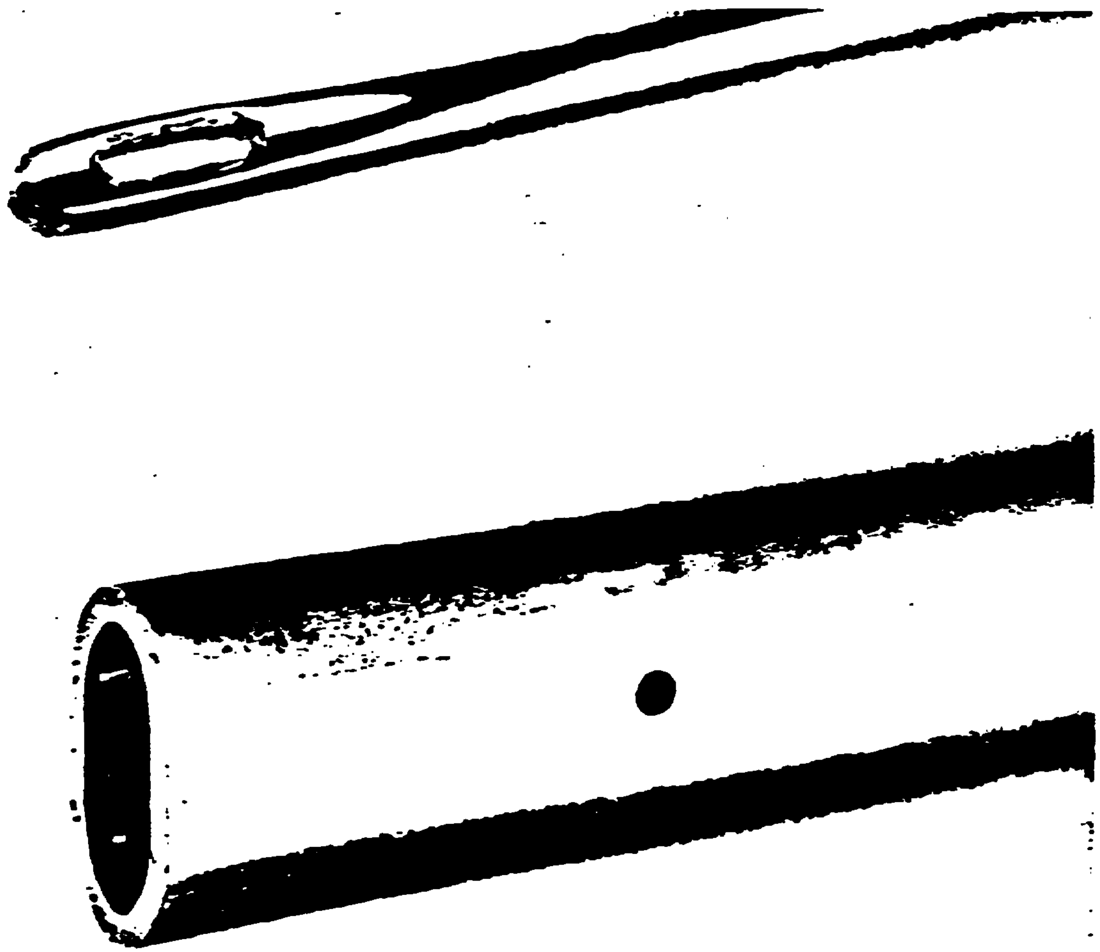


Figure 1 TOTAL TEMPERATURE PROBE

is related to its temperature and consequently to the fluid in which it is immersed. Resistance wires of tungsten, platinum and platinum/rhodium alloys have been used. Probe response times of 1-2 milliseconds have been achieved with 0.001-inch diameter wires (typically, 0.060-inch long).

Thermocouple Total Temperature Probes

Total temperature probes, consisting of very small, housed thermocouples have been developed and employed on a number of research programs. The probes are nominally 0.06-inch O.D. and utilize 0.0005-inch diameter chromel-alumel thermocouple wires. The small size, fast (~ ms) response, ruggedness, and ease of calibration make them well-suited to the subject effort.

Pressure Transducers

A variety of miniature, fast-response pressure transducers has been developed by Calspan. The sensors employ lead-zirconium-titanate piezoelectric ceramics as pressure-sensitive energy sources and integral field effect transistors (FET) as power amplifiers. In addition to their small size (nominally 0.37-inch diameter by 0.25-inch thick) they are characterized by high sensitivity and linearity and have a broad, dynamic range. Transducers of several different types are available with a combined pressure range of from 0.001 psia to several hundred psia. To provide acceleration compensation, an additional pressure-insensitive diaphragm-ceramic unit, wired in opposition to the active unit, is incorporated; this design reduces acceleration sensitivity to a measured value as low as 0.001 psi/g. A line-of-sight heat shield is used to minimize temperature and radiation effects.

Another sensor, employing similar sensing elements and signal conditioning electronics, is configured as a 1/8-inch diameter probe.

Skin Friction Sensors

The skin friction sensors developed by Calspan consist of a shear sensitive metric element (a diaphragm which is flat or contoured to conform to the wall surface profile) which is supported by piezoelectric ceramic posts. As a result of an applied shear, the piezoelectric elements are stressed and produce electrical output. In a manner similar to the pressure transducers (previously described), these sensors utilize shear-insensitive components for acceleration compensation and FET circuitry for power amplification. Transducers are available to measure shear stresses in the range of 0.0001 to 2.0 psi.

Heat Transfer Gages

The measurement of heat transfer rates to stagnation probes and model surfaces has been accomplished utilizing Calspan developed heat transfer gages. These units are basically thin-film resistance thermometers which sense transient surface temperature. A typical gauge consists of a thin film of platinum, approximately 0.1 micron thick by 5 mm by 0.5 mm, which is fused to a pyrex model insert. As the heat capacity of the gauge itself is negligible, the film temperature is a measure of the instantaneous surface temperature of the pyrex and is related to the heat transfer rate by the classical equation of heat transfer into a semi-infinite slab of known thermal characteristics. Analog networks have been developed to convert the output of the gage directly to a voltage which is proportional to heat transfer rate. Measurements of heating rates over a range of 0.1 to 1500 Btu/Ft^2 sec have been made. Multi-element gages for making measurements with high spatial resolution ($\sim$ 0.050 inch intervals) and single element gages smaller than 0.050-inch diameter have been produced.

Probe Configurations

A variety of probes have been fabricated for the measurement of free stream and boundary-layer flows. Of particular interest to the subject study are the conventional multi-element survey rake configurations which consist of an array of probes deployed in a vertical line to monitor with high spatial resolution the characteristics of a boundary layer. Figures 2 and 3 illustrate typical rake configurations. For the purpose of gas sampling, or the measurement of static or stagnation pressure, these probe arrays are simply tubes which communicate the boundary layer properties to an appropriate remotely-located sensor, for example, a gas analyzer or pressure transducer. ~~Often a second valve is employed for sequential sampling.~~ The measurement of boundary-layer total temperature can be accomplished using miniature temperature probes, as previously described, in place of the tubes.

Gas Sampling

Two basic approaches have been employed at Calspan for the determination of gas concentrations in flow fields. One method, which is generally utilized in short-duration experiments, requires the use of sampling probes which open and close rapidly to "capture" a sample of the gas and retain it for subsequent measurement of its composition. The second approach is simpler and more applicable to continuous flow experiments. It consists of sampling the flow field with probes not unlike the pitot tubes shown in Figures 2 and 3. The gas samples may be delivered to collection reservoirs for later analysis or routed directly to gas analyzers for on-line evaluation. Accurate analyses may be accomplished using standard gas chromatographs or mass spectrometers. For these measurements a variety of common gases (for example, CO_2, He, Ar) may be used as the boundary layer injectant (or alternatively, as tracers in the injectant). If mixed gases are used, sampling of the mixture prior to injection can be made to assess and ensure homogeneity. Furthermore, comparisons of the measured flow field concentrations with the free stream and injectant levels ahead of the injection station can be used to assess quantitatively the extent of free stream entrainment and the mixing of the free stream/boundary-layer flows.

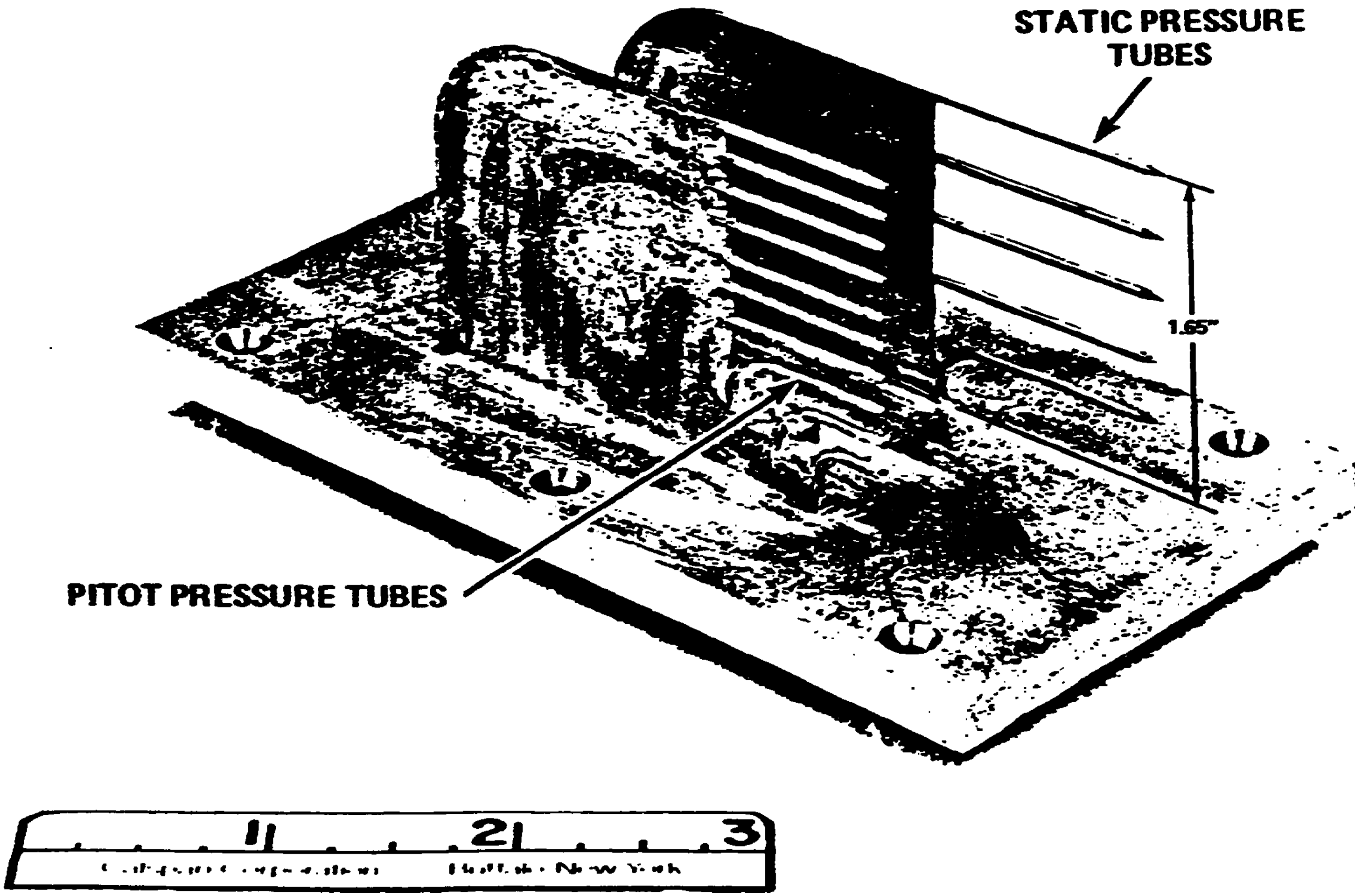


Figure 2 TYPICAL PITOT-STATIC SURVEY RAKE

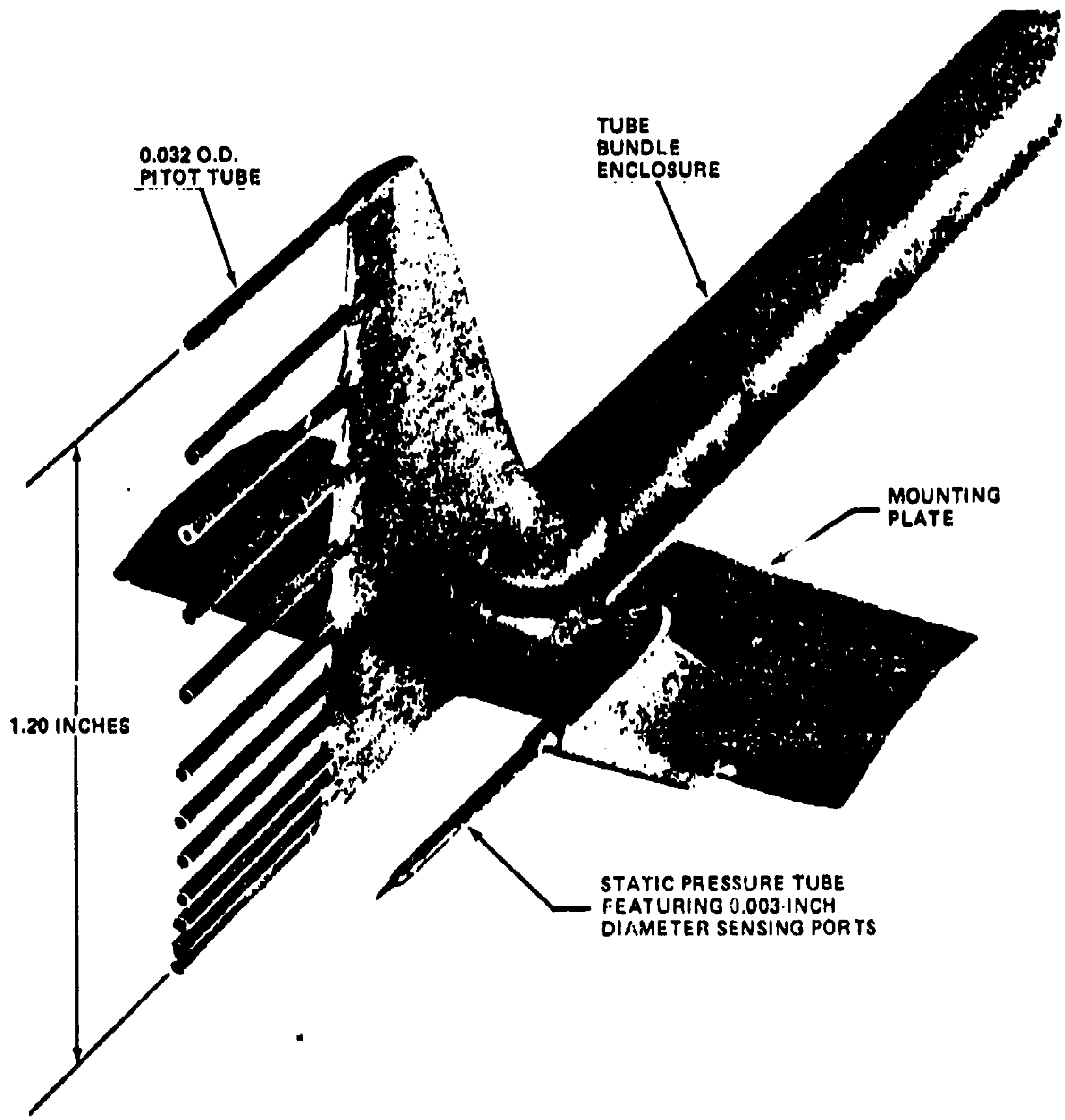


Figure 3 BOUNDARY-LAYER SURVEY RAKE

Instrumentation Calibration

A large variety of calibration equipment is available to support the instrumentation requirements of the research programs at Calspan. Several air and oil dead-weight testers, hook-gage apparatus, and high-pressure oxygen-compatible hardware allow dynamic and steady-state pressure calibrations to be performed over the range of 0.001 to 10,000 psia with uncertainties of less than 1% of the measured value. In addition, temperature calibrations up to about 1000°F can be performed to within similar accuracies.

Calspan maintains a central facility for the maintenance and calibration of laboratory instruments. A primary standards laboratory, containing reference and primary standards traceable to the National Bureau of Standards, and a secondary Standards Laboratory, providing the services necessary for the maintenance and periodic calibration of diverse electronic equipment and measuring instruments, support the activities of the technical departments.

APPENDIX D

AEROJET TECHSYSTEMS RESPONSE

AEROJET

AEROJET TechSystems COMPANY

5 January 1988

Homayun Kehtarnavez
Software and Engineering Associates
1050 E. William St.
Suite 402
Carson City, Nevada 89701

Dear Homayun:

During our recent meeting at Aerojet you described the code development effort in progress to produce tools for more accurately predicting the viscous losses in high expansion area ratio nozzles. You discussed the type of experimental program required to validate the code and obtain fundamental turbulence properties that would improve the code. You asked us to describe an experimental program to support the code development and verification and how we at Aerojet would be able to support such an experimental program.

From our standpoint, a code that predicts the drag exerted on the nozzle wall by the expanding gas to about 5 to 10% would be adequate. A useful experiment could be run by expanding hot N_2 to an expansion ratio of about 100, measuring thrust, flowrate and Pc very accurately. If the codes duplicated the measured thrust very closely it would be validated. However, if it did not, little information for improving the code would be obtained.

If the nozzle is fairly large, maybe 2 feet in diameter at the exit, point measurements of local shear stresses and heat fluxes at the wall can be made using standard techniques. A traversing hypodermic pitot probe can resolve velocity profiles very accurately for large nozzles. We have facilities on line to do the type of experiment described in the preceding.

Measurement of U' and V' at high Mach numbers is difficult. Laser doppler velocimeters collect light scattered by particles in the flow. In order to follow the high frequency oscillations at high Mach numbers, the particle size must be submicron which is the same order as the wavelength of visible light. The signal strength at these conditions is very weak. Hot wire probes work well as long as the gas total temperature is low enough to allow operating a wire at a temperature at which the wire can survive. N_2 must be heated to prevent condensation in high area nozzles. Unheated helium could be used at high expansion ratios but it is expensive. Cooled hot film probes can probably be used with heated N_2. Aerojet personnel have

P.O. Box 13222
Sacramento, California 95813
(916) 355-1000

extensive experience with hot wire probes and could make these measurements with confidence. Problems associated with LDV systems and the time and cost of putting such a system into operation seem to make LDV impractical for this experiment.

Jack Hyde
Combustion Analysis
Engineering Analysis Dept.

APPENDIX E

AEDC RESPONSE - BOUNDARY LAYER CODE
VALIDATION MEASUREMENTS (TURBULENT)

AEDC

BOUNDARY LAYER CODE VALIDATION MEASUREMENTS (TURBULENT)

C. C. Limbaugh

The detailed approach for producing the requisite code validation data naturally depends upon the specific codes requirements which are still to be determined in final form. Generally, however, the requirements can be anticipated to some degree because of the common features peculiar to boundary layers. The general sorts of measurements which are considered initially are:

nozzle heat transfer	nozzle skin friction
nozzle pressure	velocity
turbulent intensity	flow angle
static pressure	static temperature

Of perhaps greatest concern initially is the source of the gas flow for the boundary layer production. The nozzle is necessarily of relatively large area ratio to assure large boundary layer growth, but the throat must be small as possible in order to reduce mass flow and energy requirements to the minimum practical. Lower exit pressures will similarily promote boundary layer growth. With the large expansion ratio or low static pressures and temperatures, condensation of the working gas is a consideration. There are several facilities at the AEDC which will provide the pumping capacity appropriate to such an experiment, all with greatly varied costs and capabilities. Of note:

Propulsion Facilities: These are facilities that are capable of sustained mass flows of inert or combustion gases. The highest pressure altitides are reached in the R2H facility which can maintain a mass flow of 0.1 lbm/sec continuous at a pressure altitude of approximately 250,000 ft (0.005 psi). The other larger facilities for propulsion testing/reasearch scale upwards to the large facilities that can accomodate the 2nd stage Peacekeeper at a sustained altitude of approximately 90,000 ft (0.15 psi).

Space Chambers: These facilities are similarly of varied sizes that scale from the 4-x 10-ft Research Vacuum Chamber to the 80 ft Mark I chamber. These vacuum chambers can maintain near vacuum conditions (pressure altitude of 500,000 ft) for reasonable times within the pumping capacities of the mechanical and cryopumping capacities of the specific chamber. Some selectivity in the gases is required becaudse of the requirements of cryopumping. For example, the 4-x 10-ft chamber can maintain an altitude in excess of 250,00 ft for extended periods of time (minutes to hours) at a mass flow of 10 gms/sec of N2.

Relevant to the specific conditions for the boundary layer measurements, it is appropriate to note that a conceptual approach for performance testing of small scale thrusters has been previously examined for the R2H facility with the conditions:

A/A* : 100 - 1000	Po : 1200 psi
To : 1800 R	mass flow: C.1 lbm/sec air
Re >100,000	

These conditions seem, on the surface, appropriate to the issue of the production of the boundary layer. The R2H has similarly been run with small rockets with a variety of fuels.

Heat transfer, skin friction, and nozzle pressure are more or less conventional sorts of measurements that can be addressed by conventional means and are routinely addressed at the AEDC. Depending on the experimental conditions, more exotic instrumentation can be brought to bear for wall temperature measurements, such as thermal imaging cameras. There are practical considerations for application of the thermal imaging systems, but these are generally solved problems.

Other conventional measurements that are appropriate to boundary layer measurements include very small pitot probes (0.08 in dia), cone probes, hot wire anemometry, etc. These measurements provide for static pressure, Mach number, flow angularity, and other derived quantities. The extremely small probes have a limited range of application (e.g. Stagnation conditions generally need to be below the softening point of the materials) but all the techniques have been applied at the AEDC at one time or another. For extreme environments, the cone probes offer a likely avenue: Water cooled Cone probes have been designed and operated as small as 1/8 in and in total conditions to 300 psi and 3000 K. The STARTECH probes (3/8 in, 1500psi, and 3500K) are AEDC designed and calibrated, but have not been applied yet. Smaller water cooled probes are possible, with the specific design directed by the experiment. These intrusive techniques provide a means of incursions into the nozzle itseland probing upstream of any lip effects.

Conventional nonintrusive diagnostics that are well developed which might be appropriate to the determination of the boundary layer properties include broad band and narrow band Emission Absorption, Raman, Schlieren, laser fluorescence, and electron beam fluorescence. These techniques have all been applied in the test environment and application depends on the specific design of the experiment. Physical properties that can be derived from these measurement techniques include static temperature, species densities, and static pressure and density. To my knowledge, turbulent intensity has not been measured by any of these techniques. These techniques lend themselves to measurements at the nozzle exit, and it is not clear that a modification to the usual approach would allow incursion upstream of the lip. Spatial resolution of these techniques is, generally, quite small and is limited by the optics used.

Spark or laser tagging techniques have been successfully applied in some cases and may be useful here. In this technique the laser is used to make a spark or otherwise tag a flow constituent. The time development of the spark or tag is examined with high speed instrumentation and the flow properties inferred. Laser Velocimetry is not really considered for this application since the developed techniques are appropriate only for low speed flows and depend on seed particles being present in the flow. However, if required, such a technique might be appropriate for the thin subsonic portion of the boundary layer with a carefully thought out experiment.

Other nonintrusive techmiques that are under development that are appropriate for boundary layer flows includes the Sodium fluoerscecnce determination of velocity, static temperature, and turbulent fluctatyions. This is planned for development at the AEDC in Fy88 in support of hypersonic testing and has not been applied here. The approach is an outgrowth of work reported by Miles and his students (e.g. Phys of Fluids, Vol. 26, No. 4, pp.874, April, 1983). Essentially the technique depemnds on exciting the sodium (or by inference, some other molecule or atom in the flow) fluorescent line with a laser and observing the emitted light from several positions relative to the gas flow and the exciting beam. The shift in the emitted light because of the motion of the emitting molecule shifts the emitted light from its natural wavelength and the amount of the shift is directly related to the molecular velocity along the line of sight. Measurement parallel to the flow axis gives velocity, measurement normal to the flow direction will yield temperature, and observing fluctuations about the mean provides determination of the turbulent fluctuations. Present indications suggest that fluctuation times to 50 microsec are within reach. The technique is appropriate for supersonic flows and application below Mach 1 does not appear appropriate except under extreme low density conditions.

Other techniques have been reported in the literature that might be appropriate but application has been limited. Of specific note for the boundary layer measurements includes some of the small fibre optic probes which might be used upstream of the nozzle lip. These approaches utilize generally conventional emission absorption techniques with unconvention insertion of the probe beam into the flow via a fiber optic for transmitting and receiving. With the advent of the fibers that transmit into the infrared, a wide variety of molecules become available for diagnostics but it is not clear that designs that will survive extremely hostile environments exist.

Other unconventional untried approaches come to mind which may provide requisite data, but these are not generally "off the shelf". e. g. using a laser to heat a spot on the nozzle wall and the downstream flow observed with Schlieren or other density or thermally sensitive instrument; making the nozzle from some transparent or reflective material and using these as access to the interior of the nozzle. None of these have been accomplished and at best must be considered frivolous without considerable additional thought and development.

In conclusion, there are a variety of techniques that can be brought to bear on the determination of the boundary layer properties. Specific application depends on specific definition. The use of a combustion source in the chamber (an easy way to get turbulent flow) will provide a set of total conditions that will preclude, generally, intrusive probes that are uncooled and thus will necessitate a larger expansion ratio for the boundary layer growth to accomodate the larger water cooled probes. More benign chamber conditions to accomodate smaller probes begins to restrict the choice of working gas and the production of the turbulent flow with a large boundary layer becomes problematic. Nonintrusive techniques are best applied at the nozzle exit and incursion of these teschniques into the nozzle flow upstream of the lip similarly becomes problematic. The limitations and boundary conditions are generally well known for all the techniques however, and it seems reasonable that a carefully thought out experiment will provide the requisite data.

DIAGNOSTIC TECHNIQUES

TECHNIQUE	RELEVANT PHYSICAL PARAMETERS	APPLICATION RANGE
IR EMISSION/ABSORPTION	$T_s(r)$, $H_2O(r)$, $CO_2(r)$	$300° \leq T \leq 3000°K$ $10^{16} \leq n \leq 10^{20} cm^{-3}$
RESONANCE ABSORPTION	$T_s(r)$, $OH(r)$, $NO(r)$	$300° \leq T \leq 1500°K$ $10^{14} \leq n \leq 10^{17} cm^{-3}$
ELECTRON BEAM	$T_s(r)$, $N_2(r)$, $H_2(r)$	$300° \leq T \leq 1500°K$ $10^{13} \leq n \leq 10^{16} cm^{-3}$
PROBES	$T_o(r)$, $P_o(r)$, $P_s(r)$ SPECIES IDENTIFICATION FLOW ANGLE	
RAYLEIGH SCATTERING	$n(r)$	$10^{12} \leq n \leq 10^{21} cm^{-3}$
RAMAN SCATTERING	$T_s(r)$, $H_2(r)$, $O_2(r)$, $OH(r)$, $H_2O(r)$, $H_2(r)$	$100° \leq T \leq 5000°K$ $10^{14} \leq n \leq 10^{21} cm^{-3}$
HIGH RESOLUTION IR SPECTROSCOPY	SPECIES IDENTIFICATION	$300° \leq T \leq 3000°K$ $10^{15} \leq n \leq 10^{20} cm^{-3}$
UV IMAGING	DISTRIBUTION OF UV ACTIVE SPECIES	UNKNOWN
TUNABLE DIODE LASER	$T_s(r)$, $H_2O(r)$, $CO(r)$, $OH(r)$. . .	UNKNOWN
RESONANCE FLUORESCENCE	$T_s(r)$, $OH(r)$. . . .	UNKNOWN

?? 1125

[illegible]OSTIC TECHNIQUES AVAILABLE AT AEDC

GAS PHASE	PARTICLE PHASE	MECHANICAL/STRUCTURAL
IR EMISSION-ABSORPTION	SAMPLING PROBES	RADIOMETRY
RESONANCE ABSORPTION	LASER PHOTOGRAPHY	INTERFEROMETRY
ELECTRON BEAM FLUORESCENCE	LASER SCATTERING	FLASH X-RAY
SAMPLING PROBES	PARTICLE SIZING INTERFEROMETRY	
IMPACT PROBES	HOLOGRAPHY	
CONE PROBES	X-RAY	
HOT WIRE PROBES		
RAYLEIGH SCATTERING		
RAMAN SCATTERING		
SPECTROSCOPY		
ULTRAVIOLET IMAGING		
TUNABLE DIODE LASER		
RESONANCE FLUORESCENCE		

[illegible]-423

APPENDIX F

ROCKETDYNE RESPONSE - EXPERIMENTAL VERIFICATION OF CFD CODE RESULTS FOR ROCKET NOZZLE EXHAUST

ROCKWELL INTERNATIONAL

Rocketdyne Division

EXPERIMENTAL VERIFICATION OF CFD CODE RESULTS FOR ROCKET NOZZLE EXHAUST

APPROACH

In order to measure the velocities in the exit plane of a rocket nozzle exhaust, laser-based velocimetry (LV) techniques can be used. For velocities upto 5000 ft/s both the laser doppler velocimeter (LDV) and the laser-two-focus (L2F) systems can be employed. The physics regarding the principles of these techniques will not be discussed here as they are written up in many texts on the subject. The LDV technique has the inherent advantage that it can provide the Reynolds shear stress directly for a two component system. However, at such high velocities, the burst processor dictates that the fringe spacing be large, thereby yielding the measurement volume to be quite long (on the order of 0.5 inch or more). This, therefore, raises questions regarding spatial resolution of the measurements, and hence the validity of "making" point measurements. However, if the Reynolds shear stress measurement is the important parameter then one is limited to the LDV technique, in spite of the spatial resolution problem. If, instead, the mean and turbulence intensity velocity profiles would suffice, then the L2F technique would be the desired way to go provided the turbulence intensities are not in excess of 30 percent. Tables 1 and 2 show typical system specifications for the LDV and L2F techniques.

TABLE 1. LDV SYSTEM SPECIFICATIONS

Maximum doppler frequency:	60 MHz
Fringe spacing:	15.25 μm
Beam intersection half angle:	0.97 degrees
Measurment volume diameter:	252 μm
Measurement volume length:	14.9 mm
Number of fringes:	17
Main focussing lens focal length:	500 mm
Design velocity:	915 m/s
Velocity accuracy:	+0.1 % achievable
Angular accuracy:	+0.1 degree achievable
Turbulence level:	0 - 70 % +

TABLE 2. L2F SYSTEM SPECIFICATIONS

Classical System:

Beam separation:	285.7 μm
Beam diameter:	12 μm
Axial length:	762 μm
Velocity range:	1 - 3000 m/s
Turbulence range:	0 - 30 % (higher in fiber optics version)
Focal length:	470 mm
Velocity accuracy:	+0.1% achievable
Angular accuracy:	+0.1 degree achievable

TECHNICAL ISSUES

Several technical issues relevant to this measurement task require addressing. Perhaps, the most important concerns the issue of seeding. Laser velocimeters rely on the presence of micron-sized scattering particles. Often these particles are naturally present in sufficient quantity and in a desirable size range, particularly in liquid flows. In gas flows these scattering sources are often added supplementally. They may also be added in order to boost the system data rate. It is expected that supplemental seeding of the rocket engine exhaust would be desirable if not an outright requirement. The temperature of the exhaust plume would dictate the use of metal oxide particles such as zirconium oxide or titanium dioxide. These type of materials exhibit extremely high melting points and hence could be expected to survive in this environment. Injection into the flow stream could be accomplished via high pressure seeders such as a NASA invented device which produces submicron metal oxide seeds at several thousand psi output. Alternatively, it may be sufficient to inject an aqueous solution of the metal oxide into the engine model where the heat would drive off the solution and leave the metal particles.

Another issue regards the potential problem which could result from the high temperature nature of the exhaust gases. The refractive index of the gas is a function of the temperature and hence zones of varying indices can adversely affect the measurement process. For example, the laser beams may wander about as they are refracted by different zones. Thus the measurements would not be made at a set point in space. For discrete beam techniques such as the LDV the wandering of individual beams can prevent the beam pairs from crossing thereby altogether eliminating the interferometric measuring volume. Since fringe spacing is a function of the intersection angle, refraction effects could allow crossing but at varying angles. The result would be completely erroneous data. The L2F technique is considered to be less sensitive to such effects. In fact, Kugler (Ref.1) has employed the L2F technique to measure velocities in the exhaust plume of a small liquid fueled rocket engine.

For tests of short duration it will be necessary to scan the flow field quickly. For this purpose the optical head can be mounted on a computer controlled translation system. Predetermined positions can be set and attained rapidly in this manner.

If required fiber optic versions of both types of LV's are available. Use of fiber optics allows sensitive components such as lasers and photomultipliers to be remotely situated from the harsh test environments. In addition it decreases the mass of the optical head which need be translated, easing the requirements for these translation devices in turn.

Rocketdyne has extensive in-house experience with the L2F system. As the first purchaser of a Poytec L2F system in the United States, Rocketdyne has made extensive measurements in rocket engine environments. Consequently, it is envisioned that the measurements required for this test program could be done with ease at Rocketdyne test facilities. Furthermore, Rocketdyne is in the process of purchasing a fiber-optics based L2F system which could resolve turbulence intensities in excess of 30 percent.

REFERENCE:

1) Kugler, H.P., " L2F Measurements in a Rocket Exhaust Plume," 4th International Conference on Photon Correlation Techniques in Fluid Mechanics, Paper No. 13, pp.24-27, August, 1980.

Approximate Simulation of Turbulence

Computed spectra resemble von Kármán spectra of frequencies of interest.

Marshall Space Flight Center, Alabama

A numerical technique yields simulated atmospheric-turbulence spectra that closely approximate von Kármán spectra within the frequency ranges of interest for aircraft response. The technique uses approximate spectra that are especially suitable for computation in that they represent stable systems and roll off as f^{-2} (where f = frequency) at high frequencies outside the range of interest.

Real atmospheric turbulence tends to follow the von Kármán model, with spectral density proportional to $f^{-5/3}$. A simulated turbulence signal can be generated by a system like that of Figure 1, provided that the transfer function of the filter gives the required $f^{-5/3}$ dependence. For purposes of numerical simulation of the instantaneous turbulence signal, the filter transfer function is replaced by its corresponding differential equation, which is then approximated by a finite-time-step difference equation. As a result, the turbulence at the present time step is expressed as a function of the present input noise and the turbulence and input noise at the previous time steps.

Because it is computationally more efficient to simulate a rational rather than an irrational spectrum, the transfer function $(1+S)^{-5/6}$ that represents the exact $f^{-5/3}$ spectral dependence is approximated by the rational expression. For the longitudinal turbulence, this is $(1+S)^{-5/6} \approx [60+52S+(91/12)S^2]/[60+102S+(561/12)S^2+(935/216)S^3]$, where S is the Laplace-transform complex frequency. Because all the poles of this function lie in the left half of the complex S plane, the system that it represents is unconditionally stable.

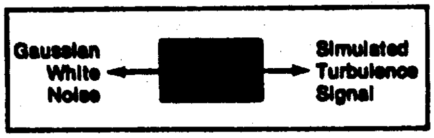


Figure 1. Monte Carlo Simulation of Turbulence can be done with digital or analog equipment by passing Gaussian white noise through a filter that has a transfer function corresponding to the turbulence spectrum.

The transfer function for transverse turbulence is obtained by multiplying the longitudinal transfer function by $[1+(8/3)^{1/2}S]/[1+S]$. This function also represents a stable system. In both the longitudinal and transverse cases, the spectral density is found by multiplying the transfer functions by their complex conjugates.

Longitudinal turbulence and transverse turbulence have been simulated by difference equations based on these transfer functions, using a sampling frequency of 5 Hz, an aircraft speed of 100 m/s, a turbulence length scale of 500 m, and a root-mean square turbulent velocity of 1 m/s. As shown in Figure 2, the spectra of the simulated turbulence closely approximate the corresponding von Kármán spectra. In fact, the statistical scatter is greater than the difference between the simulated and von Kármán spectra.

This work was done by C. W. Campbell of the American Institute of Aeronautics and Astronautics for **Marshall Space Flight Center**. *For further information, Circle 125 on the TSP Request Card.*
MFS-28172

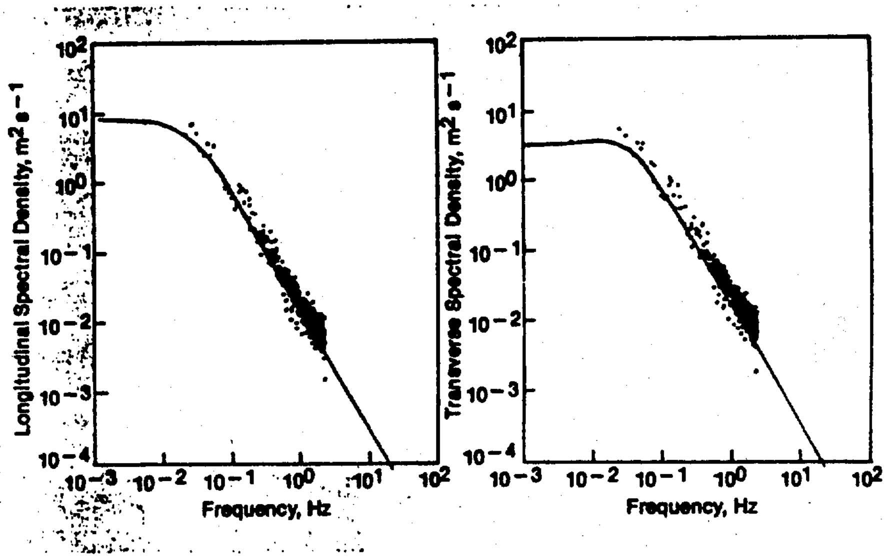


Figure 2. **Spectra of Simulated Turbulence** (dots) are plotted with the corresponding von Kármán spectra (lines).

Measuring Gases With Laser-Induced Fluorescence

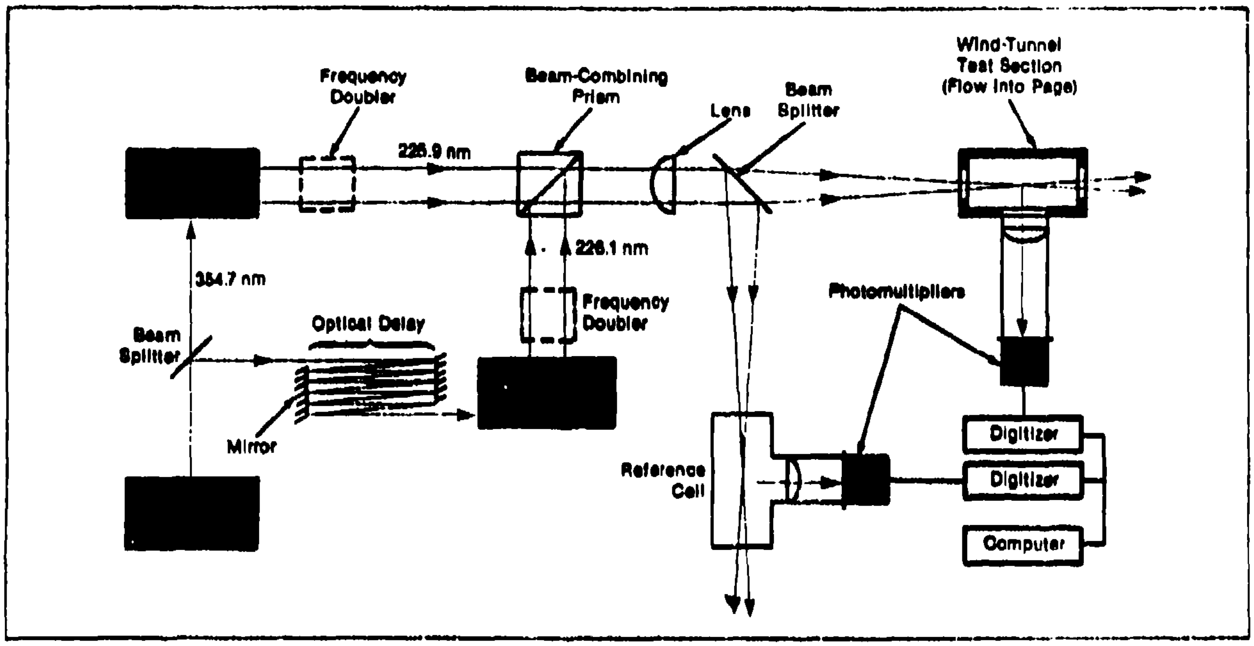
The temperature, density, and pressure are measured simultaneously in supersonic, turbulent flow.

Ames Research Center, Moffett Field, California

The temperature, density, and pressure at a selected point in a low-temperature, turbulent gaseous flow are measured simultaneously by pulsed laser-induced fluorescence (LIF). The measurements are made with spatial and temporal resolution comparable to those obtained with modern laser-anemometer techniques used for research on turbulent boundary layers. These LIF measurements are unique in that they are nonintrusive and constitute the first alternative means of measuring turbulent fluctuations in temperature and density that can be compared with conventional hot-wire-anemometer data.

The LIF technique involves seeding a bulk nitrogen flow with a low concentration (up to 100 parts per million) of nitric oxide (NO) and relies on the ultraviolet fluorescence following single-photon excitation of two rotational/vibrational electronic transitions in the NO gamma band. The test section of the small wind tunnel used for these experiments is a rectangular mach-2 nozzle with a 25- by 64-mm exit, followed by a slightly diverging channel, 762 mm in length from the nozzle throat to the optical ports.

The optical arrangement is illustrated in the figure. The laser beam is admitted through either of two 50-mm-diameter quartz windows on opposite sides of the channel. Fluorescence is observed through a similar window on a third side of the channel. The volume observed is spatially limited by the collection optics and field-stop arrangement to a 1-mm segment of the laser beam centered on



Laser Beams Focused to Small Spots in the wind tunnel and reference cell induce fluorescence in nitric oxide, a small amount of which is mixed with the main gas flow. The fluorescence radiation depends on the main-gas temperature, pressure, and density and is measured to deduce these quantities.

its focal point.

Two grating-tuned dye lasers are simultaneously pumped by the third-harmonic output of a Nd/YAG laser at a repetition rate of 10 Hz. The portion of the 354.7-nm pump beam directed to the second dye laser is optically delayed, giving a temporal separation of 125 ns between dye-laser pulses. The beams of both dye lasers are doubled in frequency, and each second harmonic is tuned to one of the NO transitions.

The two beams are combined collinearly, focused by a common lens of 500-mm focal length and partitioned into the wind-tunnel and reference paths. The reference path contains the same gas as does the wind tunnel, but the gas does not flow and is maintained at a known temperature and pressure. The focal-spot sizes were less than 0.5 mm.

The broad-band fluorescences from the wind tunnel and the reference cell were collected by nearly identical f/1 fused-silica optics and nominally filtered with ultraviolet-transmitting shortwave-pass filters. The fluorescence waveforms from each source were detected by solar-blind photomultipliers sensitive to the spectral range from 225 to 330 nm and recorded by transient digitizers interfaced to a computer.

The computer deconvolved the double-pulse waveforms to separate the contributions from each excitation, integrated to obtain the relative fluorescence energy associated with each excitation, and compared wind-tunnel with reference values to obtain normalized wind-tunnel data.

The ratio of fluorescence energies from both transitions is related to the rotational temperature of the ground-state NO molecule, with account taken of the effects of collisional quenching and transition spectral broadening. The rotational temperature, in turn, is assumed to be closely coupled to the kinetic temperature of the gas mixture. The density and pressure are obtained from the measured temperature, together with the combined use of the fluorescence energy from one excitation and the equation of state for the gas mixture.

This work was done by Robert L. McKenzie of **Ames Research Center** *and Kenneth P. Gross of Polyatomics Research Institute and Pamela Logan of Stanford University. For further information, Circle 81 on the TSP Request Card.*

Inquiries concerning rights for the commercial use of this invention should be addressed to the Patent Counsel, Ames Research Center [see page 22]. Refer to ARC-11678.

Measuring Electrostatic Discharge

A variety of materials can be tested together under controlled conditions.

Lyndon B. Johnson Space Center, Houston, Texas

An apparatus measures the electrostatic-discharge properties of several materials at once. It allows the samples to be charged either by friction or by exposure to a corona. By testing several samples simultaneously, the apparatus eliminates errors introduced by variations among test conditions.

The samples are placed on a turntable and rotated beneath a charging arm and a diametrically opposed noncontacting voltmeter probe (see figure). Positioned 6 millimeters above the turntable, the probe registers the voltage on each sample as it passes. The voltmeter output is displayed on a fast-responding chart recorder.

When the corona-charging arm is selected, it is extended to the radius of the samples; the pointed electrode of the arm is held 15 millimeters above the surface of the samples. When frictional charging is required, the corona arm is retracted and the frictional, or tribocharging, arm is extended; the abrasive tip of this arm is held against the surfaces of the samples.

As the turntable rotates, the samples are repeatedly charged by the selected arm. After about 150 seconds at a turntable speed of 8 radians per second, the charges on the samples build up to equilibrium levels. At this point, charging is stopped, and the voltmeter readings are started. The readings thus indicate the

APPENDIX G

LANL RESPONSE - BOUNDARY LAYER
CODE VALIDATION

WHITE PAPER

BOUNDARY LAYER CODE VALIDATION

INTRODUCTION

Science and Engineering Associates (SEA) of Carson City, Nevada has obtained a contract from the Air Force Astronautics Laboratory, Edwards Air Force Base, California to write an experimental test plan for making detailed measurements in rocket engine boundary layers. The primary goal of these measurements is to validate current boundary layer codes or to develop new codes if they are deemed necessary. It is understood that the contract for these measurements will be awarded directly by the Air Force. However, SEA will make technical recommendations to the Air Force on the appropriate measurements required to obtain high quality data. The Air Force Plan calls for a four year program to obtain data data to validate new boundary layer models for large area ratio nozzles. In this white paper we will give a brief description of our organization's capabilities and current technical activities, specific descriptions on how the measurements are to be made, and a brief plan on what is to be done.

TECHNICAL REQUIREMENTS

The lack of high quality boundary layer information has impeded efforts to optimize specific impulse in liquid H_2 and O_2 rocket engines used in orbital transfer vehicles. Since this information is used to validate a generalized boundary layer code, it is important that as many different detailed measurements in the boundary layer are made. The following parameters should be accurately determined by experiment:

1. u' and v' terms in turbulent flow, as well as the Reynold's stress, <u'v'>.
2. Average velocity, temperature, and possibly pressure profiles in the boundary layer.
3. Profiles of boundary layer displacement and momentum thickness as a function of axial location.
4. Local wall shear and skin friction.
5. Local heat flux at the wall for a cold wall case, and temperature at the wall for and adiabatic wall.

LOS ALAMOS CAPABILITIES AND ACTIVITIES

Los Alamos has extensive experience in the development of sophisticated diagnostics for application in supersonic flow and high temperature environments. A variety of laser diagnostic techniques have been employed, including laser-induced-fluorescence (LIF), coherent anti-Stokes Raman (CARS), and various types of transient absorption spectroscopy. The use of these laser diagnostic techniques is not unique to Los Alamos. However, much of the pioneering work in applying these techniques to extreme environments was accomplished here. For example, these techniques are commonly employed in the Los Alamos Molecular Laser Isotope Separation (MLIS) Program, which has the mission of separating various isotopes of plutonium and uranium using lasers. The MLIS program has been an on-going program for 15 years and has over 100 technical personnel assigned to it. In this program non-intrusive diagnostics were developed to measure infrared, visible, and UV spectra of the laser excited molecules and to measure number densities of PuF_6 in a nozzle cooled supersonic stream at extremely low temperatures. These diagnostics were also used in high temperature combustion environments for coal gasification research.

Laser fluorescence measurements have also been used to measure axial and lateral velocity spreads of relativistic hydrogen atoms which are used in the Neutral Particle Beam, Strategic Defense Initiative Program. We are currently planning to use these laser-based diagnostics for studying critical kinetic rates in the combustion of H_2 and O_2 and for on-line measurement of combustion efficiency in the National Aerospace Plane Program.

Since cost is a major consideration it is important that existing facilities be considered for this experimental project. For development of on-line diagnostics we are currently considering the local gasdynamics laboratory (Fig. 1), which is used to support our laser isotope separation program. This laboratory has the capability to handle 5000 CFM under continuous flow at from the 10 torr level down to several hundreths of a torr. Since a blowdown tank is part of the vacuum system, the laboratory can also operate under a blowdown mode at much higher flow rates. We therefore expect the gasdynamics laboratory to be an ideal test bed for development of diagnostics under cold and warm flow conditions. The actual measurements could be performed in the six feet long Mach 8 nozzle at our sister laboratory, Sandia National Laboratory, Albuquerque.

VELOCITY DIAGNOSTICS

Because the rocket nozzle presents a very severe environment, the standard velocity probes normally used for precision spatial measurements may have some disadvantages. Since cooling requirements will require larger than desired diameters, the probes themselves may possibly interfere with the measurement. Moreover, the measurement of turbulence quantities with an intrusive probe would be extremely difficult, if not impossible, in a high temperature flow. We will therefore limit our discussion to the use of non-intrusive laser-based velocity measurements. Because of the requirement for accurately measuring turbulence velocity components in a highly turbulent flow we have selected the use of doppler shifted laser-induced-fluorescence (LIF) as a velocity diagnostic over the more commonly used laser doppler velocimeter (LDV) using particle seedants. The coherent anti-stokes raman scattering (CARS) technique, which will be the primary diagnostic to measure temperature also serves as an excellent check on the doppler LIF technique to measure velocity.

As mentioned above, the most common method for optically measuring velocities is laser doppler velocimetry (LDV). In order to understand the problems associated with the use of LDV for measuring turbulent flows, a brief summary of the principles of operation of this device are in order. A one-dimensional LDV consists of a laser which is passed through a beam splitter to form two beams. The beams are subsequently crossed in the region of interest to form an interference pattern. Seed particles passing through the volume containing the fringes reflect the light back in a modulated pattern whose frequency corresponds to the particle's velocity projected onto an axis perpendicular to the fringes. The scattered light is collected and passed through a spectrum analyzer. Using the measured angle between the two beams and the distance from the fringe volume to the output optics, it is possible to convert frequency to velocity.

When attempting to measure turbulent flows in the kind of environment typically found in rockets, this technique suffers from several problems. First, the choice of seeding material is critical. Seed particles must be good scatterers at the wavelength being used. In addition, it is preferable from a signal-to-noise standpoint if the seed is primarily characterized by Mie, as opposed to Rayleigh, scattering. Thus, spherically symmetric seeds are preferred. It is very difficult to find a seed which meets these requirements and can withstand a rocket engine environment. Usually, a compromise is reached where soot or something similar is used. These do not provide an optimized scattering cross-section, but can survive the environment.

Second, in order to provide a reasonable amount of scattered light, seed particles must be physically large. Minimum sizes depend, of course, on input light power, but a conservative number of around 1 micron would be reasonable. Particles this large are incapable of following the kind of turbulent flow typically found in such systems. This technique has been attempted in such flows before by compensating for tracking problems during the data analysis. Such attempts, however, leave a considerable amount of uncertainty in their results since the calculated turbulence frequency spectrum then becomes only as good as the model used to analyze the data.

Laminar tracking can also be a problem. Studies have shown that seed materials lag significantly behind free stream velocities at modest Mach numbers. The established practical limit currently appears to be around Mach 4.

Finally, one of the most difficult parts of the LDV process is developing a seeding method which will not influence the flow being measured. In a wind tunnel, seeding is never performed before the experiment. Thus, the seed material must pass through one full cycle of the tunnel before it reaches the sampling volume, thereby aiding in the uniform distribution of the seed. Also, the seeding input port must be carefully designed to avoid causing turbulence.

The most promising method for measuring both the average velocity U and the turbulence quantities u' and v' inside the boundary layer is Doppler LIF. A schematic of the proposed measuring technique is shown in Figure 2. A laser beam is focused in a small volume inside the boundary layer and excites a seedant atom or molecule. The fluorescence signal is detected and filtered with an Eschell grating spectrometer. The fluorescence from the seedant will be doppler shifted in wavelength proportional to the local gas velocity. For the measurement of Reynold's stress, $<u'v'>$, two spectrometers must be set up to measure the two velocity components simultaneously.

Temperature broadening of the observed emission line will not be a problem. At the resolution levels required to measure the Doppler effect under the stated conditions, individual transition levels will be clearly separable. Thus, instead of a thermal broadening of the spectral line, a family of lines will be observed, each line corresponding to a particular excited state transition. Temperature, therefore, will only play a role in the selection of the particular transition to be observed.

Sufficient spectral resolution should be achievable. In order to obtain the complete velocity distribution at any instant of time, the recommended instrument would be an Eschell grating spectrometer. This instrument has a very limited bandwidth, but provides very high resolution. Since the spectral line to be observed will be known to high precision, and since the expected Doppler shift represents such a small fraction of the wavelength, the Eschell spectrometer seems to be ideally suited to this problem.

A calculation was performed to estimate the amount of signal which could reasonably be expected from the system. The seed material was assumed to have an observed transition of 540nm. The collection volume was taken to be 1 cubic mm. It was also assumed that sufficient laser power would be used to excite 50% of the seed material in the target volume, that the concentration of seed material would be about 1 part in 4000 of air, and that the position of the exciting laser would be adjusted so that virtually all of the excited atoms would emit while in the collection volume.

The Doppler shift due to a 1500 meter/sec velocity would be 0.00270 nm. In order to calculate the required instrumental resolution, a gaussian turbulence profile was assumed with a standard deviation of 3% of the free stream velocity. This corresponds to a Doppler shift of 81×10^{-6} nm. If we make this be one 5 micrometer pixel of a linear array, and we assume an Eschell grating with d = 5 micrometers, alpha = 15 degrees, beta = 75 degrees, and m = 100, the required spacing from the grating to the linear array would be 80cm. Such a grating is technologically feasible, but will require custom construction.

These requirements could be significantly relaxed if the turbulence standard deviation were increased to 10%. This would allow the grating specifications to be reduced to alpha = 30 degrees, beta = 60 degrees, and m = 50. The resulting 93cm spacing is still feasible, and the grating parameters are now well within the range of lower cost commercially-available instruments.

Two conditions were considered when calculating the expected signal strength, with the numbers for each taken from a provided example. For the stagnation conditions, the assumed conditions are: pressure - 3.0 atm, temperature - 1400K. This results in an air density of about 1.58×10^{19} atoms/cm^3, yielding a density of seed material of roughly 3.95×10^{12}/mm^3. Thus, the number of photons emitted in the collection volume would be 1.97×10^{12}. Assuming a 25mm diameter collecting lens is used at a distance of 10cm from the target, an approximate total of 2.9×10^{10} photons will be presented to the Eschell grating spectrometer.

Nozzle exit conditions were taken to be: pressure - 3.0×10^{-4} atm, temperature - 100K. This corresponds to an air density of about 1.1×10^{16} atoms/cm^3, yielding a density of seed material of roughly $2.7 \times 10^9/mm^3$. Thus, the number of excited atoms in the collection volume would be 1.35×10^9, resulting in collection of approximately 2.8×10^7 photons. This is still considered an adequate number for the spectrometer to produce reliable signal.

The time required for a volume element to traverse a 1mm field of view is about 670ns. For all of the excited atoms or molecules to emit during this time interval, the lifetime of the state should be approximately 1/3 of this, or about 223ns. This corresponds to a natural linewidth of 716KHz, far below the Doppler broadening. Thus, the natural linewidth can be considered to be a delta function for the purposes of analyzing the data.

It is expected, therefore, that the measured line shape will be gaussian. Accurate measurement of the centroid of such a line typically requires a minimum of 1000 counts. Thus, a minimum transmission efficiency for the Eschell grating spectrometer of 0.004% will be needed. This is not considered to be a problem.

In conclusion, the calculations indicate that it should be possible to measure the velocity distribution of the proposed flow system using an Eschell grating spectrometer specially constructed for the emission line of interest. Temperature of the gas will not be a complicating factor. Time resolutions of 50ns should be possible, with a minimum spatial resolution of .5mm, cubed.

As mentioned previously, the CARS diagnostic is also an excellent technique for measuring velocities. CARS laser tagging is a recently developed technique for the simultaneous determination of a velocity flow field. A line of molecules (or atoms) is initially tagged by excitation using a pulsed laser; after a delay time a second broad-area laser pulse produces a signal only from the excited molecules that is imaged on a detector array. The measured displacement of a tagged molecule quantitatively determines its velocity vector. For example, for laminar flow along a wall and a tagging beam perpendicular to the wall, the image detected from above following the probe pulse would be identical to the laminar flow-velocity profile. In the presence of turbulence, provided the delay between laser pulses is shorter than the turbulence coherence time, the profile will be locally distorted; these distortions provide quantitative turbulence velocities.

To determine all components of turbulence velocities, imaging detection must be provided from two (preferably orthogonal) directions, such as from above the tagged line and collinear to the tagged line. Laser tagging has been demonstrated for velocity-field profiling based upon coherent Raman tagging of O_2 molecules followed by LIF. Alternative laser-tagging schemes for velocity-field profiling may be more suitable, depending on experimental conditions, such as optical double-resonant LIF or coherent Raman transients. Comparison of laser-tagging velocity diagnostics to alternative velocity diagnostics, such as Doppler LIF, depends on experimental conditions, because they have differing limiting interferences. The accuracy in measuring turbulence velocities using laser tagging is dictated by the magnitude of turbulence velocities relative to overall downstream velocities, whereas the accuracy using Doppler LIF is dictated by turbulence Doppler shifts relative to the Doppler broadening due to translational (kinetic) temperatures.

TEMPERATURE DIAGNOSTICS

Laser-based spectroscopic techniques are well suited for the nonintrusive measurement of temperatures in a flowing gas stream. Molecules in the gas stream can often be characterized by a variety of (not necessarily equal) temperatures, including translational (kinetic), rotational, vibrational, and electronic temperatures. Spectroscopic measurement of translational temperature via Doppler broadening of spectral lines is intimately related to velocity measurements, as discussed in another section. Spectroscopic techniques to probe rotational or vibrational temperatures are generally more convenient and include coherent Raman techniques, such as coherent anti-Stokes Raman spectroscopy (CARS), and laser-induced fluorescence (LIF). In the combustion community, vibrational temperature based upon CARS of the N_2 Q-branch has been validated as the most accurate nonintrusive temperature diagnostic, with single-pulse accuracy of 40K for temperatures above 1400K. At the high pressures typical in combustion, vibrational temperatures are in equilibrium with rotational and translational temperatures. However, in supersonic gas flows as considered here, vibrational temperature is far less likely to remain in equilibrium, while equilibration of rotational and translational temperatures is still likely. Moreover, calculations of the temperature through the boundary layers predict that the temperatures will generally be lower than those readily measured using vibrational spectroscopy. Hence we believe that rotational temperature measurements using CARS or LIF will be the most meaningful and the most convenient in these conditions.

Rotational temperature measurements using CARS can, in principle, be accomplished based upon any molecular species in the gas stream, including naturally occurring species like N_2 or H_2, or seeded components like HF. Over the temperature range calculated to be of interest through the boundary layer of 100-1400 K, the most accurate rotational temperature measurements would be achieved with CARS of HF or H_2, with estimated accuracies of 5%; CARS of other molecular components would yield rotational temperatures with lower accuracy under these conditions. CARS is the generation of a laser-like beam upon illumination of the gas by two laser beams whose frequency difference matches a

Raman mode of the probed molecule. A schematic of a CARS experiment on a sample gas cell is shown in Figure 3. Temperature and density of the probed molecule are simultaneously determined if one of these laser beams is replaced by a well-chosen set of two or more frequencies and the corresponding set of generated frequencies is dispersed. To perform temperature measurements through the boundary layer, double-ended optical access to the test medium is generally required, although we have performed CARS using a single window and a retroreflecting opposing surface. The low densities expected here (about 0.2 Torr) lead to relatively small CARS signals for single-point measurements that are 10^2-10^4 times higher than typical detectability limits. The temperature profile (and automatically the density profile of the probed molecule) is readily accomplished by spatial scanning if the flow is sufficiently steady or reproducible, as planned for CARS implementation at a supersonic tunnel at NASA-Langley in the NASP program. If the flow is not steady for a sufficient time, simultaneous temperature imaging of several hundred points through the boundary layer is feasible using two intensified detector arrays.

Rotational temperature measurements using LIF can not readily be performed on most naturally occuring molecular components such as N_2 or H_2, as their transitions lie in the vacuum ultraviolet. It is conceivable that LIF temperature measurements on O_2 near 193 nm could be accomplished, but this task would be challenging due to the hard uv wavelengths involved, the lack of well-behaved tunable laser sources in this spectral region, and the low fluorescence yields due to O_2 predissociation. Thus LIF temperature measurements are best performed on a seeded molecule, such as NO excited near 220 nm. Single-point rotational temperature measurements in a supersonic flow have been demonstrated using NO over the temperature range 150-300 K; it appears likely that range can be extended to 100-1400 K. LIF is most conveniently done in a sample geometry containing two windows at 90 degrees centered on the region of interest, but the single-windowed geometry shown in Fig. 2 for LIF velocity measurements may be suitable. Temperature measurement using LIF requires illumination of the molecule at two suitably chosen wavelengths, either delayed by several fluorescence lifetimes using a single detector or simultaneously with dispersed fluorescence detection. As with CARS, the temperature profile (and automatically the density profile of the probed molecule) can be obtained either by spatial scanning or by simultaneous imaging; in the latter case the only detection alternative is the use of two intensified detector arrays coupled with fluorescence dispersion.

Both CARS and LIF appear to be capable of providing the desired rotational temperature data in the boundary layer. The choice between temperature diagnostic techniques should be based upon whether molecular seeding of the gas stream is acceptable and upon the signal levels (and hence accuracy and, in the case of imaging, number of spatial resolution elements) achievable with each technique, which depend upon conditions such as temperatures, density of the probed molecule, and composition of the gas stream.

SKIN AND HEAT TRANSFER MEASUREMENTS

Because there exist very steep gradients near the wall and the possibility of wall effects on the laser diagnostics, the boundary layer properties at the wall should be measured by techniques more standard than the laser-based ones mentioned above. Wall pressure distributions can be accurately measured by appropriate use of pressure transducers along the nozzle wall. Heat transfer to a cooled wall will involve some method of measuring the transient temperature increase when the nozzle heater is turned on. Temperature measurement of an insulated wall can be done with the use of standard wall thermocouples and the fabrication of a thermally insulated piece of the nozzle wall. If at all possible, skin friction should be independently measured. Although the method of measurement is straightforward in concept, implementation on an axisymmetric nozzle may not be. However, the technology for this measurement has been developed by the Naval Surface Weapons Center, and published in the open literature.

PRELIMINARY PROJECT PLAN

FY 1989:

-Identify and assess specific requirements of experimental plan.

-Collaborate with AFAL and SEA on prioritized list of tasks.

-Develop velocity and temperature diagnostics for boundary layer measurements and use local laboratory test-bed for optimizing measurements

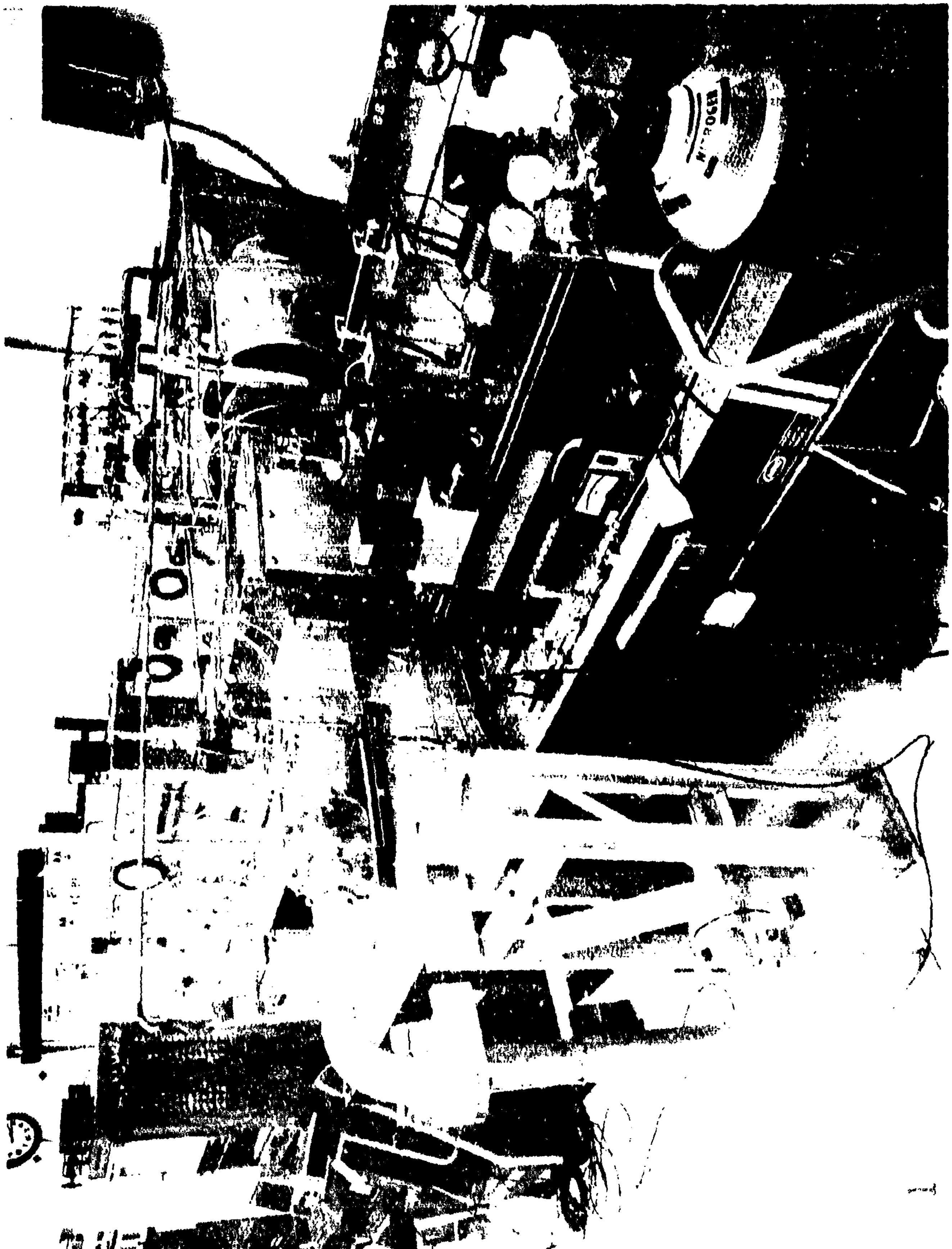
-Collaborate with Sandia, Alburquerque, or industrial partner to do experiments on full-scale high temperature nozzle. These include instrumentation on nozzle to measure skin friction, wall heat transfer, and wall pressure distribution.

FY 1990:

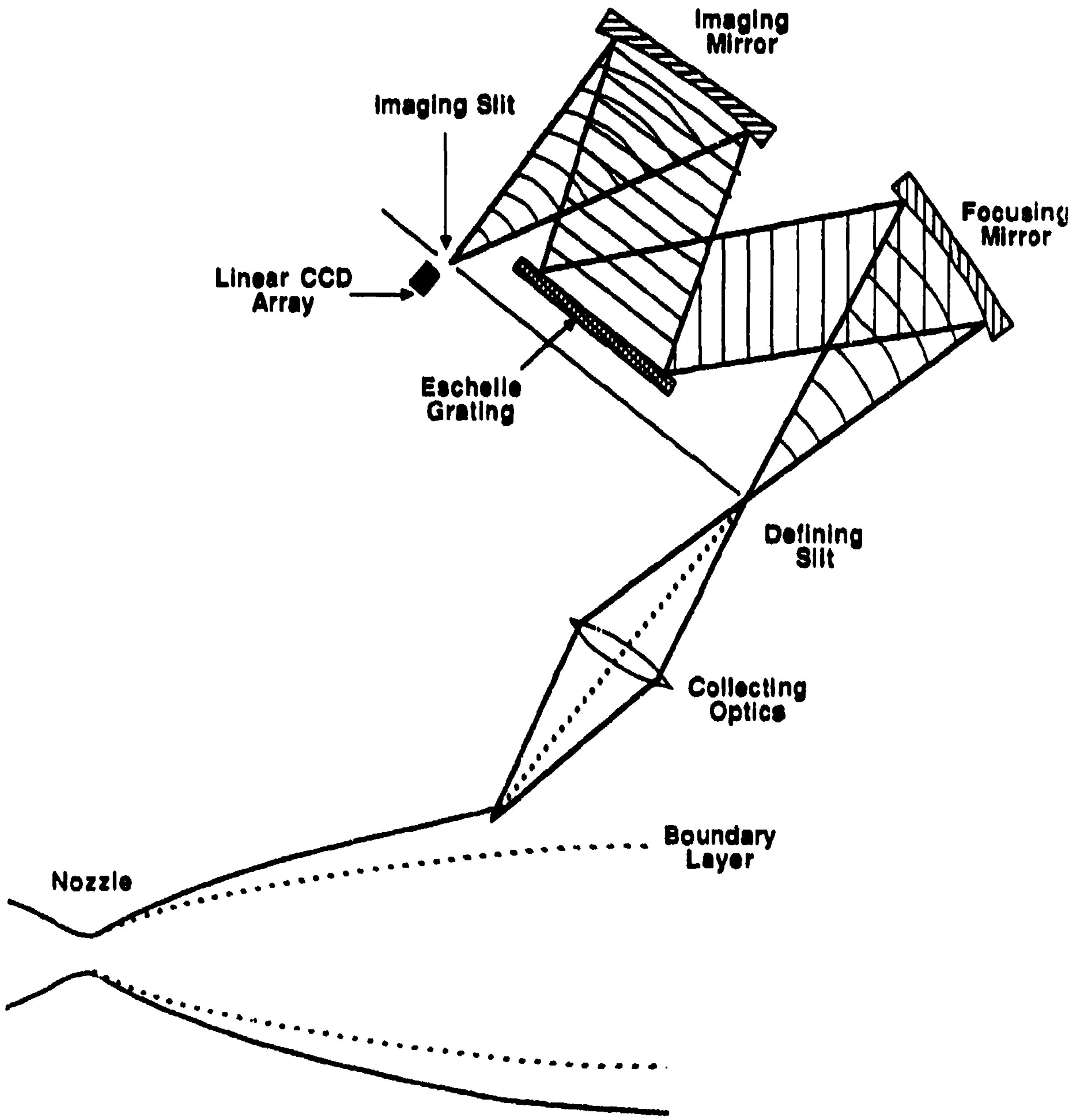
-Collaborate with AFAL and SEA on status of progress and negotiate prioritized task plan

-Carry out detailed measurements over full parameter range, including rocket nozzle stagnation pressure, temperature and throat Reynolds number.

-Prepare detailed report of results.

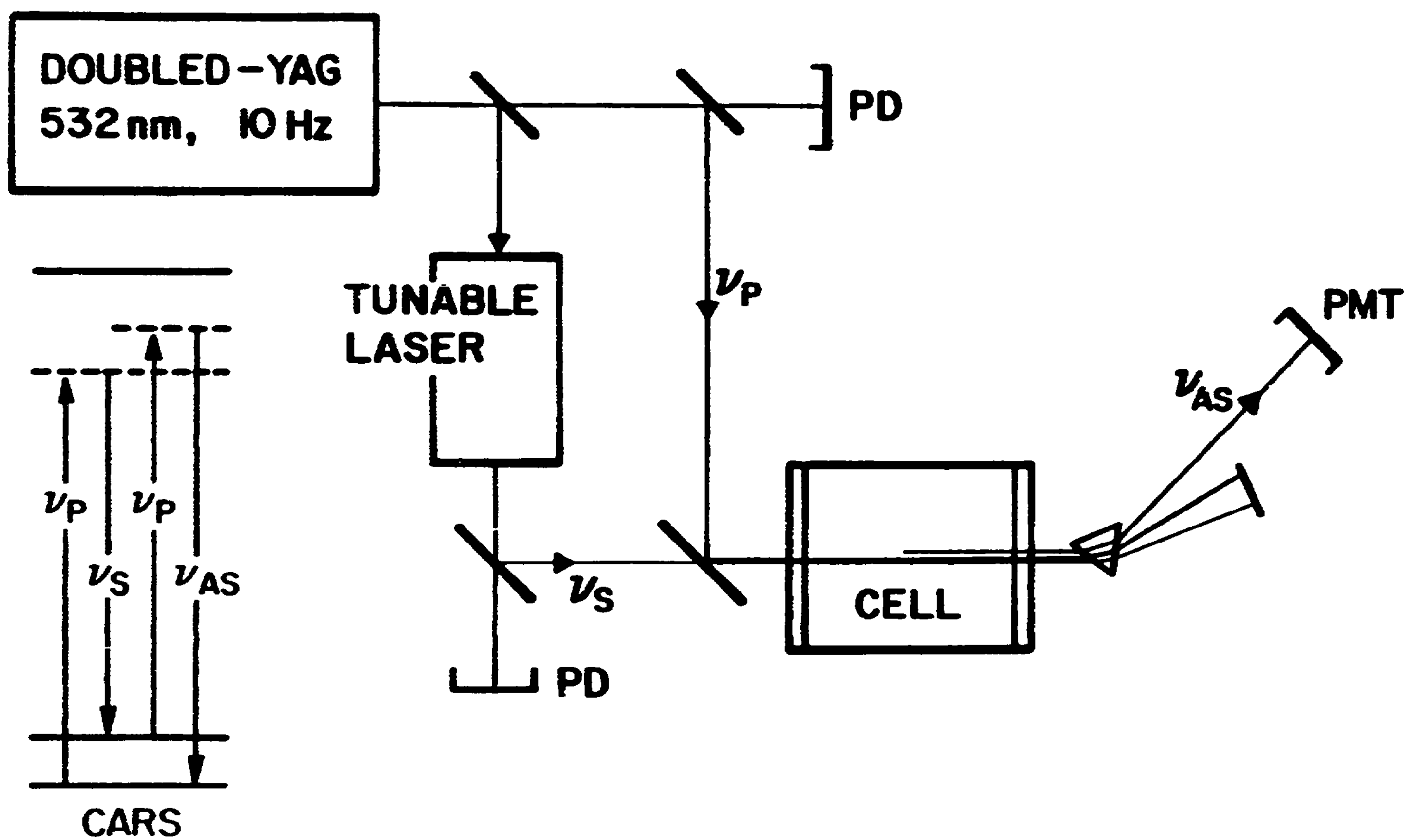


Reynolds Stress Velocity Diagnostic



CLS-88-4093

CARS MONITORING SYSTEM



AP-I-VG-4978A