

**EXPERIMENTAL INVESTIGATION OF HELIUM INJECTION
AT A LOW DOWNSTREAM ANGLE INTO SUPERSONIC FLOW**

by

Richard Bruce Mays

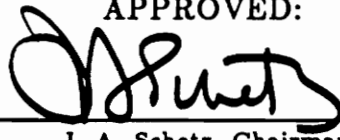
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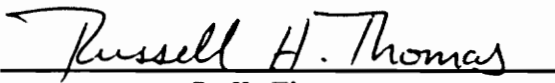
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EXPERIMENTAL INVESTIGATION OF SONIC HELIUM INJECTION AT A LOW DOWNSTREAM ANGLE INTO SUPERSONIC FLOW

by

Richard Bruce Mays

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Aerospace Engineering

(ABSTRACT)

Experiments were performed with single, sonic, helium jets at downstream angles of 15° and 30° relative to the free stream to determine their mixing, penetration and total pressure loss when injected into a supersonic air cross flow. From this information, the performance of these jets as fuel injectors in a supersonic combustion ramjet (scramjet) combustion chamber was estimated. Both injection angle jets were made flush to the wind tunnel wall. The jets were injected into a Mach 3 free stream with a total pressure of 6.5 atm, a total temperature of 283 K and a Reynolds Number of 52.5×10^6 /m. The flow field of each injection angle was documented at jet expansion ratios of one and five. Spark schlieren and nanoshadowgraph methods were used to visualize each flowfield. At axial stations 20, 40, and 90 jet diameters downstream of each jet, continuous vertical profiles of flow quantities were made. Profiles were taken at seven lateral stations including the jet centerline at each axial station. Spacing between the lateral stations was one

jet diameter. This data yielded profiles of helium concentration, Mach number, static temperature, static pressure, density, flow speed, mass flux, total pressure, and total temperature. The different injection schemes were then compared on the basis of helium mass fraction decay, the distance required to reach the stoichiometric H_2 -air concentration and total pressure loss. For all cases except the 15° jet with an expansion ratio of one, large eddies were observed to penetrate into the free stream. These eddies were believed to significantly enhance large scale mixing. The jet cores of the underexpanded jets had bifurcated 20 jet diameters downstream of the injection point, but had re-united by the 40 diameter station. Wandering of the jet core about the geometric centerline was observed for all cases. The decay rates increased rapidly with the jet to free stream dynamic pressure ratio until about 1.5 where the decay rate leveled off. This indicated that there was no significant increase in mixing from increasing the dynamic pressure ratio of the present jets past 1.5. The decay rate of the present 30° , matched pressure case was about 16 percent greater than that of a normal jet at similar dynamic pressure and expansion ratios. These results were reflected in the distances required to reach the stoichiometric H_2 -air concentration. The 15° jet with an expansion ratio of one had the lowest total pressure loss. It was concluded that injection at low downstream angle shows promise for application to scramjet fuel injection and merits further study.

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LIST OF SYMBOLS

α_{He}	helium mass fraction concentration
α_{max}	maximum helium mass fraction concentration at an axial station
a	calibration constant of concentration probe
a_1	local speed of sound
β	least squares fit constant for helium mass fraction decay
β_1	least squares fit constant for penetration
b	calibration constant of concentration probe
d	diameter of jet throat
D	nozzle discharge coefficient
γ	specific heat ratio
h	penetration height
H	height used in total pressure parameter calculation
H^+	height used in total pressure parameter calculation
l	active hot film sensor length
m	calibration constant of concentration probe
$\dot{m}$	measured mass flow of each jet
$m_{initial}$	initial mass of helium
m_{final}	final mass of helium
M	Mach number

MW_{He} – molecular weight of helium

MW_{mix} – molecular weight of helium-air mixture

n – decay rate of helium mass fraction with downstream distance

n_1 – penetration rate of jet with downstream distance

P – static pressure

P_t – total pressure

q – dynamic pressure

ρ – static density

R – gas constant of helium-air mixture

Re – free stream Reynolds number

θ – injection angle

t – time

T – static temperature

T_t – total temperature

u – flow speed

V – hot film voltage

X_{He} – helium mole fraction concentration

x – axial distance downstream of the injection point

y – lateral distance from the jet centerline

z – vertical distance from wind tunnel floor

subscripts :

1 – local property

2 – post shock local property

j – jet property

∞ – free stream property

uf – undisturbed free stream boundary layer property

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1. INTRODUCTION

Hypersonic, airbreathing flight vehicles are currently being researched for both atmospheric cruise and orbital boost applications. The most likely propulsion device for these vehicles is the supersonic combustion ramjet (scramjet) burning gaseous hydrogen fuel.^[1] In ramjet engines operating at supersonic flight speeds, the incoming air is slowed to below Mach one, so that fuel mixing and combustion can occur efficiently.^[2] If the air is slowed by more than a few percent at hypersonic speeds, prohibitively high static temperatures and pressures in the combustion chamber will result. Therefore, fuel mixing and combustion in the scramjet engine must take place at Mach numbers greater than unity. Because the combustor velocity of a scramjet engine is about equal to the flight speed of the vehicle, the residence time of the fuel in the combustor is approximately the combustor length divided by the vehicle flight speed.^[3] For a three meter long combustor, fuel must mix and burn within about 10^{-3} to 10^{-4} seconds. Otherwise, unburned fuel will be ejected from the engine, significantly reducing the engine's efficiency. Unfortunately, shear layer mixing at supersonic Mach numbers is inherently poor.^[4] Therefore, a fuel injection scheme which would augment mixing at these speeds is necessary for a scramjet engine to be practical.

Work on supersonic gas mixing is relatively sparse. An overview and analysis of high speed mixing experiments can be found in Reference 5. Injection of a gas perpendicular to a supersonic flow through a discrete, circular cross-section jet is

one of the most studied cases. This case is illustrated in Figure 1. An analysis of this class of flows was performed by Schetz and Billig,^[6] where a method for predicting the trajectory of a normal jet in a supersonic flow was presented. The method extended subsonic solid body models to supersonic flows. The results compared favorably with experiment. The concept of the effective back pressure was also introduced in this work. This pressure was defined as the average pressure between the jet interaction shock and the jet itself. It can be thought of as the pressure to which the jet will expand after leaving its orifice. An expansion ratio was then defined as the ratio of the static pressure at the jet exit plane to the effective back pressure. Expansion ratios greater than unity indicate an underexpanded condition, and those less than unity indicate an overexpanded condition. This work was extended by Billig, Orth, and Lasky^[7] to include the coordinates of the Mach disk, the angular orientation of the Mach disk and the diameter of the jet after expansion to freestream static pressure. The effective back pressure was found to correlate the penetration of the Mach disk. Unfortunately, neither of these analyses could be used to predict downstream mixing.

An experimental investigation of high-speed, normal jet flow fields was performed by Rogers.^[8,9] In these experiments, both single and multiple jet flow fields were examined. Rogers found that the normal jet mixed and penetrated well, but suffered large total pressure loss. The total pressure downstream of the jet was about 10 percent that of the freestream. Another major disadvantage of this scheme is that the momentum from the fuel injection provides no thrust to the vehicle. Rogers also found that closely spacing the jets significantly reduced the rate of mixing. He

stated that this reduction was caused by "the lateral restriction imposed by adjacent jets on air entering the mixing region from each side."^[8] He also found that increasing the jet spacing from $6.25d$ to $12.5d$ made the mixing rate approach that of a single jet.

Another scheme which has been studied injects the fuel parallel to the freestream through a downstream facing slot. This flow field was recently studied by Kwok^[10] and Smith^[11]. This scheme has the advantage of low total pressure loss, but the mixing and penetration of this method are poor. The momentum from fuel injection contributes to the thrust of the vehicle in this case. This can comprise a significant amount of the thrust in a hypersonic vehicle at high Mach numbers.^[3]

In an attempt to gain the advantages of each injection scheme, King, Thomas, Schetz, and Billig^[12] examined the flow field produced by a combination of parallel slot and normal injection. The normal jets were positioned to inject into the injectant-free stream shear layer just behind the slot. At certain normal jet and slot total pressures, large amounts of freestream air were entrained into the jets. The increase in entrainment coincided with the appearance of large eddies in the shear layer. It was concluded that simultaneous normal and parallel injection resulted in better mixing than that of the slot alone.

Another compromise between normal and parallel injection is to angle the jet downstream. McClinton^[13] studied arrays of closely spaced sonic jets at downstream angles of 90° , 60° , 45° , and 30° . He found that total pressure loss decreased as the injection angle decreased. Also, the penetration and mixing were greater at the lower downstream angles. Since McClinton's tests were run at a constant dynamic pressure ratio, lowering the injection angle caused weaker jet bow shocks,

which in turn lowered the effective back pressure of the jets. This increased the expansion ratio suggesting that it might be an important parameter in downstream mixing.

Based on past work, the effect of injection angle and expansion ratio on low injection angle, single jets in a supersonic crossflow was selected here for investigation. In order to simulate hydrogen fuel injection safely in the laboratory, helium was used as the injectant.

2. DESCRIPTION OF THE EXPERIMENT

2.1 General Description

Tests were conducted in a supersonic wind tunnel at the following free stream conditions:

$$M_{\infty} = 3.0$$

$$P_{t\infty} = 6.5 \text{ atm}$$

$$T_{t\infty} = 283 \text{ K}$$

$$Re = 52.5 \times 10^6 / \text{m}$$

These conditions correspond to those of a hypersonic cruise flight vehicle operating at a Mach number of 9 and an altitude of 190 kft. The inlet diffusion ratio for this vehicle is three. Unfortunately, it was not possible to simulate the 5000 K total temperature that would be found in the combustor of the actual vehicle. These experiments are useful, however, to establish the trends and relative magnitudes of the mixing and penetration, and to assess the influence of various parameters for the flow fields of interest.

Tests were made on single, sonic, helium jets at downstream angles of 15° and 30° relative to the horizontal. Both injection angle jets were flush to the wind tunnel floor. The total temperature of all jets was equal to 285 K. Jet exit pressure was based on an estimation of the effective back pressure from Reference 14. This estimation took the effective back pressure equal to the pressure on the surface of a cone in the test free stream conditions where the cone half angle was equal to the

injection angle. Test cases were run with the static pressure at the exit plane of the jet equal to the estimated effective back pressure. These cases shall be referred to as the matched pressure cases. Other cases held the jet static pressure equal to five times the estimated effective back pressure. These cases shall be referred to as the underexpanded cases. At each injection angle, both cases were documented.

Both spark schlieren and nanoshadowgraph methods were used to photograph the flow fields. Photographs were made for approximately 100 jet throat diameters downstream of the jet for each test case.

At axial locations 20, 40 and 90 jet throat diameters downstream of the jet, continuous vertical profiles of flow field quantities were made. Profiles were taken at the jet centerline, and at three lateral stations off each side of the centerline. Spacing between lateral stations was one jet throat diameter. Helium concentration, Pitot pressure, cone static pressure, and total temperature were measured. Helium concentration, Mach number, local speed of sound, static temperature, static pressure, density, flow speed, mass flux, total pressure, and total temperature were calculated from this information.

2.2 Facilities and Equipment

2.2.1 *The Wind Tunnel*

The present experiments were performed in the Virginia Tech 23 cm x 23 cm Supersonic Wind Tunnel illustrated in Figure 2. The tunnel is a blowdown type which exhausts to the atmosphere. It can be run at Mach numbers ranging from 2.4 to 4.0 and total pressures of up to 8 atm. A supply of air to be used in the tunnel is compressed by an Ingersoll Rand Type 40 water-cooled, reciprocating compressor. The compressed air is piped through a dryer to remove moisture and a prefilter to remove oil. Particles of dust and dirt were removed by an afterfilter. The air is then placed in sixteen steel tanks with a combined volume of 79 m³ for storage. During a run, the air from these tanks is released to a settling chamber by a computer-controlled pneumatic butterfly valve. A hydraulic valve that is controlled by a feedback servo control circuit sets and holds settling chamber pressure. Proper valve position is determined by a control signal from a computer and a settling chamber total pressure signal from a pressure transducer. This system allows a variation of tunnel total pressure of less than four percent during a typical run. A transition cone and set of five screens in the settling chamber reduce flow angularity and turbulence. Next, air enters a two-dimensional, converging-diverging Mach 3 nozzle. For the present experiments, the bottom half of this nozzle is replaced by a flat plate insert (see Figure 3). The nozzle has a throat area of 61.5 cm² and is designed to compensate for boundary layer displacement thickness growth. The flow then enters the test section which contained the model and instrumentation. The test section is a 11.4 cm x 23.0 cm rectangular cross-section, constant area

duct. The sides of the test section are covered by large doors which provide access to the section and contained glass windows to allow schlieren and shadowgraph photography of the flow field. Flow then enters a step diffuser and exhausts into the atmosphere through an shrouded exit duct.

2.2.2 The Model

The model was designed to inject helium into a flat plate flow at downstream angles of 15° and 30° relative to the horizontal. A gas supply system (described in Section 2.2.3) injected compressed helium into a cubic plenum chamber with an internal volume of 4929 cm^3 . The gas was injected into the flow through a sonic nozzle with a conical, converging inlet. This nozzle is illustrated in Figure 4. The half angles of the converging sections of the 15° and 30° injection angle jets were 14° and 24° , respectively. The throat diameter was 0.318 cm and was of constant cross-sectional area for one throat diameter. Nozzles were drilled flush with the tunnel floor into interchangeable nozzle blocks. The nozzle block covered the top of the plenum chamber.

A test plate was bolted to the downstream side of the plenum chamber. This plate was flush with the top surface of the plenum chamber and extended approximately 100 throat diameters downstream of the jet (see Figure 5). Slots in the plate allowed a probe to move both laterally and vertically. The slots were located 45, 65, and 115 throat diameters downstream of the jet. Probe sensors extended 25 throat diameters upstream of the slots, thus allowing measurements at axial stations 20, 40 and 90 throat diameters downstream of the jet. The slots allowed probe placement up to 12 throat diameters off the jet centerline. When in use, the slots were covered

with a flat plate which allowed vertical movement of a probe. When not in use, the slots were plugged flush with brass inserts and sealed with vacuum grease.

2.2.3 The Helium Supply System

Compressed helium was supplied by a bank of twelve, standard, commercial helium bottles. All of these bottles fed into a common manifold. Manifold pressure was reduced from a range of 34 to 170 atm to 20 atm by a Grove RBX 204-015 dome pressure regulator. This regulator required a reference pressure which was provided by a regulated air bottle. The output pressure was monitored with an oil filled pressure gage. A manually operated needle valve provided further pressure reduction and fine tuning. Helium entered the plenum chamber through two 1.3 cm diameter, straight, copper tubes which stood perpendicular to the bottom of the plenum chamber. This system allowed less than four percent variation in the jet total pressure.

2.2.4 The Traversing System

Probes containing transducers were automatically raised and lowered with a computer controlled traverse system. The probe attached to a rack which could only move vertically. The rack was geared to a Computer Devices 4D-9200A stepper motor. This combination moved the probe 0.013 cm per step. The entire traverse system was fastened beneath the model test plate. The motor was run by an American Precision Industries DMA-64 controller. The controller was instructed by a UAI 3071 Stepper command processor board which communicated with an IBM PC computer through a standard RS-232C serial port. With the proper software, the user could specify stepper motor speed, traversing distance and direction.

2.3 Instrumentation

2.3.1 The Data Acquisition System

Conditioned voltages from the transducers used to measure flow field quantities were read by a MetraByte DAS-16F, High Speed, Analog to Digital (A/D) conversion board. This board was installed in an IBM PC computer with two 5.25 inch floppy disk drives. The DAS-16 had 16 channels, each of which converted a 0 to 10 volt analog signal to a 12 bit binary number. Thus, the board had a resolution of 0.0024 volts. Voltage signals were read through a simple patchboard and converted to integers which were read and stored on floppy diskette by a FORTRAN driver program.

The DAS-16 also had two digital to analog (D/A) conversion channels, one of which was used to supply a control voltage to the wind tunnel total pressure controller board mentioned earlier. Digital outputs on the DAS-16 were used to activate a relay that opened the pneumatic butterfly valve on the wind tunnel, thus initiating a run.

2.3.2 Stagnation Properties

Tunnel stagnation pressure was measured through a Pitot tube in the wind tunnel settling chamber and converted to a voltage signal by a Setra Systems 0 to 100 psia, 50 mV/psia pressure transducer. A circuit in the transducer housing filtered the signal voltage. This voltage was read by the DAS-16 A/D system, and used by the wind tunnel servo-controller circuit.

An Omega Type K thermocouple with a 0.13 mm bead measured tunnel total temperature. The thermocouple was connected to an Omega Omni II 13 thermocouple amplifier and electronic icepoint. The voltage from the icepoint was amplified by an Ectron Differential D.C. Amplifier Model 562 and was low pass filtered by a four pole Bessel filter with a cutoff frequency of 340 Hz.

Total pressure of the helium jet was measured with a Pitot tube in the injection model plenum chamber. A Statham 0 to 100 psia PA822-100 pressure transducer converted the pressure information into a voltage signal. The voltage was amplified by the Ectron amplifier and filtered by the Bessel filter. An excitation voltage was supplied to the transducer from an Ectron Model 516-5SG Excitation Power Supply. Jet total pressure was also visually monitored using a Heise C-53332 Analog Pressure Gage.

All conditioned voltage signals were fed into the DAS-16 A/D system.

2.3.3 Discharge Coefficient

In order to measure the discharge coefficient of each nozzle, the plenum chamber was fitted with the appropriate nozzle block and connected to a single, commercial, regulated helium bottle. Jet total pressure was measured with a Heise 0-100 psia CMM-11112C analog pressure gage, and the helium bottle pressure was measured with a Heise 0-4000 psia CMM-4386 analog pressure gage. Jet total temperature was measured with an Omega Type K thermocouple which was fastened inside the plenum chamber. The thermocouple was read with an Omega HH-80K thermocouple thermometer. For an explanation and description of the discharge coefficient measurement see Section 2.4.1.

2.3.4 Schlieren and Shadowgraph Systems

The spark schlieren and nanoshadowgraph systems used for these experiments are illustrated in Figures 6 and 7.

A General Radio Company Strobotac Type 1531 strobe lamp was the light source for the spark schlieren photographs. This lamp provided a 10^{-6} second light pulse. A lens focused the light onto a thin slit. A parabolic mirror with a focal length of 1.8 m reflected the light through the wind tunnel test section to strike a second parabolic mirror. A knife edge intercepted part of the light reflected from the second mirror. A flat mirror directed the remaining light into a modified Burke and James View Camera fitted with a Polaroid Model 545 film holder. Polaroid Type 57 High Speed Instant Film recorded the image.

A Xenon Novatron 739-B Nanopulse Lamp powered by a Xenon Model 437A Nanopulser was the light source for the nanoshadowgraph pictures. The lamp provided a 30×10^{-9} second light pulse. This lamp made it possible to examine phenomena that occurred too rapidly for the spark schlieren to clearly record. The light pulse was reflected through the wind tunnel test section by the parabolic mirror described above. The resulting image was recorded by the same camera and film used for the spark schlieren photographs. Through trial and error, it was found that the nanoshadowgraph picture was well focused when the plane of the film was 33 cm from the test section window.

2.3.5 The Concentration Probe

An aspirating, hot film, concentration probe was used to measure continuous, vertical, helium concentration profiles at each axial and lateral station. This probe is illustrated in Figures 8 and 9. A continuous stream of the gas to be analyzed entered the probe tip through a 0.028 mm diameter hole. The probe tip expanded to a circular cross-section duct of diameter 1.2 mm. A Thermo Systems, Inc. 101212 Hot Film Sensor was placed inside the duct. The hot film was diameter 0.051 mm and had an active sensor length of 1.0 mm. The sensor was made of platinum on a cylindrical quartz substrate. The probe was designed to pull its bow shock into the hot film chamber, so that the zone of silence extended to the inside of the probe. This insured that the hot film was exposed to the same gas composition that would be found at the measurement point if the flow was undisturbed by the probe. Just behind the hot film sensor was a 0.56 mm diameter choked orifice which fixed the Mach number at the hot film. A vacuum was applied downstream of the orifice to aid in choking the orifice and pulling in the probe bow shock. A pressure vessel of volume 10^5 cm^3 evacuated by a Duo Seal Model 1405 pump provided the vacuum. For a more detailed description of the probe and its theory of operation, see Reference 15.

Pressure measurements were made both upstream and downstream of the choked orifice. The upstream pressure, P_1 , was used along with hot film voltage to calculate helium concentration. The ratio of downstream to upstream pressure, P_2/P_1 , was used to check that the orifice was choked. A Statham PA285TC-50-350, 0 to 50 psia pressure transducer measured the pressure, P_1 . An MB Electronics

151-EBAP-236 0 to 10 psia pressure transducer measured the pressure, P_2 . Both transducer voltages were amplified by Ectron amplifiers and filtered by Bessel filters before being read by the DAS-16 A/D system.

A Dantec DISA Model 55M10 Standard CTA Bridge connected to a Dantec DISA Model 55M01 Main Unit drove the hot film sensor. A Thermo Systems Inc. IFA 100 signal conditioner low pass filtered and offset the signal from the constant temperature bridge. The filter cutoff frequency was 300 Hz. The DAS-16 A/D system read the output voltage of the IFA 100.

2.3.6 Other Mean Flow Instrumentation

Continuous vertical profiles of total pressure were made using the Pitot probe illustrated in Figure 10. This probe was made from a section of 1.6 mm diameter stainless steel tubing. A 0.64 cm stainless steel sleeve was soldered to the outside of the probe to prevent excessive probe deflections during tests. The inlet diameter of this probe was 0.081 cm, indicating a capture area of 0.0052 cm^2 . The time response of the probe was calculated as approximately 0.015 seconds.^[16] A fin was soldered to the back of the probe to reduce flow angularity error. Total pressure was read by a Statham PA 285TC-50-350 0 to 50 psia pressure transducer. Voltage from this transducer was amplified by the Ectron amplifier and filtered by the Bessel filters before being read by the DAS-16 A/D system.

The total temperature probe was based on the design of Reference 17 and is illustrated in Figure 11. A section of 0.32 cm diameter stainless steel tubing was used as the probe housing. A conical, ceramic cap was epoxied to the flow end of the housing to reduce heat loss by radiation. At the tip of the cap, there was a 1.0

mm orifice which allowed the flow to enter and stagnate inside the cap. The inlet orifice expanded to a 0.53 cm diameter chamber which contained an Omega Type K thermocouple with a bead diameter of 0.38 mm. The thermocouple was epoxied so that it extended approximately 4.0 mm from the stainless steel housing. The thermocouple was connected to an Omega Omni II 13 thermocouple Amplifier and electronic icepoint. The voltage output of the icepoint was amplified by the Ectron amplifier and filtered by the Bessel filter. Two vent holes of diameter 1.1 mm were placed just behind the thermocouple bead. The probe had a recovery factor of 98 percent.

The cone static probe, illustrated in Figure 12, consisted of a 10° half angle brass cone soldered to a 1.6 mm diameter stainless steel probe. The cone had four 0.33 mm diameter pressure taps located 2.7 cm from its vertex. The pressure taps were spaced 90° apart around the cone circumference. These taps emptied into a common chamber to reduce error due to flow angularity. The probe was soldered into a 0.64 cm stainless steel sleeve to prevent excessive deflection during tests. The probe had a capture area of 0.012 cm² and a time response of 0.08 seconds.^[16] Cone static pressure was read by an MB Electronics 151-EPAB-236 0 to 10 psia pressure transducer. The resulting voltage was amplified by the Ectron amplifier and filtered by the Bessel filter before being read by the DAS-16 A/D system.

2.3.7 Position Measurement Instrumentation

Lateral probe position was fixed by a scale scratched on the surface of the test plate in front of each slot. The scale had nine lines; one at the jet centerline, and four to each side of the jet centerline. Spacing between the lines was one throat

diameter. The slot cover plate (see Section 2.2.2) had a similar mark aligned with the probe centerline. To place the probe at a lateral station, the cover plate mark was matched to the appropriate mark on the test plate.

A Trans-Tek Model 0246-0000 G-6 Linear Voltage Displacement Transducer (LVDT) measured vertical displacement of the probes. The housing of the transducer was attached to a part of the traverse that did not move relative to the tunnel. The core was fixed to the traverse rack and therefore moved with the probe. The LVDT could measure probe displacements up to 15 cm at an accuracy of 0.5 percent.^[18] A power supply provided a 12 VDC excitation voltage to the LVDT. Voltage from the LVDT was amplified and low pass filtered by the IFA 100. The filter cutoff frequency was 50 Hz. The resulting signal was read by the DAS-16 A/D system.

2.4 Experimental Methods

2.4.1 Instrument Calibration

Electronic pressure transducers were used to measure the wind tunnel settling chamber total pressure, the jet total pressure, Pitot pressure profiles, cone static pressure profiles, and concentration probe pressures, P_1 and P_2 . Calibrations were performed by exposing the transducer to several known pressures and recording each output voltage. A least squares fit program calculated coefficients for a linear equation that related transducer voltage to pressure. Pressures were provided by a combination of a commercial air bottle and an Ametek Mk100 pneumatic pressure tester. The tester provided a range of pressures from 1 to 7 atm in 0.7 atm increments. These pressures were accurate to 0.017 atm. The transducer was exposed to the tester output pressure. For calibrations requiring pressures below 1 atm, both the transducer and a sensor from a Pressure Systems, Inc. (PSI) Model 780B Pressure Measurement System were connected to a pressure vessel. The PSI system relayed pressures to the IBM PC computer through an IEEE-488 port. The pressure vessel was connected through an on/off valve to a vacuum pump. After each pressure and voltage reading, the on/off valve was slightly opened to bleed some air out of the vessel, thus lowering the pressure. Voltages were amplified and filtered by the same methods used when taking actual data, before being read by the DAS-16 A/D system.

Thermocouple temperature transducers measured total temperature profiles and settling chamber total temperature. Calibrations were performed by exposing the thermocouple to several known temperatures and recording each resulting

output voltage. A least squares fit program calculated the coefficients for a linear equation that related voltage to temperature. The thermocouple to be calibrated was immersed in distilled water which was initially cooled with an icepack. A Omega HH-80 K thermocouple thermometer was placed as close as possible to the calibration thermocouple bead, and after a short settling period, temperature was read from the thermocouple thermometer and voltage was read by the DAS-16 A/D system. The temperature of the distilled water was increased with a hot plate, and the procedure was repeated. The thermocouple was connected to the same circuitry used to collect the actual data.

Concentration probe hot film voltage is related to Reynolds number by the following equation:

$$V^2 = \frac{(R_s + R_w)^2}{R_w} \pi l k (a Re^m + b) (T_w - T_t) \quad [2.1]$$

R_s , R_w , l , and T_w were known, k was a function of gas composition and T_t was measured with a separate probe.^[16] Constants a , b , and m were determined by the following calibration procedure. The probe tip was inserted into a 11500 cm³ pressure vessel which was filled with a gas of known helium concentration at 2 atm. Helium concentration was determined by the partial pressure of each gas in the vessel. Openings in the vessel permitted measurement of vessel pressure and temperature. A bank of mercury manometers measured all pressures, and a thermocouple thermometer measured vessel temperature. The entire calibration setup is illustrated in Figure 13. Vacuum was applied, so that the gas in the pressure vessel was drawn through the probe. Measurements were made of pressures P_1 and

P_2 , hot film voltage, and total temperature at several different vessel pressures. Since total temperature variation of the flow field was small (see Section 3.3.3), its effect on hot film voltage was neglected. This procedure was repeated for five different helium concentrations. A computer program fit a logarithmic curve to the data for each helium concentration. Figure 14 shows a set of curves and data from a typical calibration.

Calibration of the LVDT took place immediately before probe data was taken. The probe and traverse were completely installed and all electrical connections were made. A PTI Cat. No. 2210 Cathetometer measured probe displacement accurately to 0.001 cm. A 1.3 cm square cross-section block was placed in front of the probe tip. The cathetometer was leveled by adjusting cathetometer attitude until the both ends of the block read the same. A measurement of the top of the block was used to calculate the cathetometer reading of the wind tunnel floor. Cathetometer readings of the probe tip were then made for four vertical probe positions. Corresponding voltages were measured by the DAS-16 A/D system. Cathetometer readings were subtracted from the floor reading to give probe displacement. A least squares fit program calculated coefficients for a linear equation that described voltage variation with displacement.

The discharge coefficient for a nozzle is the ratio of the actual mass flow through the nozzle to the inviscid mass flow through the nozzle. This coefficient accounts for the reduction in cross-sectional area caused by the boundary layer displacement thickness. The definition of the discharge coefficient for a nozzle is as follows:

$$D = \frac{\dot{m}_{actual}}{\dot{m}_{theoretical}} \quad [2.2]$$

The quantity in the denominator was calculated with isentropic, calorically perfect equations, so that only the actual mass flow of each nozzle needed to be measured. A single regulated helium bottle was connected to the plenum chamber which was fitted with the appropriate nozzle block. The helium bottle pressure and temperature were measured and the density of the gas in the bottle was calculated using the perfect gas law. The density was multiplied by the volume of the helium bottle which gave the initial mass of helium in the bottle. The nozzle was then run at a specific jet total pressure for approximately two minutes. A more accurate time was measured with a stopwatch. At the end of the run the helium bottle was given about twenty minutes to equilibrate to room temperature, and then the mass of helium in the bottle was determined in the same manner as before the run. The actual mass flow was then approximated by:

$$\dot{m}_{actual} = \frac{m_{initial} - m_{final}}{\Delta t} \quad [2.3]$$

For the 15° injection angle nozzle, the discharge coefficient was 0.90, and for the 30° injection angle nozzle, the discharge coefficient was 0.91.

2.4.2 Data Acquisition Procedures

Spark schlieren and nanoshadowgraph photographs were taken by the following procedure. A nozzle block containing the desired incidence angle jet was installed. The spark schlieren or nanoshadowgraph systems were set up as described in Section 2.3.3 and optically aligned. The compressor was started, so that storage tank pressure was great enough to run the tunnel on completion of the set up procedure.

Once the optics were correct, the hydraulic pump for the $P_{t\infty}$ control valve was activated. Jet total pressure was set with the tunnel off using the needle valve and the Heise pressure gage. A simple BASIC DAS-16 driver program was loaded onto the IBM PC computer. This program could only open the pneumatic butterfly valve to run the wind tunnel, wait a specified amount of time, and close the valve. The camera film holder was loaded, and the camera operator signaled the tunnel operator to run the tunnel. The tunnel operator then turned on the servo control circuit and executed the computer program. He then opened the valve that released compressed helium into the model plenum chamber. Approximately six seconds after the pneumatic butterfly valve opened, the camera operator took the photograph. Finally, the computer closed the butterfly valve and the tunnel operator turned off the servo controller circuit. A typical photographic run lasted a total of ten seconds. After a duplicate picture was made, the jet total pressure was changed, and the process was repeated. Each picture covered about 40 throat diameters of the flow. To photographically record a flow field, eight runs were made with each method. A total of sixty four photographic runs were required.

Probe runs were executed in a similar manner. For these runs, the FORTRAN driver program listed as Program 1 in Appendix B was used. This program not only operated the wind tunnel and traverse, but also read data from the DAS-16 A/D system, and stored it on floppy diskette. The timing of all events was computer controlled. The probe was raised at a speed of 3.8 mm/s to a height of approximately eight throat diameters. This speed was found by repeating probe traverses at sequentially lower speeds until the profile was repeated. This eliminated error due to the slow time response of the pressure instrumentation. The computer

issued the commands to raise the probe and initiate data taking five seconds after the run began. The delay insured that any $P_{t\infty}$ oscillations were damped out while the probe was taking data. A typical probe run lasted approximately thirteen seconds. Spark schlieren photographs of the $\theta = 30^\circ$, underexpanded, $x/d = 90$ case indicated jet penetration of approximately nine throat diameters. Therefore, for this case, the probe was raised at the same speed to a height of approximately ten throat diameters. This increased the total run time to fifteen seconds. All probe data was taken at a sampling rate of 150 Hz.

2.4.3 Data Reduction

To find helium concentration, raw data representing probe displacement, pressure P_1 , hot film voltage, and total temperature were converted to engineering units and stored in a single computer file. Since T_{t2} was taken in a separate run, a computer program calculated a value of T_{t2} for each concentration probe displacement by linear interpolation. For concentration displacements not covered by the T_{t2} profile, the program assumed a T_{t2} value at the profile extreme. The FORTRAN program listed as Program 2 in Appendix B calculated helium concentrations from this data. For each probe displacement, the program would start with the calibration curve of lowest helium concentration (see Figure 14), and sequentially search for the two curves that bounded the hot film voltage at the appropriate P_1 . The helium concentrations of the bounding curves were used to interpolate a concentration for the hot film voltage, P_1 data pair.

Helium concentration, cone-static pressure, Pitot pressure, and total temperature profiles were used to calculate profiles of Mach number, mass flux, static

temperature, static pressure, density, and total pressure. The calculations were performed by the FORTRAN program listed as Program 3 in Appendix B under the assumptions of calorically perfect, adiabatic flow. First, cone-static pressure, Pitot pressure, and total temperature profiles were aligned with concentration probe displacements as described earlier. Values of γ and R were computed according to the helium concentration at each point. Mach number was found with the cone-flow and Rayleigh-Pitot equations. The cone-flow equation relates Mach number to the pressure on the surface of a cone as follows:

$$\frac{P_c}{P_1} = 1 + \frac{\gamma M_1}{2} \frac{(P_c - P_1)}{q_1} \quad [2.4]$$

To eliminate static pressure dependence, this equation was combined with the Rayleigh-Pitot equation:

$$\frac{P_1}{P_{t2}} = \frac{\left(\frac{2}{\gamma+1}M_1^2 - \frac{\gamma-1}{\gamma+1}\right)^{\frac{1}{\gamma-1}}}{\left(\frac{\gamma+1}{2}M_1^2\right)^{\frac{\gamma}{\gamma-1}}} \quad [2.5]$$

Through algebraic manipulation, a relationship between Mach number, M_1 and the known quantities P_c , P_{t2} , and γ was derived. This relationship was used to generate a table of Mach numbers as a function of γ , and the ratio $\frac{P_c}{P_{t2}}$ for a 10° half angle cone. At sufficiently low Mach numbers, the shock wave on the cone-static probe detaches, thus making the above relationships invalid. For the data reduction program used, this condition was indicated when $\frac{P_c}{P_{t2}}$ was greater than a critical value, $\frac{P_c}{P_{t2}}_{crit}$. The program calculated $\frac{P_c}{P_{t2}}_{crit}$ for a given γ by interpolating in the Mach number table.

If the pressure ratio was less than the critical value, then the Mach number was determined by interpolation over γ and $\frac{P_e}{P_{t2}}$ in the Mach number table. Static pressure was then determined from the Rayleigh-Pitot Equation [2.3].

If the pressure ratio was greater than the critical value, then the program interpolated P_1 from points which surround the unknown point. The code then compares the $\frac{P_1}{P_{t2}}$ to the ratio necessary for sonic flow, $\frac{P_1}{P_{t2 \text{ crit}}}$. $\frac{P_1}{P_{t2 \text{ crit}}}$ was found from the normal shock relation:

$$\frac{P_1}{P_{t2 \text{ crit}}} = \left(\frac{\gamma + 1}{2} \right)^{\frac{-\gamma}{\gamma - 1}} \quad [2.6]$$

If $\frac{P_1}{P_{t2}}$ was less than $\frac{P_1}{P_{t2 \text{ crit}}}$, then the flow at that point was supersonic, and a Mach number was calculated using the Rayleigh-Pitot Formula.

If $\frac{P_1}{P_{t2}}$ was greater than $\frac{P_1}{P_{t2 \text{ crit}}}$, then the flow at that point was subsonic, and a Mach number was calculated from:

$$M_1 = \left[\frac{2}{\gamma - 1} \left(\frac{P_1}{P_{t2}} \right)^{\frac{1-\gamma}{\gamma}} - 1 \right]^{\frac{1}{2}} \quad [2.7]$$

which is simply the isentropic equation for Mach number with P_{t1} equal to P_{t2} .

At this point, complete profiles of both Mach number and static pressure have been computed. Using the fact that $T_{t1} = T_{t2}$ across a normal shock, the program calculated static temperature from the isentropic relation:

$$T_1 = \frac{T_{t2}}{1 + \frac{\gamma - 1}{2} M_1^2} \quad [2.8]$$

The local speed of sound was determined from its definition:

$$a_1 = \sqrt{\gamma RT_1} \quad [2.9]$$

With this information, velocity was calculated from the definition of the Mach number:

$$u_1 = M_1 a_1 \quad [2.10]$$

Density was calculated using the perfect gas law:

$$\rho_1 = \frac{P_1}{RT_1} \quad [2.11]$$

Mass flux was calculated by simply multiplying the density by the velocity. Total pressure was calculated from Pitot pressure by the following normal shock equation:

$$P_{t1} = P_{t2} \left[\frac{(\gamma - 1)M_1^2 + 2}{(\gamma + 1)M_1^2} \right]^{\frac{\gamma}{\gamma - 1}} \left[\frac{2\gamma M_1^2 - (\gamma - 1)}{\gamma + 1} \right]^{\frac{1}{\gamma - 1}} \quad [2.12]$$

The program paired each quantity with its corresponding probe displacement and wrote the data to computer disk files.

Every fifteen points of both flow quantity and probe displacement data were averaged into a single data pair. This method sufficiently smoothed the data without distorting it.

2.4.4 Nondimensionalization Scheme

Helium concentration was converted from mole fraction to mass fraction by the following definition:

$$\alpha_{He} = X_{He} \frac{MW_{He}}{MW_{mix}} \quad [2.13]$$

where α_{He} is the concentration in mass fraction.

Distances x , y , and z were nondimensionalized by the jet throat diameter. All other quantities were nondimensionalized by their free stream values. Free stream Mach number was determined from the Mach number profiles averaging all Mach numbers above a user specified penetration height. This information was used with settling chamber total pressure and temperature to calculate the free stream quantities. Settling chamber total pressure and temperature were read along with probe data for all runs, so that there was a value of $P_{t\infty}$ and $T_{t\infty}$ for every point in every profile. Thus, the slight time variation in these quantities was taken into account. Each point in the total temperature profile was nondimensionalized by the settling chamber total temperature, $T_{t\infty}$, measured during the total temperature probe runs. Free stream static temperature was calculated from the isentropic relation:

$$T_{\infty} = \frac{T_{t\infty}}{1 + \frac{\gamma-1}{2} M_{\infty}^2} \quad [2.14]$$

where $T_{t\infty}$ was measured during the total temperature probe runs.

The free stream speed of sound follows from its definition:

$$a_{\infty} = \sqrt{\gamma R T_{\infty}} \quad [2.15]$$

and free stream velocity was calculated from the definition of the Mach number:

$$u_{\infty} = M_{\infty} a_{\infty} \quad [2.16]$$

Free stream static pressure was found from the isentropic equation:

$$P_{\infty} = \frac{P_{t\infty}}{\left(1 + \frac{\gamma-1}{2} M_{\infty}^2\right)^{\frac{\gamma}{\gamma-1}}} \quad [2.17]$$

where $P_{t\infty}$ was measured during the Pitot pressure probe runs. Free stream density was calculated with the perfect gas law:

$$\rho_{\infty} = \frac{P_{\infty}}{R T_{\infty}} \quad [2.18]$$

Finally, free stream mass flux was found by simply multiplying the free stream static density by the free stream velocity.

3. RESULTS

Composite spark schlieren and nanoshadowgraph pictures of the flow field were assembled. Contour plots of concentration were made for all cases at each axial station. Plots of maximum concentration and maximum penetration at each axial station were also made. Vertical profiles of the other mean flow data were plotted for each axial station at the jet centerline.

3.1 Spark Schlieren and Nanoshadowgraph Photographs

Figures 15 through 23 are spark schlieren photographs of each test case. The Mach 3 free stream runs from the left of the photographs to the right. The jet entry point and axial stations are indicated by arrows and labeled.

Figure 15 shows a Mach 3 undisturbed flat plate flow in the wind tunnel. The light band on the tunnel floor is the boundary layer. The boundary layer thickness was $2.5d$ at the jet entry point and grew to $3.8d$ by $x/d = 90$. Eddies which are too small to accurately measure from the photograph are visible in the boundary layer. A disturbance originated from the floor at approximately $x/d = 10$, and extended into the free stream. Since the origin of this disturbance corresponded to the mating point of the test plate and model plenum chamber, it was probably caused by a small leak, or a step. Because the disturbance was very weak as determined by the wave angle compared to the Mach angle and did not significantly disrupt the boundary layer, its effect on the results was neglected.

Figure 16 shows the $\theta = 15^\circ$, underexpanded case. The barrel shock and separation region typical of underexpanded jets cannot be seen in this photograph. This was probably due to the large boundary layer thickness. Large density gradients in the boundary layer tended to wash out the jet disturbance. The jet shockwave angle was 36° in the boundary layer, decreasing to 22° in the free stream. There was some curvature in the part of the jet bow shock in the boundary layer, and the shock was observed to thicken in the free stream.

The jet left the boundary layer at approximately $x/d=20$, and penetrated into the free stream creating a region of high turbulence and large eddies. These eddies were roughly oval with horizontal lengths 1.55 times the vertical. The minor axis of the average eddy was $2.3d$. Past $x/d=60$, the turbulent region became less distinct and by $x/d=90$ was nearly indistinguishable from the free stream. This was due to a reduction in the density gradient magnitude and therefore indicated mixing between the free stream and the jet.

The effect of doubling the injection angle to 30° while maintaining the expansion ratio can be seen in Figure 17. The shock wave angle inside the boundary layer was about 46° , although, again, the shock wave was curved. The free stream shockwave angle was approximately 26° , increasing only 18 percent over the $\theta = 15^\circ$ case. The free stream shock appears much thicker in this case. Again, no barrel shock or separation region near the jet were visible.

In this case, the jet leaves the boundary layer almost immediately. As in the $\theta = 15^\circ$ case, the jet penetrates into the free stream and creates a region of high turbulence. The eddies in this region were also oval shaped, and measured $3.7d$ in the vertical direction, an increase of 38 percent over the $\theta = 15^\circ$ case. The eddies

were about 1.55 times larger in the horizontal direction and began to break up at about $x/d=80$, making the jet indistinguishable from the free stream.

Reducing the exit static pressure of the jet to match the effective back pressure, while maintaining an injection angle of 30° , produced the flow field pictured in Figure 18. The angle of the shock wave inside the boundary layer for this case was 31° . The free stream shock wave angle was 21° , a 24 percent decrease from the $\theta = 30^\circ$, underexpanded case. The shock was weakened because the matched pressure jet did not plume out as much as the underexpanded jet, therefore it presented a smaller disturbance to the free stream.

The jet was out of the boundary layer by $x/d=40$, but the exit point is unclear due to picture quality. The turbulent region was much smaller for this case, and there were not enough clearly defined eddies in the picture to attempt to find an average eddy size. At about $x/d=65$, the jet became indistinguishable from the free stream.

The spark schlieren shown in Figure 19 recorded the $\theta = 15^\circ$, matched pressure case. The jet seems to have barely disturbed the free stream in this case. The jet shockwave angle was 20° , only 0.5° greater than the angle of a Mach line at the free stream conditions. The shockwave angle for this case was 7 percent less than for the $\theta = 15^\circ$, underexpanded case, and it was essentially the same as the shock angle of the $\theta = 30^\circ$, matched pressure case. Turbulent region penetration into the free stream is questionable judging from this picture, and there are no clearly defined large scale eddies visible.

The nanoshadowgraphs recorded structures that moved too rapidly for the spark schlieren photographs to clearly record. Some sensitivity was sacrificed for

that speed because the nanoshadowgraph can sense only second order density gradients. Figure 20 is the nanoshadowgraph of the $\theta = 15^\circ$, underexpanded case. As in the spark schlierens, the free stream runs from left to right. The jet and axial stations are marked by arrows. The boundary layer is the layer bounded by the wind tunnel wall.

The faster exposure time revealed that the jet shock wave was curved in some places, and a thin secondary shock branched off parallel to it. As in the spark schlieren pictures, the jet left the boundary layer forming a highly turbulent region between the boundary layer and the free stream. While the spark schlieren photographs showed a somewhat smoother border between the jet and the free stream, the nanoshadowgraph shows this border to be very irregular, with large eddies penetrating the free stream at apparently periodic intervals. The difference between the two pictures was mainly caused by the much shorter exposure time of the nanoshadowgraph system, which "froze" the rapid movement of the eddies and turbulent structures in the jet. By introducing large scale turbulence into the mixing zone, the penetrating eddies would tend to enhance entrainment and mixing. A wavelength of $5.5d$ was measured for these eddies. By $x/d=20$, the turbulent region penetrated $4d$ into the free stream. At $x/d=40$, penetration was $5d$, and by $x/d=90$, it was $6.2d$. The turbulent region penetration increased 35 percent between $x/d = 20$ and $x/d = 90$.

The $\theta = 30^\circ$, underexpanded nanoshadowgraph shown in Figure 21, had many of the same features of the $\theta = 15^\circ$ case, however, there are some significant differences. The jet shock wave had much more curvature, and the separation between the jet shock and the secondary wave increased dramatically. Careful examination

reveals small waves emanating perpendicular to the jet bow shock. These may have been caused by a possible unsteadiness in the jet effective back pressure as a result of jet bow shock/boundary layer interaction and local separation. Large eddies penetrated the free stream of this case, also. The wavelength of these eddies was $7.1d$, an increase of 23 percent over the $\theta = 15^\circ$, underexpanded case. Turbulent region penetration at $x/d=20$ was $6.4d$, which increased to $7.8d$ by $x/d=40$ and reached $10d$ by $x/d=90$. The turbulent region grew 36 percent between $x/d = 20$ and $x/d = 90$, about the same rate as the $\theta = 15^\circ$, underexpanded case. The turbulent region for this case penetrated 41 percent more than its $\theta = 15^\circ$ counterpart at a typical axial station.

The nanoshadowgraph of the 30° , matched pressure case is shown in Figure 22. Once again, the jet shockwave was curved in some places. The secondary wave was also present, although separation between it and the jet shock was much less than for the underexpanded case. The small waves perpendicular to the 30° , underexpanded jet shock cannot be detected. The turbulent region barely penetrates the free stream in this case. By $x/d=20$, the turbulent region penetrated $2.8d$; by $x/d=40$, penetration was $3.8d$, and by the last station, $x/d=90$, turbulent region penetration was only $5d$. The turbulent region grew 44 percent between $x/d = 20$ and $x/d = 90$; a rate of change significantly greater than those of the underexpanded cases. Average penetration of the turbulent region for the 30° , matched pressure case was 52 percent less than that of the 30° , underexpanded case for the axial distance observed.

Figure 23 shows the nanoshadowgraph for the 15° , matched pressure case. As in the spark schlieren, the jet appears to have very little affect on the free stream.

Although the jet shock was weak, it branched into a main shock and a thinner secondary shock. Separation between the two waves was much smaller than all other cases, however. From about $x/d=70$ to the end of the picture, the boundary layer-free stream border appeared slightly rougher. This was probably caused by slight turbulent region penetration into the free stream, which was too weak to accurately measure.

3.2 Helium Concentration Data

3.2.1 General Flowfield Structure

Helium concentration data is presented for all cases with contour plots. The concentration profiles of each axial station were combined to make a grid of 55 x 7 points. For the 30°, underexpanded case, the grid was 76 x 7 points. These grids were processed by the Surfer contour plotting program of Reference 19. The plots extend laterally 3d off both sides of the jet centerline, and vertically 10d from the wind tunnel floor. These distances adequately bounded each jet.

The 15°, underexpanded case is shown in Figures 24 - 26. The core of the jet is defined as the region of high helium mass fraction near the jet center. At $x/d = 20$, there were two such regions - one located at the jet centerline and the other at $y/d = 2$. This split core could be an indication of strong vorticity in the jet-free stream mixing zone. The measurements at this station were repeated because of this unusual structure. The results matched the original data. The core centers, here defined as the points of maximum helium mass fraction, were both located at $z/d = 2.0$. Both cores had completely separated from the tunnel floor. Large concentration gradients were observed at this station. No attempt was made to find overall penetration from these graphs due to resolution problems near the jet edge.

At $x/d=40$, the core had reunited and was centered at $y/d=1$ as seen in Figure 25. This was about the average lateral position of the two cores found at $x/d = 20$. The core center penetrated to $z/d = 2.7$. The helium concentration gradient magnitudes were much smaller at $x/d = 90$ in Figure 26, indicating a large amount

of mixing between the jet and free stream. The jet core was centered at $y/d = 0.5$, and $z/d = 3.8$.

The 30° , underexpanded case is shown in Figures 27 - 29. The contour plot at $x/d = 20$ in Figure 27 shows the same kind of bifurcation observed for the 15° , underexpanded jet. The jet core does not completely split in this case, however. The vorticity in the jet-free stream mixing region was probably too small relative to the jet's inertia to cause it to split completely. The jet was roughly symmetric about the centerline. The core penetrated to $z/d = 4.1$, about twice that noted for the 15° , underexpanded case at this station. As at the first station of the 15° , underexpanded jet, large helium mass fraction gradients were evident.

Due to time considerations, only a single vertical profile in Figure 28 was made for the $x/d = 40$ station. A jet core penetration of $z/d = 4.1$ was estimated from this profile.

At $x/d = 90$, there were no signs of jet bifurcation in Figure 29. Helium mass fraction gradients were on the order of one tenth the gradients found at $x/d = 20$. This large reduction in mass fraction gradient is a sign of good, large scale mixing. Unfortunately, the core of the jet at this station was not distinct, so that no measurement of core position could be made from this contour plot. A value of $z/d = 4.8$ was estimated for this value from the original profiles.

The 15° , matched pressure case is shown in Figures 30 - 32. At the first station, $x/d = 20$, Figure 30 shows that the jet barely disturbed the free stream flow. There was no bifurcation of the jet core as in the underexpanded cases. The shock wave measured from the spark schlieren was straight relative to the underexpanded cases, thus indicating reduced the levels of vorticity in the jet. This could result in the

lack of jet core splitting for this case. The core rested on the tunnel floor and was centered at $y/d = 0$, $z/d = 0.3$.

At $x/d = 40$, the core center penetration had increased to $z/d = 0.93$ in Figure 31. The core still had not completely separated from the floor, but had drifted laterally to $y/d = 0.93$.

By $x/d = 90$, the jet core seemed about to separate from the tunnel floor in Figure 32. The core center penetrated to $z/d = 1.6$, and continued to drift laterally. Lateral displacement of the core center at this station was $1.1d$ in the positive direction.

Figures 33 - 35 are the contour plots of the 30° , matched pressure case. There was no indication of jet core bifurcation for this case. The plot of $x/d = 20$ in Figure 33 shows a core roughly symmetric about the jet centerline. The core was separated from the wind tunnel floor, and its center had penetrated to $z/d = 1.3$. The large helium mass fraction gradients typical of this close station were observed.

As for the 30° , underexpanded case, only a single profile shown in Figure 34 was taken at the $x/d = 40$ station. From this profile, a core center penetration of $2d$ was estimated.

As in all of the other cases, the helium mass fraction gradient magnitudes at the $x/d = 90$ in Figure 35 station were much lower than those at the $x/d = 20$ station, indicating large scale mixing. The jet was centered laterally at $y/d = 0.5$, and vertically at $z/d = 2.6$.

3.2.2 Penetration of the Jet Core Center

Core center penetration as a function of axial distance is shown in Figure 36 for all cases. Each penetration distance was nondimensionalized by the jet throat diameter, d . Overall penetration of the jets increased with increasing jet to free stream dynamic pressure ratio, q_r . Apparently, the $q_r = 3.0$ jet core initially penetrated farther than those of the lower q_r jets. This observation gains support from the larger turbulent region penetration noted for the $q_r = 3.0$ case in the spark schlieren photographs. Assuming the penetration rates remain constant downstream of the $x/d = 90$ station, the $q_r = 1.4$ jet core center penetration would exceed that of the $q_r = 3.0$ jet at about $x/d = 250$. The $q_r = 0.6$ jet core center penetration would be greater past $x/d = 1000$. Since both the initial penetration and penetration rate of the lowest q_r jet were less than those of the $q_r = 3.0$ jet, it will never penetrate more than the $q_r = 3.0$ jet.

The rates of change of core center penetration also seem to be largely dependent on q_r . The two jets with intermediate dynamic pressure ratios, $q_r = 1.4$ and $q_r = 0.6$, had similar rates of change of core center penetration. The two jets with the highest and lowest q_r have much lower core penetration growth rates. This suggests that there is a q_r corresponding to a maximum core penetration growth rate within the range of q_r 's tested in the present experiments. Further tests with a finer q_r resolution might reveal this ratio. The larger penetration growth rates of the two intermediate dynamic pressure ratio jets over the $q_r = 3.0$ jet might be explained by the fact that a significant portion of the core penetration of the lower q_r jets occurred while their cores were immersed in the boundary layer. Because the inertial

forces in the boundary layer are lower than in the free stream, the intermediate q_r jets retain more of their vertical momentum, thus allowing a greater rate of change of core penetration far downstream of the jet. Since the $q_r = 3.0$ jet core penetrated into the free stream almost immediately, it suffered a larger initial reduction in vertical momentum, thus retarding its downstream rate of core penetration growth.

3.2.3 Helium Concentration Decay

The variation of the maximum helium concentration with axial distance for all cases is displayed in Figures 37 - 40. Since the maximum helium concentration decayed exponentially, the data were fitted to equations of the form:

$$\alpha_{max} = \beta \left(\frac{x}{d} \right)^{-n} \quad [3.1]$$

where β and n were constants determined by a curve fit. The exponent of the equation, n , represents the decay rate of the jet. The higher the decay rate, the faster the jet mixed with the free stream. Since these experiments were intended to simulate hydrogen fuel injection into a combustion chamber, the hydrogen concentration necessary for complete combustion with air was marked on each decay plot for reference.

The effect of increasing the injection angle from 15° to 30° for the underexpanded jets is shown in Figure 37. The rate of helium concentration decay of the 15° jet was $n = 1.2$. For the 30° jet, the decay rate was essentially the same at $n = 1.3$. The overall helium concentration of the $\theta = 30^\circ$ jet was about 16 percent greater than that of the $\theta = 15^\circ$ jet at all axial stations. Assuming that the decay rate remained constant past the $x/d = 90$ station, the 15° underexpanded

jet would reach the stoichiometric H_2 - air concentration at $x/d = 140$. The 30° , underexpanded jet would reach this point at $x/d = 160$.

Figure 38 shows the helium concentration decay of the matched pressure jets at each injection angle. The decay rate of the 15° jet was $n = 0.8$, while that of the 30° jet was $n = 0.9$. At this expansion ratio, doubling the injection angle increased the decay rate by 23 percent. At $x/d = 20$, the overall helium concentration of the 30° jet was 32 percent greater than that of the 15° jet. By $x/d = 90$, the helium concentrations of the two jets were nearly the same. Again under the assumption of a constant decay rate past $x/d = 90$, the 15° , matched pressure jet would reach the stoichiometric H_2 - air concentration by $x/d = 215$. The 30° , matched pressure jet would reach this concentration at $x/d = 170$.

Figure 39 compares the decay curves of the underexpanded and matched pressure jets for an injection angle of 15° . At this injection angle, changing the expansion ratio changed both the magnitude and rate of decay of the helium concentration. Quintupling the expansion ratio of the 15° jet resulted in a 60 percent increase in the decay rate. At $x/d = 20$, the helium concentration of the underexpanded jet was 104 percent greater than that of the matched pressure jet. By $x/d = 90$, both cases reached essentially the same concentration. The underexpanded jet would reach the stoichiometric H_2 - air concentration 74d ahead of the matched pressure jet.

Figure 40 shows the result of varying the expansion ratio for the $\theta = 30^\circ$ jets. As with the 15° jets, a change in the expansion ratio affected both the rate of decay and overall level of helium concentration. The underexpanded jet decay rate was 36 percent greater than the matched pressure jet decay rate. The helium concentration

of the underexpanded jet was 88 percent larger than that of the matched pressure jet at $x/d = 20$. This difference shrank to 13 percent by $x/d = 90$. Again assuming constant decay rate, the underexpanded jet helium concentration would be equal to the matched pressure helium jet concentration at $x/d = 144$. The underexpanded jet would reach the H_2 - air stoichiometric concentration only 7d ahead of the matched pressure jet.

In considering decay to a certain maximum concentration level, it is important to note that changing the expansion ratio while holding the throat area and Mach number of the jet constant, changes the injectant flow rate. Thus, the cases with expansion ratios of five here have five times the injectant flow rates of the matched pressure cases. Obviously, it takes better mixing to reduce α_{max} for the high flow rate cases to the same value as for the low flow rate cases at the same axial station. Therefore, Figures 39 and 40 indicate that the underexpanded cases are showing much higher mixing rates than the matched pressure cases. One could attempt to normalize out the effects of changes in the mass flow rate by using $\frac{(x/d)}{\sqrt{\lambda}}$ as the distance coordinate for the decay plots, where λ is the mass flux ratio of the jet to the free stream.

3.2.4 Overall Penetration

Figures 41 - 44 are graphs of the maximum outer penetration height of the helium jet at each axial station for all of the test cases. The maximum helium penetration point was defined to be the first point above the jet core center which had a helium mass fraction less than 0.0007 by Reference 12. This definition will

be used in the present work to be consistent. This distance was normalized by the injector throat diameter, d . The data fit equations of the form:

$$\frac{h}{d} = n_1 \log\left(\frac{x}{d}\right) + \beta_1 \quad [3.2]$$

where n_1 and β_1 were determined by a curve fit. The coefficient, β_1 , represents the rate of growth of the penetration height of the jet.

The penetration of the underexpanded jets is shown in Figure 41. The rate of penetration growth of the 30° injection angle jet was $n_1 = 2.8$. The rate of the 15° jet was $n_1 = 2.3$, within 23 percent of the 30° jet. It is interesting to note that rates of change of both concentration decay and penetration of the underexpanded jets were similar despite the 30° jet having a q_r more than twice that of the 15° jet. The overall penetration of the 30° jet was 29 percent greater than the 15° jet penetration at a typical axial station.

The matched pressure jet penetration is shown in Figure 42. The 30° jet penetration growth rate was very small, with $n_1 = 0.1$. Reducing the injection angle by half increased the rate of penetration growth to 3.2. The 30° jet experienced a greater initial penetration, however. At $x/d = 20$, the 30° injection angle jet penetrated 115 percent more than the 15° jet. By $x/d = 90$, this difference reduced to 30 percent. Assuming the penetration growth rates remain constant past $x/d = 90$, the 15° jet penetration would have reached that of the 30° at $x/d = 176$.

Varying the expansion ratio at an injection angle of 15° results in the graph of Figure 43. The rate of penetration growth of the matched pressure jet was 42 percent greater than that of underexpanded jet. The underexpanded jet's initial penetration was greater than the matched pressure jet's, so that at $x/d = 20$, the

underexpanded jet penetration was 2.2 times that of the matched pressure jet. This factor decreased to 1.6 by $x/d = 90$.

The effect of quintupling the expansion ratio of the 30° injection angle jets is shown in Figure 44. In this case, varying the expansion ratio changed both the growth rate and magnitude of penetration. The underexpanded jet penetration growth rate was 23 times that of the matched pressure jet. The underexpanded jet had penetrated 30 percent more than the matched pressure jet at $x/d = 20$. By $x/d = 90$, this difference increased to 54 percent.

3.3 Other Mean Flow Results

Vertical profiles of other important flow quantities are shown in Figures 45 - 62. These profiles were made at the jet centerline at each axial station for all cases.

3.3.1 Total Pressure Loss

The total pressure loss due to fuel injection can seriously affect the thermodynamic efficiency of a scramjet. Large total pressure losses in the combustion chamber reduce the pressure energy of the working fluid, resulting in a loss of vehicle efficiency. The total pressure loss of the incoming air can be caused by viscous forces in the boundary layer, the jet shock wave, and mixing with lower total pressure gas from the jets. These losses can be determined by an examination of the nondimensionalized centerline total pressure profiles shown in Figures 45 and 46.

To compare the total pressure loss of each jet at its respective injection conditions, a nondimensional total pressure parameter was developed by Reference 20. This parameter was defined as follows:

$$P_{tp} = \frac{\int_0^H \rho u P_t dz}{\int_0^{H^+} \rho_{uf} u_{uf} P_{tuf} dz + \rho_j u_j P_{tj} d_j} \quad [3.3]$$

The first term in the denominator of this parameter represents the total pressure of an undisturbed free stream boundary layer flow. This was found by integrating a single vertical profile of the mass weighted total pressure flux of an undisturbed free stream boundary layer. The second term in the denominator represents the jet total pressure. It was calculated from the stagnation properties of the each jet using isentropic, perfect gas equations. The sum of these two terms represent the total pressure of the free stream and the jet without any losses due to interaction

between the two. It can be thought of as the total pressure imported into the flow field from both the free stream boundary layer and the jet.

The numerator of this parameter represents the total pressure of the flow including the total pressure losses caused by the interaction of the jet and free stream. This was calculated by integrating the mass weighted total pressure flux calculated from vertical profiles measured on the jet geometric centerline at the $x/d = 90$ station for each case.

The ratio of the two represents the total pressure of the actual flow field relative to the the total pressure imported by the free stream and the jet. Any loss of total pressure as represented by this parameter is caused by the interaction between the free stream and the jet. If there was no total pressure loss due to the interaction of the two streams, then the total pressure parameter would be equal to unity. A total pressure parameter of zero corresponds to a complete loss of total pressure due to jet free stream interaction. It follows that large total pressure parameters indicate small total pressure losses and *vice versa*.

Reference height, H , was calculated iteratively from the following definition:

$$\frac{\int_0^H \alpha_{He} \rho u \, dz}{\int_0^H (1 - \alpha_{He}) \rho u \, dz} = \text{Stoichiometric } H_2 - \text{air ratio} \quad [3.4]$$

where the integrands were calculated from data profiles taken on the jet centerline at the $x/d = 90$ station. Since it is desired that the simulated fuel-air ratio reach the stoichiometric hydrogen-air ratio, the height was chosen such that the total pressure loss that is quantified by the total pressure parameter applies only to the masses of fuel and air required for complete combustion.

Reference height, H^+ , was found iteratively from the relation:

$$\int_0^{H^+} \rho_{uf} u_{uf} dz = \int_0^H (1 - \alpha_{He}) \rho u dz \quad [3.5]$$

where the integrand of the lefthand side of equation [3.5] was calculated from profile data taken in an undisturbed free stream boundary layer, and the integrand on the righthand side of the equation was found from profiles measured on the jet geometric centerline at the $x/d = 90$ station for each case. The height, H^+ , is the height required to capture a mass of air in an undisturbed free stream boundary layer which is equal to the mass of air captured over the distance, H , for each case.

Both reference heights were calculated using the FORTRAN computer program listed as Program 4 in Appendix B. The total pressure parameter, P_{tp} , was calculated by Program 5 in Appendix B.

It must be stressed that the total pressure parameter was calculated using information from single, vertical data profiles for each case. This must be considered when drawing conclusions about a three-dimensional flow field from the results of these calculations.

For each case, the total pressure at the outer edge of each profile was about equal to the free stream total pressure, and it decreased from this value with decreasing height above the wall. Near $z/d = 0$, the total pressure approached the free stream static pressure.

The 15°, matched pressure jet, shown in Figure 45, had very little total pressure loss above the boundary layer edge at all axial stations. This fact, coupled with the facts that this jet did not significantly penetrate out of the boundary layer and mixed very little with the free stream, indicates that most of the total pressure

loss resulted from boundary layer viscous forces and mixing. The total pressure parameter for this case was 0.42.

The 15° , underexpanded jet is also shown in Figure 45. In this case, the sharp drop in total pressure occurred much further into the free stream at all axial stations. Recalling the significant amount of mixing and penetration noted for this case, most of this total pressure loss probably resulted from the lower total pressure gas in the jet mixing with the free stream. Of course, within the boundary layer, the viscous forces must also have contributed to total pressure loss. The pressure parameter for this case was 0.37.

Figure 46 illustrates the results for the 30° jets. The matched pressure jet for this injection angle behaved similarly to the 15° , matched pressure jet. The greater penetration and higher levels of mixing found for the 30° injection angle jet resulted in greater free stream total pressure losses, however. The total pressure parameter for this case was 0.35, a decrease of 20 percent over the 15° , matched pressure case. It is interesting to note that the two cases with similar q_r , the 15° , underexpanded and this case, also had pressure parameters within 5 percent of one another.

The 30° , underexpanded case had the worst total pressure loss of all the cases studied. While this case had the most jet-free stream mixing and the largest penetration, the total pressure of the jet was much higher than that of the free stream. This suggests that jet-free stream mixing would increase the total pressure of the free stream. It was noted earlier, however, that the jet bow shock angle for this case was at least 18 percent greater than that of the other cases. The stronger bow shock of the 30° , underexpanded case must have been the cause of the greater total pressure loss. The total pressure parameter for this case was 0.25, a decrease of

about 30 percent over both the 15°, underexpanded, and the 30°, matched pressure cases.

3.3.2 Mach Number Profiles

The Mach number profiles at the geometric jet centerline of all cases are shown in Figures 47 and 48. The Mach number was about equal to its free stream value at the top of the profile, and decreased with decreasing height for all cases. Each profile had a point below which the Mach number decreased rapidly. Since this point corresponded approximately to the edge of the jet, the sharp decrease in Mach number was probably caused for the most part by mixing of low Mach number gas from the jets with higher Mach number gas from the free stream. Other reasons for the decrease are viscous forces in the boundary layer and the variation of the jet bow shock strength.

The 15° injection angle jet Mach number profiles are shown in Figure 47. At $x/d = 20$, both the underexpanded and matched pressure jets have large Mach number gradients. Further downstream, these gradients became smaller, again indicating large scale mixing. The underexpanded case experienced a much larger decrease in Mach number from its free stream value than did the matched pressure case at a given axial station. The decrease also occurred at a greater height for the underexpanded case. This reflects the larger mixing and penetration noted for the underexpanded jets earlier.

The 30° injection angle jet Mach number profiles, shown in Figure 48, behaved much the same as the 15° injection angle jets. The greater penetration and mixing of the 30° jets, at a given expansion ratio, caused the height and magnitude of the

Mach number decrease to be greater than in the 15° cases. The large Mach number gradients observed at the first axial station decreased with distance downstream of the jet.

3.3.3 Total Temperature and Static Properties

Figures 49 and 50 show the total temperature profiles at the geometric jet centerline for all cases. The total temperature variation from its free stream value was less than two percent at each axial station for all cases.

Centerline static temperature, shown in Figures 51 and 52, increased from its free stream value at the top of the profile to about twice that value near the wind tunnel floor for all cases. The profiles varied little with axial distance. The static temperature of the underexpanded jets increased from the free stream to the floor temperature more gradually than that of the matched pressure jets.

Figures 53 and 54 show the local speed of sound at each axial station on the jet centerline. The speed of sound increased dramatically over its free stream value at the first station. The maximum decreased with increasing axial distance. The increase in this quantity was caused by high concentrations of helium in the mixing region. Downstream of the first station, the helium concentrations decreased as a result of the jet mixing with the free stream thus making the speed of sound increase less dramatic.

The centerline static pressure graphs in Figures 55 and 56, show a decrease from its value in the free stream for the underexpanded jets, and a slight increase for the matched pressure jets at $x/d = 20$. The static pressure decrease of the underexpanded jets was probably caused by the stronger shocks noted for these

cases. Downstream of the first station, the static pressure remained about constant at its free stream value.

The centerline density profiles in Figures 57 and 58 reflect the penetration and mixing results described earlier. The density dropped significantly from its free stream value for the 15° , underexpanded and 30° , matched pressure and underexpanded jets. This decrease in density was for the most part caused by penetration of the low molecular weight gas of the jets into the free stream. As downstream distance increased this gas mixed with the free stream, so the density in the mixing zone approached a median value. The decline in density was not significant in the 15° , matched pressure jet because of its lower penetration.

Centerline velocity profiles are shown in Figures 59 and 60. At $x/d = 20$, the velocity increased above its free stream value to a maximum, then started decreasing at about $z/d = 2$ to approach zero at the wind tunnel floor. As the jet and free stream mixed downstream of this station, the velocity increase became smaller. By $x/d = 90$, sufficient mixing had occurred so that the velocity profile resembled that of an undisturbed boundary layer.

The centerline mass flux profiles are shown in Figures 61 and 62. The mass flux dropped dramatically from its free stream value due to the density drop noted above. It increased to a median value as the jet and free stream mixed.

4. DISCUSSION

4.1 Trends and Best Cases

The present experiments were performed to investigate the cold flow performance of fuel injectors for a supersonic combustion ramjet engine. Some characteristics desirable for such injectors include rapid fuel-air mixing with minimal air total pressure loss. These qualities are used to compare each test case of the present experiments.

The most commonly used basis of comparison for gas mixing is the rate at which the mass fraction of the injectant decays with axial distance. Large decay rates indicate large amounts of fuel-air mixing. For the matched pressure jets, raising the injection angle by a factor of two increased the decay rate by 23 percent. In the underexpanded cases, doubling the injection angle resulted in a negligible increase in decay rate. Increasing the injection angle increased the component of jet momentum perpendicular to the free stream, thus creating a stronger disturbance. This resulted in the stronger shocks noted for the higher injection angle jets in the spark schlieren photographs. The stronger shocks also had more curvature, which in turn created more vorticity in the mixing zones of the higher injection angle jets. Since increasing the injection angle did not increase the decay rate of the underexpanded jets, mechanisms other than shock induced vorticity must dominate mixing in these cases. These mechanisms might be linked to the unsteadiness suggested by the spark schlieren and nanoshadowgraph photographs.

The expansion ratio changed the decay rates for both the 15° and 30° cases. Quintupling the expansion ratio for the 15° cases resulted in a 60 percent increase in decay rate. The 30° jet decay rates only increased 36 percent for the same increase in expansion ratio. Increasing the expansion ratio would make the jet plume out more and thus create a greater disturbance. This would increase the vorticity in the mixing zone as explained above. The nanoshadowgraphs showed that the jet bow shocks of the underexpanded cases had much more curvature in the free stream than the matched pressure cases. This would add even more vorticity into the underexpanded jet mixing region, thus further increasing the mixing over that of the matched pressure jets.

For the range of parameter variation of the present experiments, increasing the injection angle increased the decay rate by a different amount at different expansion ratios. The same was true for variation of expansion ratio at different injection angles. The 30° , underexpanded case had the greatest decay rate of the cases studied, but its rate was only 5 percent more than that of the 15° , underexpanded case.

Another basis of comparison for fuel-air mixing is the mixing distance, here defined as the downstream distance at which the fuel-air ratio reaches the value required for complete combustion with air. For the present experiments, this is defined as the stoichiometric ratio for hydrogen and air. The smaller this distance is, the more rapid the fuel-air mixing. Doubling the injection angle from 15° to 30° for the underexpanded cases increased this distance by 22d. The opposite trend was observed for the matched pressure cases. Here, doubling the injection angle

reduced the mixing distance by 45d. These trends mimic those of the decay rates for the same reasons.

The influence of increasing expansion ratio was to decrease mixing distance even though the injectant mass flow was increased. In the 15° cases, quintupling the expansion ratio reduced the distance by 74d. The same change in expansion ratio at an injection angle of 30° resulted in about one-tenth the decrease in mixing distance observed for the 15° cases. Again, these trends agree with those found by comparing decay rates.

The trend and the magnitude of the changes in mixing distance with injection angle were dependent on the expansion ratio, but the change in expansion ratio influenced only the magnitude of the change of the mixing distance for different injection angles. Based on the distance to reach the stoichiometric H_2 -air concentration, the 15° , underexpanded case had the best mixing.

Jet penetration into the free stream is critical for large scale mixing. Greater jet penetration results in greater free stream entrainment, which in turn results in greater mixing. One basis for comparing jet penetration is the rate of change at which the jet penetrates. As with the decay rates of the jets, injection angle variation had little effect on the underexpanded jets. Doubling the injection angle increased the penetration growth rate by only 23 percent. The injection angle had the opposite effect on the matched pressure jets. Doubling the injection angle for this case reduced the rate of penetration growth by 260 percent.

The increase in the penetration growth rate of the 30° , underexpanded jet over that of the 15° , underexpanded jet was caused by a combination of this jet's greater q_r , and the greater component of jet momentum in the vertical direction.

The matched pressure case is not as simple, however. Reference 4 has shown that the penetration growth of co-flowing streams is dramatically reduced if the Mach number of one of the streams is large relative to the Mach number of the other. Eddies which attempt to penetrate the boundary of the streams are pushed back if the relative Mach number of the two streams is greater than unity. The larger the difference in Mach numbers, the stronger the restorative force. The same mechanism may be responsible for the surprisingly large penetration growth rate of the 15°, matched pressure case. It was observed in the nanoshadowgraphs that the turbulent region of the 15°, matched pressure jet stayed within the boundary layer over most of the downstream axial distance. Since the Mach numbers in the boundary layer are closer to that of the jet, the relative Mach number between the jet and the fluid in which it was immersed was much lower than if the turbulent region had penetrated into the free stream, thus allowing the jet to penetrate more rapidly.

For the 15° cases, quintupling the expansion ratio decreased the penetration growth rate by 42 percent. In the 30° cases, the same increase in expansion ratio caused a 230 percent increase in penetration growth rate. The increase in expansion ratio indicated a large increase in the dynamic pressure ratio of the jets. This resulted in an overall increase in the momentum of the jet which was responsible for the increased penetration growth rate of the 30° cases. The relative Mach number phenomena discussed earlier may have dominated the rate of penetration growth of the 15°, matched pressure jet, so that the increase in dynamic pressure ratio was not enough to make the underexpanded jet penetrate more rapidly. The largest penetration growth rate was observed for the 15°, matched pressure case.

The total pressure loss of the free stream due to fuel injection was quantified with the total pressure parameter, P_{tp} , described in Section 3.3.1. Larger values of P_{tp} indicate lower total pressure losses.

Doubling the injection angle of both cases resulted in a decrease in P_{tp} . The total pressure parameter of the 30°, underexpanded case was 30 percent lower than that of the 15°, underexpanded case. At matched pressure exit conditions, the same increase in injection angle resulted in a decrease in P_{tp} of 20 percent. In general, increasing the injection angle increased the total pressure loss, although the magnitude of the loss was dependent on the expansion ratio.

Raising the expansion ratio by a factor of five at an injection angle of 15° worsened the total pressure loss by 15 percent. For the 30° cases, the same increase in expansion ratio decreased P_{tp} by 30 percent. Therefore, an increase in expansion ratio resulted in an increase in total pressure loss, but again the magnitude of the loss was related to a combination of the test parameters. According to the total pressure parameter, the case with the lowest total pressure loss was the 15°, matched pressure case.

The most desirable injector design would be the result of a trade off between the penetration and mixing properties of the design and total pressure loss. The 30°, underexpanded case had the largest decay rate of the cases studied in the present experiment, but did not have the highest penetration growth rate, and caused large free stream total pressure losses. The 15°, matched pressure case caused the lowest total pressure loss and had the largest penetration rate, but had poor mixing rates and minimal overall penetration. The 15°, underexpanded case reached the stoichiometric H_2 -air concentration in the smallest downstream distance,

and had a concentration decay rate essentially the same as the 30° , underexpanded case. This case also suffered relatively low total pressure losses, and penetrated at a rate comparable to the 15° , matched pressure case. For these reasons, the 15° , underexpanded case offers the best compromise of cost and benefits of the cases studied in the present work.

4.2 Comparison with Past Work

Comparisons with other scramjet fuel injection schemes were made. The experiments noted along with information about the injection methods are shown in Table 3.

McClinton^[13] studied an array of five sonic jets spaced $6.25d$ apart. These jets were injected into a Mach 4 free stream at several different injection angles. The $\theta = 30^\circ$ case from these experiments compares with the 30° , matched pressure case of the present experiments. The dynamic pressure ratios are about the same for these two cases, but the expansion ratio of McClinton's jet was about 2.3 times greater than that of the present jet. This makes it possible to study the effects of closely spacing low angle jets.

Rogers^[8] experiments used a single, sonic jet to inject perpendicular to a Mach 4 crossflow. The expansion and dynamic pressure ratios of this scheme were similar to the 30° , matched pressure case of the present experiments. This set of data allows comparison with jets of large injection angles.

The experiments of McClinton and Rogers were performed with hydrogen as the injectant. Reference 21 recorded penetration heights, lateral spreading, and height

of maximum concentration for normal, sonic, helium and hydrogen jets injected into a Mach 4 free stream. They found that the height of maximum concentration and the lateral spreading were significantly higher for hydrogen, but that the penetration heights were unaffected. This would indicate more jet-free stream entrainment for the hydrogen jets, and thus would tend to increase mixing.

The flow field studied by Kwok^[10] was generated by injecting helium through a downstream facing rectangular cross-section slot parallel to a wall bounded Mach 3 free stream.

Figure 63 shows the fuel mass fraction decay rate of the present cases and those above as a function of the dynamic pressure ratio, q_r . The cases of the present experiment rose rapidly with q_r until about $q_r = 1.5$. The decay rate past this point was essentially constant with q_r . This suggests that for low angle jets, there is no significant advantage to increasing the dynamic pressure ratio past 1.5.

The decay rate of the present 30°, matched pressure case was about 16 percent larger than that of Rogers' jet. This result is surprising because a normal jet with a comparable expansion ratio should produce a shock with more curvature than a low angle jet which would create stronger vorticity in the fuel-air mixing region. This suggests that there is a fundamental difference in the mechanics of the low angle jet and normal jet flow fields. A further increase can be gained by simply increasing the expansion ratio of the low angle jet. The 30° jet with an expansion ratio of five has a decay rate which is 63 percent greater than that of Rogers' normal jet.

It was found in the present experiments that increasing the expansion ratio of a low angle jet increased its decay rate. Using hydrogen as the injectant gas also would increase mixing because of the greater spreading and core penetration noted

by Reference 21. Despite the fact that McClinton's jets had a higher expansion ratio and used hydrogen as the injectant, the decay rate of the 30°, matched pressure case of the present experiment was 2.3 times that of McClinton's jets. This was for the most part the caused by the close spacing of McClinton's jets. For a single jet, entrainment of the free stream and mixing occurs on the sides of the jet as well as the top. At some point downstream, the jets of a closely spaced array merge, so that the sides of each jet entrain and mix with gas from neighboring jets. Thus, the mixing of the free stream and jet is retarded.

The matched pressure, parallel slot injection scheme of Kwok resulted in a decay rate of 0.33. The decay rates of the present matched pressure cases were about 2.4 times greater than that of Kwok. In this case, there is little or no penetration of the jet into the free stream. This significantly reduced free stream entrainment which resulted in little large scale mixing. Another reason for the poor mixing was that the slot jet was exposed to the free stream on its top surface only. As with McClinton's closely spaced jets, this reduced the area of free stream entrainment resulting in a reduction in mixing.

The distance required to reach the stoichiometric H_2 -air concentration is shown as a function of q_r in Figure 64. Shorter distances indicate more rapid fuel-air mixing. For the present cases, this distance decreases rapidly with q_r until about $q_r = 1.5$, then slowly increases. The minimum distance occurs near the 15°, under-expanded q_r . The trend implies that low angle jets with q_r much greater than 1.5 would yield inferior mixing results.

Roger's jet reaches the stoichiometric H_2 -air concentration before any of the present cases. This was due to the large amount of initial mixing caused by the stronger shock of the normal jet.

The low angle jets of McClinton also required a greater distance to reach the desired concentration. As explained earlier, the relatively slower mixing of McClinton's jets was caused by the reduction of entrainment area resulting from the close spacing of the jets. The distance of the best present case was $55d$ less than that of McClinton's array of jets.

5. CONCLUSIONS

These experiments documented the flow field and performance of four low angle injection schemes. Important performance parameters, such as the decay rate and the total pressure loss, were used to compare the present cases with each other and cases studied in past work. Several interesting features of low angle injection flow fields were observed. It was found in the spark schlieren photographs that doubling the injection angle from 15° to 30° increased the jet interaction wave angle by only 18 percent in the underexpanded cases. Also, large eddies penetrated the free stream, which would increase the free stream entrainment of the jet, and thus increase the mixing.

The jet core bifurcated and split completely for the 15° injection angle case 20d downstream of each underexpanded jet. The core was reunited by 40d downstream of each jet. The jet core wandered about the geometric centerline for all cases. Both of these phenomena could be indications of strong vorticity in the jet-free stream mixing region.

The core penetration was a function of the dynamic pressure ratio. The rate of core penetration growth was greatest between the highest and lowest q_r cases studied in the present experiment. For the range of dynamic pressure ratios studied, the 30° , underexpanded case had the largest core penetration.

It was found that the decay rate increased rapidly with q_r to about $q_r = 1.5$, where the decay rate leveled off. As a result, the decay rates of the 15° and 30° ,

underexpanded cases were about the same despite the 30° case having a q_r twice that of the 15° case. The distance required to reach the stoichiometric H_2 -air concentration decreased with increasing q_r until about $q_r = 1.5$ where the distance began to slowly increase with q_r . Therefore, there was no significant increase in mixing from increasing the dynamic pressure ratio past about 1.5.

The 30°, matched pressure jet had a decay rate 16 percent greater than a normal jet with similar injection conditions. Since the shock of the normal jet should induce more vorticity in the mixing zone, there was probably some additional mixing mechanism in the low angle jet that was not present in the normal jet.

By comparison with past work, it was found that injecting fuel through an array of closely spaced low angle jets led to a decrease in mixing. The reduction of entrainment area caused by the merging of the jets downstream of the injection point was probably the reason for this reduction.

The lowest total pressure loss came from the 15°, matched pressure jet. In general, increasing the expansion ratio or the injection angle increased the total pressure loss. The total pressure loss did not increase directly with q_r , but jets with similar q_r experienced similar total pressure loss.

The best injector of the cases studied was the 15°, underexpanded jet. This jet had decay and penetration rates about the same as the 30°, underexpanded case. It reached the stoichiometric H_2 -air concentration in the shortest distance, and produced a relatively low total pressure loss. It also retained more of the thrust from fuel injection than the 30° cases. This injector offered the best compromise of cost and benefit of the present cases.

In summary, fuel injection at low downstream angle shows great promise. The cases studied in this investigation had large decay and penetration rates compared to other injection schemes at similar conditions. Further study of these injectors is suggested to better establish the trends indicated by the present work. More cases with dynamic pressure ratios between 1 and 3 might lend more confidence to the trends discussed in Section 4.2. Tests run with more injection angles and effective back pressure ratios would define with some detail their influences on the flow field.

Other augmentation methods might also be tried. Injecting through a jet with sharp corners in its cross-section might increase the vorticity in the mixing region, thus enhancing the mixing.

BIBLIOGRAPHY

1. Ferri, A., "Possible Directions of Future Research in Air-Breathing Engines," Combustion and Propulsion fourth AGARD Colloquium, Pergamon Press, 1961, pp. 3-15.
2. "The Pocket Ramjet Reader," United Technologies Chemical Systems, 1978.
3. Swithenbank, J., "Hypersonic Air-Breathing Propulsion," Progress in Aeronautical Sciences, Vol. 8, 1967, pp. 229-294.
4. Papamoschou, D. and Roshko, A., "Observations of Supersonic Free Shear Layers," AIAA Technical Paper 86-0162, January 1986.
5. Thomas, R.H. and Schetz, J.A. and Billig, F.S., "Gaseous Injection in High Speed Flow," Paper presented at the Ninth International Symposium on Air Breathing Engines, 1989.
6. Schetz, J.A. and Billig, F.S., "Penetration of Gaseous Jets Injected into a Supersonic Stream," J. Spacecraft Rockets, Vol. 3, No. 11, November 1966, 1658-1664.
7. Billig, F.S., Orth, R.C. and Lasky, M., "A Unified Analysis of Gaseous Jet Penetration," AIAA Journal, Vol. 9, No. 6, June 1971, pp. 1048-1058.
8. Rogers, R.C., "A Study of the Mixing of Hydrogen Injected Normal to a Supersonic Airstream," NASA TN L-7386, Langley Research Center, March 1971.
9. Rogers, R.C., "Mixing of Hydrogen Injected from Multiple Injectors Normal to a Supersonic Airstream," NASA TN L-7896, Langley Research Center, September 1971.

10. Kwok, F.T., Andrew, P.L., Ng, W.F., and Schetz, J.A., "Experimental Investigation of a Supersonic Shear Layer with Slot Injection of Helium," AIAA Technical Paper 90-0093, January 1990.
11. Smith, B.R., "Mean Flow Measurements of Heated Supersonic Slot Injection into a High Reynolds Number Supersonic Stream," M.S. Thesis, Virginia Polytechnic Institute and State University, February, 1989.
12. King, P.S., Thomas, R.H., and Schetz, J.A., "Combined Tangential-Normal Injection into a Supersonic Flow," AIAA Technical Paper 89-0-622, January 1989.
13. McClinton, C.R., "The Effect of Injection Angle on the Interaction Between Sonic Secondary Jets and a Supersonic Free Stream," NASA TN L-8125, Langley Research Center, February 1972.
14. Thomas, R.H., Personal Communication, January 1988.
15. Ng, W.F., Kwok, F.T. and Ninneman, T.A., "A Concentration Probe for the Study of Mixing in Supersonic Shear Flows," AIAA Technical Paper 89-2459, July 1989.
16. Campbell, R.L., "Experimental Study of Supersonic Slot Injection into a Supersonic Stream," M.S. Thesis, Virginia Polytechnic Institute and State University, 1987.
17. Winkler, E.M., "Design and Calibration of Stagnation Temperature Probes for Use at High Supersonic Speeds and Elevated Temperatures," Journal of Applied Physics, Vol. 25, No. 2, February 1954, pp. 231-232.
18. Trans-Tek, Inc., "Displacement Transducer DC-DC Series 240," Bulletin S012-0030-KHD, May 1989.

19. Davis, J.C., "Surface III Computer Software," Kansas Geological Survey, University of Kansas, 1988.
20. Schetz, J.A., Personal Communication, April 1989.
21. Torrence, M.G., "Effect of Injectant Molecular Weight on the Mixing of a Normal Jet in a Mach 4 Airstream," NASA TN D-6061, January 1971.

TABLES

Table 1: Injection Conditions for Some Past Experiments

Symbol	Reference	Injectant	Θ	P_{cr}	$\frac{s}{d}$	q_r	M_∞	M_j	$\frac{\delta}{d}$
Υ	McClinton	Hydrogen	30°	2.3	6.3	1.0	4.0	1.0	3.4
Υ	Rogers	Hydrogen	90°	1.1	∞	1.0	4.0	1.0	2.7
$\bigcirc$	Kwok	Helium	0°	0.8	∞	0.4	3.0	1.7	N/A
$\bigcirc$	Present	Helium	15°	1.0	∞	0.3	3.0	1.0	2.2
$\wedge$	Present	Helium	15°	5.0	∞	1.4	3.0	1.0	2.2
$\times$	Present	Helium	30°	1.0	∞	0.6	3.0	1.0	2.2
$\star$	Present	Helium	30°	5.0	∞	3.1	3.0	1.0	2.2

Table 2: Decay Rates and Mixing Distances for the Present Cases

Case	Decay Rate, n	Mixing Distance, x_{stoc}
15°, Underexpanded	1.2	140d
15°, Matched Pres.	0.8	215d
30°, Underexpanded	1.3	160d
30°, Matched Pres.	0.9	170d

Table 3: Penetration Growth Rate and P_{tp} for the Present Cases

Case	Penetration Rate, n_1	Total Pres., P_{tp}
15°, Underexpanded	2.3	0.37
15°, Matched Pres.	3.2	0.42
30°, Underexpanded	2.8	0.35
30°, Matched Pres.	0.1	0.25

FIGURES

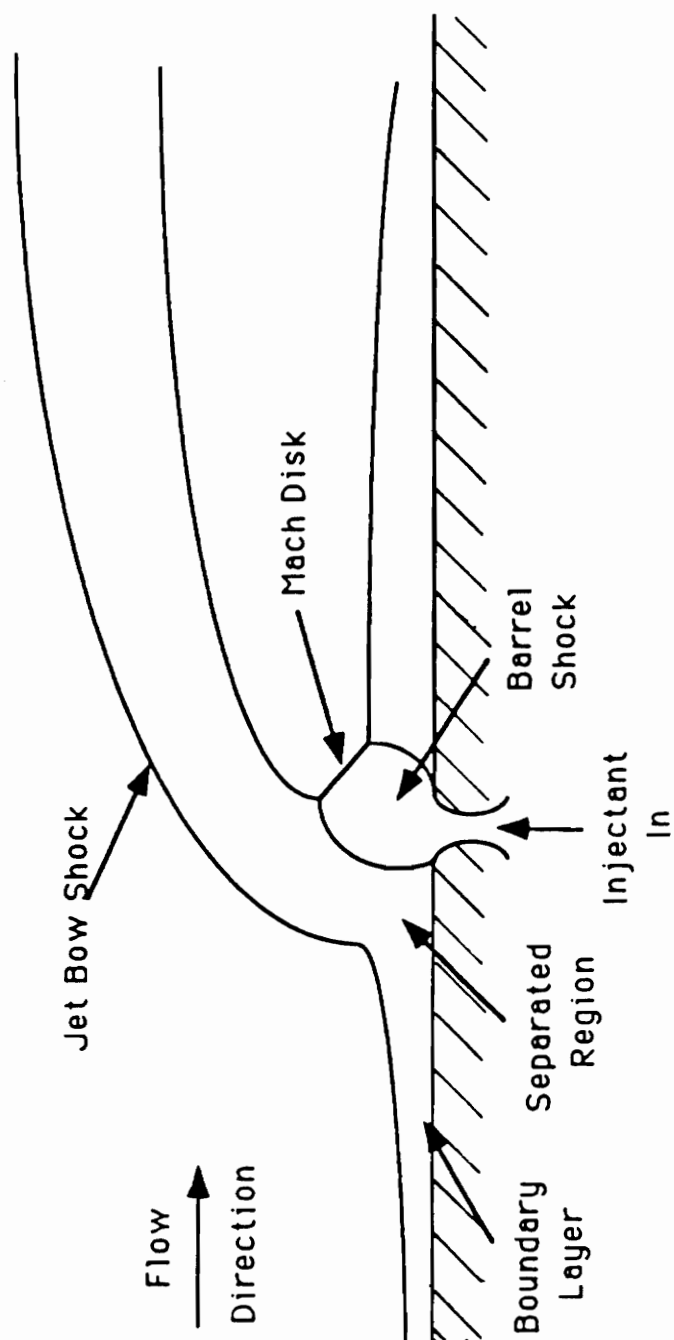


Figure 1: Generalized Normal Injection Schematic

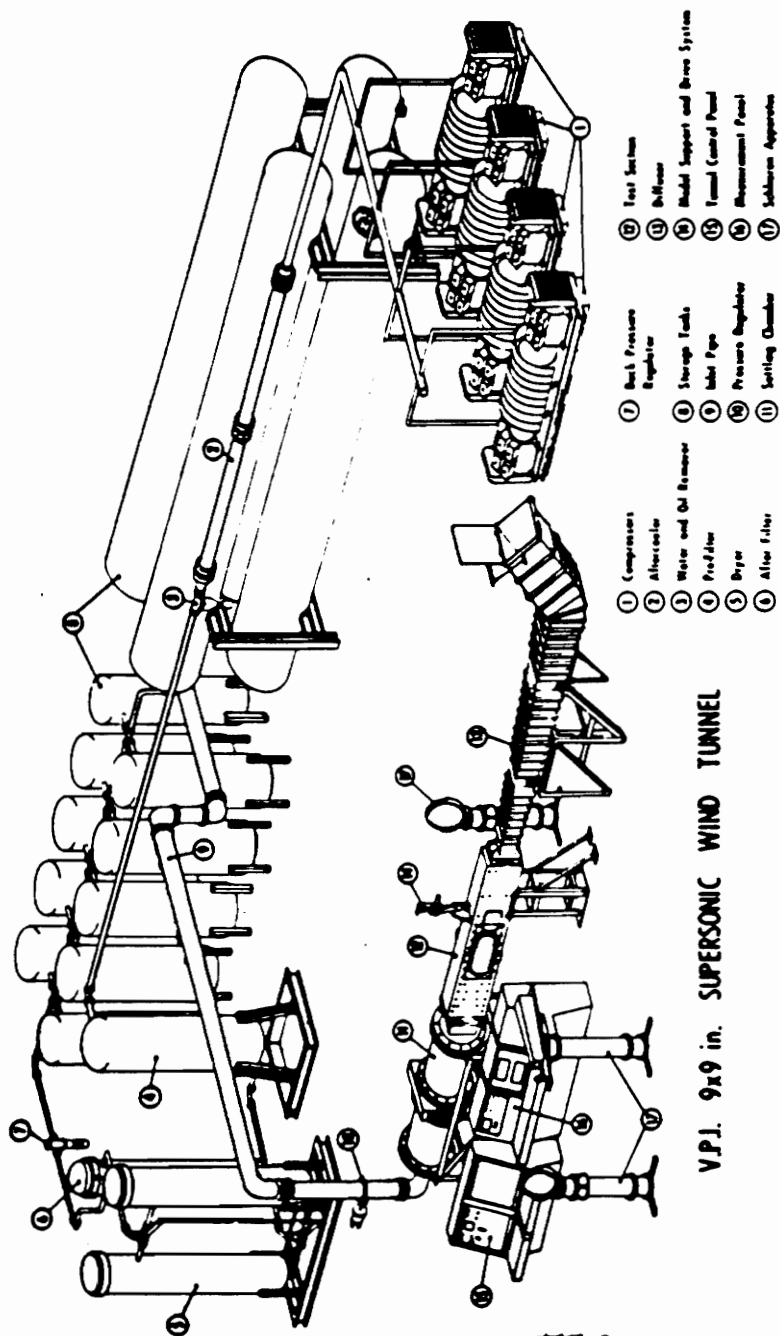


Figure 2: The Wind Tunnel Facility

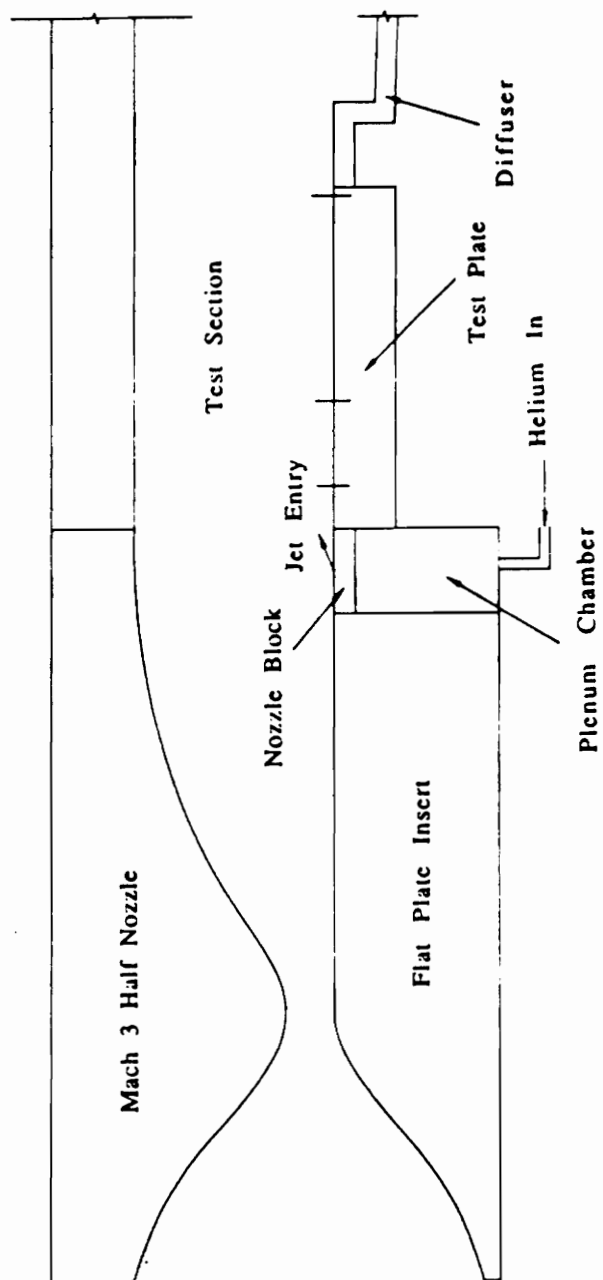
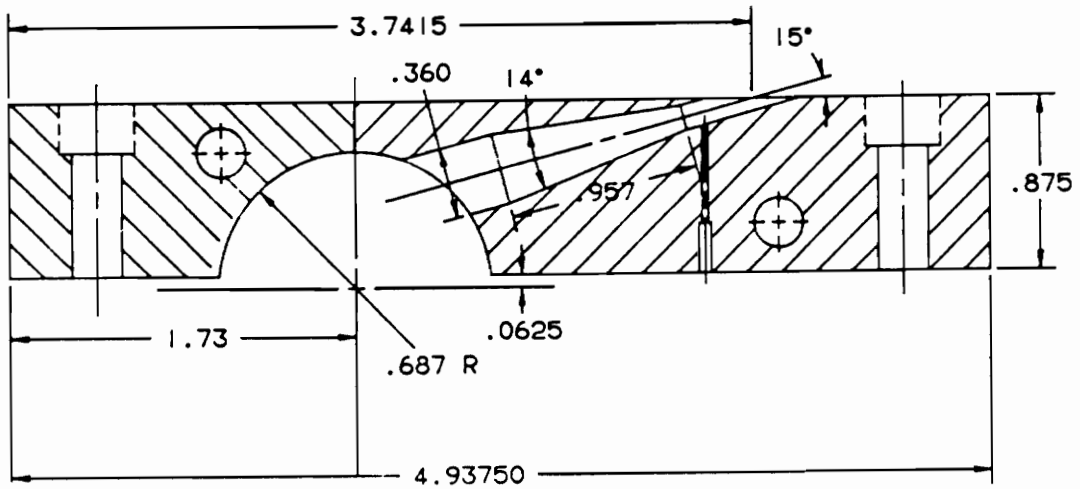
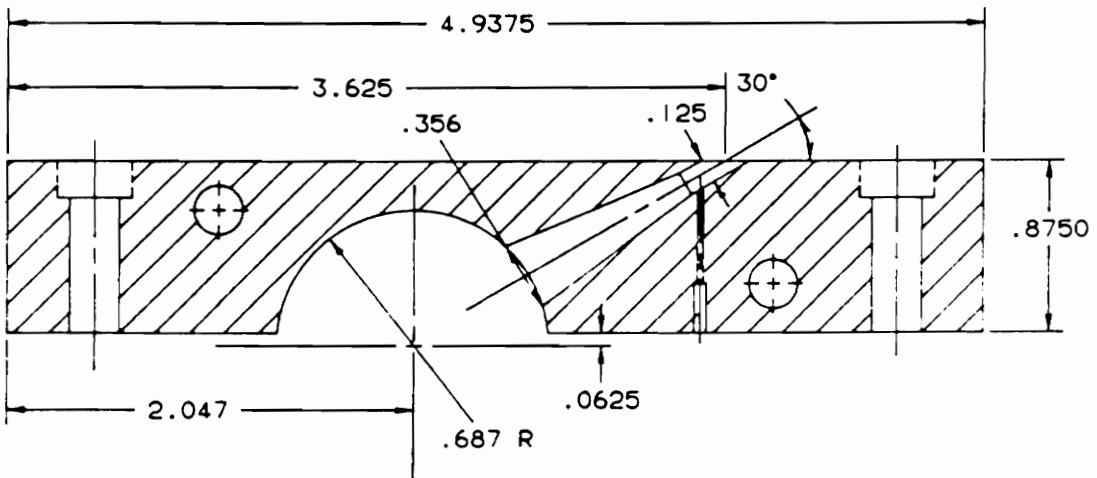


Figure 3: Sketch of the Half Nozzle Arrangement



a) Cross-section of the 15° Nozzle Block



b) Cross-section of the 30° Nozzle Block

Figure 4: Sketch of the Injectors (Dimensions in inches)

The Schlieren Optical Configuration

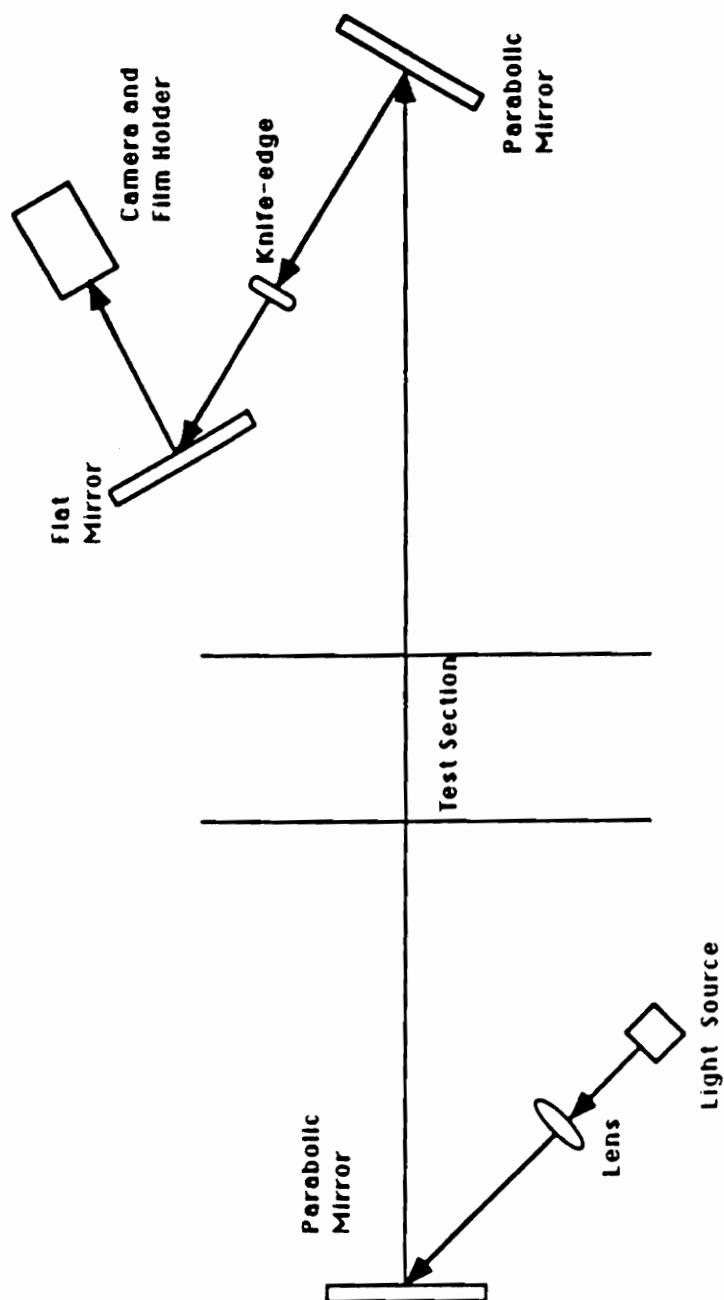


Figure 6: Sketch of the Schlieren Optical System

The Nanoshadowgraph Optical Configuration

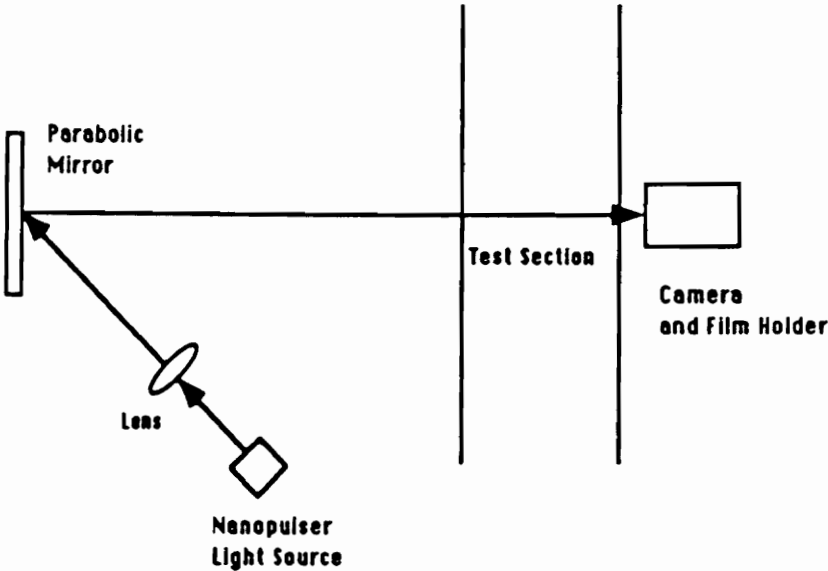


Figure 7: Sketch of the Nanoshadowgraph Optical System

Schematic of the Concentration Probe

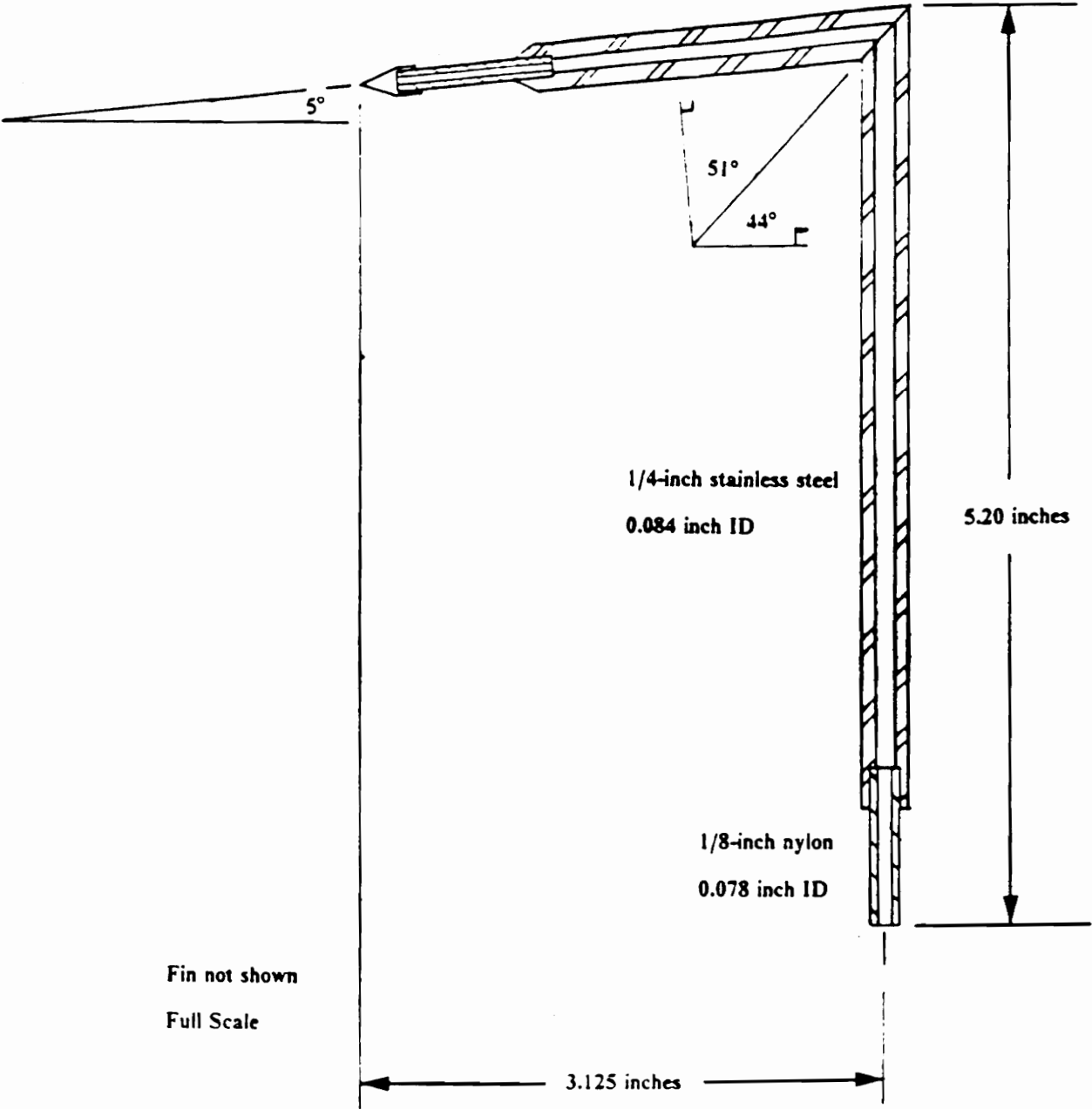


Figure 8: Sketch of the Concentration Probe

The Concentration Probe Tip and Diffuser Cap

Scale: 6 to 1
All Dimensions in Inches

Aluminum Cap
Stainless-steel Outer Tubing
Nylon End Insert

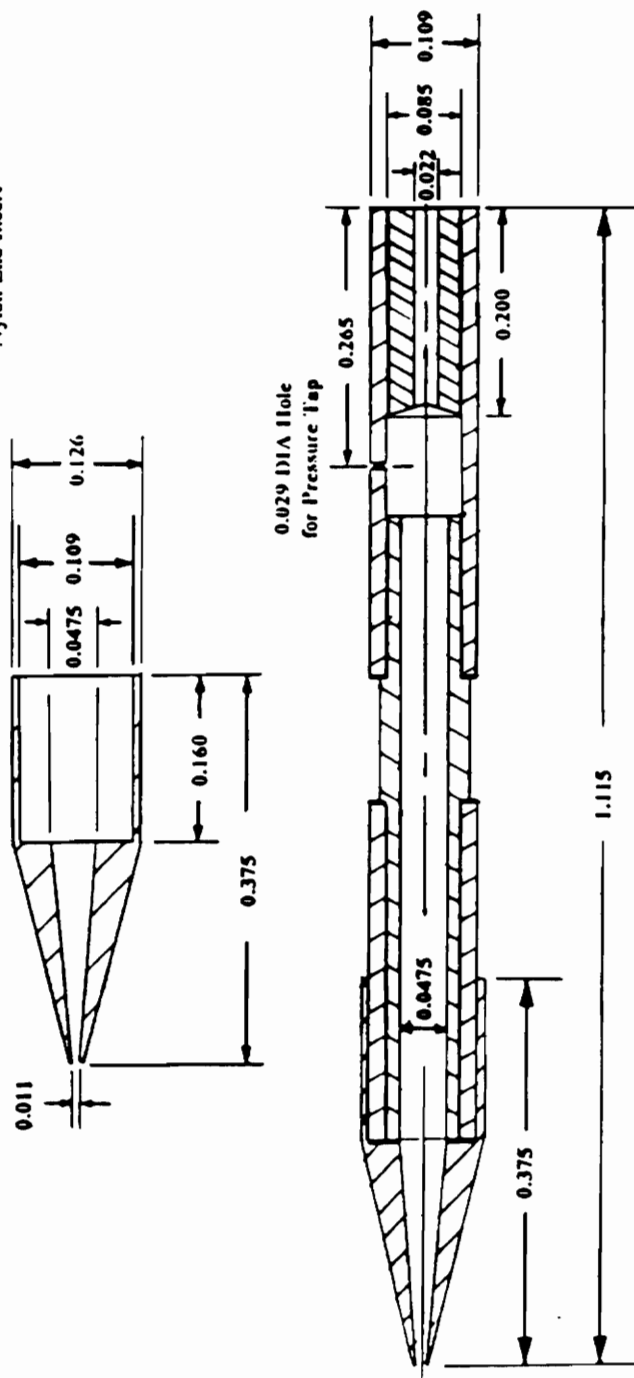


Figure 9: Cross-section of the Concentration Probe

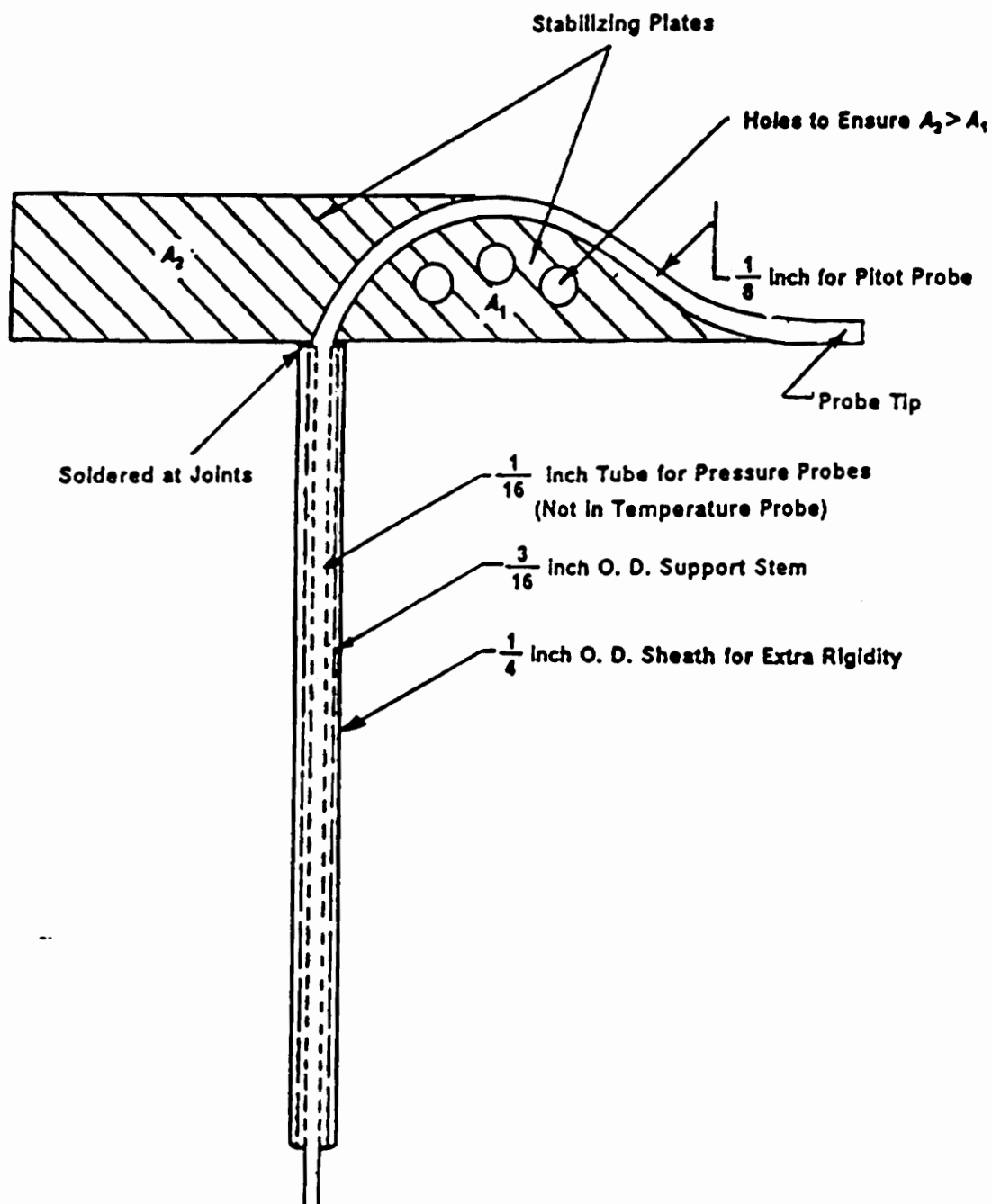


Figure 10: Sketch of the Pitot Pressure Probe

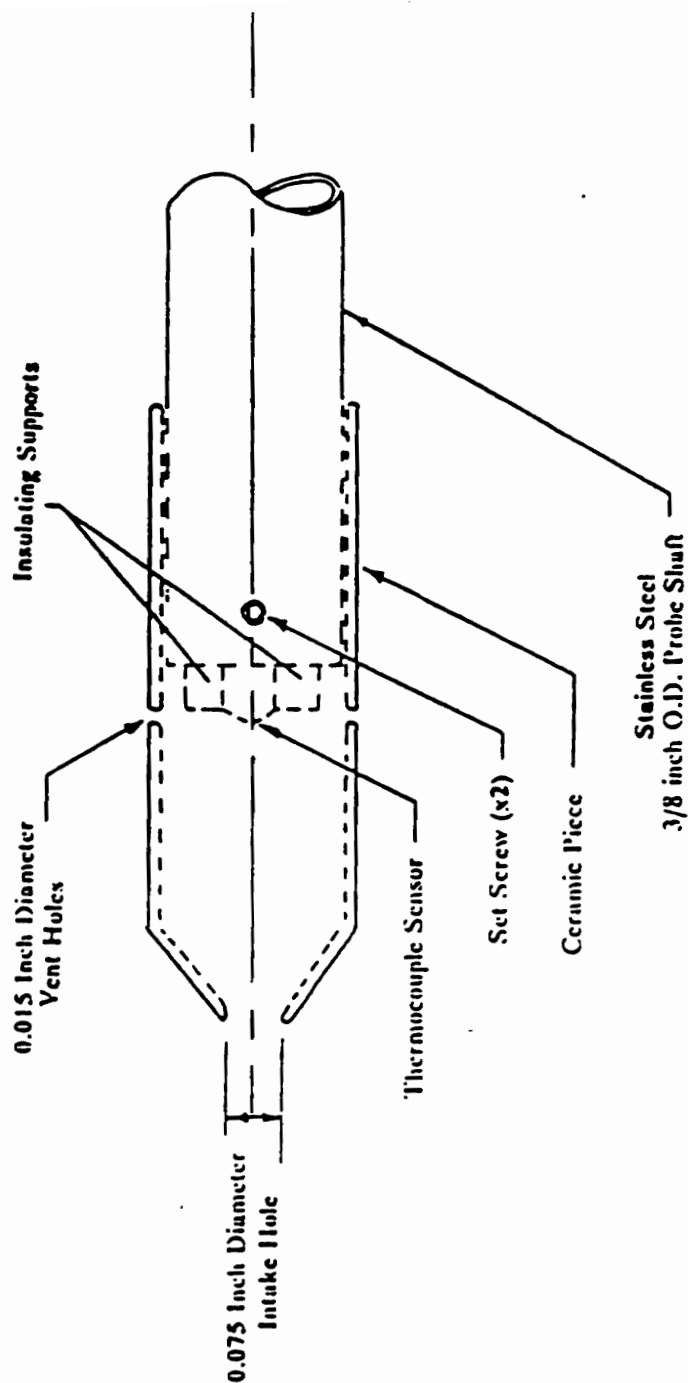


Figure 11: Sketch of the Total Temperature Probe

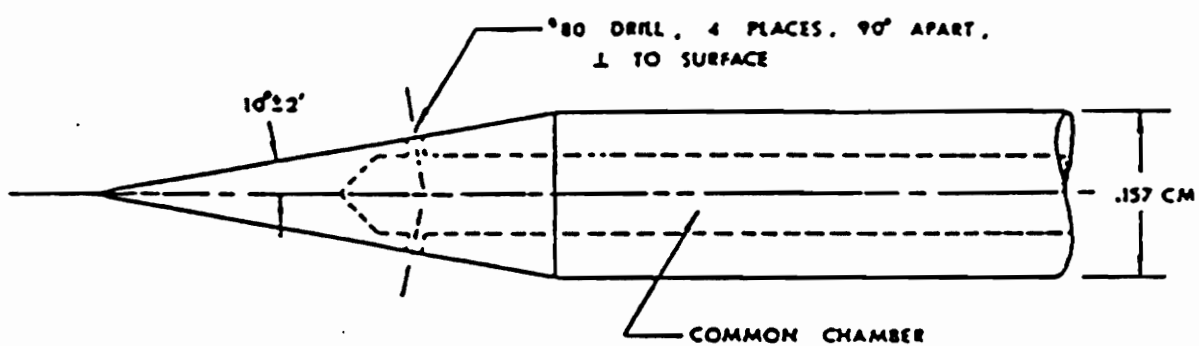


Figure 12: Sketch of the Cone-Static Probe

The Concentration Probe Calibration Setup

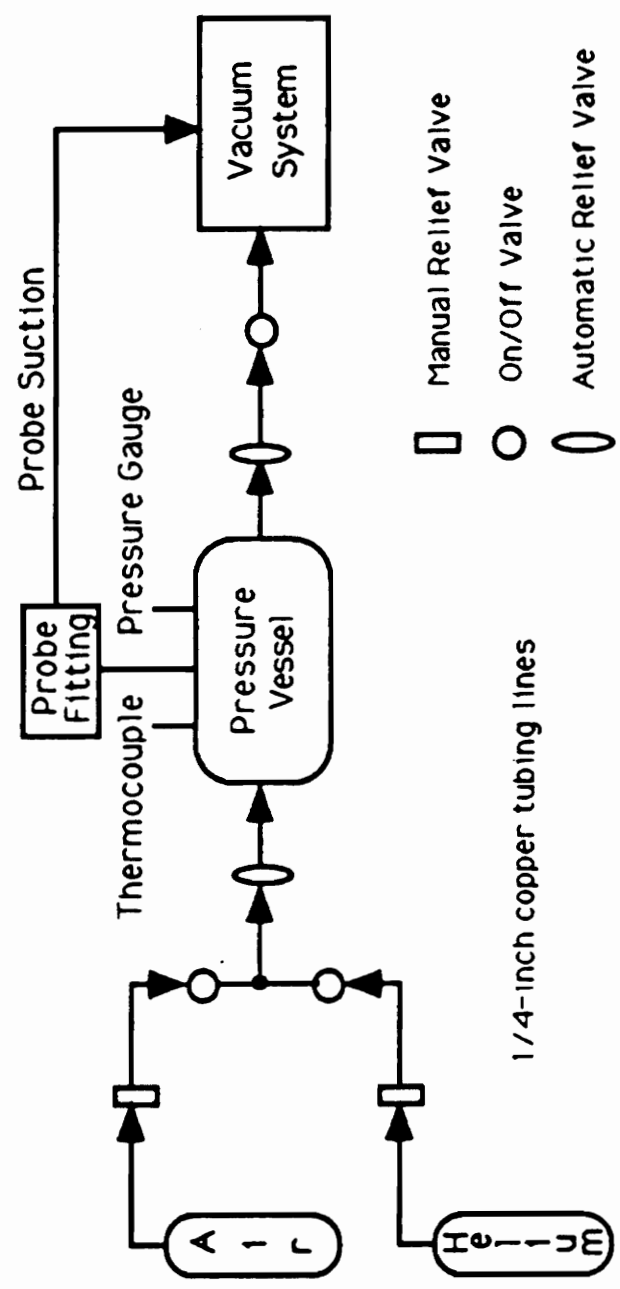


Figure 13: Concentration Probe Calibration Apparatus

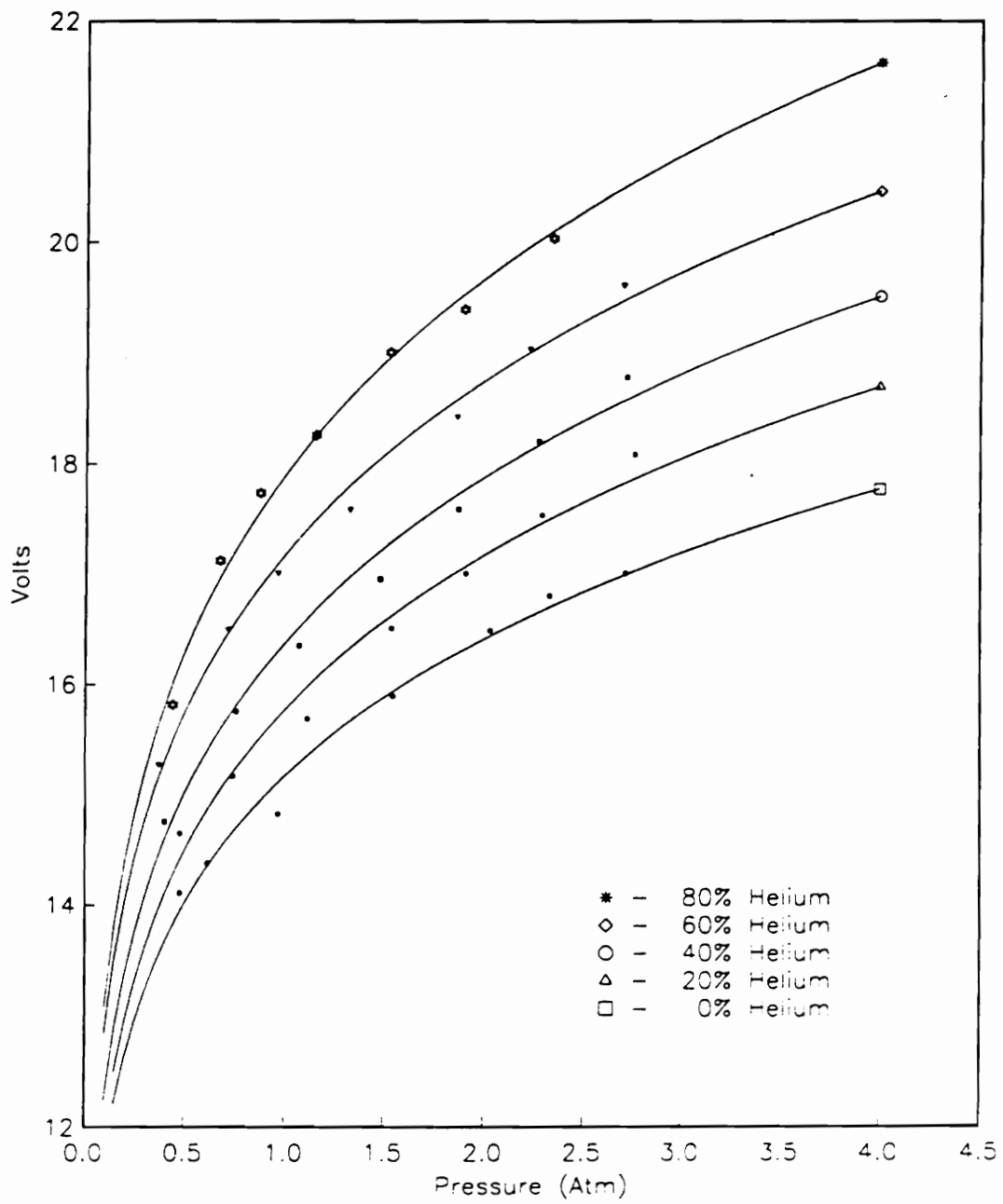
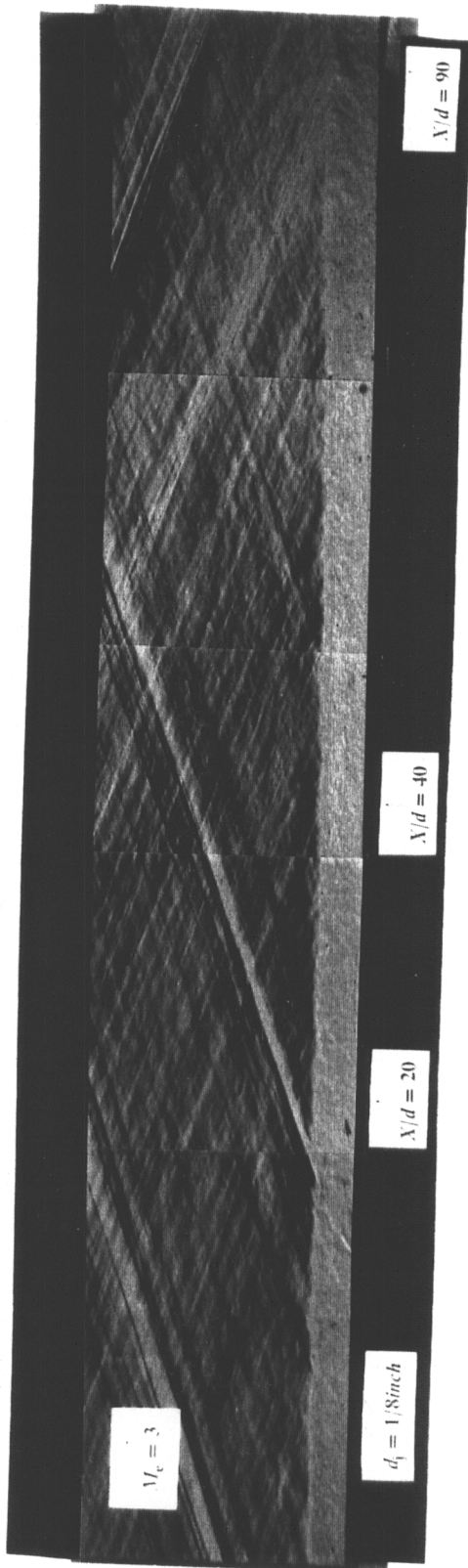
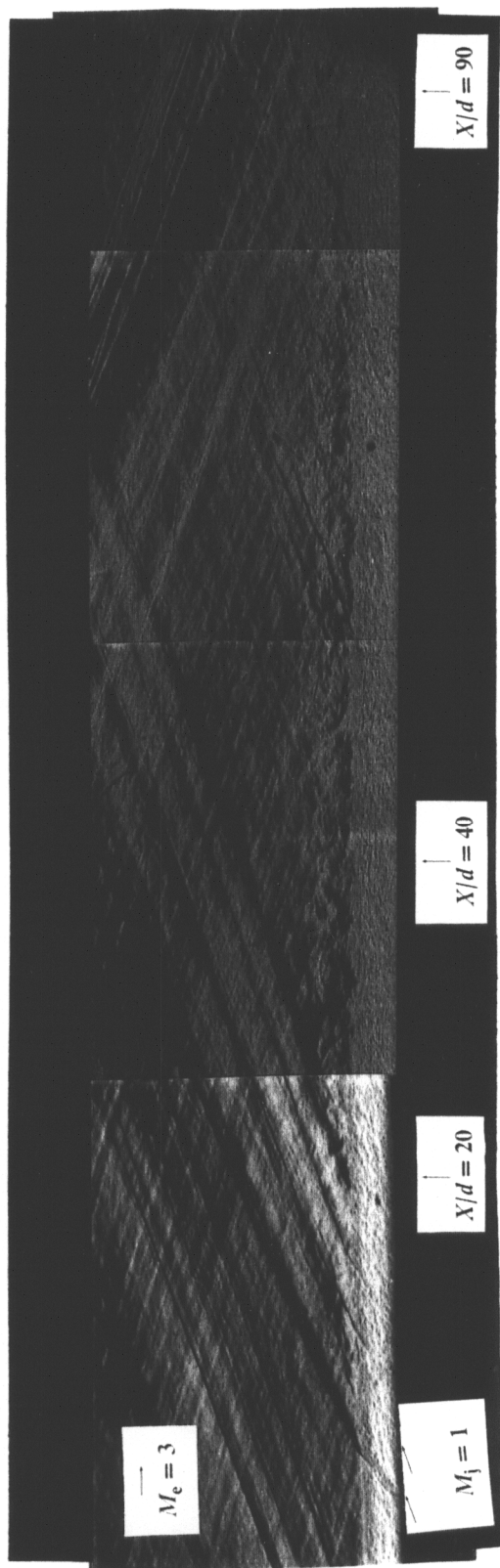


Figure 14: Concentration Probe Calibration Curves



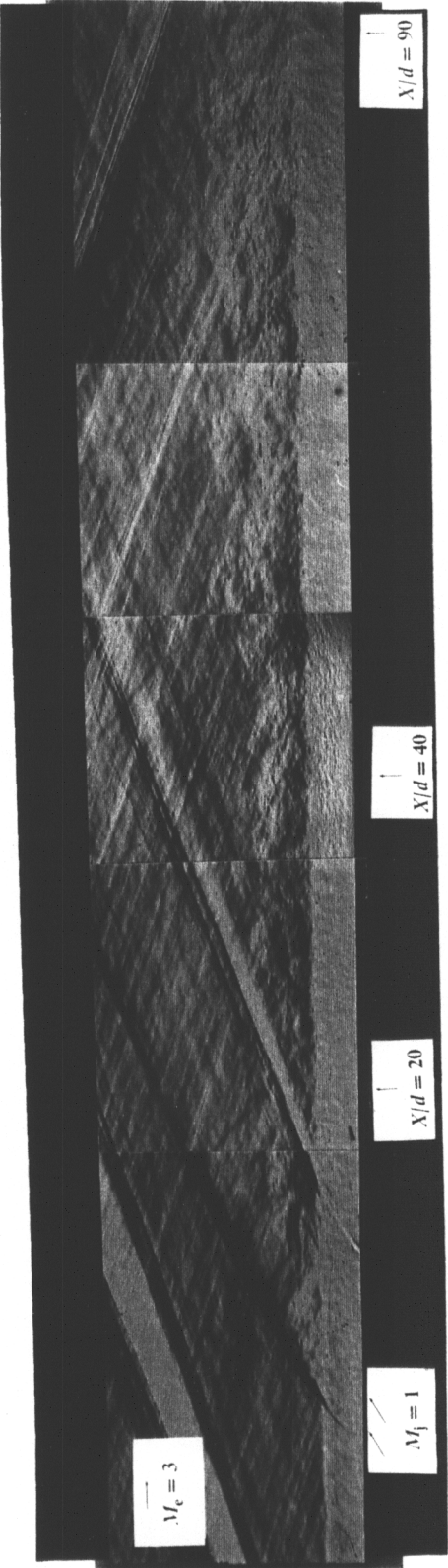
Spark Schlieren Photograph of a Fully Developed
Boundary Layer with a Freestream Airflow of
Mach 3

Figure 15: Spark Schlieren of an Undisturbed Boundary Layer



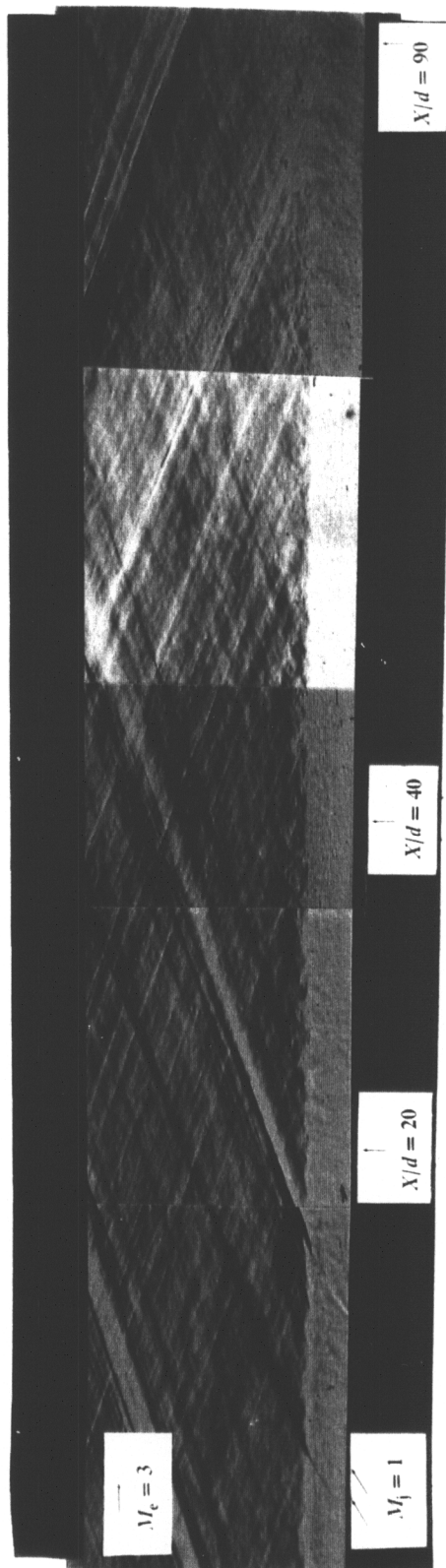
Spark Schlieren Photograph of Sonic, Underexpanded
Injection of Helium at a Downstream Angle of 15 Degrees

Figure 16: Spark Schlieren of the 15°, Underexpanded Case



Spark Schlieren Photograph of Sonic, Underexpanded
Injection of Helium at a Downstream Angle of 30 Degrees

Figure 17: Spark Schlieren of the 30°, Underexpanded Case



Spark Schlieren Photograph of Sonic, Matched Pressure
Injection of Helium at a Downstream Angle of 30 Degrees

Figure 18: Spark Schlieren of the 30°, Matched Pressure Case

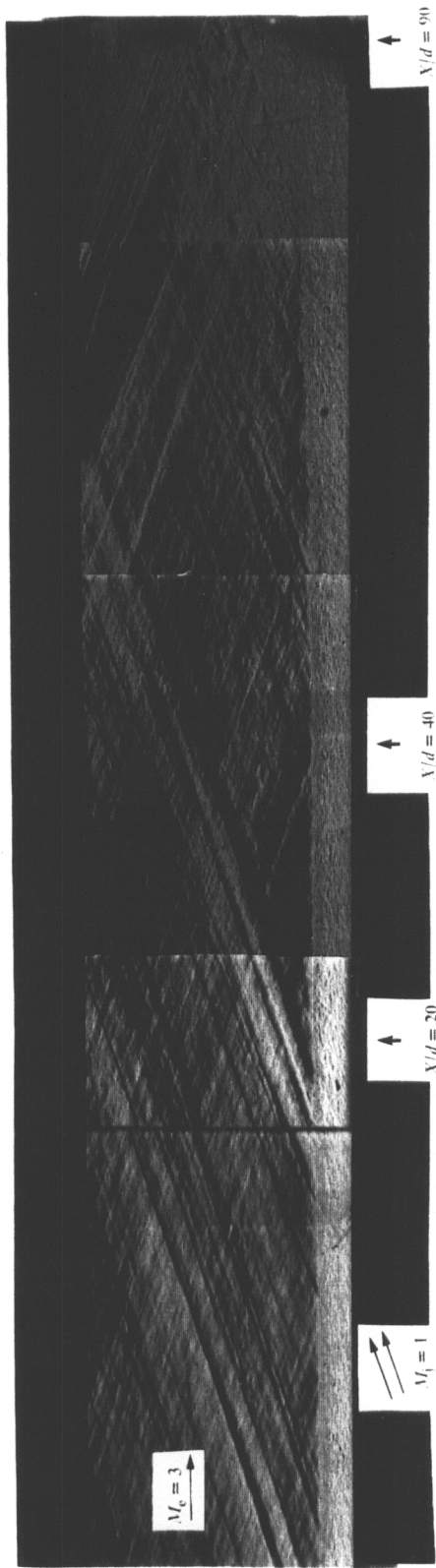
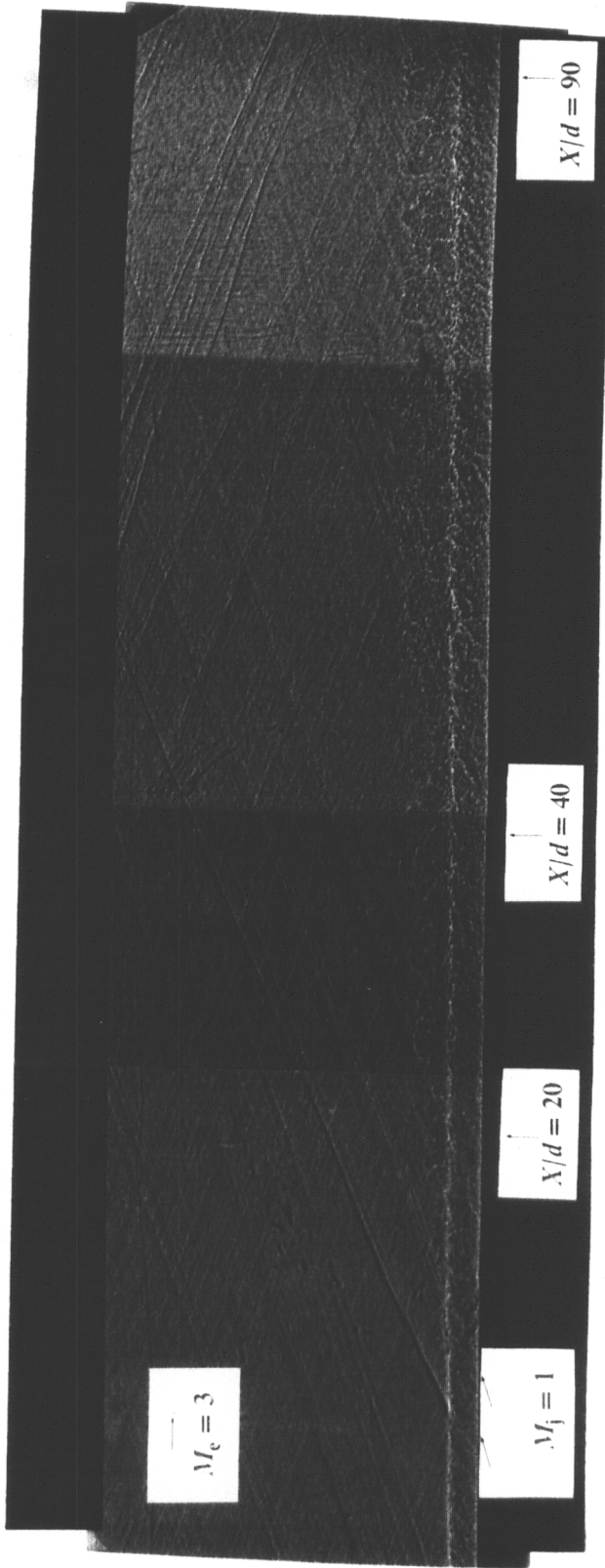
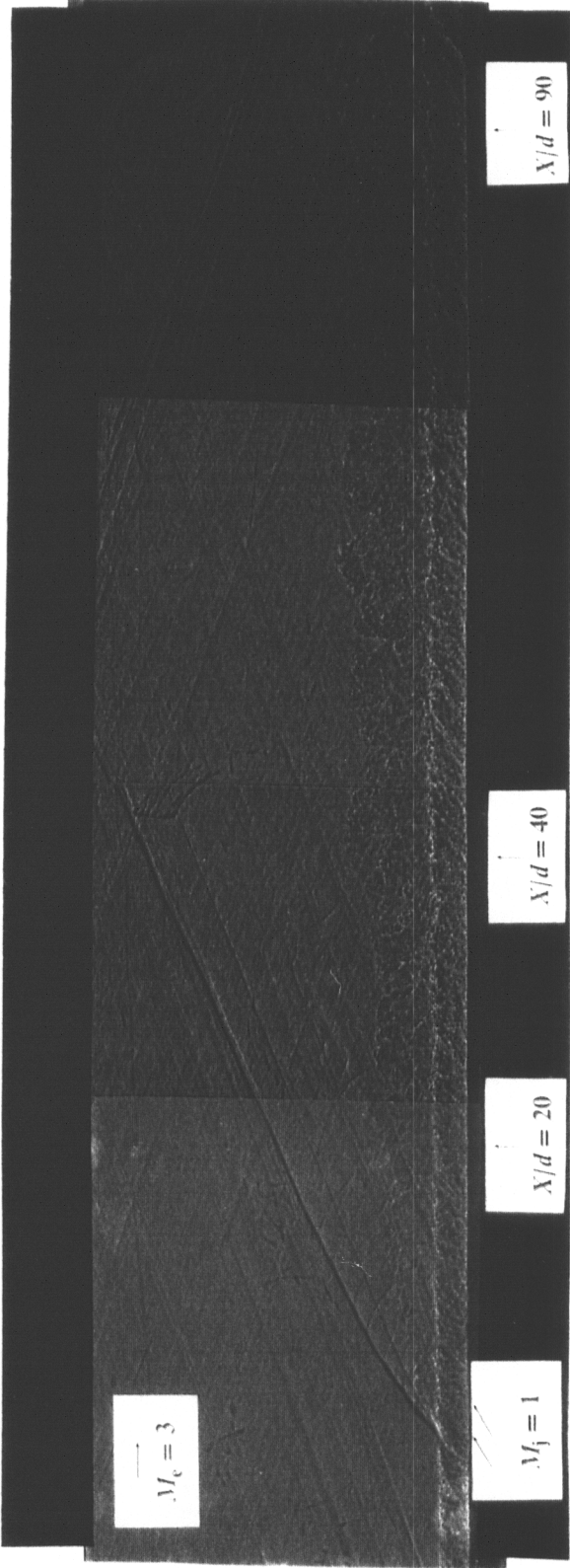


Figure 19: Spark Schlieren of the 15°, Matched Pressure Case



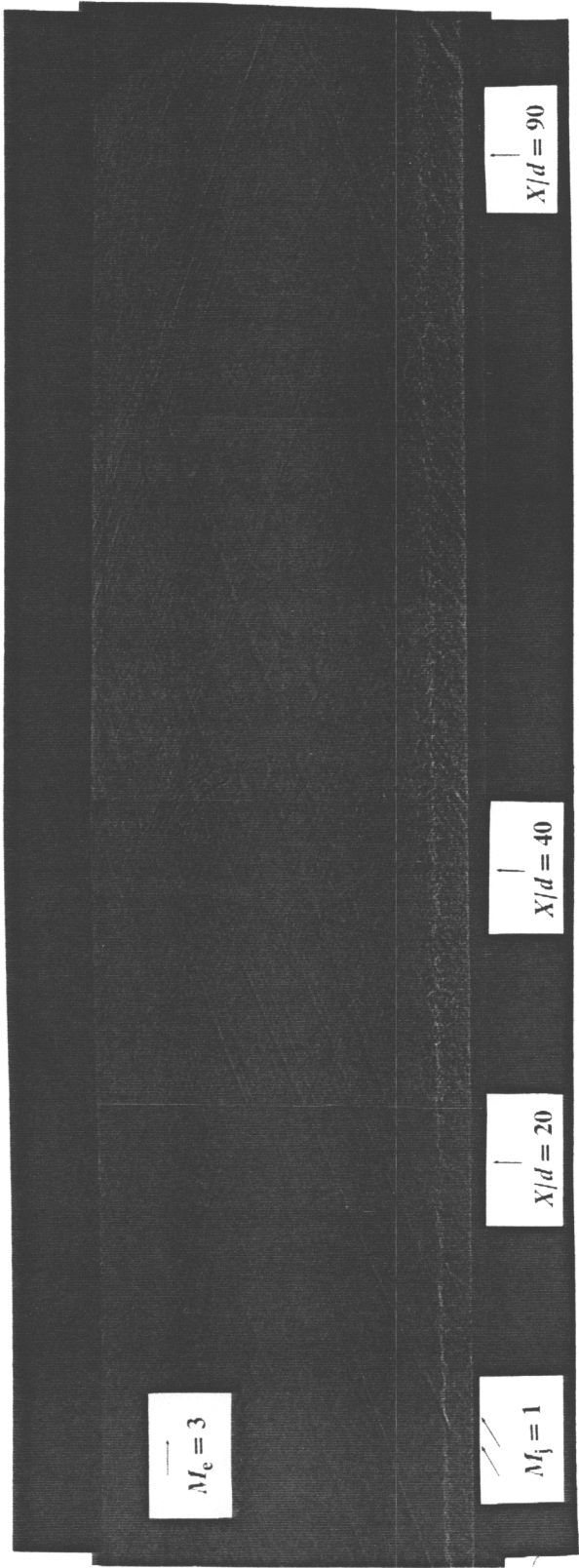
Nanoshadowgraph of Sonic, Underexpanded Injection
of Helium at a Downstream Angle of 15 Degrees

Figure 20: Nanoshadowgraph of the 15°, Underexpanded Case



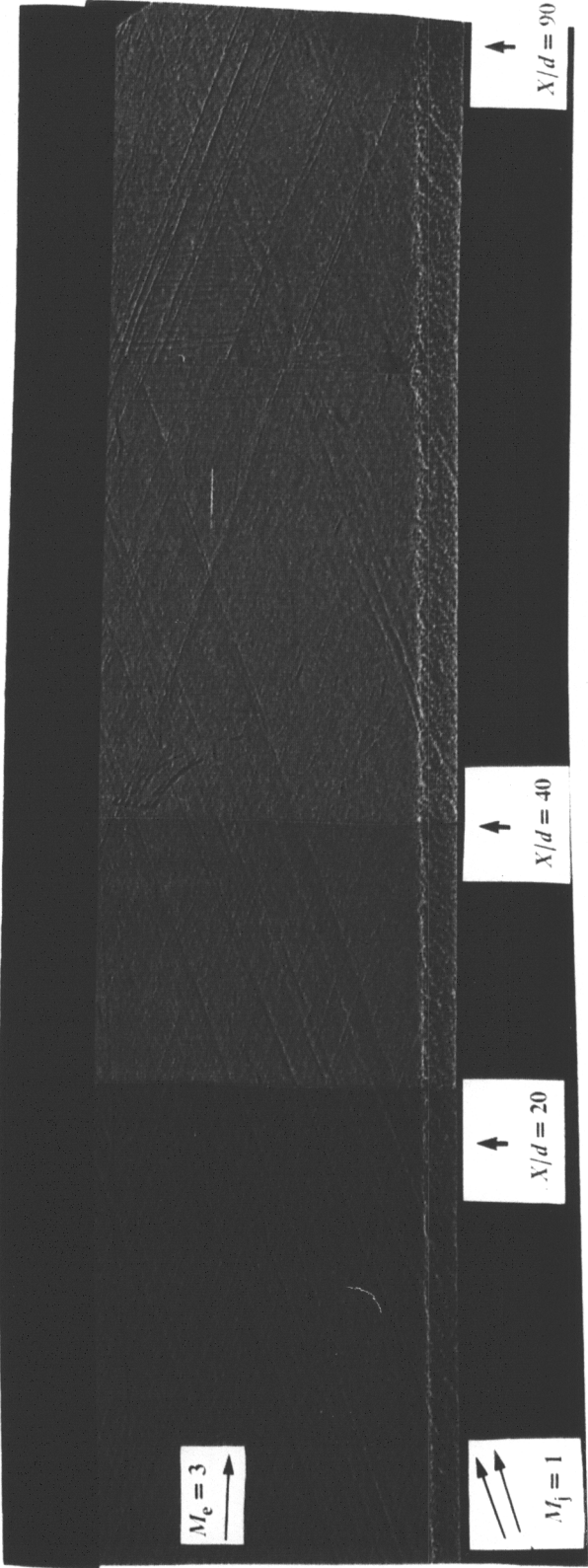
Nanoshadowgraph of Sonic, Underexpanded Injection
of Helium at a Downstream Angle of 30 Degrees

Figure 21: Nanoshadowgraph of the 30°, Underexpanded Case



Nanoshadowgraph of Sonic, Matched Pressure Injection
of Helium at a Downstream Angle of 30 Degrees

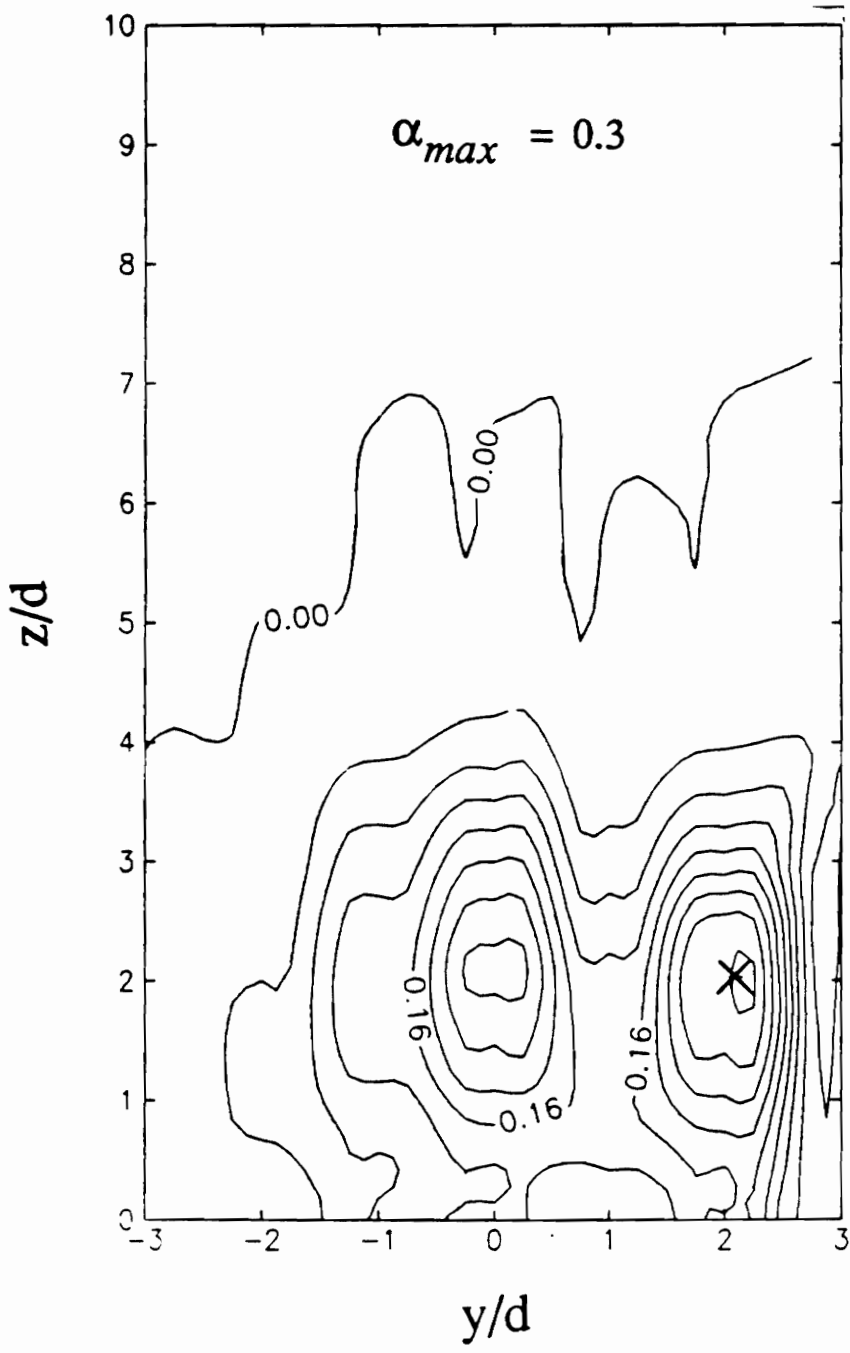
Figure 22: Nanoshadowgraph of the 30°, Matched Pressure Case



Nanoshadowgraph of Sonic, Matched Pressure Injection
of Helium at a Downstream Angle of 15 Degrees

Figure 23: Nanoshadowgraph of the 15°, Matched Pressure Case

Contour Interval: 0.04 Helium Mass Fraction



×- location of maximum He mass fraction

Figure 24: Helium Concentration for the 15°, Underexpanded Case, $x/d = 20$

Contour Interval: 0.01 Helium Mass Fraction

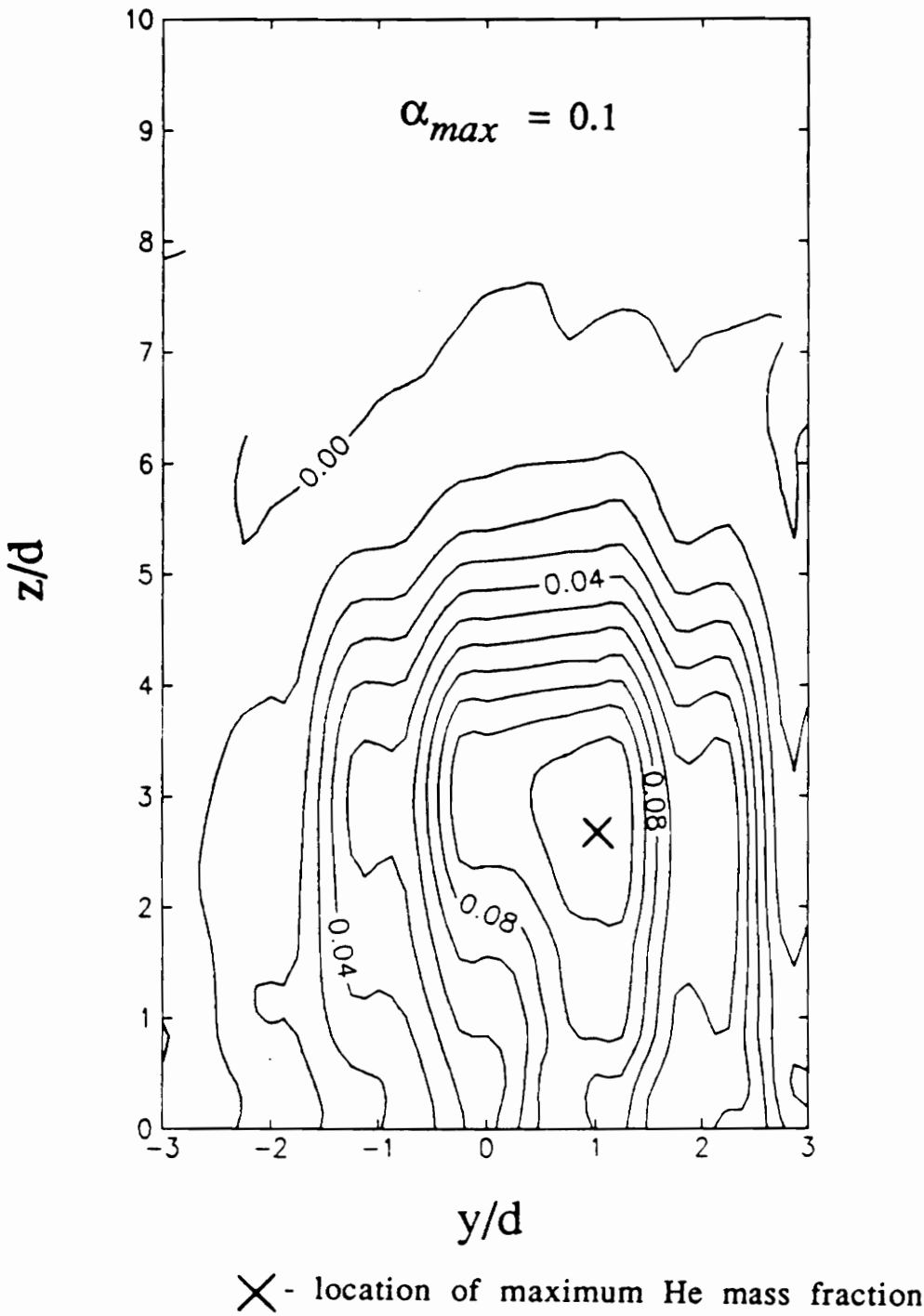
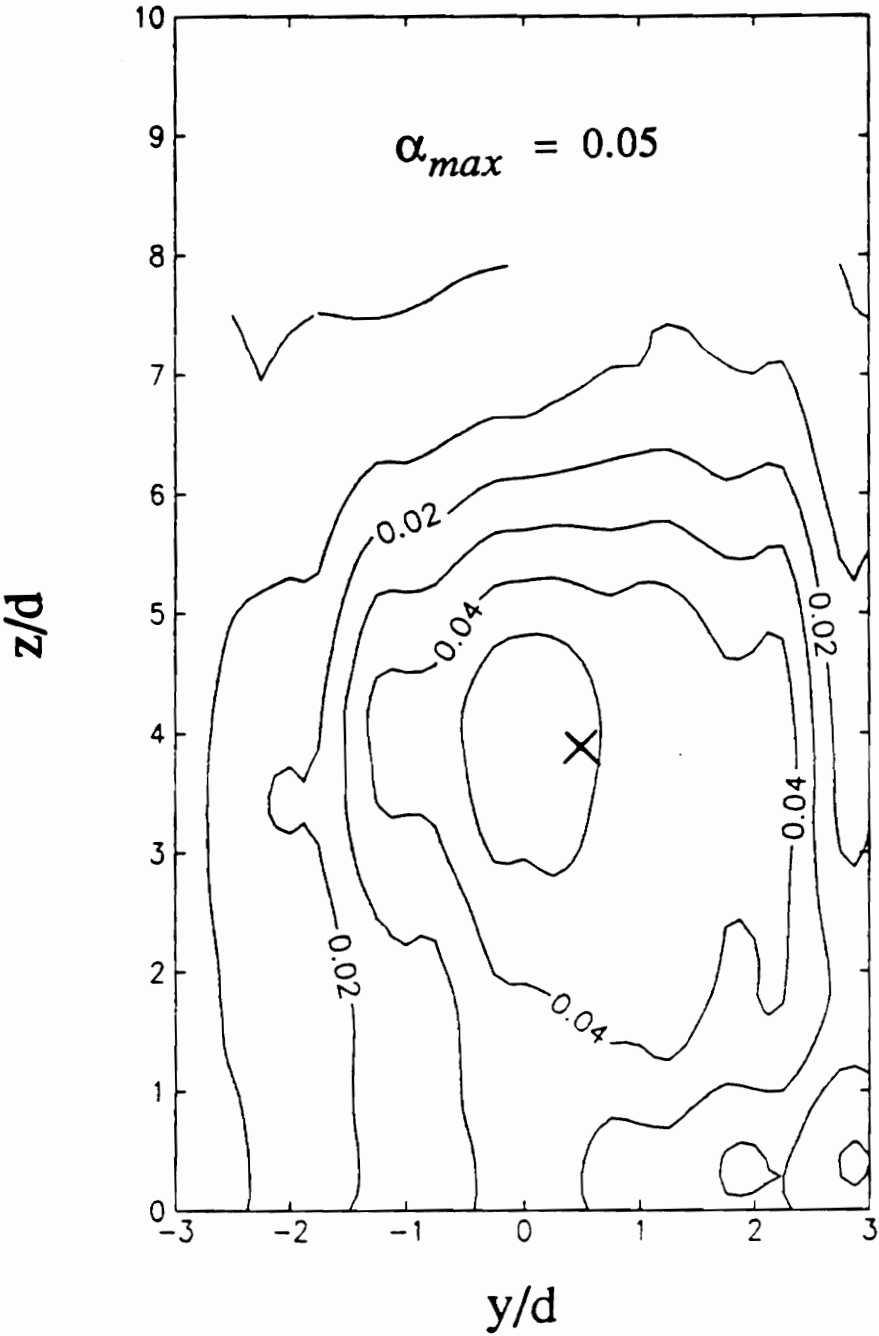


Figure 25: Helium Concentration for the 15°, Underexpanded Case, $x/d = 40$

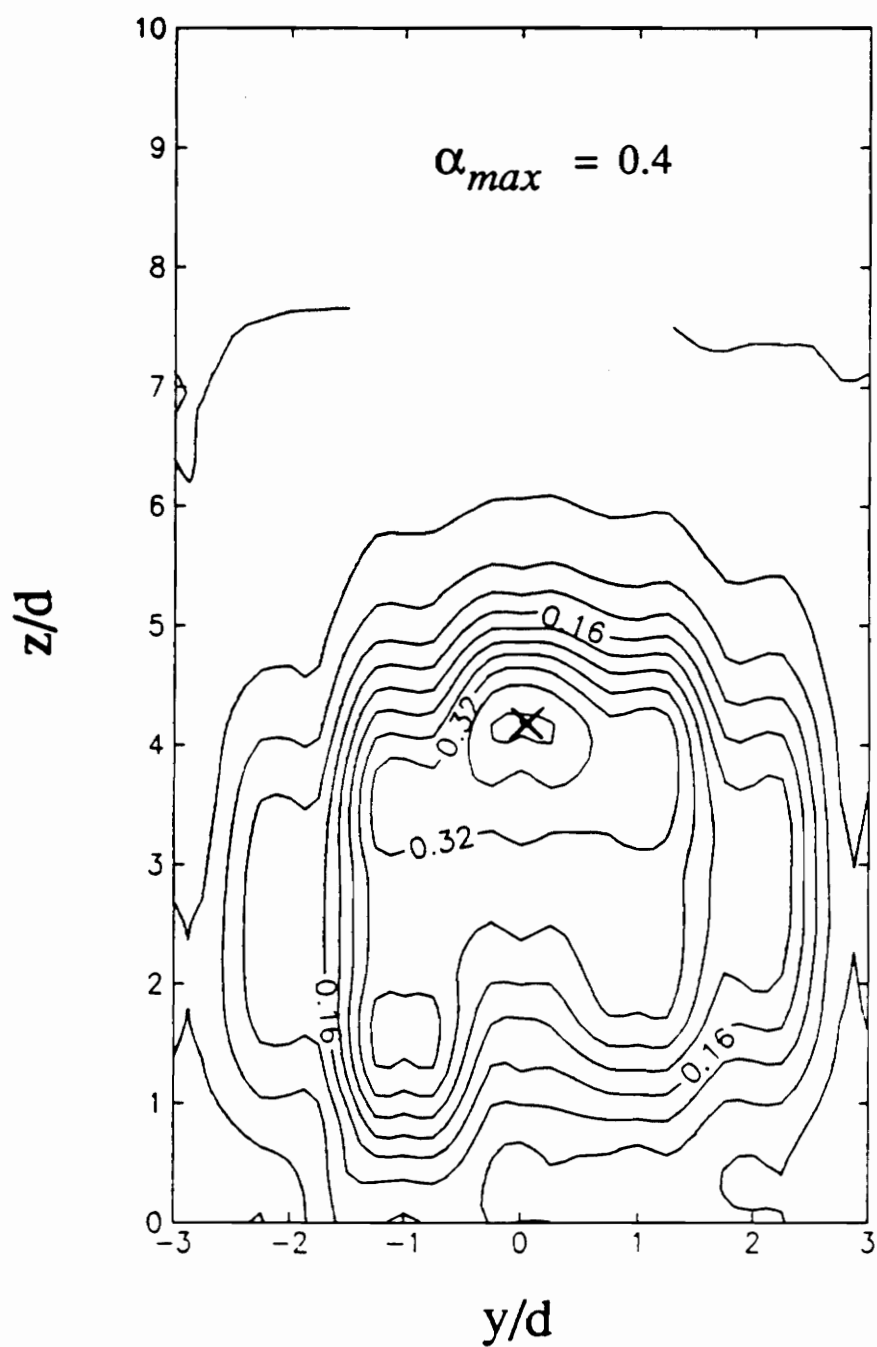
Contour Interval: 0.01 Helium Mass Fraction



X - location of maximum He mass fraction

Figure 26: Helium Concentration for the 15°, Underexpanded Case, $x/d = 90$

Contour Interval: 0.04 Helium Mass Fraction



X - location of maximum He mass fraction

Figure 27: Helium Concentration for the 30°, Underexpanded Case, $x/d = 20$

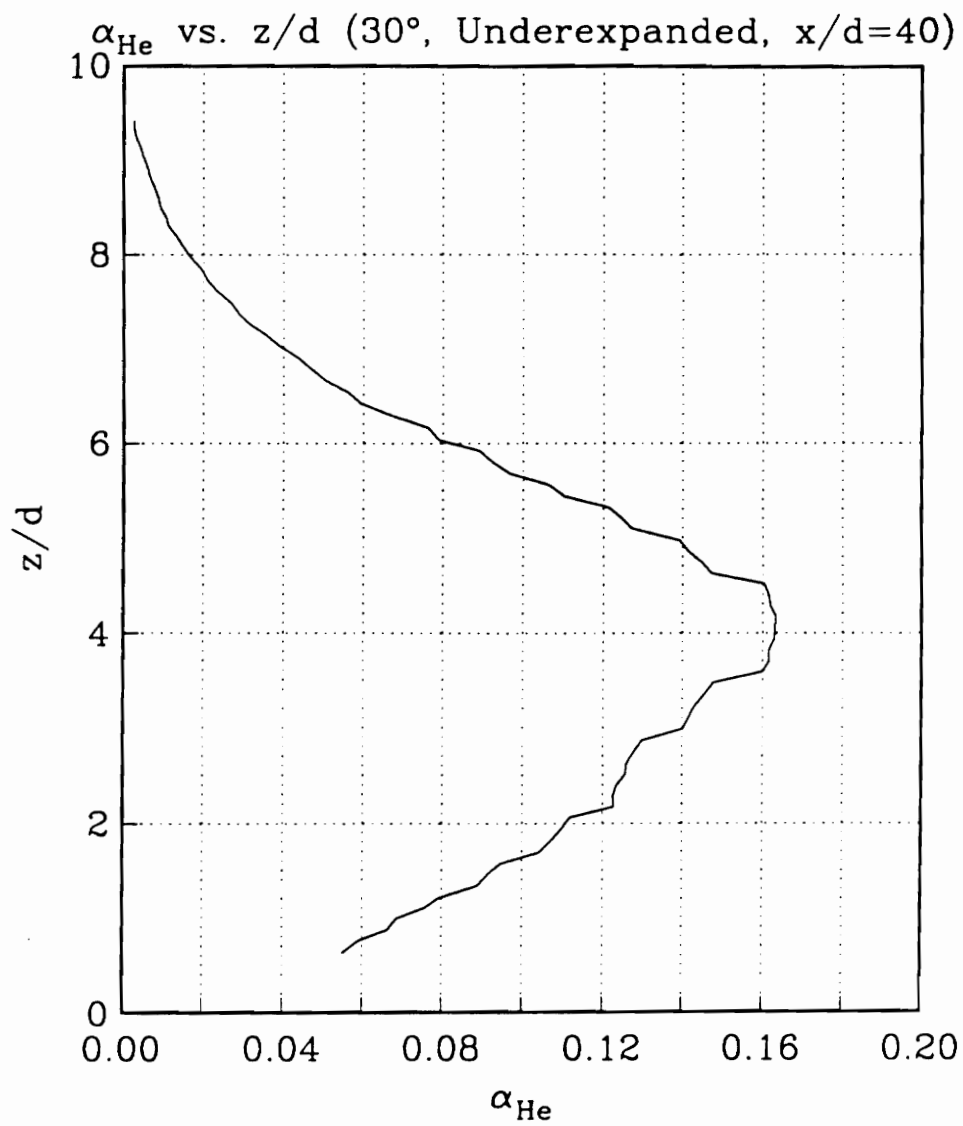


Figure 28: Helium Concentration for the 30° Underexpanded Case, $x/d = 40$

Contour Interval: 0.01 Helium Mass Fraction

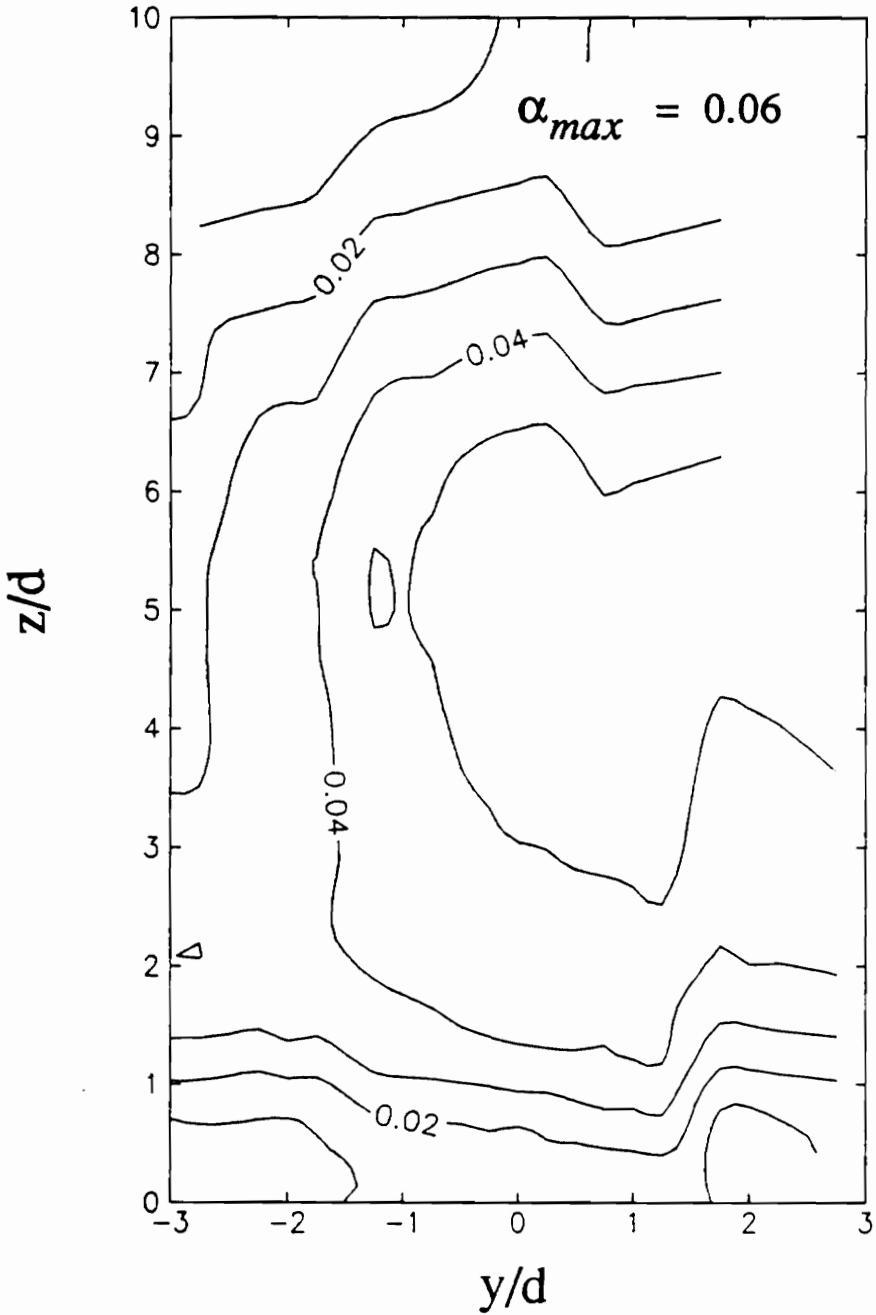
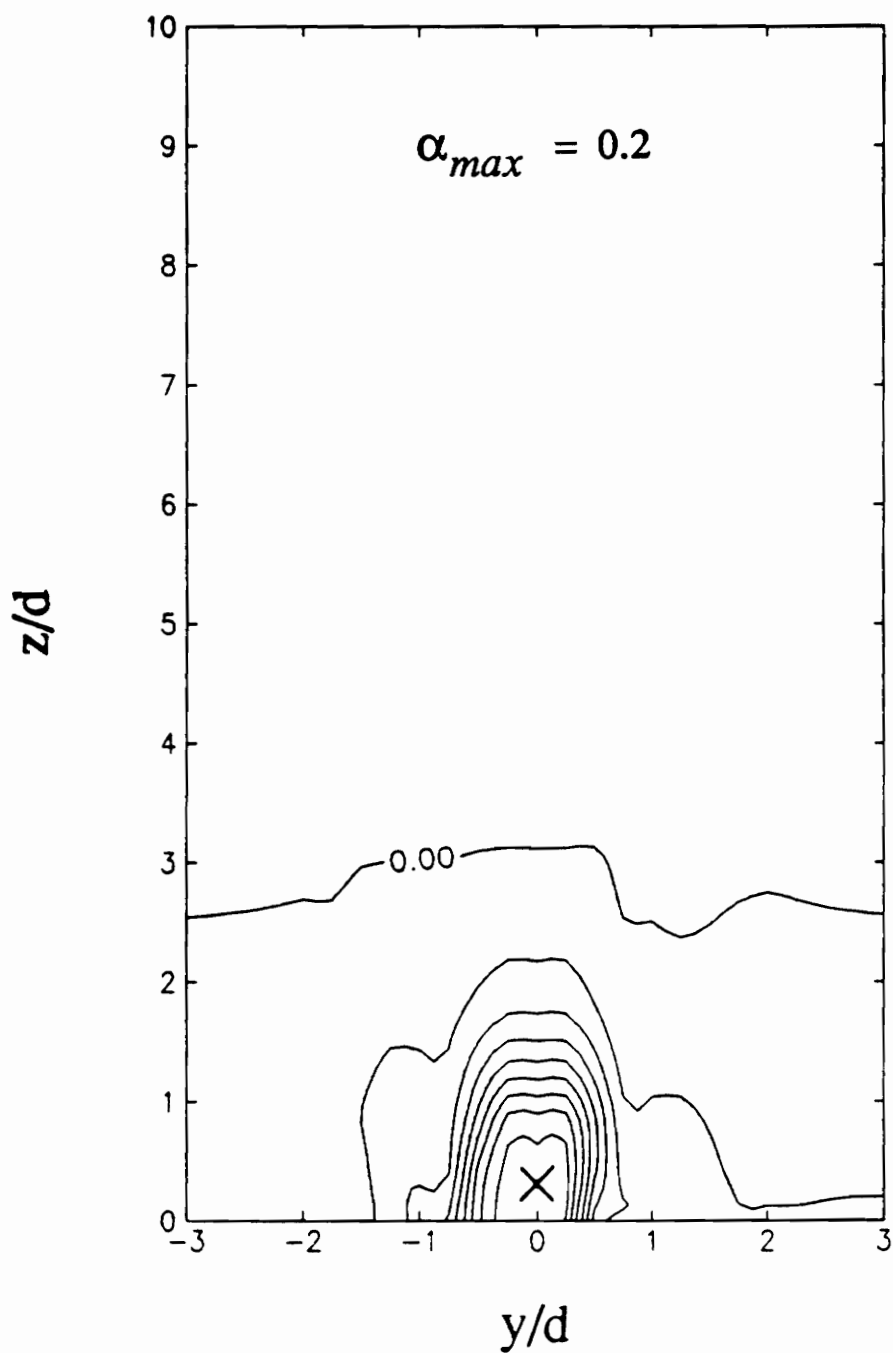


Figure 29: Helium Concentration for the 30°, Underexpanded Case, $x/d = 90$

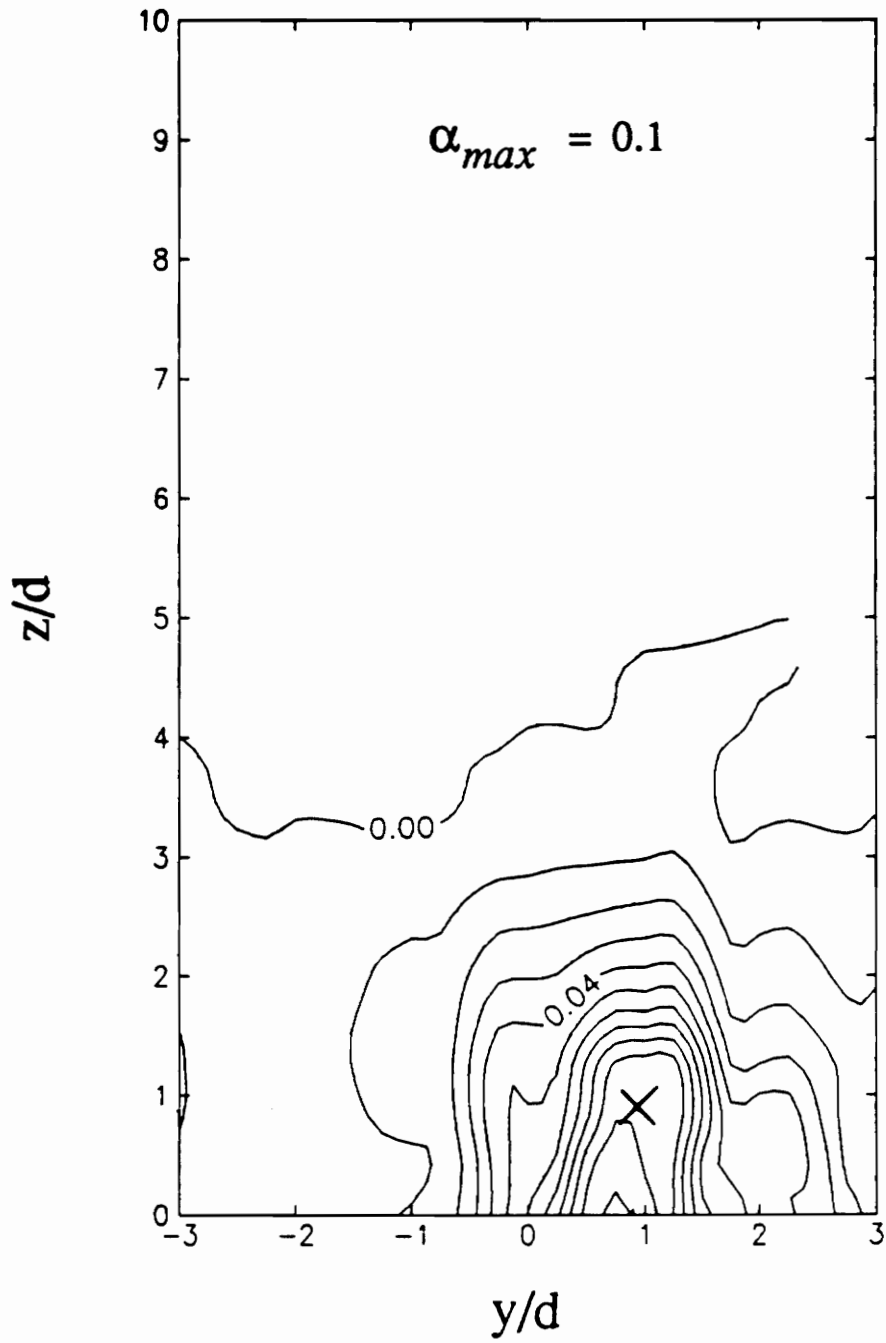
Contour Interval: 0.02 Helium Mass Fraction



X - location of maximum He mass fraction

Figure 30: Helium Concentration for the 15°, Matched Pressure Case, $x/d = 20$

Contour Interval: 0.01 Helium Mass Fraction



X- location of maximum He mass fraction

Figure 31: Helium Concentration for the 15°, Matched Pressure Case, $x/d = 40$

Contour Interval: 0.01 Helium Mass Fraction

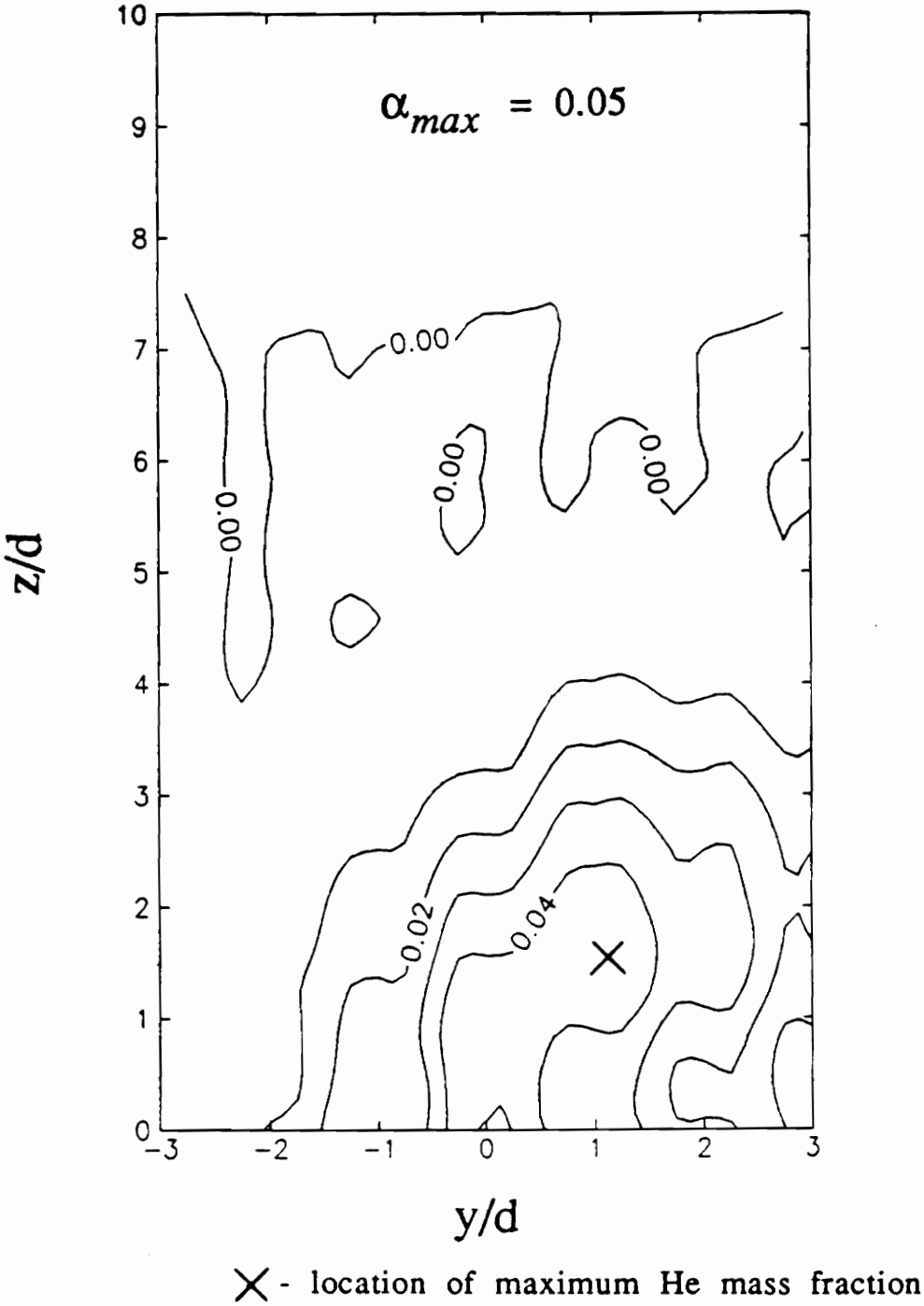
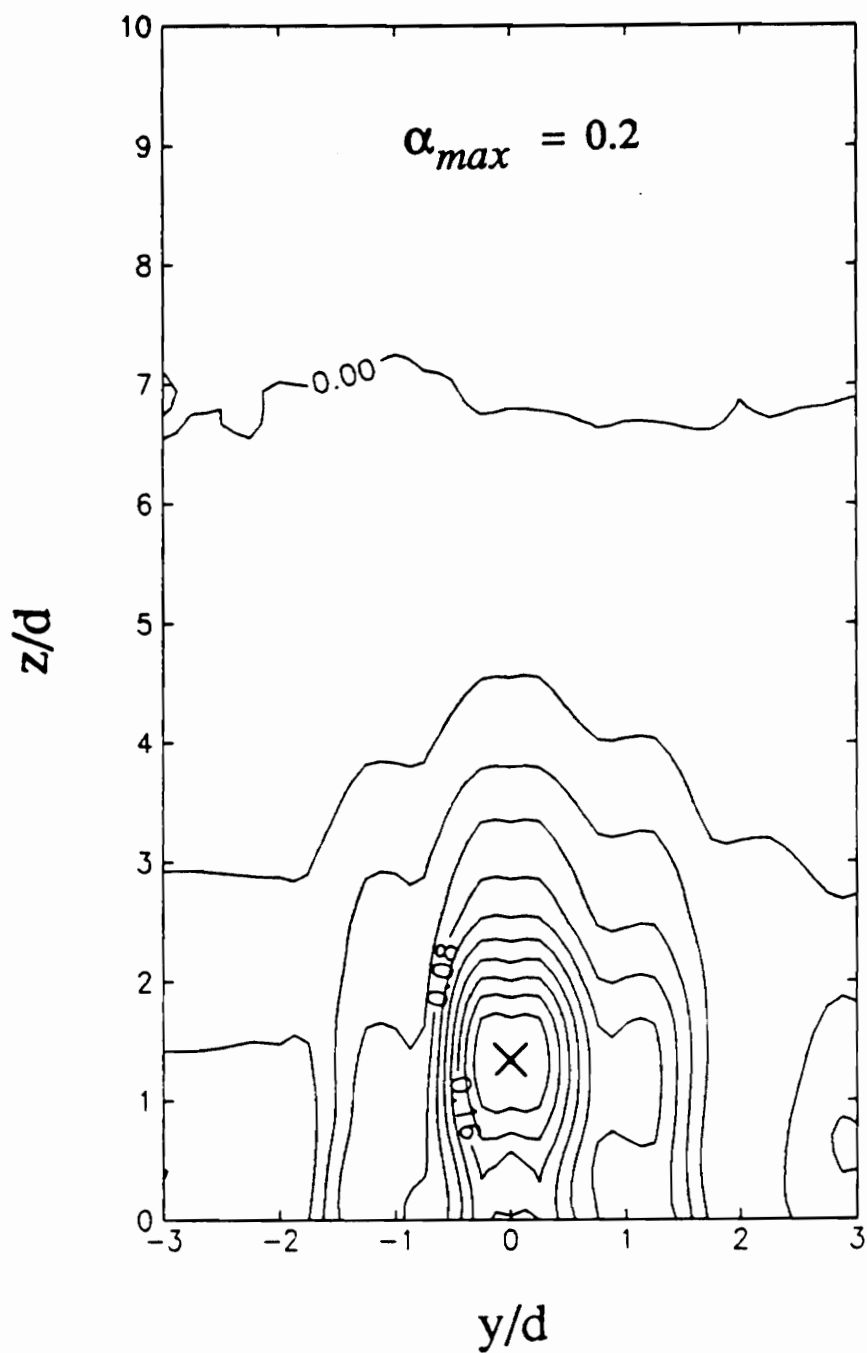


Figure 32: Helium Concentration for the 15°, Matched Pressure Case, $x/d = 90$

Contour Interval: 0.02 Helium Mass Fraction



X- location of maximum He mass fraction

Figure 33: Helium Concentration for the 30°, Matched Pressure Case, $x/d = 20$

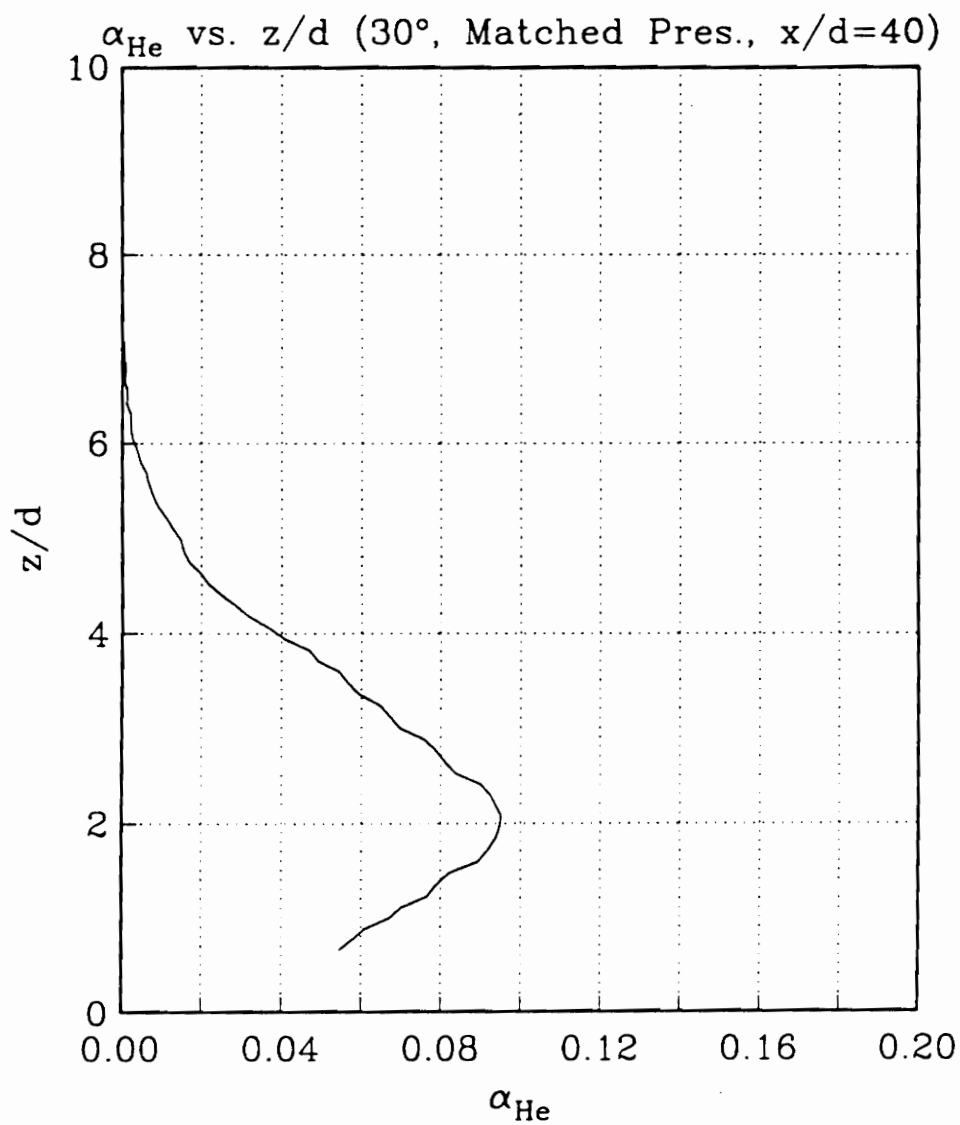


Figure 34: Helium Concentration for the 30°, Matched Pressure Case, $x/d = 40$

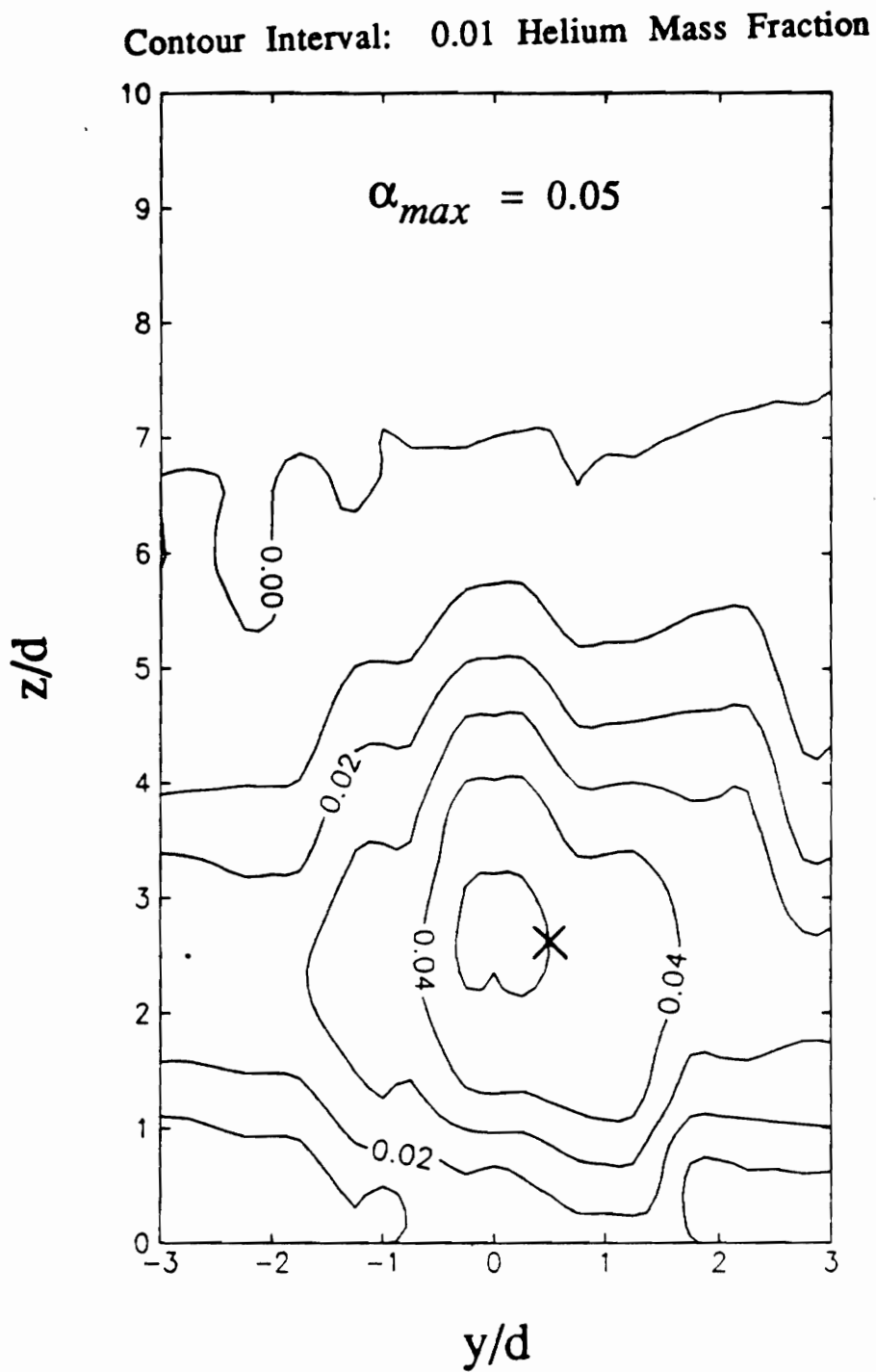


Figure 35: Helium Concentration for the 30°, Matched Pressure Case, $x/d = 90$

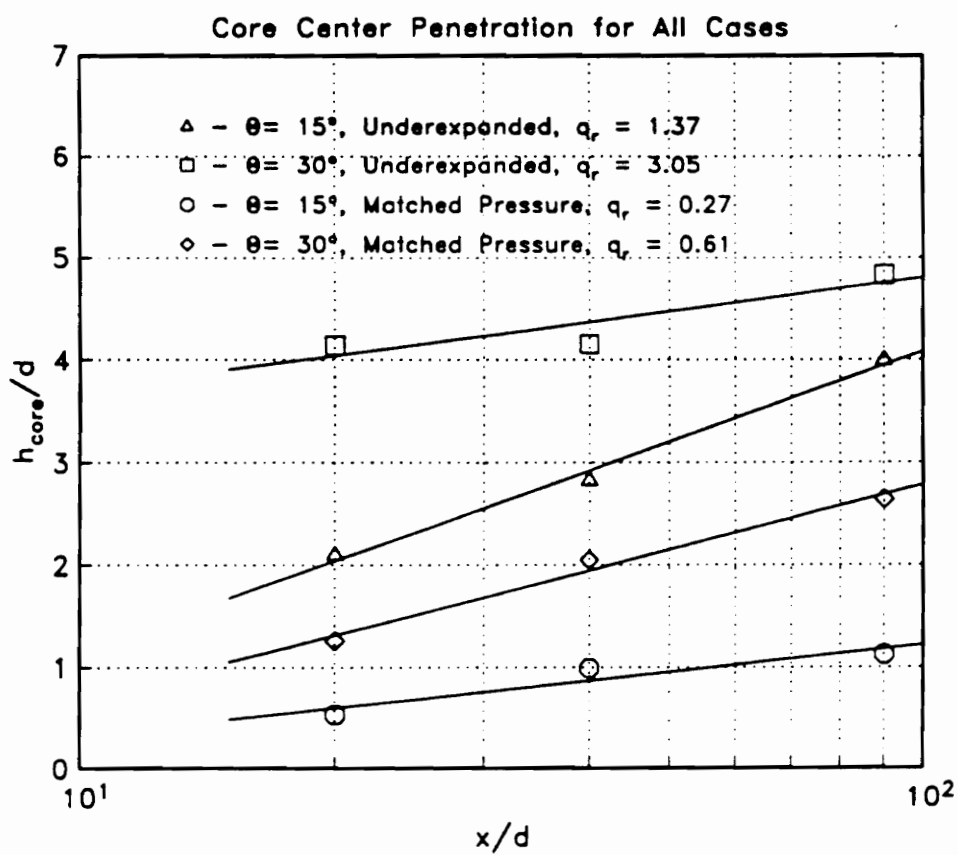


Figure 36: Core Penetration for All Cases

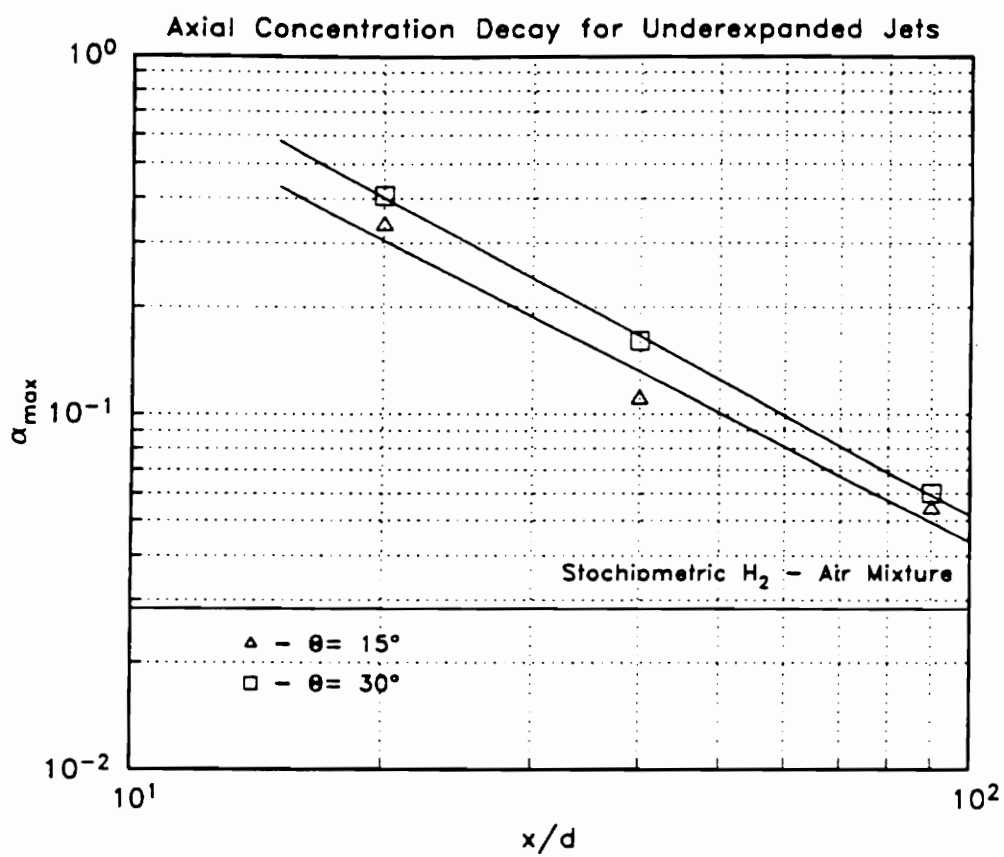


Figure 37: Decay of Helium Concentration, Underexpanded Cases

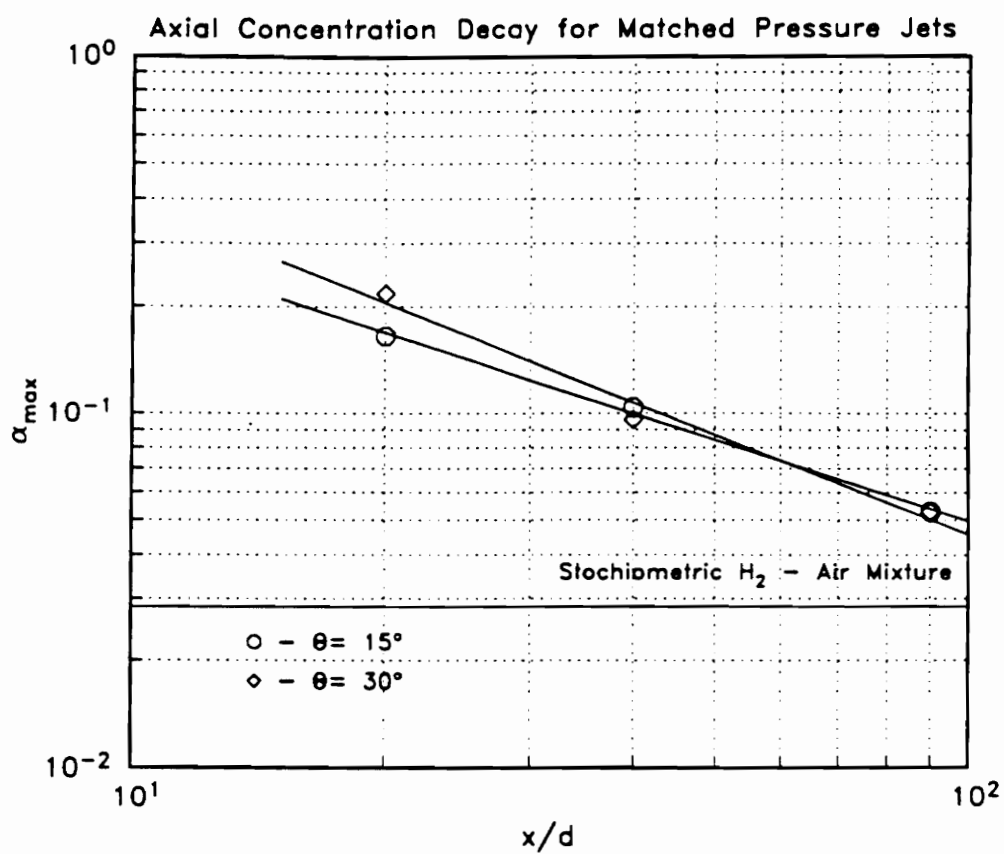


Figure 38: Decay of Helium Concentration, Matched Pressure Cases

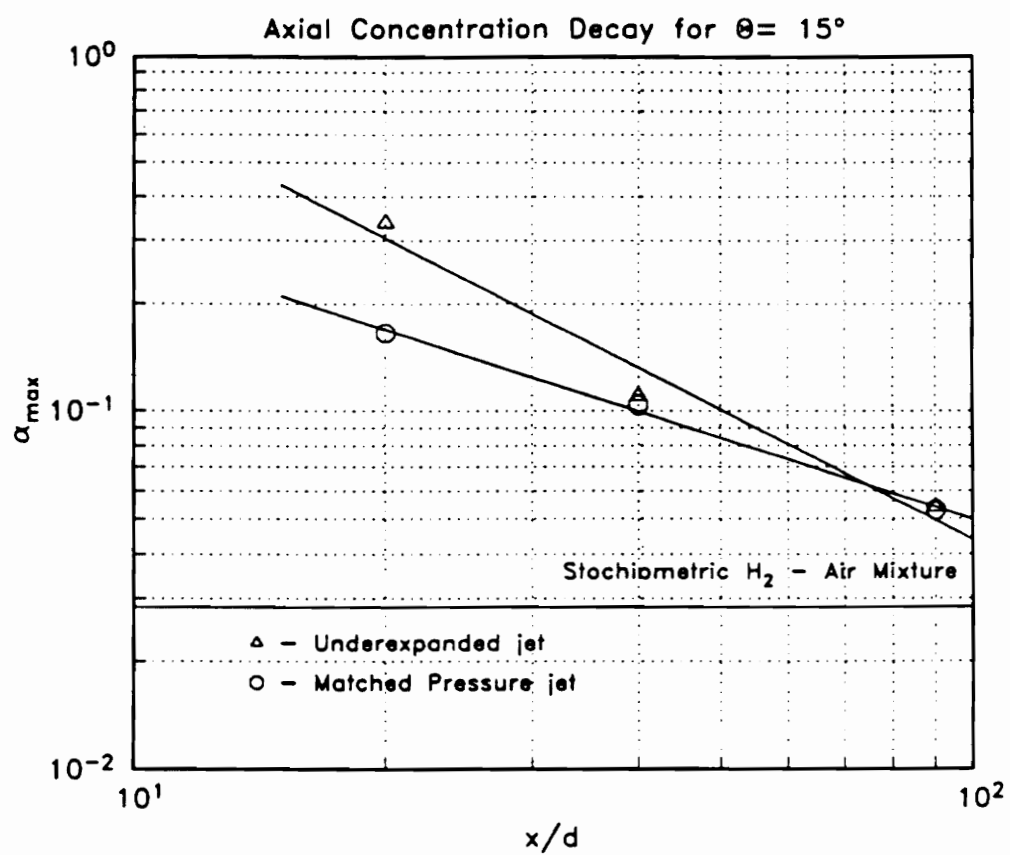


Figure 39: Decay of Helium Concentration, 15° Injection Angle Cases

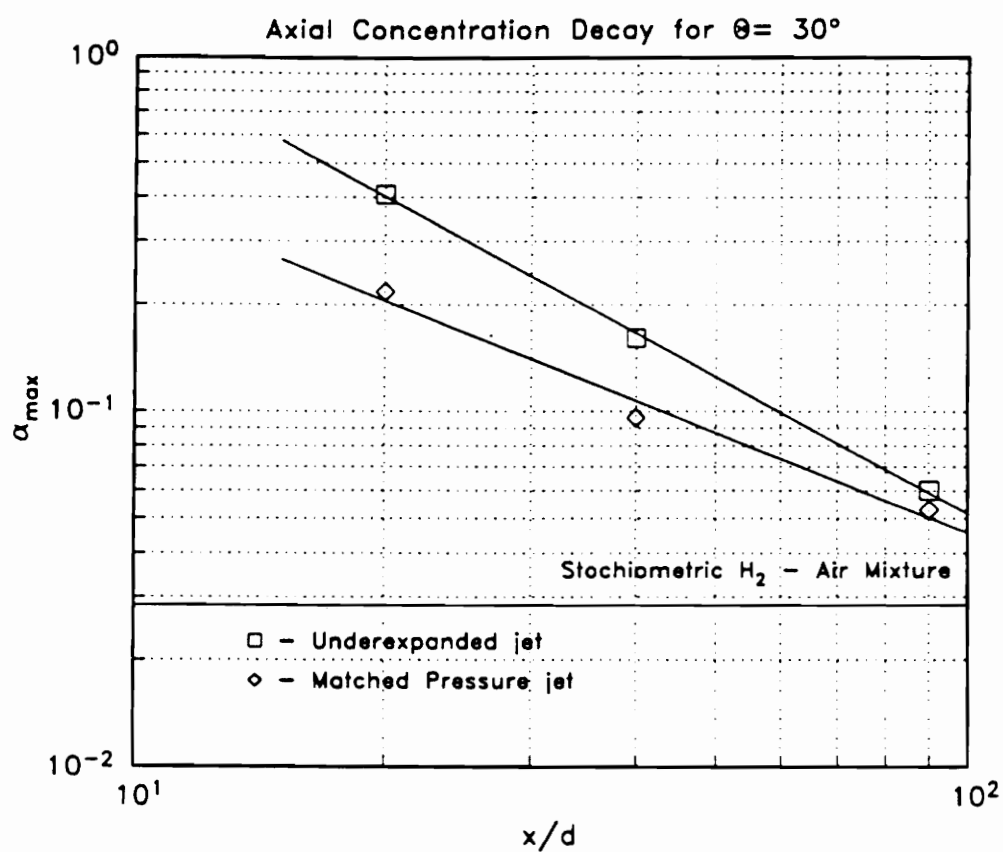


Figure 40: Decay of Helium Concentration, 30° Injection Angle Cases

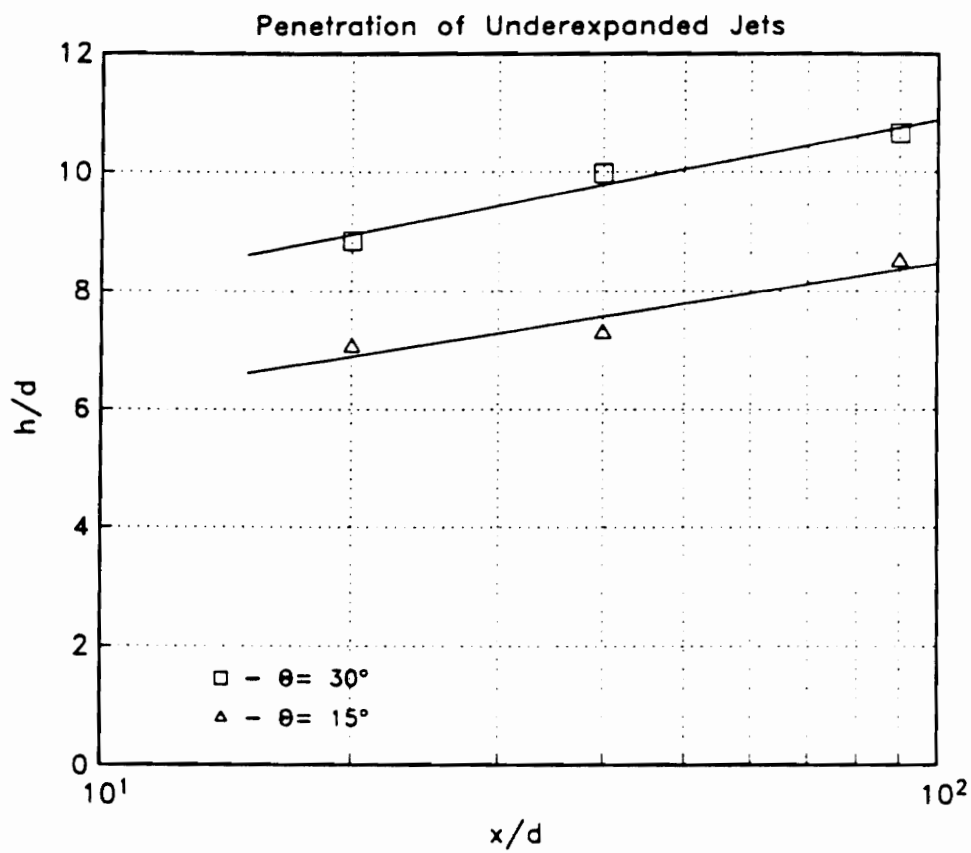


Figure 41: Penetration of Underexpanded Cases

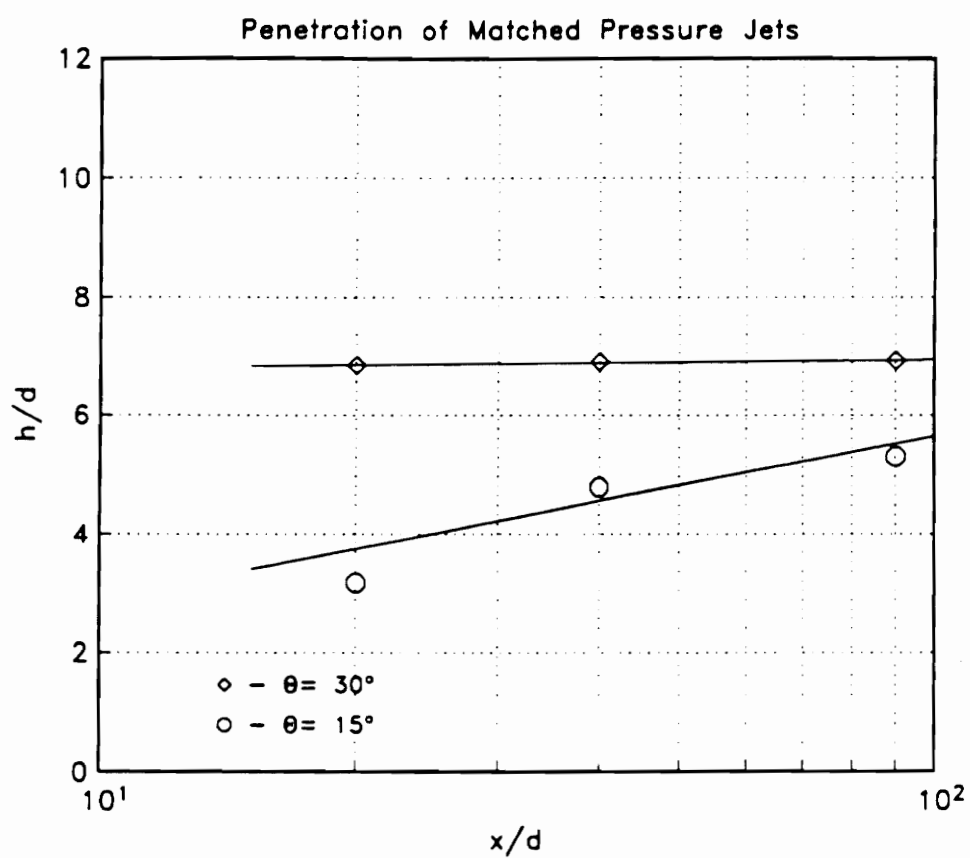


Figure 42: Penetration of Matched Pressure Cases

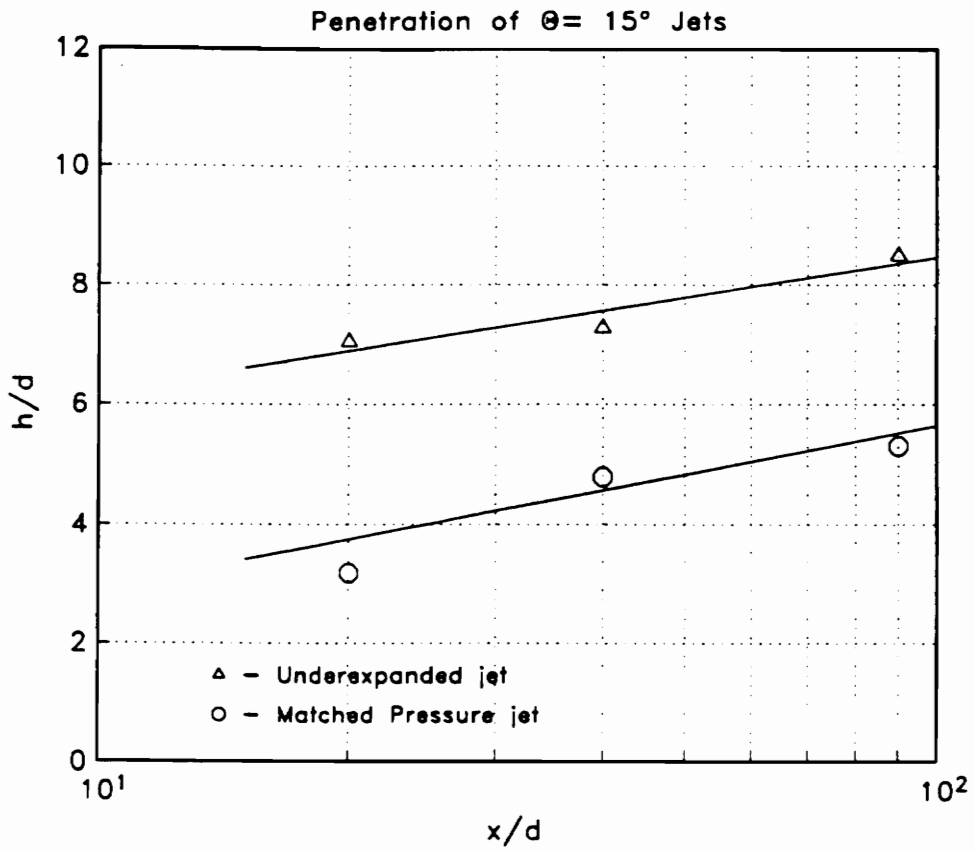


Figure 43: Penetration of 15° Injection Angle Cases

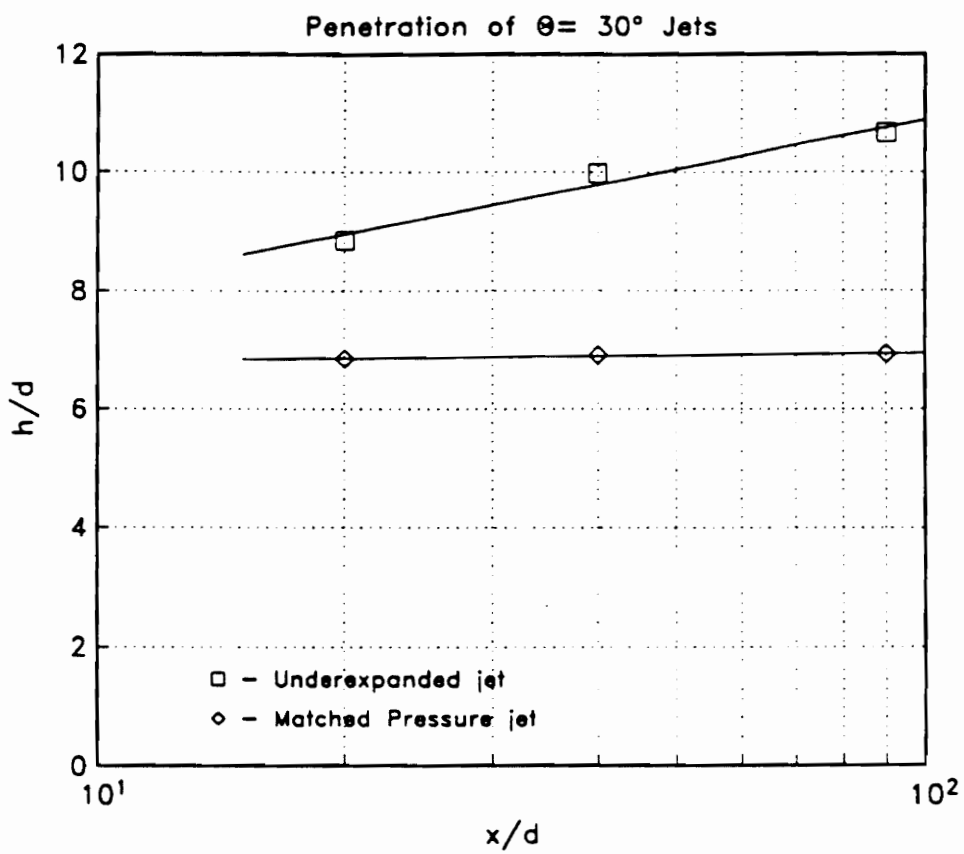


Figure 44: Penetration of 30° Injection Angle Cases

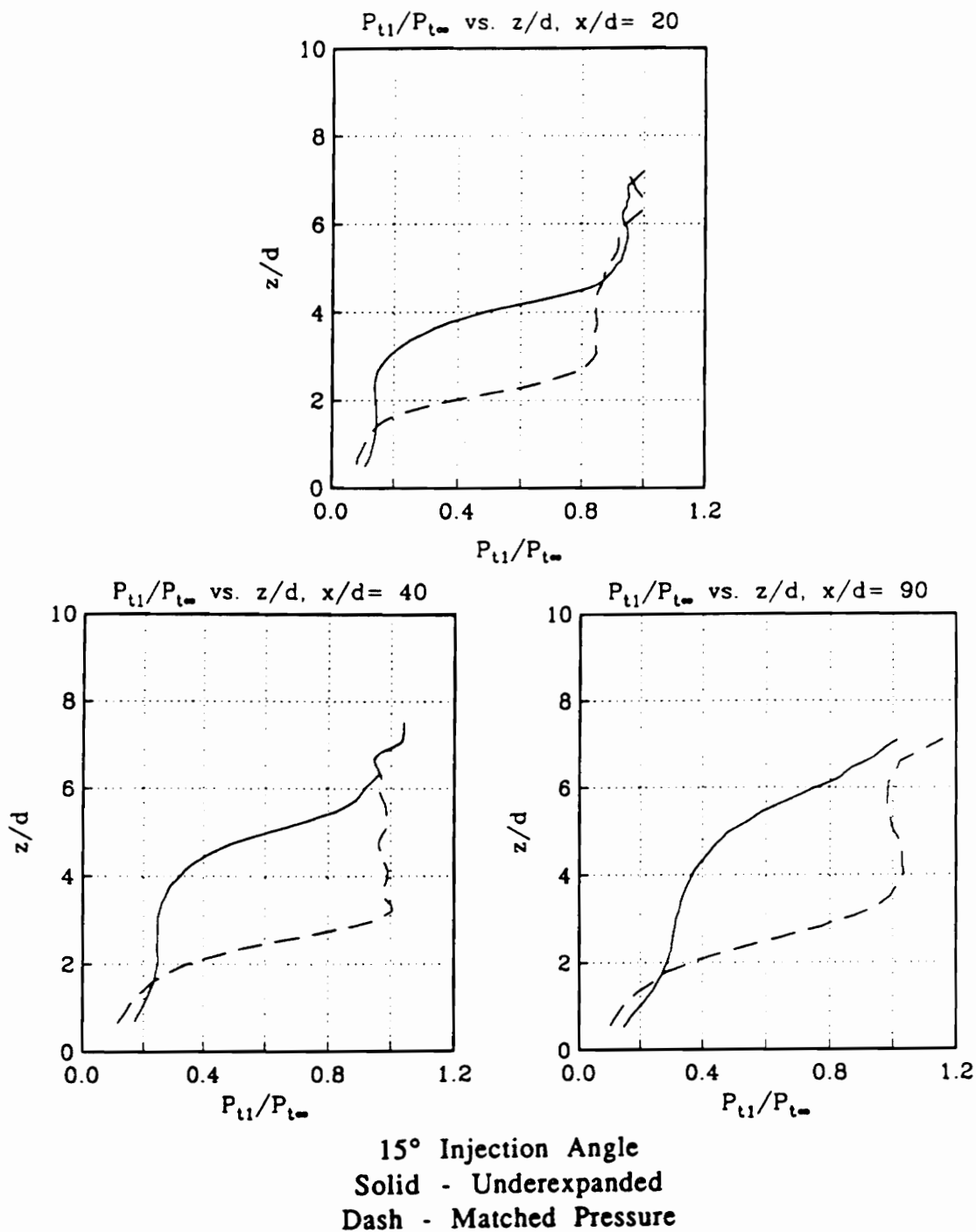


Figure 45: Total Pressure Profiles of the 15° Injection Angle Cases

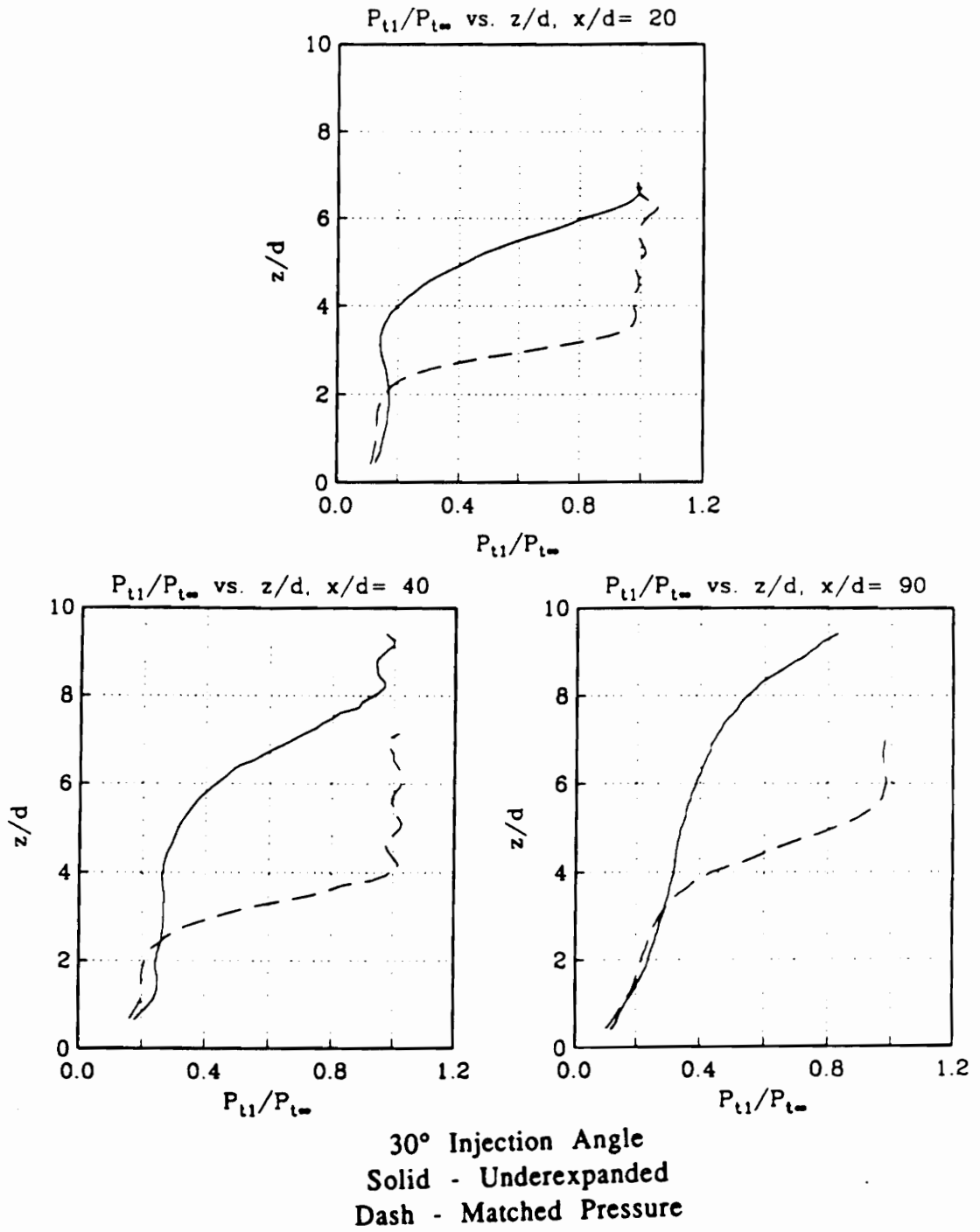


Figure 46: Total Pressure Profiles of the 30° Injection Angle Cases

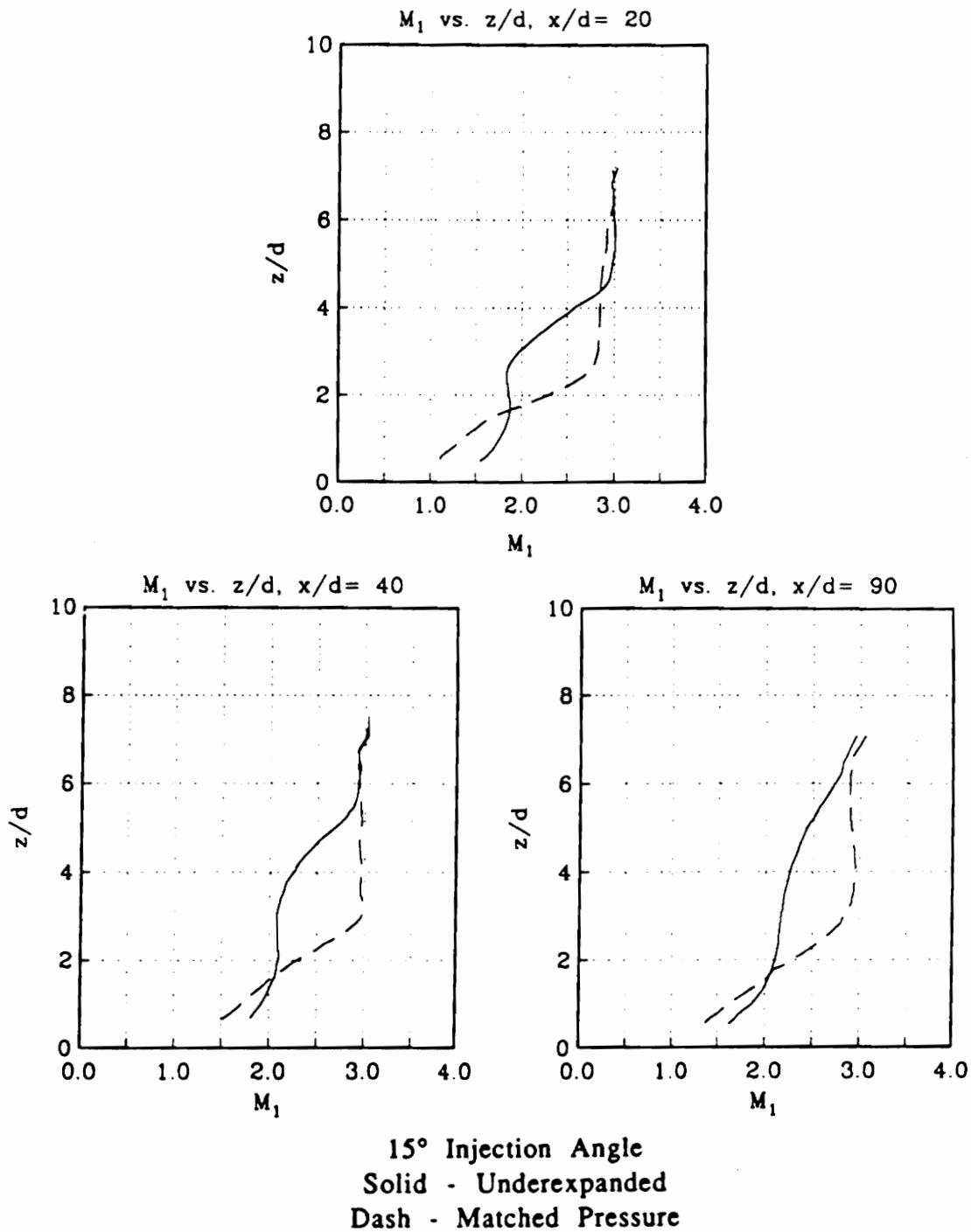


Figure 47: Mach Number Profiles of the 15° Injection Angle Cases

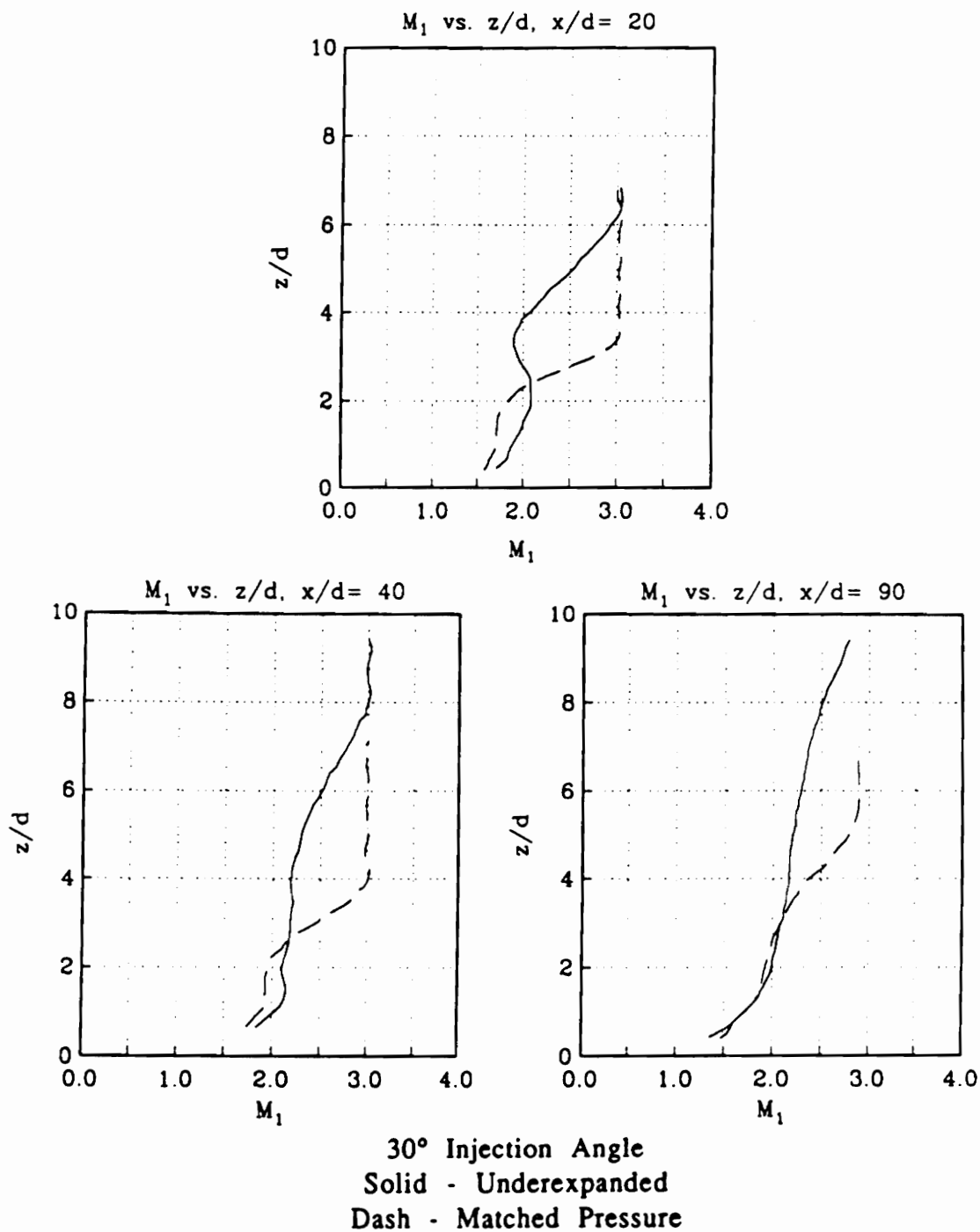


Figure 48: Mach Number Profiles of the 30° Injection Angle Cases

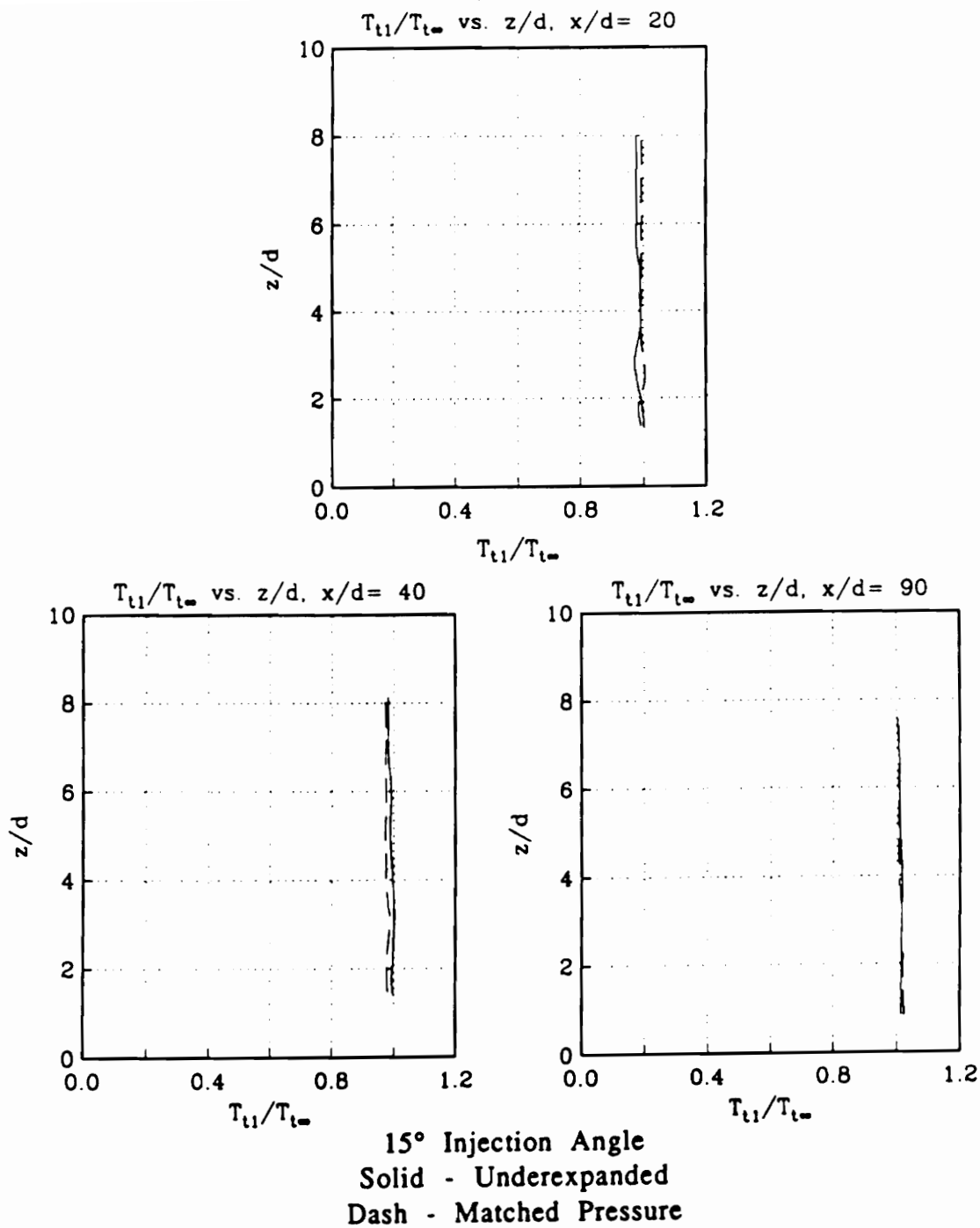


Figure 49: Total Temperature Profiles of the 15° Injection Angle Cases

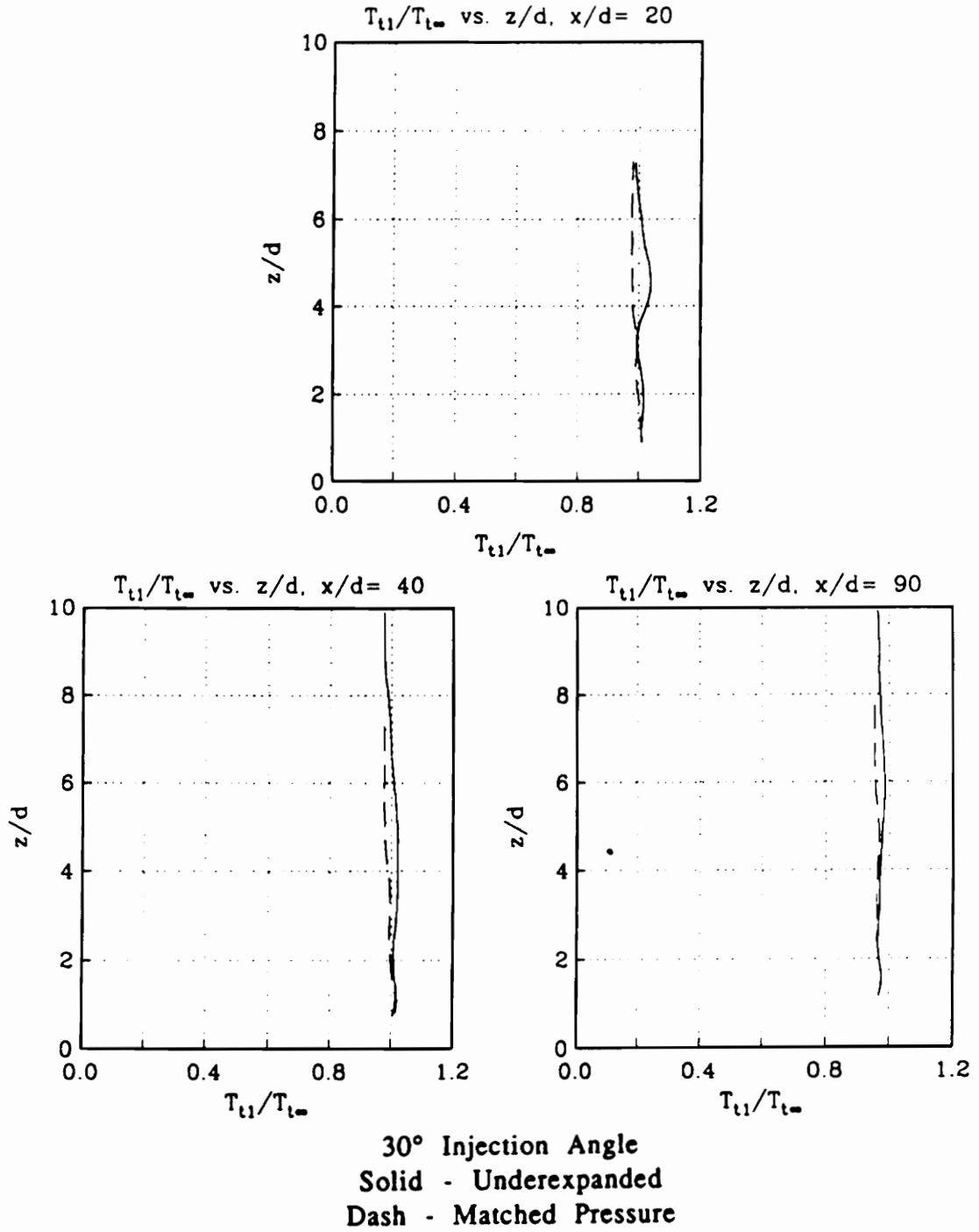


Figure 50: Total Temperature Profiles of the 30° Injection Angle Cases

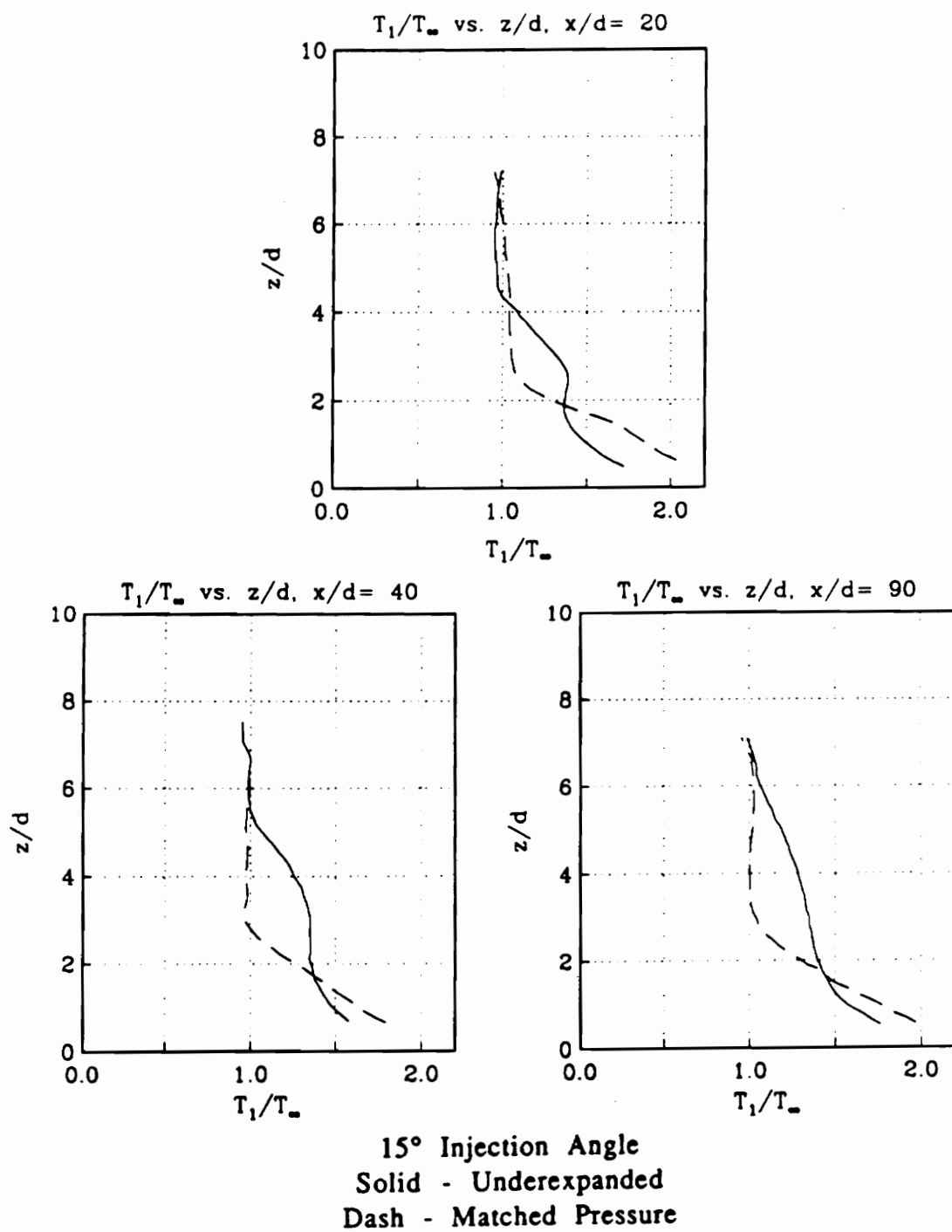


Figure 51: Static Temperature Profiles of the 15° Injection Angle Cases

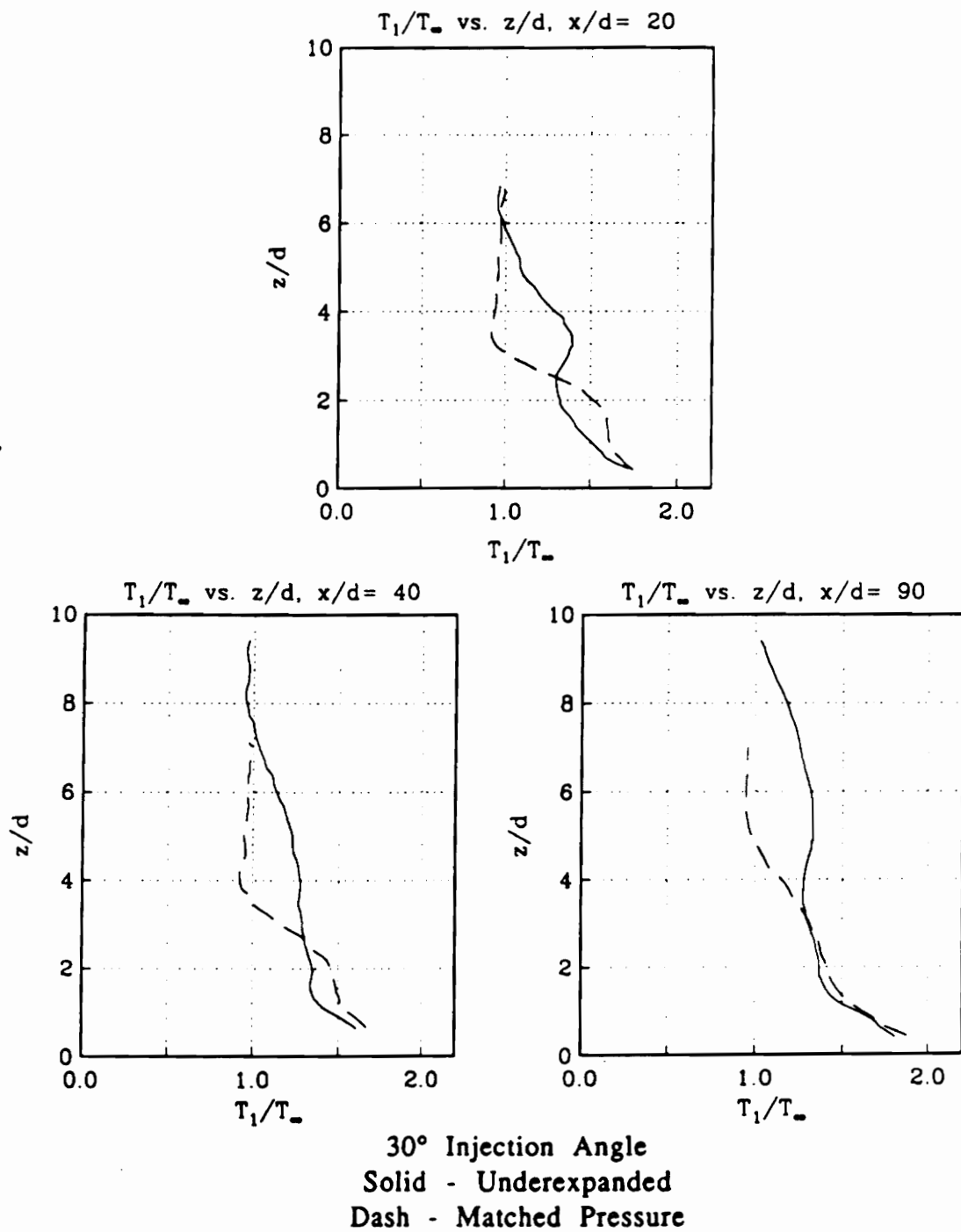


Figure 52: Static Temperature Profiles of the 30° Injection Angle Cases

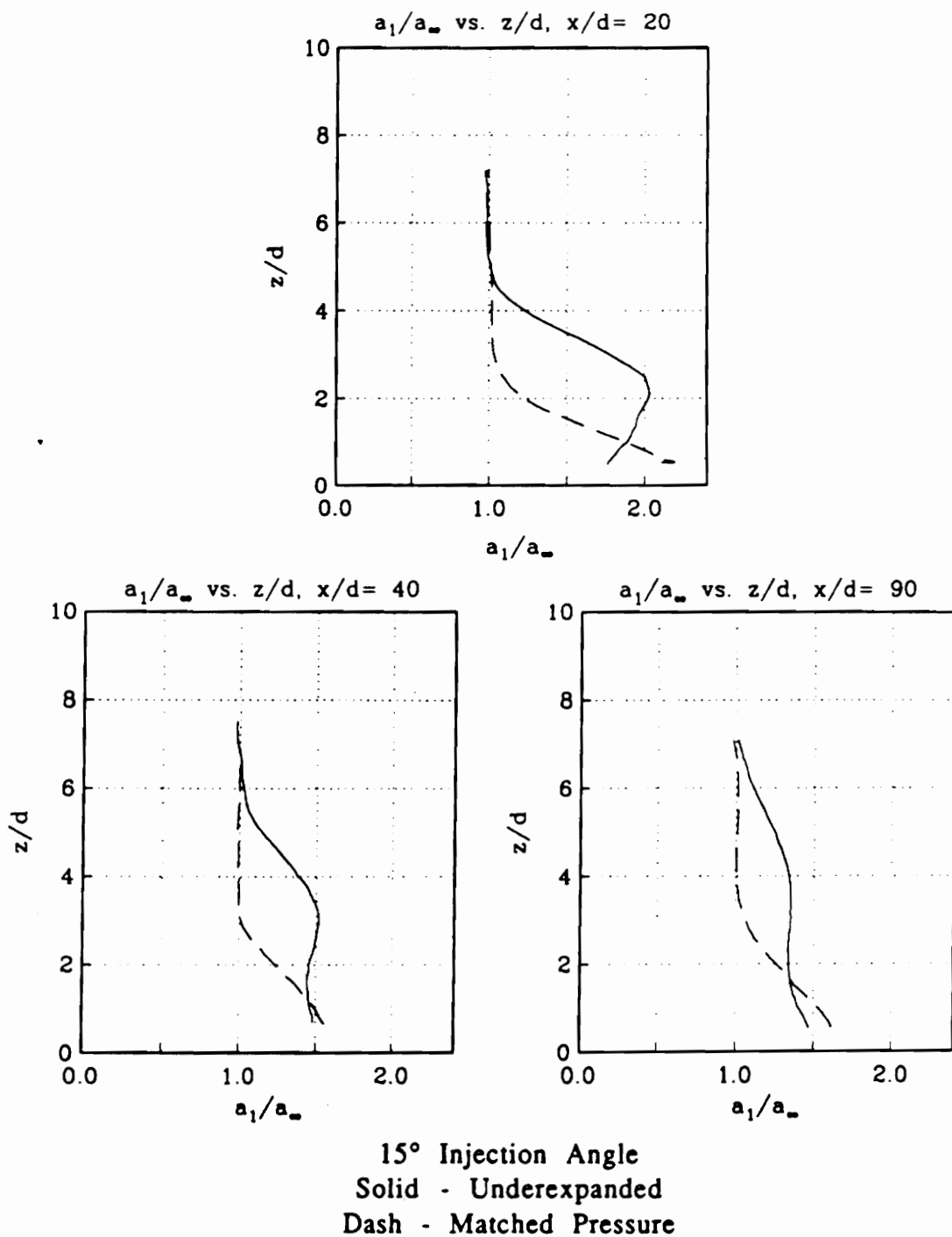


Figure 53: Speed of Sound Profiles of the 15° Injection Angle Cases

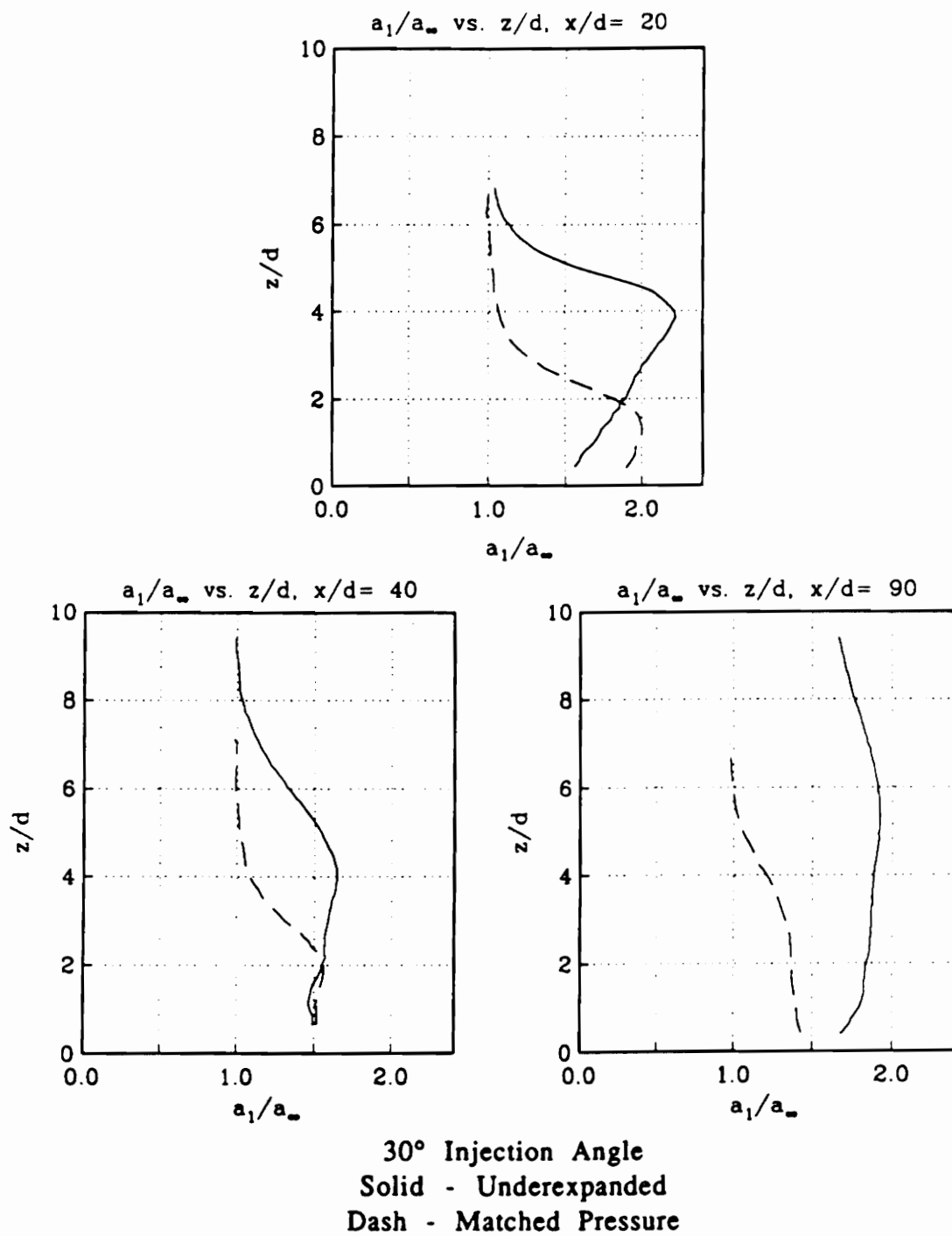


Figure 54: Speed of Sound Profiles of the 30° Injection Angle Cases

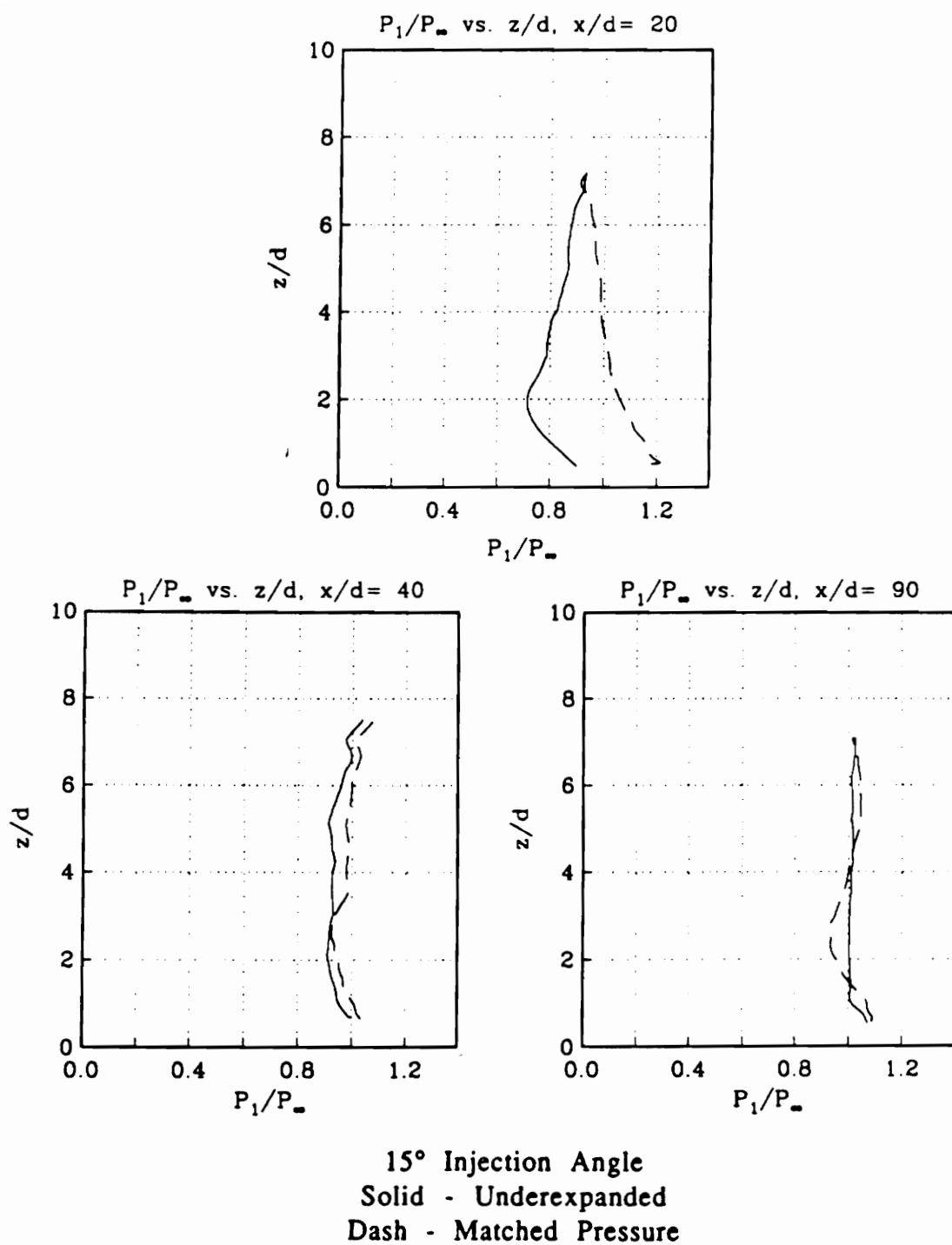


Figure 55: Static Pressure Profiles of the 15° Injection Angle Cases

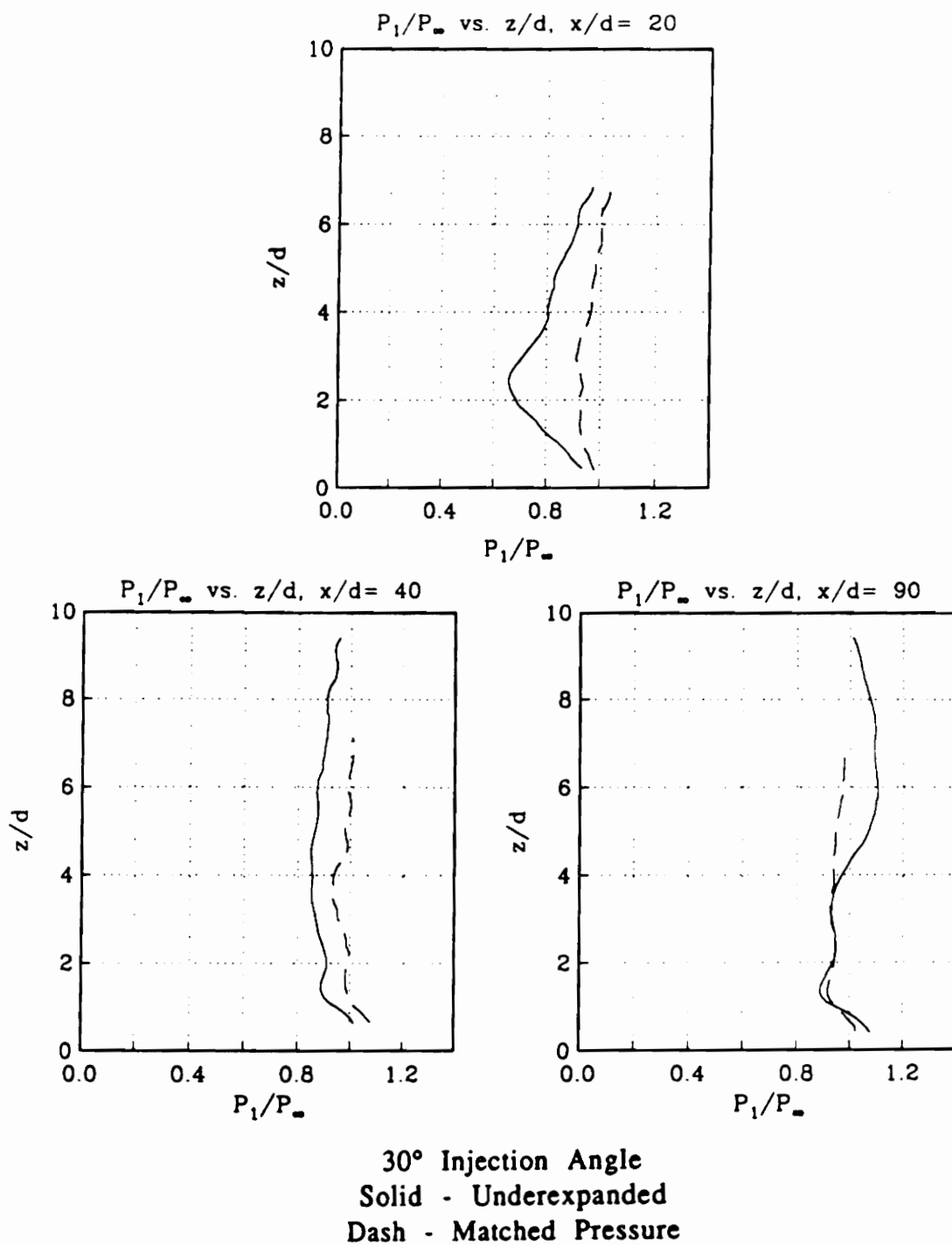


Figure 56: Static Pressure Profiles of the 30° Injection Angle Cases

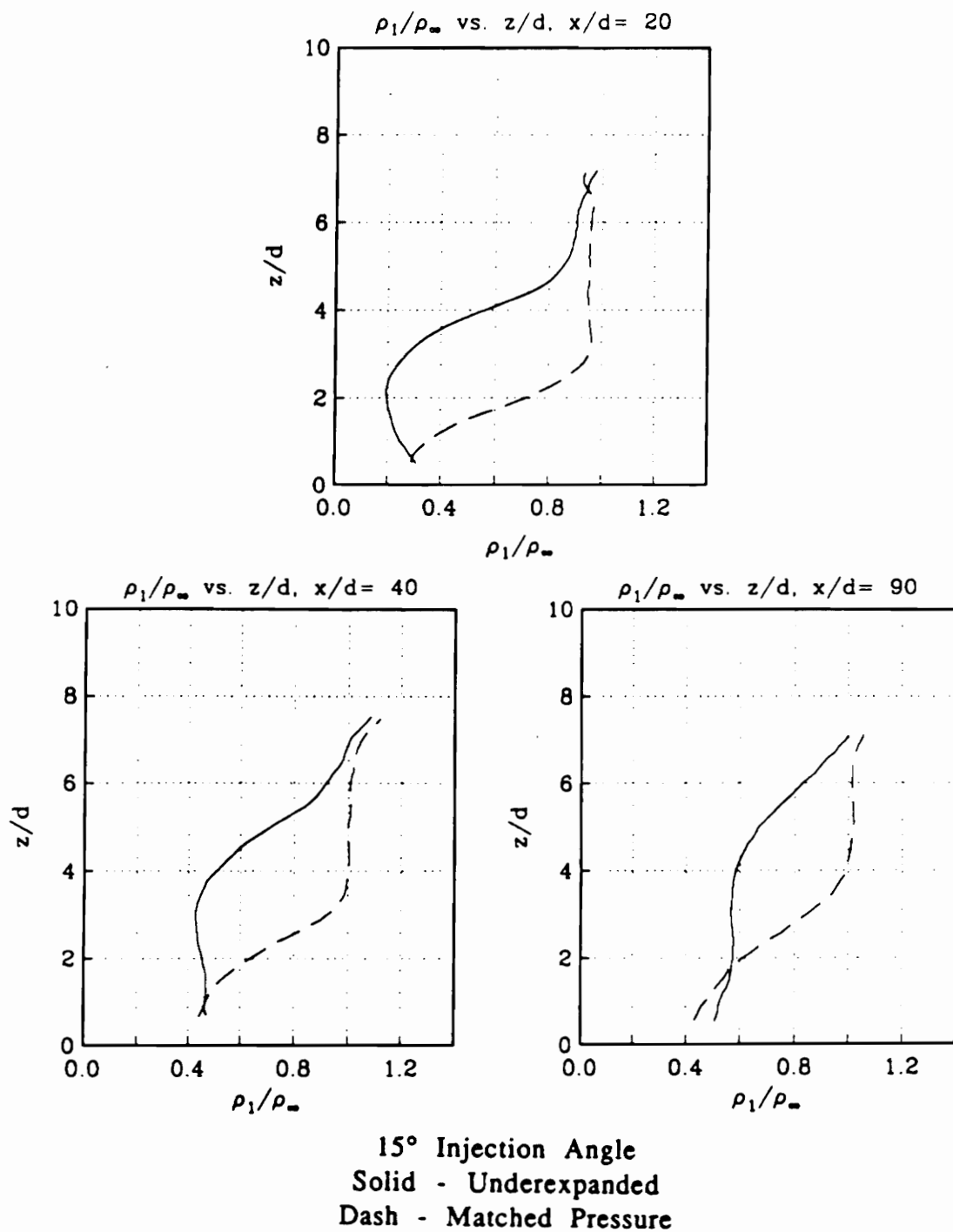


Figure 57: Static Density Profiles of the 15° Injection Angle Cases

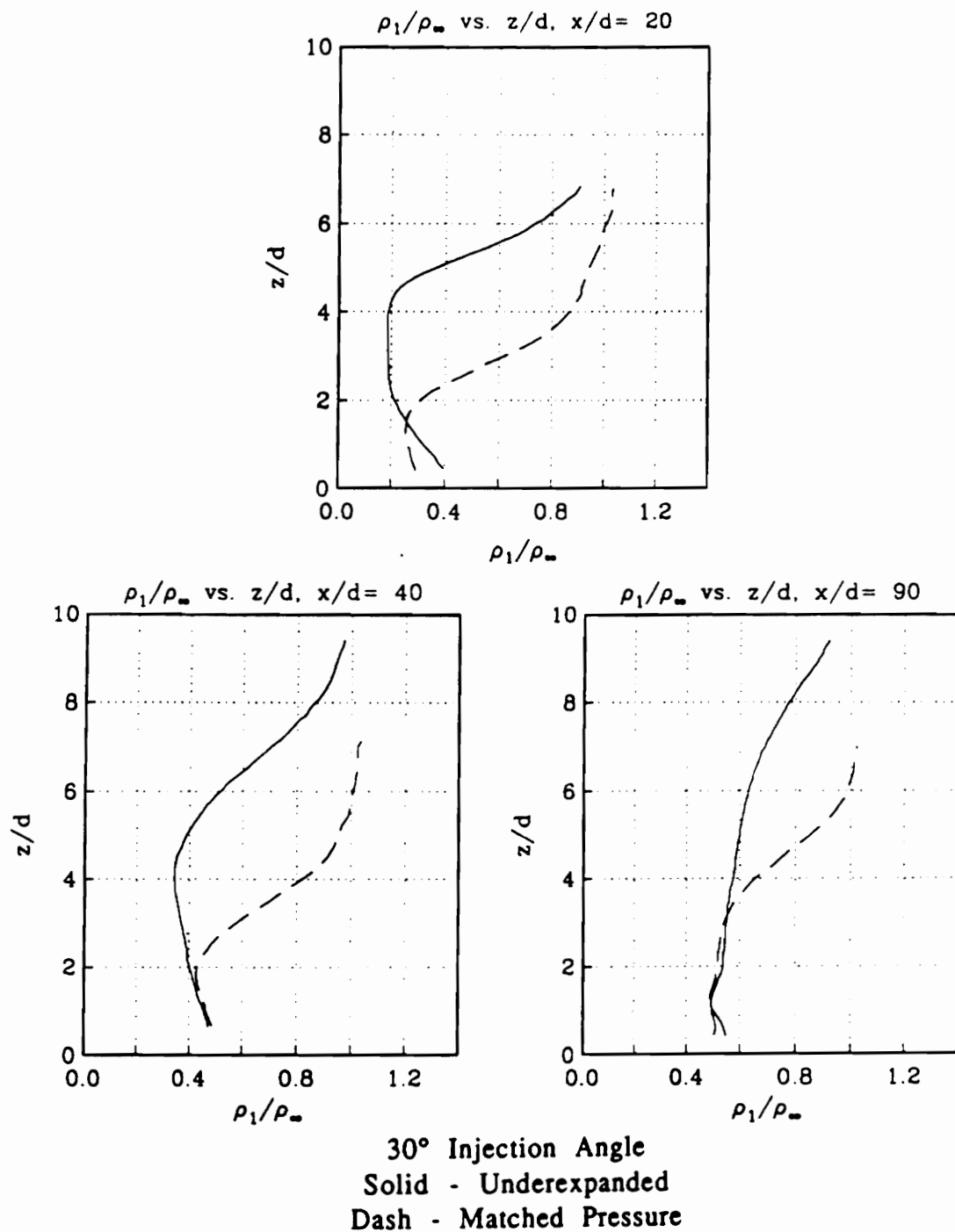


Figure 58: Static Density Profiles of the 30° Injection Angle Cases

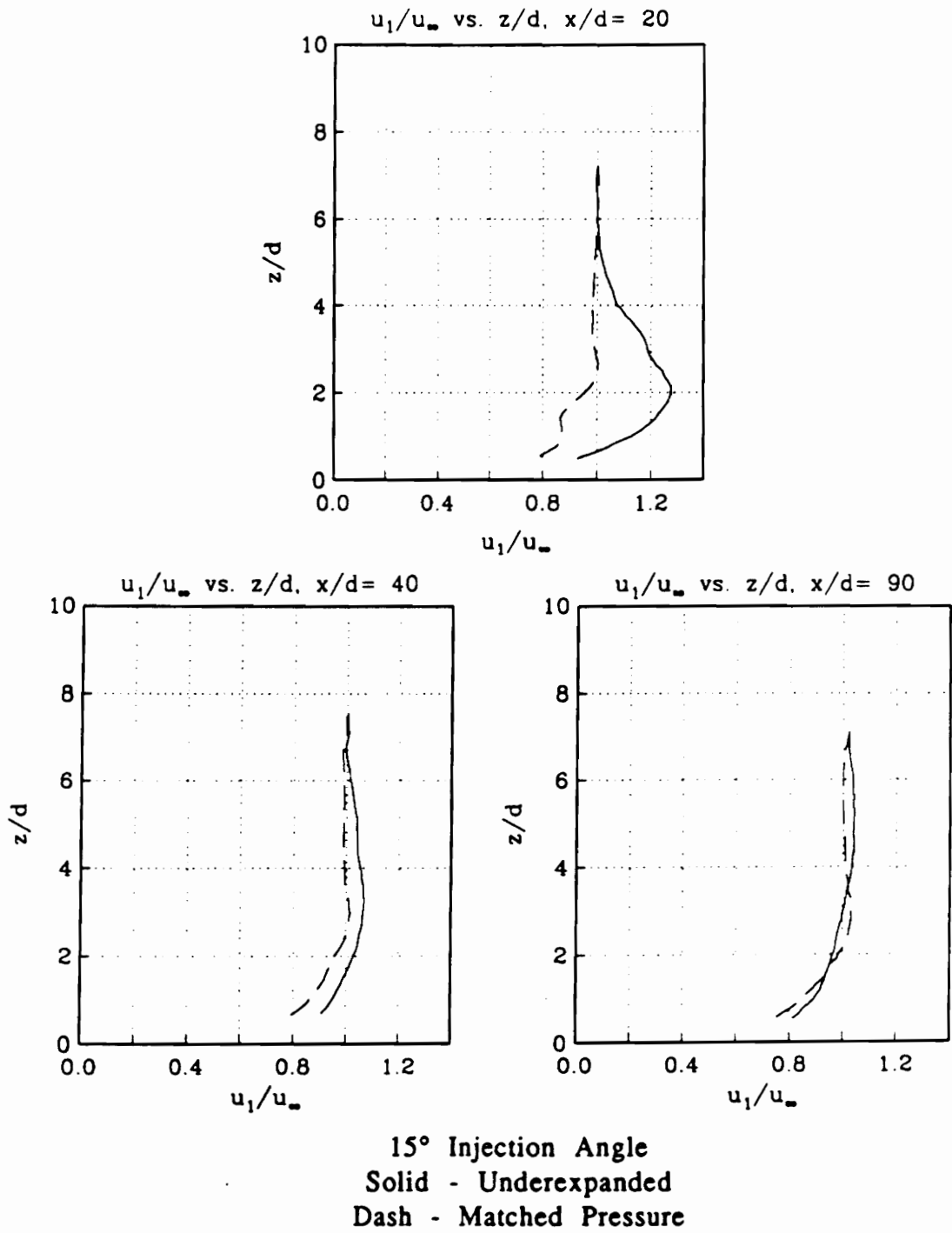


Figure 59: Flow Speed Profiles of the 15° Injection Angle Cases

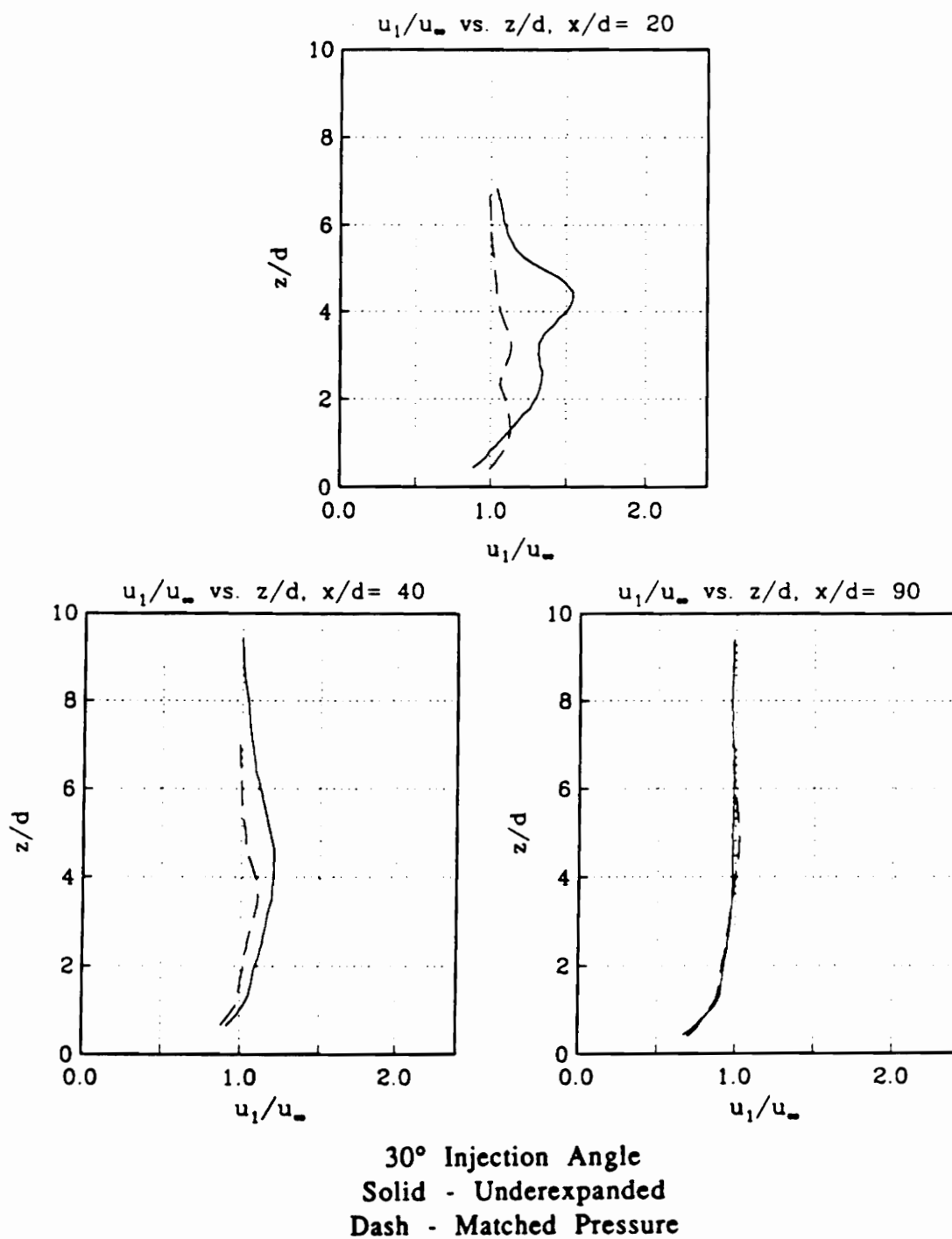


Figure 60: Flow Speed Profiles of the 30° Injection Angle Cases

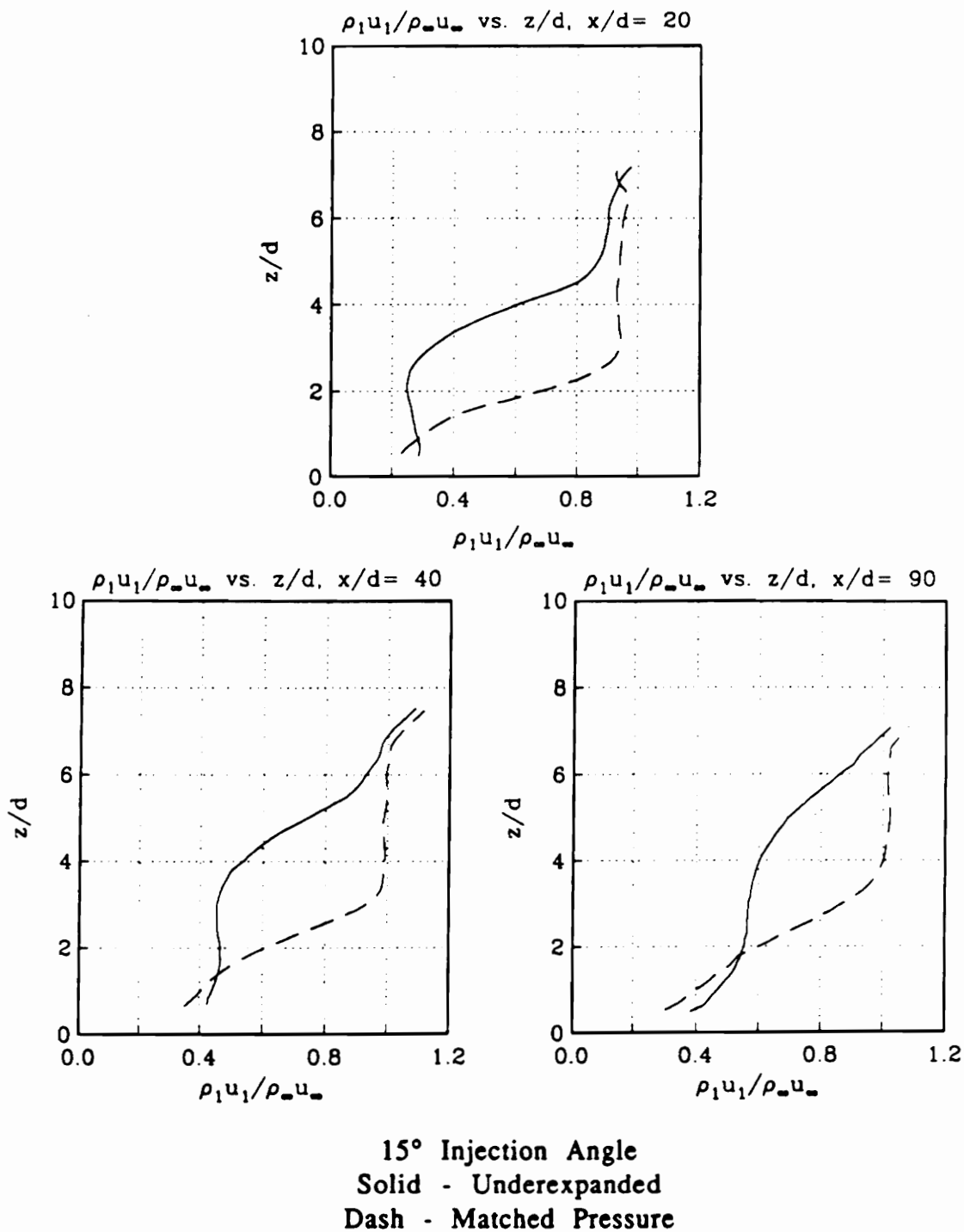


Figure 61: Mass Flux Profiles of the 15° Injection Angle Cases

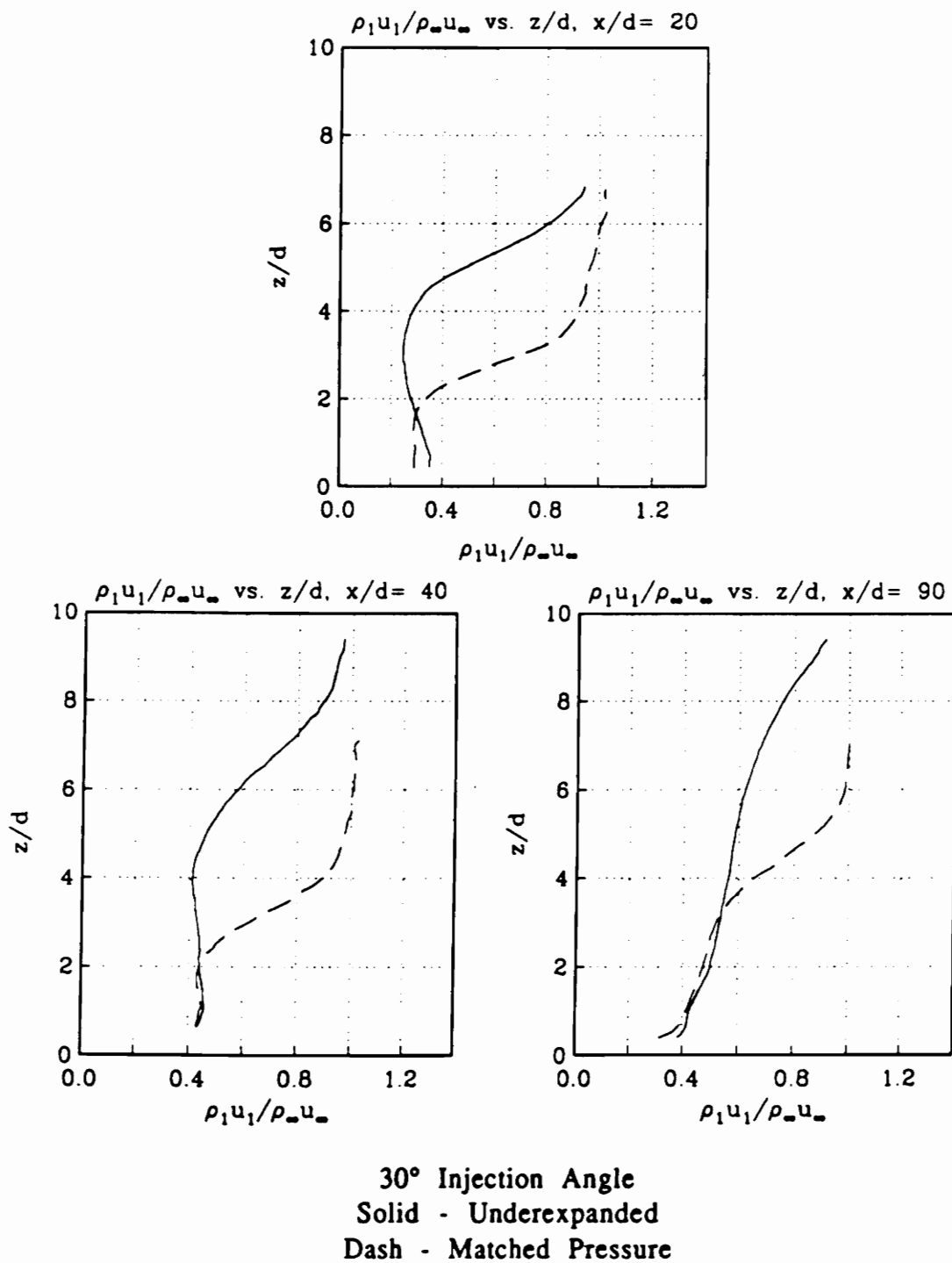


Figure 62: Mass Flux Profiles of the 30° Injection Angle Cases

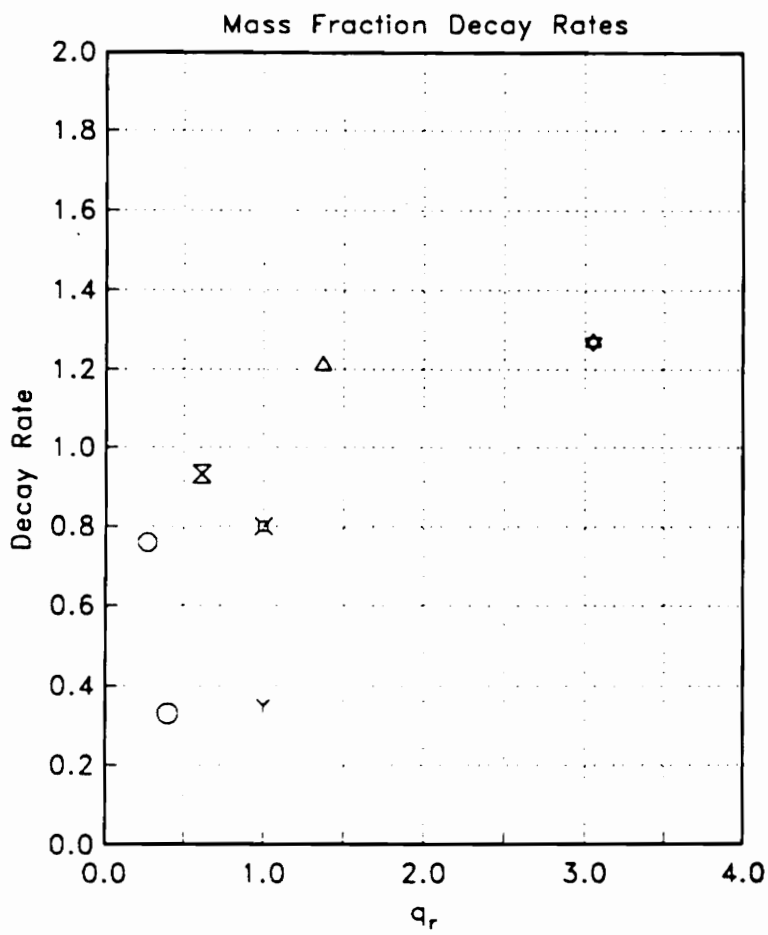


Figure 63: Comparison of the Decay Rates with Past Work (See Table 1)

Distance Required to Reach Stoichiometric H₂-Air Mixture

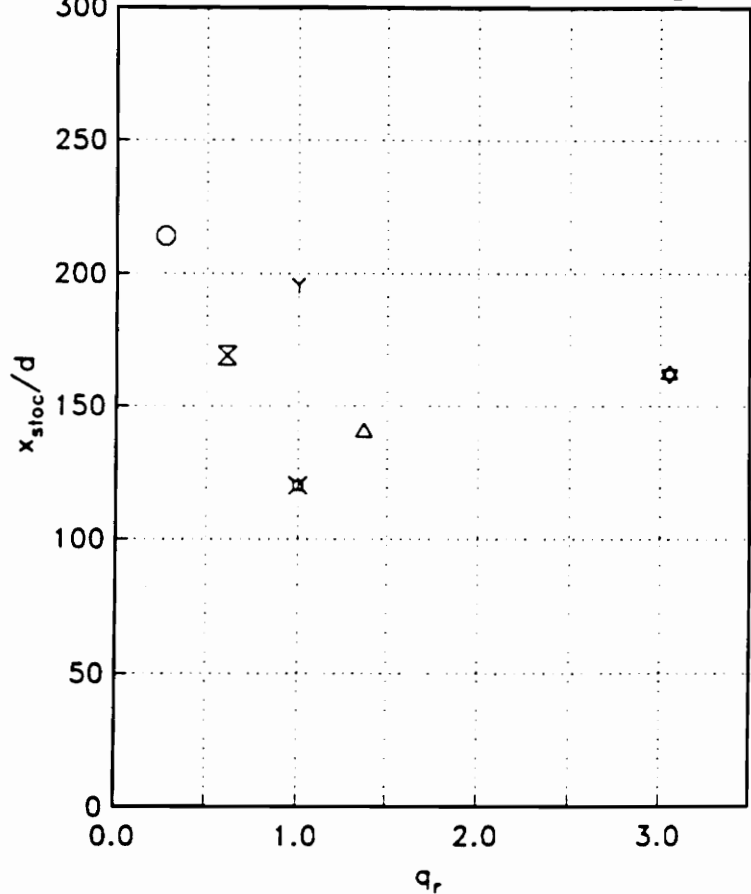


Figure 62: Comparison of Mixing Distance with Past Work (See Table 1)

Appendix A: Error Analysis

Error must be expected to occur in any real-world experiment. Much of the time spent in preparing for these experiments was used to try to minimize these errors. Possible error sources are the $P_{t\infty}$ controller system, the helium injection system, cathetometer measurements used to calibrate the LVDT, concentration probe accuracy, lateral probe placement techniques, nonuniformities in the test section wall, amplifier and transducer drift and noise, probe angularity, Pitot and cone-static time response, total temperature probe heat radiation, calibration curve fits, and electrical noise induced in transducer cables.

As stated in Section 2.2.1, the $P_{t\infty}$ controller circuit allowed less than four percent error in this quantity in a typical run. This was determined by picking the maximum and minimum $P_{t\infty}$ from the data of several randomly chosen runs. The total temperature, $T_{t\infty}$ also varied by less than four percent. This was found in the same way as the $P_{t\infty}$ error. The helium supply system allowed less than four percent variation in P_{tj} as well.

An estimation of the error introduced by the cathetometer was obtained by taking repeated readings of a point. The maximum error was found to be 0.6 percent. According to Reference 18, the LVDT added another 0.5 percent to the vertical position error. The calibration curve fit introduced not more than 0.01 percent error because any calibration that was less than 99.99 percent linear was redone. The maximum error in the vertical position measurements was therefore approximately 1.1 percent.

Error in the concentration measurements was reported by Reference 10 to be about 1 to 2 percent mole fraction of helium. The error of the Pitot and cone static measurements were dominated by transducer accuracy, time response, and electrical drift and noise. According to the manufacturers the pressure transducers used to measure these quantities were accurate to one percent. The effect of time response was to shift the profiles vertically. Since the cone-static probe must be sensitive to smaller pressure changes and its pressure taps are much smaller than the Pitot probe, the cone-static probe would have a worse time response than the Pitot probe. Reference 16 measured the time response of the the cone-static probe, and found it to be about 0.1 seconds. Since the probes were traversed at a speed of 3.8 mm/sec, the maximum position shift of the Pitot and cone-static pressure profiles was 0.38 mm.

The error in the total temperature measurement was caused by insufficient venting of gas through the probe, heat loss through the thermocouple wires and to a lesser extent, the time response of the thermocouple and inaccuracy of the calibration curve fit. Reference 11 estimated the error for the probe used for the present experiments to be about 2 percent for a flow field with small total temperature gradients.

All of these factors resulted in errors in the computation of the Mach number, flow speed, speed of sound, static density, static pressure and static temperature. According to Reference 10, these errors are as follows:

	All Helium	All Air
Mach number	0.54%	0.71%
Static Density	10%	1.7%
Flow Speed	6.7%	1.5%
Mass Flux	2.7%	0.52%
Speed of Sound	6.5%	2.4%
Static Pressure	2.9%	2.3%
Static Temperature	1.5%	2.7%

All of these errors are acceptable for the range of concentrations found in the present experiments.

Appendix B: Computer Programs

The computer programs used to reduce and manipulate the data from these experiments are given on the following pages. Program 1 was written in FORTRAN 77 on an IBM PC personal computer. Programs 2 - 5 were written in FORTRAN 77 on a SUN microsystems computer.


```

C      DACN = 1
      DACNO = 0
      BASEADDR = 768
      DMALEV = 3
      INTLEV = 2
      CALL LOCATE(15,2)
      MODE = 18
      RTNFLG = 0
C
C  ** Initialize Metrabyte **
C
      CALL ADINIT(BASEADDR,DMALEV,INTLEV,RTNFLG)
      IF (RTNFLG.NE.0) GOTO 200
C
      CALL DIGOUT(0)
10  CALL CLRSCN(7,0)
      CALL LOCATE(5,5)
C
C  ** Show default time parameters and change if necessary **
C
      WRITE(*,*)'DEFAULT TIME PARAMETERS ARE AS FOLLOWS:'
      WRITE(*,*)' '
      WRITE(*,*)TDEL,' SECONDS DELAY BEFORE TUNNEL VALVE'
      WRITE(*,*)TVAL,' VALVE OPENS AT T=0'
      WRITE(*,*)TRUP,' SECONDS TRAVERSE UP'
      WRITE(*,*)TDATA,' SECONDS UNTIL DATA STARTS'
      WRITE(*,*)SHUTD,' SECONDS DIGITAL OUTPUTS OFF'
      CALL LOCATE(15,5)
      WRITE(*,*)'WANT TO CHANGE PARAMETERS? ENTER (1) IF YES'
      READ(*,*(F2.0))CHA
      IF(CHA.NE.1.) GO TO 20
C
      CALL CLRSCN(7,0)
      CALL LOCATE(5,5)
      WRITE(*,*)'TIME IS SET AT ZERO WHEN WIND TUNNEL VALVE OPEN'
      WRITE(*,*)' '
      WRITE(*,*)'ENTER TIME FOR TRAVERSE UP'
      READ(*,*)TRUP
      WRITE(*,*)'ENTER TIME TO START TAKING DATA'
      READ(*,*)TDATA
      WRITE(*,*)'ENTER TIME FOR TUNNEL SHUTDOWN'
      READ(*,*)SHUTD
      WRITE(*,*)'ENTER TIME DELAY BEFORE TIMER IS ENABLED'
      READ(*,*)TDEL
      WRITE(*,*)' '
      WRITE(*,*)'TIMES OK AS ENTERED? ENTER (2) TO CORRECT.'
      READ(*,*(F2.0))CORR
      IF(CORR.EQ.2.)GOTO 10
C
C  ** Set up A/D sampling parameters **
C
20  CALL CLRSCN (7,0)
      CALL LOCATE (4,0)
      WRITE(*,*(A))' ENTER THE START CHANNEL = '
      READ(*,*(I2))STARTC
      WRITE(*,*(A))' ENTER THE END CHANNEL = '
      READ(*,*(I2))ENDCH
      WRITE(*,*)
      WRITE(*,*)' # OF DATA POINTS PER CHANNEL'
      READ(*,*(I5))NOS
C
C  ** Set sample rate **
C
250 CALL CLRSCN(7,0)
      CALL LOCATE (0,0)

```

Program 1: Data Collection Program

```

WRITE(*,*)' SET SAMPLE RATE.....'
WRITE(*,*)' '
WRITE(*,*)' '
WRITE(*,*)' RATE IS ESTABLISHED BY DIVIDING THE CLOCK RATE'
WRITE(*,*)' (1 MHZ) BY THE PRODUCT OF THE TWO COUNTS. '
WRITE(*,*)' AS AN EXAMPLE:'
WRITE(*,*)' '
WRITE(*,*)' HIGH COUNT = 10, LOW COUNT = 10 '
WRITE(*,*)' SAMPLE RATE = (1000000/(10*10)) = 10000 '
WRITE(*,*)' SAMPLES PER SECOND PER CHANNEL'
WRITE(*,*)' '
WRITE(*,*(A\))' ENTER THE LOW COUNT - '
READ(*,*(I6))CNT1
WRITE(*,*(A\))' ENTER THE HIGH COUNT - '
READ(*,*(I6))CNT2
DELTA = 1000000./FLOAT(CNT1*CNT2)
SECS = NOS/DELTA
ISECS = INT(SECS*100.)
WRITE(*,*)
WRITE(*,*)' THE COUNT SELECTION AS ENTERED WILL PROVIDE...'
WRITE(*,*)' '
WRITE(*,*)' ,DELTA,' SAMPLES PER SECOND PER CHANNEL'
WRITE(*,*)'FOR '
WRITE(*,*)' ,SECS,' SECONDS'
WRITE(*,*)' '
WRITE(*,*)' IF PARAMETERS OK, PRESS RETURN. IF NO, ENTER 1'
READ(*,*(I2))IPAR
IF(IPAR.EQ.1)GOTO 250
666 CALL CNTMO1 (2,CNT1)
CALL CNTMO2 (2,CNT2)
C
C ** Countdown to start **
C
WRITE(*,*)'ENTER (1) WHEN READY TO BEGIN COUNTDOWN'
READ(*,*(F1.0))BEGIN
IF(BEGIN.NE.1.)GOTO 10
CALL GTIME(IHOUR0,IMIN0,ISEC0,IHUND0)
TIME0 = IHOUR0*3600.+IMIN0*60.+ISEC0+IHUND0/100.
51 CALL GTIME(IHOUR1,IMIN1,ISEC1,IHUND1)
TIME1 = IHOUR1*3600.+IMIN1*60.+ISEC1+IHUND1/100.
TIMDIF = TIME1 - TIME0
IF(TIMDIF.LT.TDEL)GOTO 51
CALL CLRSCN(7,0)
CALL LOCATE(10,10)
IHOUR0=0
IMIN0=0
ISEC0=0
IHUND0=0
IHOUR1=0
IMIN1=0
ISEC1=0
IHUND1=0
TIME0=0
TIME1=0
C
C WRITE(*,*)' ***** TIMER ENABLED *****'
C
CALL GTIME(IHOUR0,IMIN0,ISEC0,IHUND0)
TIME0 = IHOUR0*3600.+IMIN0*60.+ISEC0+IHUND0/100.
C
C ** Set tunnel pressure **
C
VOLT = MAXPSI / (10. * fudge)
DATOUT = INT(VOLT/2.96E-3)
CALL DAOUT(DACN,DATOUT,RTNFLG)

```

Program 1: Data Collection Program

```

C  ** Switch valve on  **
C
C      WRITE(*,*)'VALVE ON'
C      CALL DIGOUT(1)
C
C 39 CALL GTIME(IHOUR1,IMIN1,ISEC1,IHUND1)
C      TIME1 = IHOUR1*3600.+IMIN1*60.+ISEC1+IHUND1/100.
C      TIMDIF = TIME1 - TIME0
C      IF(TIMDIF.LT.TRUP)GOTO 39
C
C  ** Traverse up  **
C
C      WRITE(*,*)'TRAVERSE UP'
C      WRITE(*,*)
C
C          call outexe (exel)
C          call outexe (exel0)
C
C      CALL DIGOUT(11)
C 159 CALL GTIME(IHOUR1,IMIN1,ISEC1,IHUND1)
C      TIME1 = IHOUR1*3600.+IMIN1*60.+ISEC1+IHUND1/100.
C      TIMDIF = TIME1 - TIME0
C      IF(TIMDIF.LT.TDATA)GOTO 159
C
C  ** Perform A/D conversions (take data)  **
C
C      NCONV = NOS * (ENDCH - STARTC + 1)
C      CALL ADCONV(MODE,STARTC,ENDCH,NOS,DATARRAY(1),RTNFLG)
C      IF(RTNFLG.NE.0) GO TO 200
C
C          call outpgm (pgm(2))
C      WRITE(*,*)
C
C  ** Traverse down  **
C
C      WRITE(*,*)'TRAVERSE DOWN'
C          call outexe (exel)
C          call outexe (exel0)
C      CALL DIGOUT(5)
C 29 CALL GTIME(IHOUR1,IMIN1,ISEC1,IHUND1)
C      TIME1 = IHOUR1*3600.+IMIN1*60.+ISEC1+IHUND1/100.
C      TIMDIF = TIME1 - TIME0
C
C  ** Switch everything off  **
C
C      IF(TIMDIF.LT.SHUTD)GOTO 29
C      CALL DIGOUT(0)
C      WRITE(*,*)'ALL DIGITAL OUTPUTS OFF'
C      WRITE(*,*)
C
C  ** Write to files  **
C      -- 6 channels of data
C      -- form of write:
C          1st line -- channel #
C          2nd line -- sample rate
C          3rd line -- voltage offset
C          4th line -- number of points
C          5th and up lines -- digital data in one column
C
C      NSTEPS = 1
C      write(*,*)'WRITING TO FILES . . .'
C      nch = endch - startc + 1
C      fname(1) = 'b:ch0.run'
C      fname(2) = 'b:ch1.run'
C      fname(3) = 'b:ch2.run'
C      fname(4) = 'b:ch3.run'

```

Program 1: Data Collection Program

```

        fname(5) = 'b:ch4.run'
        fname(6) = 'b:ch5.run'
        do 23 j = 1, nch
            open(j,file=fname(j),status='new', form = 'FORMATTED')
            in2 = j
            write(j,'(I3)') j-1
            write(j,*)delta
            if(j.eq.1)then
                write(j,*)hoffset
            else
                write(j,*)offset
            end if
            write(j,'(i5)') nos
            do 13 i = 1,nos*steps
                write(j,'(i5)') datarray(in2)
                in2 = in2 + nch
            13 continue
            close (j)
        23 continue
        GO TO 188

C
C ** Display any errors in Metrabyte setup **
C
200 CALL CLRSCN(7,0)
    CALL DIGOUT(0)
    CALL LOCATE(2,2)
    WRITE(*,*) '** THERE HAS BEEN AN ERROR NUMBER ',RTNFLG
    WRITE(*,*)
    WRITE(*, '(A\)' )' HIT <ENTER> TO RETURN TO MAIN MENU '
    READ(*, '(I2)') IERR
188 CONTINUE
    END

C
C
C *****
C ****          Traverse Subroutines          ****
C *****
C
C -- outpgm
C
        subroutine      outpgm (pgm)
        character*42    pgm
            do 100 i = 1,42
                call cout (pgm(i:i))
            100 continue
            call cout (13)
            return
        end

C
C -- outexe
C
        subroutine      outexe (exe)
        character*2      exe
            do 100 i = 1,2
                call cout (exe(i:i))
            100 continue
            call cout (13)
            return
        end

```

Program 1: Data Collection Program

```

C*****
C
C   Program : XREDUCE1T.F
C
C   This program reduces the hot film voltage, total
C   pressure and total temperature into helium
C   concentration.
C
C   One set of constants at one temperature
C
C   For new TSI sensor -20
C
C   Input file = xrun.run#    which is of the form:
C
C       ylvdt - Sensor voltage - sensor P (psia) - sensor T (K)
C
C   Output file = xrunout.run#    which is of the form:
C
C       Xhe (mole fracation He) - ylvdt
C
C   by:      JOEL C. ROSSON      BEGUN      2/19/85
C           FEI T. KWOK          MODIFIED    10/20/88
C           Eric J. Fuller       Modified    1/19/90
C           Eric J. Fuller       Modified    5/10/90
C
C*****
C
C       character*3 run
C       Character*15 calfile,filein,fileout,limitout
C
C       DIMENSION TT(2000),PT(2000),AP1(2000),XHE(2000),YLVDT(2000)
C       DIMENSION CCl(10) , XN1(10)
C
C       DIMENSION VIS(39,2), CON(39,2)
C       DIMENSION VISA(39,2),CONA(39,2),VISHE(39,2),CONHE(39,2)
C
C   Set Calibration file name, input file name and
C   output file name.
C
C       write(6,*)
C       write(6,*) ' Calibration file name = '
C       read(5,*) calfile
C
C   open hfrun.num containing the Hot film run numbers to be reduced
C
C       open (1,file='hfrun.num',status='old')
C       read (1,*)
C       read (1,*) numrun
C
C       write(6,*)
C
C   Big loop for each run #
C
C       do 9999 jrun = 1,numrun
C           read (1,'(a3)') run
C           write (6,'(a3)') run
C
C   open files
C
C       filein = 'xrun.'//run
C       fileout = 'xrunout.'//run
C       limitout = 'limit.'//run
C
C       OPEN(2,FILE=calfile)
C       OPEN(3,FILE=filein)
C       OPEN(7,FILE=fileout)

```

Program 2: Concentration Data Reduction Program

```

      OPEN(8,FILE=limitout)
C
C   Read in the calibration file containing the
C   calibration constants for different temperatures.
C   -- NR      = 1
C   -- L       = number of data values from experimental run
C   -- D       = static temp./stagnation temp.
C   -- TOL     = tolerance limit on iteration
C   -- NCONST  = number of concentration levels per calibration
C               temperature = # of calibration constants sets
C   -- RSET1   = anemometer operating resistance setting
C   -- RCAB    = Cable Resistance
C   -- SRES0   = Film resistance @ 0 deg C
C   -- Sdelr   = film R100-R0
C   -- DELX    = Increment of Xhe between Calibration levels
C
      READ(2,*) NR,L,D,TOL,NCONST,DELX,rcab,rset1,sres0,sdelr
      do 1 i=1,nconst
        read(2,*) ccl(i), xnl(i)
1     continue
      close (2)
C
C   Read in the data values:
C   ylvdt = lvdt location
C   apl   = sensor voltage
C   pt    = sensor pressure (psia)
C   tt    = sensor temperature (deg K)
C
      WRITE(*,*)
      WRITE(*,*)' LOADING DATA VALUES . . .'
      WRITE(*,*)
      DO 10 I=1,L
        READ(3,*) YLVDT(i),AP1(I),PT(I),TT(I)
10     CONTINUE
      close (3)
C
C*****
C
C   THIS Section contains the properties of AIR and HELIUM
C
C               Eric Fuller      Modified 10/20/89
C*****
C
C   VISCOSITY FOR AIR IN KG/M*S OR N*S/M**2
      DATA VISA/140.,150.,160.,180.,200.,220.,240.,260.,280.,
1     290.,300.,310.,320.,330.,340.,350.,
1     360.,370.,380.,390.,400.,410.,420.,430.,440.,450.,460.,
1     470.,480.,490.,500.,510.,520.,530.,540.,550.,560.,570.,
1     580.,
1     .96112E-5,1.0283E-5,1.08842E-5,1.20866E-5,1.3289E-5,
1     1.43694E-5,1.54498E-5,1.64844E-5,1.74732E-5,1.79676E-5,
1     1.8462E-5,1.89196E-5,1.93772E-5,1.9834E-5,2.02924E-5,
1     2.075E-5,
1     2.117E-05,2.159E-05,2.202E-05,2.244E-05,2.286E-05,
1     2.326E-05,2.365E-05,2.405E-05,2.444E-05,2.484E-05,
1     2.521E-05,2.559E-05,2.596E-05,2.634E-05,2.671E-05,
1     2.706E-05,2.742E-05,2.777E-05,2.813E-05,2.848E-05,
1     2.882E-05,2.916E-05,2.950E-05/
C
C   THERMAL CONDUCTIVITY FOR AIR IN W/M*K
      DATA CONA/140.,150.,160.,180.,200.,220.,240.,260.,280.,
1     290.,300.,310.,320.,330.,340.,350.,
1     360.,370.,380.,390.,400.,410.,420.,430.,440.,450.,460.,
1     470.,480.,490.,500.,510.,520.,530.,540.,550.,560.,570.,
1     580.,
1     .0128372,.013735,.014606,.016348,.01809,.019762,

```

Program 2: Concentration Data Reduction Program

```

1 .021434,.023064,.024652,.025446,.02624,.026998,
1 .027756,.028514,.029272,.03003,
1 .030754,.031478,.032202,.032926,.033650,.034334,
1 .035018,.035702,.036386,.037070,.037732,.038394,
1 .039056,.039718,.040380,.041024,.041668,.042312,
1 .042956,.043600,.044198,.044796,.045394/
C
C VISCOSITY FOR HELIUM IN KG/M*S
DATA VISHE/140.,150.,160.,180.,200.,220.,240.,260.,280.,
1 290.,300.,310.,320.,330.,340.,350.,
1 360.,370.,380.,390.,400.,410.,420.,430.,440.,450.,460.,
1 470.,480.,490.,500.,510.,520.,530.,540.,550.,560.,570.,
1 580.,
1 1.22E-5,1.288E-5,1.344E-5,1.455E-5,1.566E-5,
1 1.657E-5,1.749E-5,1.839E-5,1.927E-5,1.971E-5,2.015E-5,
1 2.059E-5,2.103E-5,2.147E-5,2.191E-5,2.235E-5,
1 2.279E-5,2.321E-5,2.361E-5,2.401E-5,2.441E-5,
1 2.481E-5,2.522E-5,2.562E-5,2.601E-5,2.642E-5,
1 2.682E-5,2.722E-5,2.760E-5,2.792E-5,2.824E-5,
1 2.857E-5,2.889E-5,2.922E-5,2.954E-5,2.987E-5,
1 3.019E-5,3.051E-5,3.084E-5/
C
C THERMAL CONDUCTIVITY FOR HELIUM IN W/M*K
DATA CONHE/140.,150.,160.,180.,200.,220.,240.,260.,280.,
1 290.,300.,310.,320.,330.,340.,350.,
1 360.,370.,380.,390.,400.,410.,420.,430.,440.,450.,460.,
1 470.,480.,490.,500.,510.,520.,530.,540.,550.,560.,570.,
1 580.,
1 9.07E-2,9.5E-2,9.92E-2,1.072E-1,1.151E-1,
1 1.228E-1,1.304E-1,1.374E-1,1.447E-1,1.484E-1,1.52E-1,
1 1.555E-1,1.591E-1,1.626E-1,1.662E-1,1.697E-1,
1 1.732E-1,1.766E-1,1.801E-1,1.835E-1,1.870E-1,
1 1.904E-1,1.937E-1,1.971E-1,2.004E-1,2.038E-1,
1 2.071E-1,2.104E-1,2.136E-1,2.169E-1,2.202E-1,
1 2.234E-1,2.266E-1,2.297E-1,2.329E-1,2.361E-1,
1 2.392E-1,2.423E-1,2.453E-1/
C
C *****
C
C System Parameters
C
C RS - SERIES RESISTANCE (OHMS)
C
C RS= 50.0
C
C RCAB - CABLE RESISTANCE (OHMS)
C RSET1 - ANEMOMETER RESISTANCE SETTING (OHMS)
C RWIRE - HOT WIRE RESISTANCE AT THE OPERATING TEMP.
C
C RWIRE1=RSET1-RCAB
C
C TOPC - film operating temperature (deg C)
C TWIRE1 - film operating temperature (deg K)
C
C topc = (rwire1 - sres0) * 100. / sdelr
C TWIRE1 = topc + 273.1
C
C XL - WIRE LENGTH (INCHES CONVERTED TO METERS)
C R - GAS CONSTANT (KJ/KG*K) CONVERT TO J/KG*K
C A - RATIO OF SPECIFIC HEATS
C D - RATIO OF STATIC TO TOTAL TEMP FOR ISENTROPIC CHOKE
C B - RATIO OF THROAT AREA TO WIRE PLANE AREA
C XD - WIRE DIAMETER (INCHES CONVERTED TO METERS)
C
C XL=0.040*0.0254

```

Program 2: Concentration Data Reduction Program

```

      XD=0.002*0.0254
      B=0.0069
      D=0.9725
      PI=3.141593
      A = 0.
      R = 0.
C
C*****
C
C      Reduction
C
      V = 0.0
      C = 0.0
      G = 0.0
C
      input shift voltage to correct for drift
      SH ideally = 0.0
C
      WRITE(*,*)
      WRITE(*,*)' INPUT SHIFT VALUE IN VOLTS (EXP-CALC)'
      WRITE(*,*)
      READ(*,*) SH
      WRITE(8,*) SH
      WRITE(*,*) SH
C
      NCOUNT = 0
      NC0 = 0
      NC1 = 0
C
      Loop to interpolate for XHe according to calculated
      bounds from the Calibration.
C
      DO 1000 I=1,L
C
        T=D*TT(I)
        PT(I)=PT(I)*6894.757
C
      Loop to get proper Temperature range for air & He constants
C
      DO 50 J=1,38
      IF((T.GE.VISA(J,1)).AND.(T.LE.VISA(J+1,1))) GO TO 55
50  CONTINUE
55  CONTINUE
C
      Loop to compute upper and lower concentration bounds
      and then to interpolate to get XHe
C
      XLOW = 0.0
      XUP = DELX
      DO 253 ILIMS = 1 , NCONST-1
C
      Calculate lower bound
C
      CALL MIXTURE(VISA,CONA,VISHE,CONHE,A,R,J,XLOW,T,V,C,G)
C
      VLOW = ((RS+RWIRE1+RCAB)**2/RWIRE1*PI*XL*C*CC1(ILIMS)*(TWIRE1-
1      T)*(XD/V*B*G*PT(I)*(A/(R*TT(I)))**0.5)**XN1(ILIMS))**0.5
2      + SH
C
      Calculate upper bound
C
      CALL MIXTURE(VISA,CONA,VISHE,CONHE,A,R,J,XUP,T,V,C,G)
C
      VUP = ((RS+RWIRE1+RCAB)**2/RWIRE1*PI*XL*C*CC1(ILIMS+1)*(TWIRE1-
1      T)*(XD/V*B*G*PT(I)*(A/(R*TT(I)))**0.5)**XN1(ILIMS+1))**0.5
2      + SH

```

Program 2: Concentration Data Reduction Program

```

C
c   Account for values that fall below XHe=0. and exceed
c   XHe =1. due to experimental errors
c
      IF (ILIMS.EQ.1.AND.AP1(I).LT.VLOW) THEN
        XHE(I) = 0.0
        NC0 = NC0 + 1
        WRITE(8,*) I,XHE(I),AP1(I)-VLOW
        GO TO 1600
      ELSE IF (ILIMS.EQ.NCONST-1.AND.AP1(I).GT.VUP) THEN
        XHE(I) = 1.0
        NC1 = NC1 + 1
        WRITE(8,*) I,XHE(I),AP1(I)-VUP
        GO TO 1600
      END IF
c
c   interpolate to get XHe
c
      IF (AP1(I).EQ.VLOW) THEN
        XHE(I) = XLOW
        GO TO 1600
      ELSE IF (AP1(I).EQ.VUP) THEN
        XHE(I) = XUP
        GO TO 1600
      ELSE IF (AP1(I).GT.VLOW.AND.AP1(I).LT.VUP) THEN
        XM = (XUP - XLOW) / (VUP - VLOW)
        XHE(I) = XM * (AP1(I) - VLOW) + XLOW
        GO TO 1600
      END IF
      XLOW = XUP
      XUP = XLOW + DELX
253 CONTINUE
c
c   Write data to output file
c
1600 WRITE(7,*) XHE(I),ylvdt(i)
      NCOUNT = NCOUNT + 1
c
      if (i/50*50.eq.i) write (*,*) i
1000 CONTINUE
      WRITE(*,*) ' Number of pts used = ',NCOUNT,' out of ',L
      WRITE(*,*)
      WRITE(*,*) ' Number of pts. forced to 1.0 = ',NC1
      WRITE(*,*)
      WRITE(*,*) ' Number of pts. forced to 0.0 = ',NC0
c
      CLOSE(7)
      CLOSE(8)
c
9999 continue
      close (1)
c
999  STOP
      END
c
c *****
c           Subroutine MIXTURE
c *****
c
c   - determines mixture properties
c
      SUBROUTINE MIXTURE(VISA,CONA,VISHE,CONHE,A,R,J,TT,T,V,C,G)
      DIMENSION VIS(39,2), CON(39,2)
      DIMENSION VISA(39,2),CONA(39,2),VISHE(39,2),CONHE(39,2)
      REAL MHE,MA,M,MUA,MUHE,KHE,KA

```

Program 2: Concentration Data Reduction Program

```

C  HELIUM PROPERTIES
C
  XHE = TT
  MHE = 4.00260
  RHE = 8317./MHE
  CPHE = 5200.
C
C  AIR PROPERTIES
C
  XA = 1. - XHE
  MA = 29.
  RA = 8317./MA
  CPA = 1005.7
C
C  MIXTURE PROPERTIES
C
  M = XHE * MHE + XA * MA
  CP = ( XHE * CPHE * MHE + XA * CPA * MA ) / M
  R = 8317./M
  CV = CP - R
  A = CP / CV
C
c  calculate the bounds on the mixture viscosity and thermal
c  conductivity
C
  IXHE = NINT(100. * XHE)
  DO 10 I = J , J+1
    VIS(I,1) = VISHE(I,1)
    CON(I,1) = CONHE(I,1)
  IF (IXHE.EQ.100) THEN
    VIS(I,2) = VISHE(I,2)
    CON(I,2) = CONHE(I,2)
  ELSE IF (IXHE.EQ.0) THEN
    VIS(I,2) = VISA(I,2)
    CON(I,2) = CONA(I,2)
  ELSE
    MUA = VISA(I,2) / (1+XHE/XA*(1+SQRT(VISA(I,2)/VISHE(I,2))
1      *(MHE/MA)**.25)**2/(2.82843*SQRT(1+MA/MHE)))
    MUHE = VISHE(I,2) / (1+XA/XHE*(1+SQRT(VISHE(I,2)/
1      VISA(I,2))* (MA/MHE)**.25)**2/(2.82843*
2      SQRT(1+MHE/MA)))
    VIS(I,2) = MUA + MUHE
    KA = CONA(I,2) / (1+XHE/XA*(1+SQRT(CONA(I,2)/CONHE(I,2))
1      *(MHE/MA)**.25)**2/(2.82843*SQRT(1+MA/MHE)))
    KHE = CONHE(I,2) / (1+XA/XHE*(1+SQRT(CONHE(I,2)/CONA(I,2)
1      )*(MA/MHE)**.25)**2/(2.82843*SQRT(1+MHE/MA)))
    CON(I,2) = KA + KHE
  END IF
10 CONTINUE
C
  G=(2.0/(A+1.0))**((A+1.0)/(2.0*(A-1.0)))
C
c  calculate the mixture viscosity and thermal conductivity
C
  VIS1=VIS(J,2)
  VIS2=VIS(J+1,2)
  CON1=CON(J,2)
  CON2=CON(J+1,2)
  TEMP1=VIS(J,1)
  TEMP2=VIS(J+1,1)
  V=VIS1+(VIS2-VIS1)*(T-TEMP1)/(TEMP2-TEMP1)
  C=CON1+(CON2-CON1)*(T-TEMP1)/(TEMP2-TEMP1)
C
C  WRITE(*,*) V , C
C
  RETURN

```

Program 2: Concentration Data Reduction Program

```

C
C   Program : MEAN.F
C
C   This program reduces mean-flow variables from
C   given concentration, Pitot, cone-static, and
C   total temperature profiles.
C
C   ml.dat (file #1) is a reference file containing Pc/Pt2
C   values versus Mach numbers and gamma, as defined by
C   the Rayleigh Pitot Formula and the Cone Flow
C   equation.
C
C           Written :      Fei T. Kwok      9/1/89
C           Revised :      Eric J. Fuller   4/4/90
C
C-----
C
C   Dimension all needed variables
C
C       REAL  G(20) , M1(20,20) , PCPT2C(20,20) , PT2(2000) , PC(2000) ,
1       TT2(2000) , XHE(2000) , LVDT(2000) , M(2000) , P1(2000) ,
2       GS(2000) , RS(2000) , T1(2000) , A1(2000) , RHO1(2000) ,
3       U1(2000) , ptlcalc(2000)
C
C       INTEGER NP1(200) , CH
C       character*3 rn
C
C   Open file HFRUN.NUM and read total number of runs to reduce
C
C       open (20,file='hfrun.num',status='old')
C       read (20,*)
C       read (20,*) numrun
C
C   Loop to reduce each run number
C
C       do 1 jrun = 1,numrun
C         read (20,'(a3)') rn
C         write (6,'(a3)') rn
C
C   Open input files
C
C       OPEN(1,FILE='ml.dat',STATUS='OLD',FORM='FORMATTED')
C       OPEN(2,FILE='concen.'//rn,STATUS='OLD',FORM='FORMATTED')
C       OPEN(3,FILE='pt2.'//rn,STATUS='OLD',FORM='FORMATTED')
C       OPEN(4,FILE='pc.'//rn,STATUS='OLD',FORM='FORMATTED')
C       OPEN(5,FILE='tt2.'//rn,STATUS='OLD',FORM='FORMATTED')
C
C   Open output files
C
C       OPEN(15,FILE='ml.'//rn,STATUS='NEW',FORM='FORMATTED')
C       OPEN(7,FILE='p1.'//rn,STATUS='NEW',FORM='FORMATTED')
C       OPEN(8,FILE='u1.'//rn,STATUS='NEW',FORM='FORMATTED')
C       OPEN(9,FILE='rho1.'//rn,STATUS='NEW',FORM='FORMATTED')
C       OPEN(11,FILE='t1.'//rn,STATUS='NEW',FORM='FORMATTED')
C       OPEN(12,FILE='a1.'//rn,STATUS='NEW',FORM='FORMATTED')
C       OPEN(13,FILE='rlul.'//rn,STATUS='NEW',FORM='FORMATTED')
C       OPEN(14,FILE='g.'//rn,STATUS='NEW',FORM='FORMATTED')
C       OPEN(16,FILE='r.'//rn,STATUS='NEW',FORM='FORMATTED')
C       OPEN(17,FILE='ptlcalc.'//rn,STATUS='NEW',FORM='FORMATTED')
C
C
C       npts = 1650
C
C   Read input files (xhe, lvdt, pt2, pc, tt2)
C
C       DO 2 I = 1 , npts

```

Program 3: Program to Calculate Other Mean Flow Values

```

        READ(2,*,end=111) xhe(i) , lvd(i)
        READ(3,*) PT2(I)
        READ(4,*) PC(I)
        READ(5,*) TT2(I)
    2 CONTINUE
111 continue
C
C   Read M1.DAT reference file
C
    READ(1,*) NG , NP
    DO 3 IG = 1 , NG
        READ(1,*) G(IG)
        DO 3 IP = 1 , NP
            READ(1,*) M1(IG,IP) , PCPT2C(IG,IP)
    3 CONTINUE
C
C   Loop using gas mixture properties and Pc/Pt2 ratio to
C   determine Mach number and P1
C
    NMC = 0
    DO 4 I = 1 , NPTS
C
C   From concentration, determine gamma and R values
C
        CALL MIXTURE( XHE(I) , GAM , RS(I) )
C
        GS(I) = GAM
        PCPT2 = PC(I) / PT2(I)
C
C   From gamma, Pc/Pt2 and reference values from M1.DAT,
C   determine Mach numbers
C
        CALL MACH1( GAM,PCPT2,NG,NP,G,M1,PCPT2C,M(I),NMC,I,NP1 )
C
        GAMM1 = GAM - 1.
        GAMP1 = GAM + 1.
C
C   If Mach number is reasonable, find P1 from Ray. Pitot Equ.
C
        IF( M(I).GT.-0.1) P1(I) = (2.*GAM/GAMP1*M(I)**2 - GAMM1/
1      GAMP1)**(1./GAMM1) / (GAMP1/2.*M(I)**2)**(GAM/GAMM1) *
2      PT2(I)
    4 CONTINUE
C
C   Loop to find any remaining values of P1 not found previously
C   because of M = -1.0 (used to mark values where Cone flow
C   Equation does not apply
C
    IF(NMC.NE.0) THEN
        NI = 1
    10 IFLAG = 0
        DO 5 I = NI , NMC
            IF( NP1(I+1).NE.NP1(I)+1 ) THEN
                IF(IFLAG.EQ.0)THEN
                    N1 = NP1(I)
                    N2 = NP1(I)
                END IF
                GO TO 6
            ELSE
                IF(IFLAG.EQ.0) N1 = NP1(I)
                N2 = NP1(I+1)
                IFLAG = 1
            END IF
        5 CONTINUE
C
C   Interpolate for remaining P1's

```

Program 3: Program to Calculate Other Mean Flow Values

```

C
6   IF(N1.EQ.1) THEN
    DO 7 I2 = NI , I
      P1(NP1(I2)) = P1(N2+1)
7   CONTINUE
    ELSE IF( N2.EQ.NPTS ) THEN
      DO 8 I2 = I , NI , -1
        P1(NP1(I2)) = P1(N1-1)
8   CONTINUE
    ELSE
      DO 9 I2 = NI , I
        CALL INTERP( LVDT(N2+1),LVDT(N1-1),LVDT(NP1(I2)),
1  P1(N2+1),P1(N1-1),P1(NP1(I2)) )
9   CONTINUE
    END IF
C
    NI = I + 1
    IF( I.LT.NMC ) GO TO 10
    END IF
C
c   Loop to find remaining M's with interpolated P1's from above
c
    DO 11 I = 1 , NMC
      N = NP1(I)
C
c   with gamma, Pt2, and new P1, find M
C
      CALL MACH2( GS(N) , P1(N) , PT2(N) , M(N) )
11 CONTINUE
C
c   Loop to determine other variables from standard
c   isentropic flow equations and ideal gas equ.
c
    DO 12 I = 1 , NPTS
      T1(I) = TT2(I) / (1.+(GS(I)-1.)/2.*M(I)**2)
      A1(I) = SQRT( GS(I)*RS(I)*T1(I) )
      U1(I) = M(I) * A1(I)
      RHO1(I) = P1(I)*6894.757 / (RS(I)*T1(I))
      ptlcalc(i) = p1(i)*(1.+(gs(i)-1.)/2.*m(i)**2)**(gs(i)/
1  (gs(i)-1.))
12 CONTINUE
C
c   Loop to write to output files:
c   -- lvdt . . nondimensionalized by injector diameter
c   -- P1, Pt1 . psia
c   -- U1, A1 . m/sec
c   -- rho1 . . kg/m^3
c   -- T1 . . . deg Kelvin
c   -- Xhe . . . mole fraction of helium
c   -- R . . . . J/(kg*deg K)
C
    DO 13 I = 1 , NPTS
      YL = LVDT(I)
      WRITE(15,*) M(I) , YL
      WRITE(7,*) P1(I) , YL
      WRITE(8,*) U1(I) , YL
      WRITE(9,*) RHO1(I) , YL
      WRITE(11,*) T1(I) , YL
      WRITE(12,*) A1(I) , YL
      WRITE(13,*) RHO1(I) * U1(I) , YL
      write (14,*) gs(i), yl
      write (16,*) rs(i), yl
      write (17,*) ptlcalc(i), yl
13 CONTINUE
C
C   close all the files

```

Program 3: Program to Calculate Other Mean Flow Values

```

C      DO 1000 I = 1 , 17
C          if (i.ne.6) CLOSE(I)
1000 CONTINUE
C
C      1 continue
C
C      STOP
C      END
C
C-----
C
C      Subroutine MIXTURE :
C
C          determines gamma and R
C
C      SUBROUTINE MIXTURE(XHE,G,R)
C      REAL M , MHE , MA
C
C      Molecular weight (kg/kmole) and Cp (J/kg/Kelvin) of
C      Helium and air
C
C      MHE = 4.0026
C      CPHE = 5200.
C      MA = 29.0
C      CPA = 1005.7
C
C      calculate mixture molecular weight from mole fraction helium
C      and then retrieve R and gamma
C
C      XA = 1. - XHE
C      M = XHE * MHE + XA * MA
C      CP = ( XHE * CPHE * MHE + XA * CPA * MA ) / M
C      R = 8317. / M
C      CV = CP - R
C      G = CP / CV
C      RETURN
C      END
C
C-----
C
C      Subroutine : MACH1
C
C      determines Mach number over profile, if applicable
C
C      SUBROUTINE MACH1(GAM,PCPT2,NG,NP,G,M1,PCPT2C,M,NMC,I,NP1)
C      REAL G(20) , M1(20,20) , PCPT2C(20,20) , M , PCPT2L(20) ,
1      ML(20)
C      INTEGER NP1(200)
C
C      Loop to find proper interval of gamma as compared to
C      values in M1.DAT
C
C      DO 1 IG = 1 , NG-1
C          IF(GAM.GE.G(IG).AND.GAM.LE.G(IG+1)) GO TO 2
1      CONTINUE
2      GIG = G(IG)
      GIG1 = G(IG+1)
C
C      Interpolate for proper interval of Pc/Pt2 references
C
C      CALL INTERP(GIG,GIG1,GAM,PCPT2C(IG,1),PCPT2C(IG+1,1),PCPT2L(1))
C
C      Loop to check experimental Pc/Pt2 against critical Pc/Pt2
C      from M1.DAT to determine if Cone Flow applies
C

```

Program 3: Program to Calculate Other Mean Flow Values

```

        IF(PCPT2.GT.PCPT2L(1)) THEN
            M = -1.0
            NMC = NMC + 1
            NP1(NMC) = I
            RETURN
        END IF
C
C   Loop to determine Pc/Pt2 and Mach number intervals
C
        DO 3 IP = 1 , NP
            CALL INTERP(GIG,GIG1,GAM,PCPT2C(IG,IP),PCPT2C(IG+1,IP),
1             PCPT2L(IP))
            CALL INTERP(GIG,GIG1,GAM,M1(IG,IP),M1(IG+1,IP),ML(IP))
        3 CONTINUE
C
C   Loop to find final Mach number value according to
C   corresponding Pc/Pt2 ratio
C
        DO 4 IP = 1 , NP-1
            IF(PCPT2.LE.PCPT2L(IP).AND.PCPT2.GE.PCPT2L(IP+1)) THEN
                CALL INTERP(PCPT2L(IP),PCPT2L(IP+1),PCPT2,ML(IP),
1             ML(IP+1),M)
                RETURN
            END IF
        4 CONTINUE
C
        RETURN
        END
C
C-----
C
C   Subroutine : MACH2
C
C   determine remaining unknown Mach numbers
C
        SUBROUTINE MACH2( G , P1 , PT2 , M )
            REAL M , M1 , M2
            GM1 = G - 1.
            GP1 = G + 1.
            P1PT2 = P1 / PT2
            sonic = (2.*g/gp1-gm1/gp1)**(1./gm1) / (gp1/2.)*(g/gm1)
C
C   Loop to see if flow is subsonic, supersonic or sonic, then
C   determine Mach number accordingly
C
            IF(P1PT2.GT.sonic) THEN
C
C   If subsonic, then M from isentropic flow
C
                IF(P1PT2.GT.1.0) P1PT2 = 1.0
                M = SQRT( 2./(G-1.)*(P1PT2**((1.-G)/G)-1.))
                RETURN
            ELSE
C
C   If supersonic, then M iterated from Ray. Pitot Equ.
C
                M1 = 2.0
C
C   Use shooting method to iterate for M
C
                DO 1 I = 2 , 4
                    DELM = 10. * 0.1**I
                    M2 = M1 - DELM
                    PM1 = (2.*G/GP1*M1*M1 - GM1/GP1)**(1./GM1) /
2             (GP1/2.*M1*M1)**(G/GM1)
                    1 PM2 = (2.*G/GP1*M2*M2 - GM1/GP1)**(1./GM1) /

```

Program 3: Program to Calculate Other Mean Flow Values

```

1      (GP1/2.*M2*M2)**(G/GM1)
      DM1 = PM1 - P1PT2
      DM2 = PM2 - P1PT2
      IF (ABS(DM1).LE.1E-3) THEN
        M = M1
        GO TO 3
      ELSE IF (ABS(DM2).LE.1E-3) THEN
        M = M2
        GO TO 3
      END IF
      IF ((DM1*DM2).LT.0.0) GO TO 1
      M1 = M2
      GO TO 2
1     CONTINUE
      IF (ABS(DM1).LE.ABS(DM2)) THEN
        M = M1
      ELSE
        M = M2
      END IF
      END IF
3     IF (M.GT.1.12) M = 1.10
      RETURN
      END

```

C

C-----

C

C Subroutine : INTERP

C

C interpolation routine

C

```

      SUBROUTINE INTERP(X2,X1,X,Y2,Y1,Y)
      SM = (Y2-Y1) / (X2-X1)
      Y = SM * (X-X1) + Y1
      RETURN
      END

```

Program 3: Program to Calculate Other Mean Flow Values

```

c
c*****
c*** Program to find total pressure parameter heights H and ***
c*** H+ ***
c*** written by R.B. Mays on 6-14-89 ***
c*****
c
c
      real zmf(1200),mf(1200),zxhe(1200),xhe(1200)
      real zint(2501),rlulint(2501),heint(2501),mfhe(1200),mfair(1200)
      real brlul(1200),bzrlul(1200)
      character rn*10
      write(*,*) 'Enter run number'
      read(*, '(a10)') rn
      open(1,file='/people/mays/data.d/rlul.d/rlul.'//rn)
      open(2,file='/people/mays/data.d/concen.d/concen.'//rn)
      maxrlul=1

c
c      Read in data convert distances to metric
c
10  read(1,*,end=20) mf(maxrlul),zmf(maxrlul)
    zmf(maxrlul)=zmf(maxrlul)*.0254
    maxrlul=maxrlul+1
    go to 10
20  maxcon=1
30  read(2,*,end=40) zxhe(maxcon),xhe(maxcon)
    mwmix=4.003*xhe(maxcon)+28.97*(1-xhe(maxcon))
    mfhe(maxcon)=4.003*xhe(maxcon)/mwmix
    mfair(maxcon)=28.97*(1-xhe(maxcon))/mwmix
    zxhe(maxcon)=zxhe(maxcon)*.0254
    maxcon=maxcon+1
    go to 30
40  maxrlul=maxrlul-1
    maxcon=maxcon-1
    close (1)
    close (2)

c
c      Find height of jet
c      Defined as z point where xfhe <= .005
c
    do 50 i=1,maxcon
50   if (xhe(i).le.0.005) go to 60
      write(*,*) 'Edge of jet not found, please enter height in meters'
      read(*,*) pht
      go to 65
60   pht=zxhe(i-1)+(.005-xhe(i-1))*(zxhe(i)-zxhe(i-1))/(xhe(i)-xhe(i-1)
1)
65   dy=pht/351
      maxint=351
      write(*,*) pht

c
c      Line up Mass flux and total pressure profiles with concentration
c      profiles
c
    do 70 i=1,maxint
70   zint(i)=i*dy
      call liner(mf,zmf,maxrlul,zint,rlulint,maxint)
      call liner(mfhe,zxhe,maxcon,zint,heint,maxint)
      do 80 i=1,maxint
80   rlulint(i)=rlulint(i)*heint(i)

c
c      Find mass of helium in profile
c
      call simp(rlulint,maxint,dy,tothe)
      dht=1.0
      htmax=1.00

```

Program 4: Program to Calculate P_{tp} Reference Heights

```

      maxint=1001
85  dy=htmax/maxint
      do 86 i=1,maxint
86  zint(i)=i*dy
c
c    Find Parameter H by iterating on equation [3.4]
c
      call liner(mfair,zxhe,maxcon,zint,heint,maxint)
      call liner(mf,zmf,maxrlul,zint,rlulint,maxint)
      do 90 i=1,maxint
90  rlulint(i)=heint(i)*rlulint(i)
      call simp(rlulint,maxint,dy,stocair)
      write(*,*) dy*maxint,stocair/tothe
      if (stocair/tothe.ge.34.246) then
          htmax=htmax-dht
          dht=dht/10
      end if
      if (dht.ge.0.00001) then
          htmax=htmax+dht
          go to 85
      end if
      write(*,*) 'H=',htmax
c
c    Read in values of massflux for undisturbed freestream
c
      open(1,file='/people/mays/data.d/rlul.d/rlul.278')
      maxbl=1
100  read(1,*,end=110) brlul(maxbl),bzrlul(maxbl)
      bzrlul(maxbl)=bzrlul(maxbl)*.0254
      maxbl=maxbl+1
      go to 100
110  maxbl=maxbl-1
      dht=1.0
      htmax=1.00
      maxint=1001
120  dy=htmax/maxint
      do 130 i=1,maxint
130  zint(i)=i*dy
c
c    Find parameter H+ by iteration on equation [3.5]
c
      call liner(brlul,bzrlul,maxbl,zint,rlulint,maxint)
      call simp(rlulint,maxint,dy,xmassair)
      write(*,*) dy*maxint,xmassair
      if (xmassair.ge.stocair) then
          htmax=htmax-dht
          dht=dht/10
      end if
      if (dht.ge.0.00001) then
          htmax=htmax+dht
          go to 120
      end if
      write(*,*) 'H!=',htmax
      stop
      end

      subroutine simp(f,n,h,ans)
c
c    Simpson's Rule Integration Routine
c
      real f(2500),h,ans
      integer n,ik

      ik=n-1
      ans=h/3*(f(1)+f(ik+1))
      do 10 i=2,ik

```

Program 4: Program to Calculate P_{tp} Reference Heights

```

        xi=float(i)
        if (xi/2.eq.float(int(xi/2))) then
            ans=ans+4*h/3*f(i)
        else
            ans=ans+2*h/3*f(i)
        end if
10 continue
return
end

```

```

subroutine liner(dt,dtht,ndt,otht,ot,nt)
c
c Routine to line up profiles
c
real dt(1200),dtht(1200),otht(1200),ot(1200)
do 150 i=1,nt
    if (otht(i).lt.dtht(1)) go to 200
    if (otht(i).gt.dtht(ndt)) go to 225
    do 250 j=1,ndt
        if (otht(i).lt.dtht(j)) go to 320
250    continue
320    ot(i)=dt(j)-(dt(j)-dt(j-1))*(dtht(j)-otht(i))/
1      (dtht(j)-dtht(j-1))
        go to 150
200    ot(i)=dt(1)
        go to 150
225    ot(i)=dt(ndt)
150 continue
return
end

```

Program 4: Program to Calculate P_{tp} Reference Heights

```

c
c*****
c***  Program to find the total pressure parameter      ***
c***  using equation [3.3]                             ***
c***  written by R.B. Mays on 6-14-89                  ***
c*****
c
c
      real pt1(1200),zpt1(1200),rlul(1200),zrlul(1200)
      real zint(1200),ptlint(1200),rlulint(1200)
      real bzpt1(1200),bpt1(1200),bru(1200)
      real bzru(1200)
      character rn*10
      write(*,*) 'Enter run number'
      read(*, '(a10)') rn
c
c  Open relavent data files (All units must be metric)
c
      open(1,file='/people/mays/data.d/pt1.d/xpt1.'//rn)
      open(2,file='/people/mays/data.d/rlul.d/rlul.'//rn)
      open(3,file='/people/mays/data.d/pt1.d/xpt1.278')
      open(4,file='/people/mays/data.d/rlul.d/rlul.278')
      maxdat=1
c
c  Read in data
c
      10 read(1,*,end=20) pt1(maxdat),zpt1(maxdat)
         zpt1(maxdat)=zpt1(maxdat)
         pt1(maxdat)=pt1(maxdat)*1000
         maxdat=maxdat+1
         go to 10
      20 maxdat=maxdat-1
         maxru=1
      90 read(2,*,end=100) rlul(maxru),zrlul(maxru)
         zrlul(maxru)=zrlul(maxru)*.0254
         maxru=maxru+1
         go to 90
      100 maxru=maxru-1
          maxbpt=1
      110 read(3,*,end=120) bpt1(maxbpt),bzpt1(maxbpt)
          bzpt1(maxbpt)=bzpt1(maxbpt)
          maxbpt=maxbpt+1
          go to 110
      120 maxbpt=maxbpt-1
          maxbr=1
      130 read(4,*,end=140) bru(maxbr),bzru(maxbr)
          bzru(maxbr)=bzru(maxbr)*.0254
          maxbr=maxbr+1
          go to 130
      140 maxbr=maxbr-1

      write(*,*) 'Enter parameter H (meters)'
      read(*,*) h
      write(*,*) 'Enter parameter H! (meters)'
      read(*,*) hprime
      write(*,*) 'Enter jet mass flux (kg/m^2s)'
      read(*,*) xmfj
      write(*,*) 'Enter jet total pressure (N/m^2)'
      read(*,*) ptj
      write(*,*) 'Enter jet diameter (meters)'
      read(*,*) dj
c
c  Find denominator of total pressure parameter
c
      maxint=1001

```

Program 5: Program to Calculate Total Pressure Parameter

```

dy=hprime/maxint
do 40 i=1,maxint
40 zint(i)=dy*i
   call liner(bpt1,bzpt1,maxbpt,zint,ptlint,maxint)
   call liner(bru,bzru,maxbr,zint,rlulint,maxint)
   do 50 i=1,maxint
50 ptlint(i)=rlulint(i)*ptlint(i)
   call simp(ptlint,maxint,dy,hpint)
   write(*,*) hpint
c
c Find numerator of total pressure parameter
c
dy=h/maxint
do 60 i=1,maxint
60 zint(i)=dy*i
   call liner(ptl,zptl,maxdat,zint,ptlint,maxint)
   call liner(rlul,zrlul,maxdat,zint,rlulint,maxint)
   do 70 i=1,maxint
70 ptlint(i)=rlulint(i)*ptlint(i)
   call simp(ptlint,maxint,dy,hint)
   bot=hpint+xfj*ptj*dj
   write(*,*) hint
c
c Calculate total pressure parameter
c
ptparam=hint/bot
write(*,80) ptparam
80 format(1x,'The Total pressure parameter is ',f8.6)
stop
end

subroutine liner(dt,dtht,ndt,otht,ot,nt)
c
c Routine to line profiles up
c
real dt(1200),dtht(1200),otht(1200),ot(1200)
do 150 i=1,nt
   if (otht(i).lt.dtht(1)) go to 200
   if (otht(i).gt.dtht(ndt)) go to 225
   do 250 j=1,ndt
   if (otht(i).lt.dtht(j)) go to 320
250 continue
320 ot(i)=dt(j)-(dt(j)-dt(j-1))*(dtht(j)-otht(i))/
1 (dtht(j)-dtht(j-1))
   go to 150
200 ot(i)=dt(1)
   go to 150
225 ot(i)=dt(ndt)
150 continue
return
end

subroutine simp(f,n,h,ans)
c
c Routine to perform Simpson's Rule numerical integration
c
real f(2500),h,ans
integer n,ik

ik=n-1
ans=h/3*(f(1)+f(ik+1))
do 10 i=2,ik
   xi=float(i)
   if (xi/2.eq.float(int(xi/2))) then
      ans=ans+4*h/3*f(i)

```

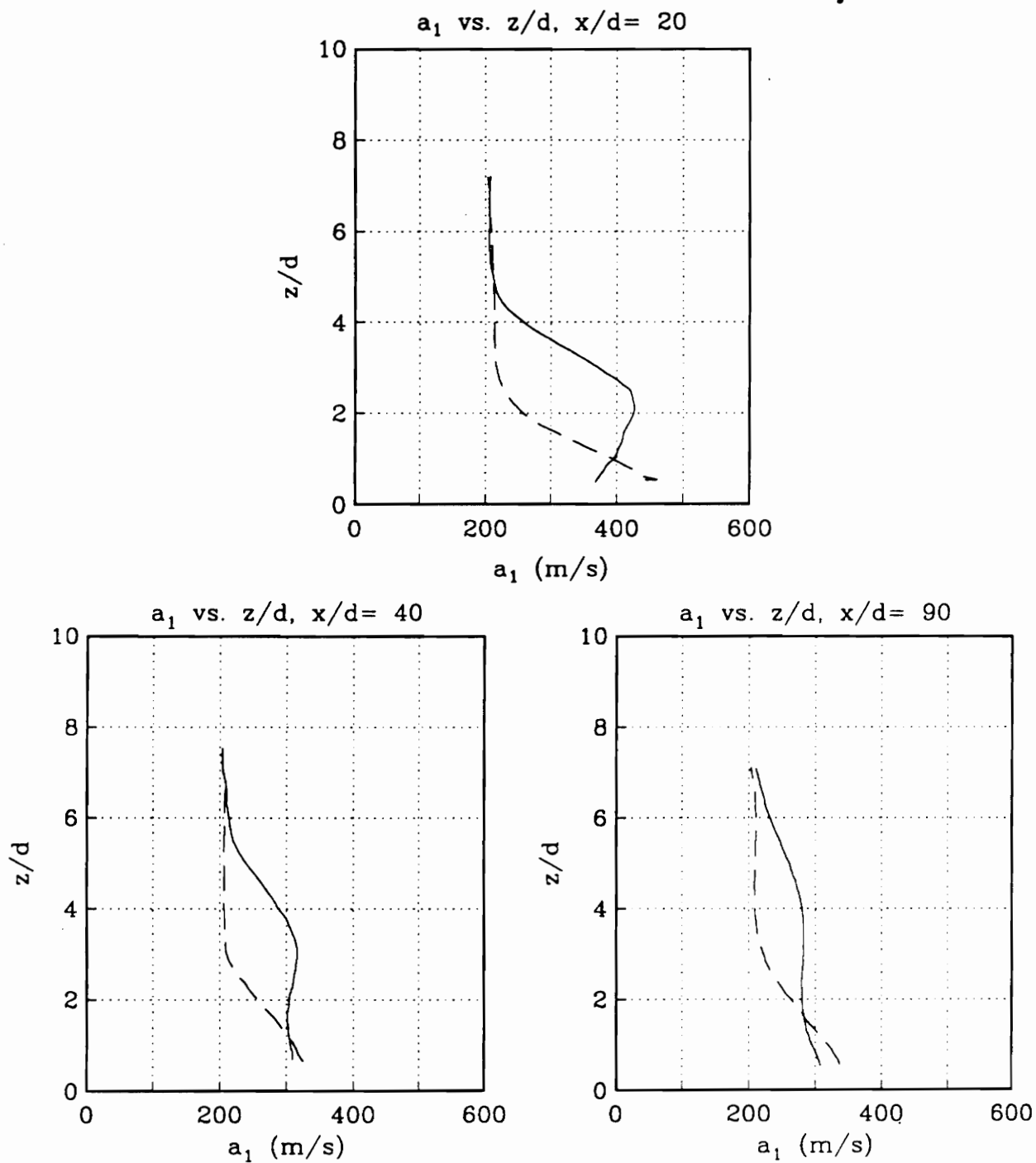
Program 5: Program to Calculate Total Pressure Parameter

```
        else
            ans=ans+2*h/3*f(i)
        end if
10 continue
return
end
```

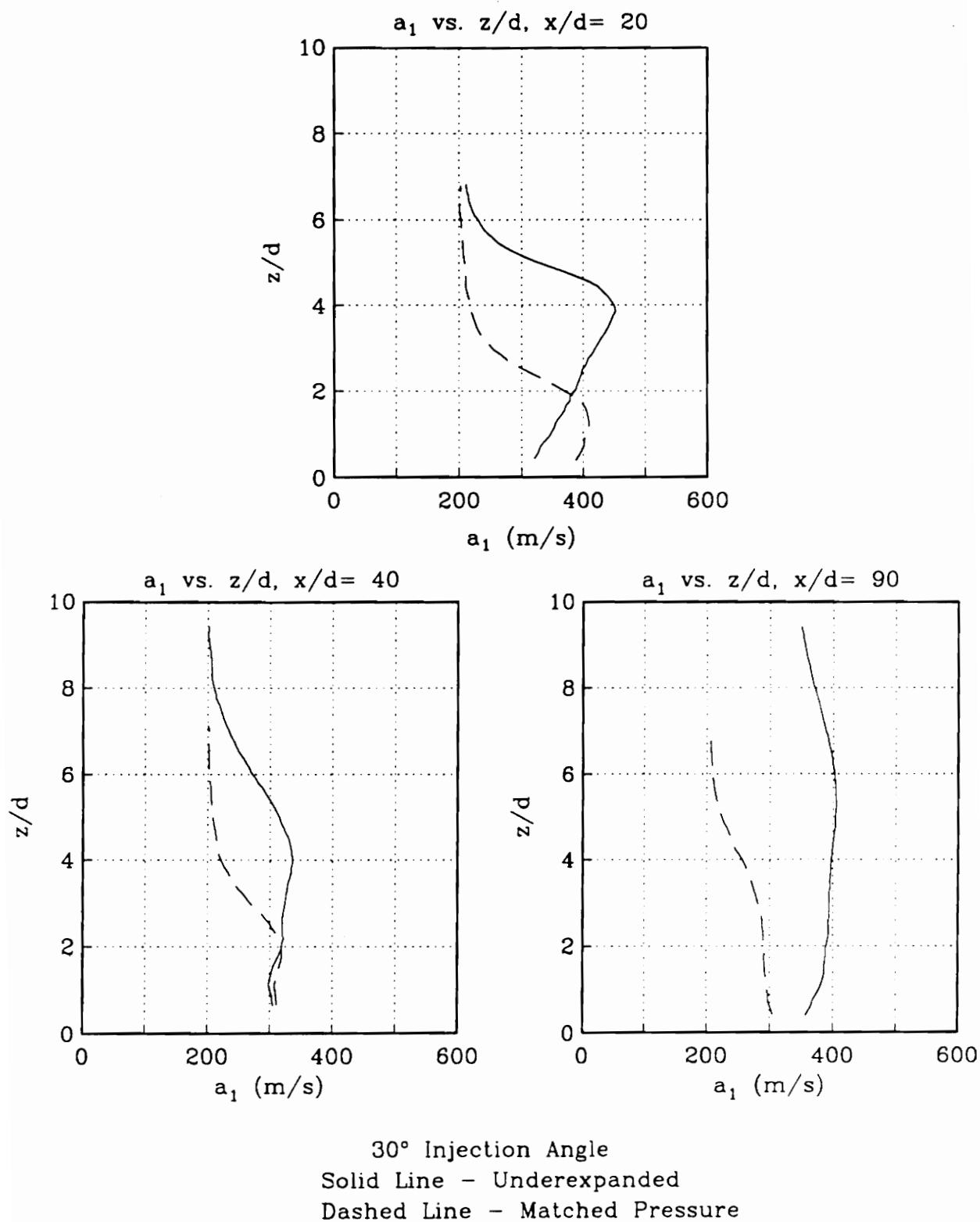
Program 5: Program to Calculate Total Pressure Parameter

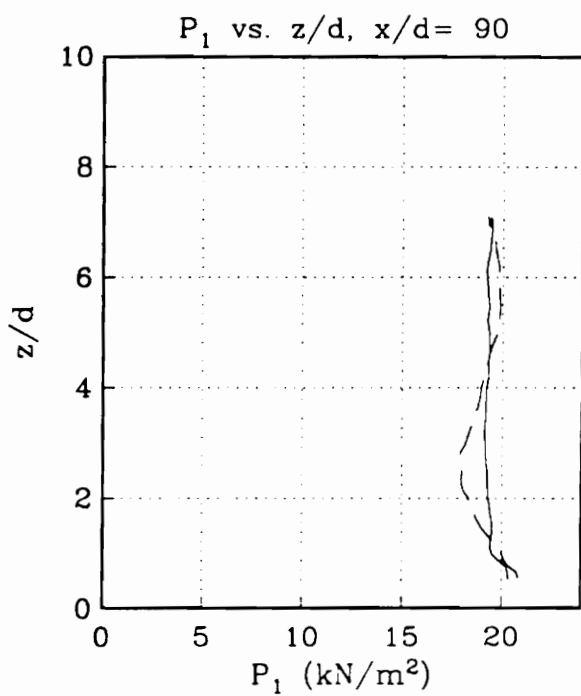
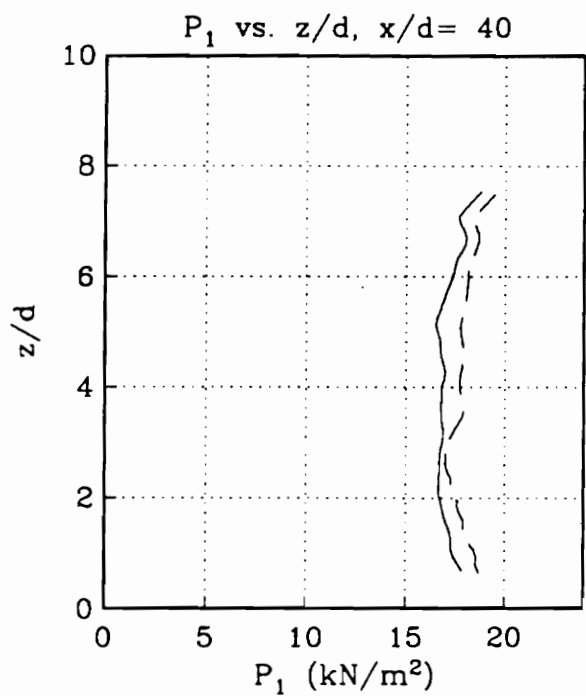
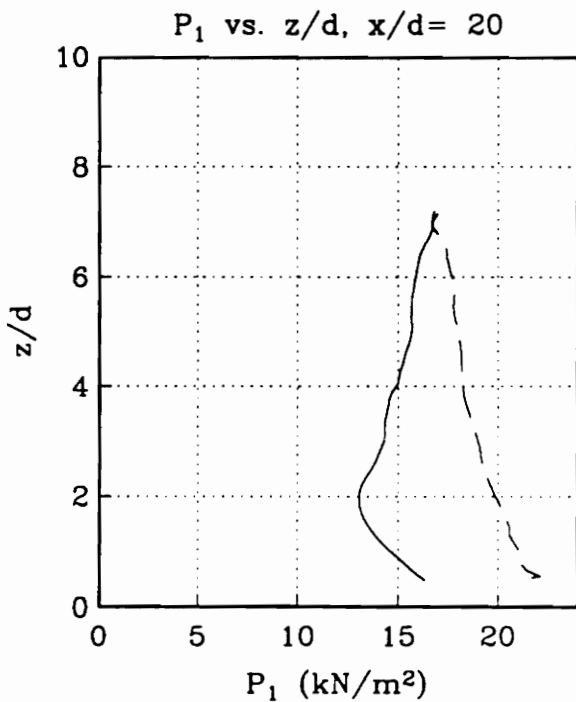
Appendix C: Dimensional Data

Dimensional, centerline vertical profiles of the speed of sound, static pressure, total pressure, density, static temperature, total temperature, mass flux, and velocity are presented in the following pages. All units are metric and are indicated on each graph. Vertical profiles of the helium mass fraction for all cases at each axial and lateral station are also given.

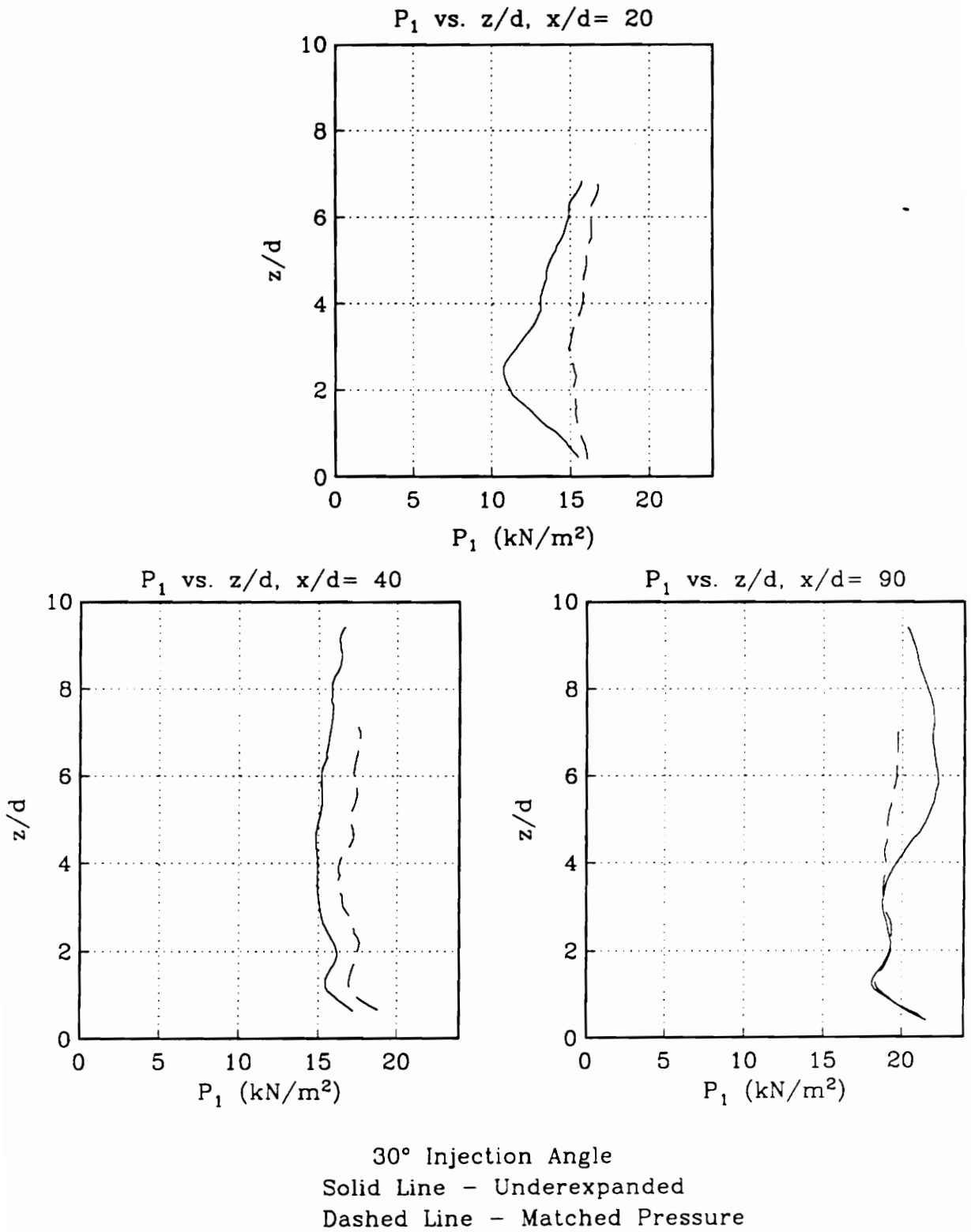


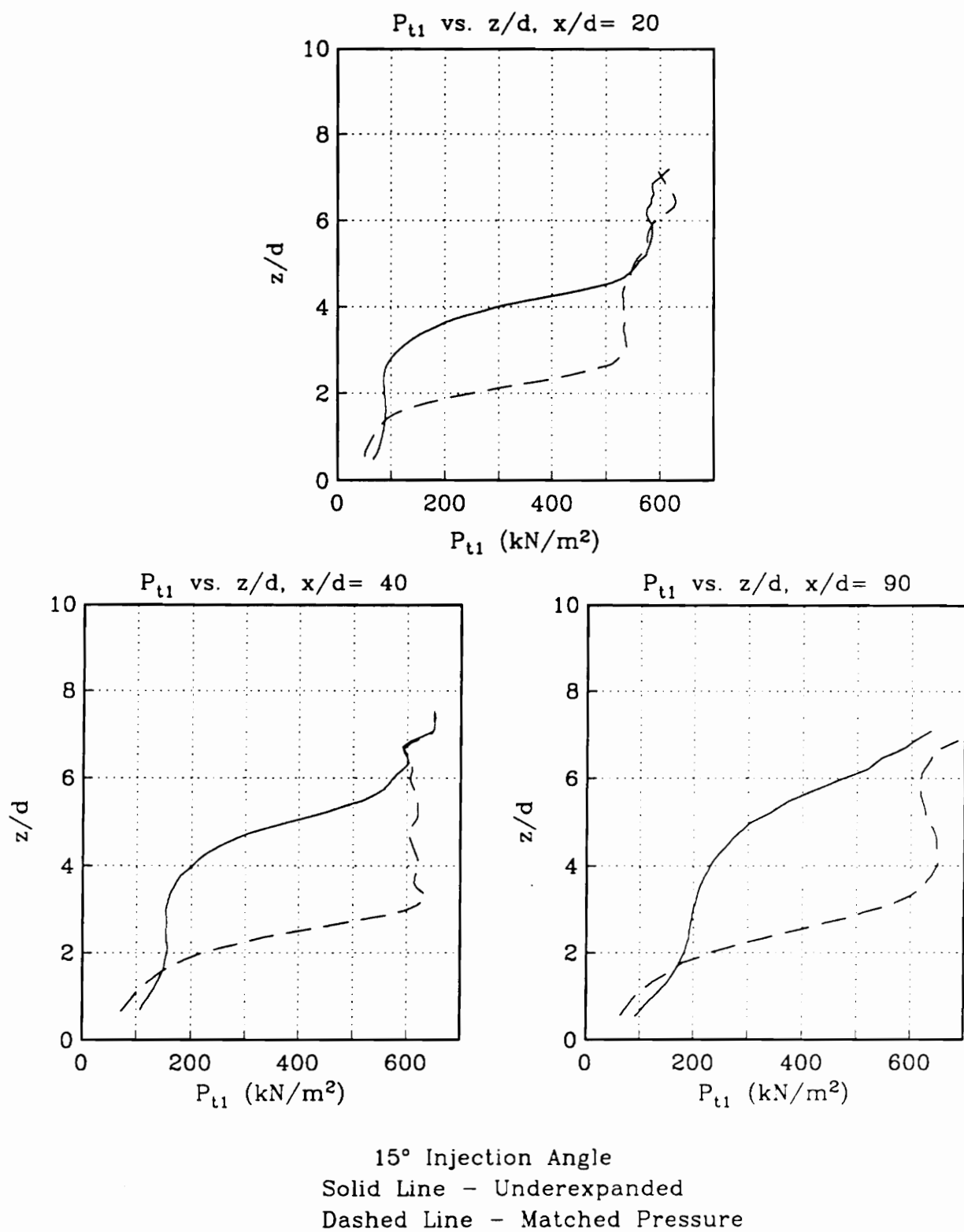
15° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure

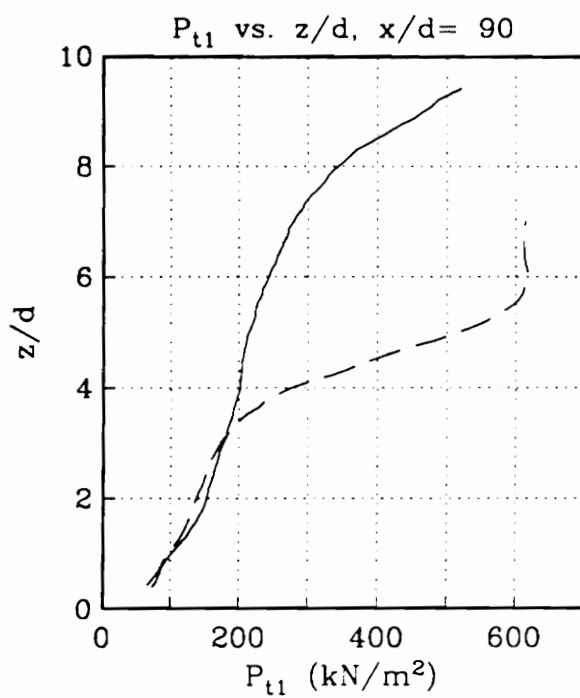
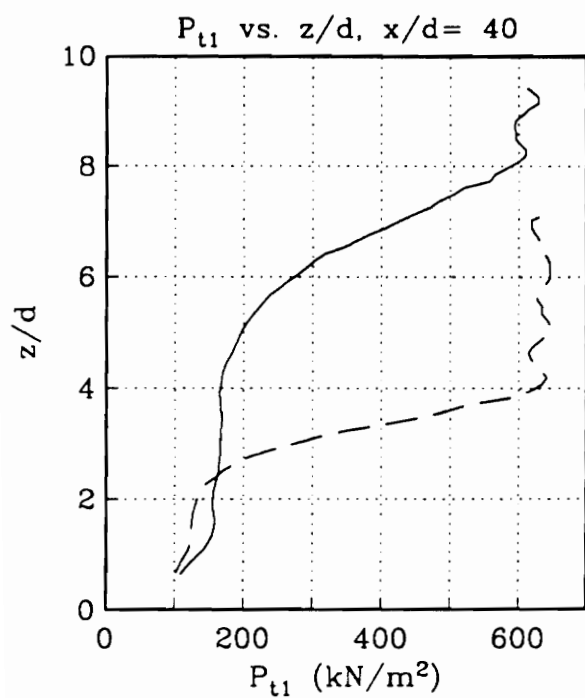
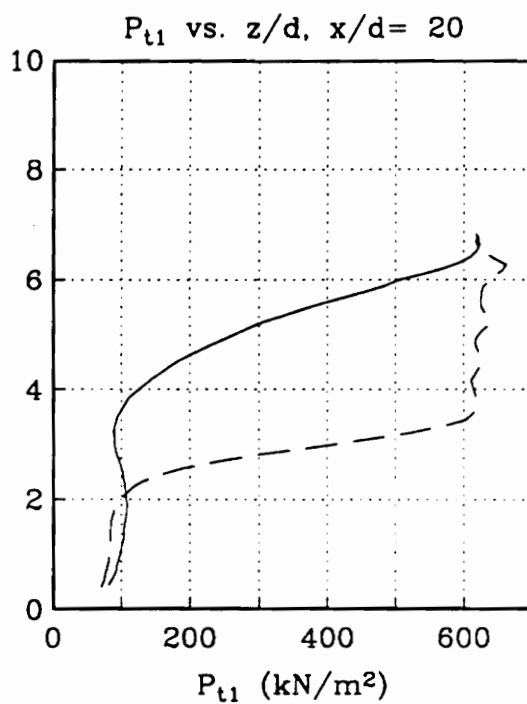




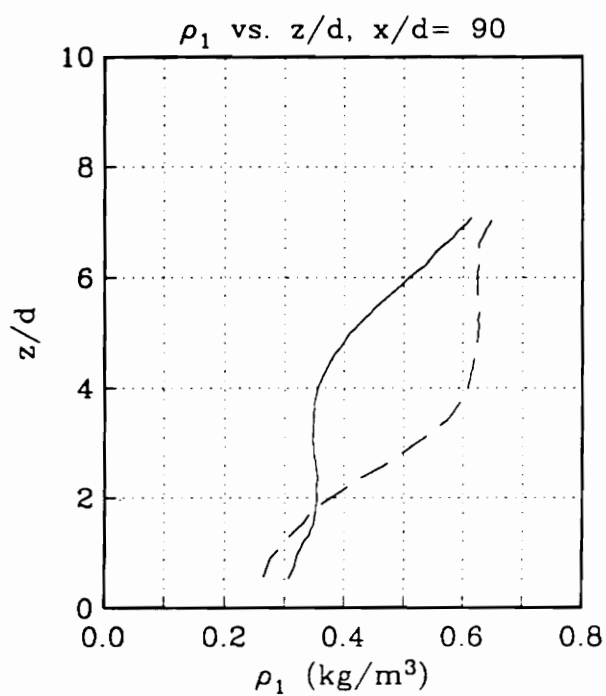
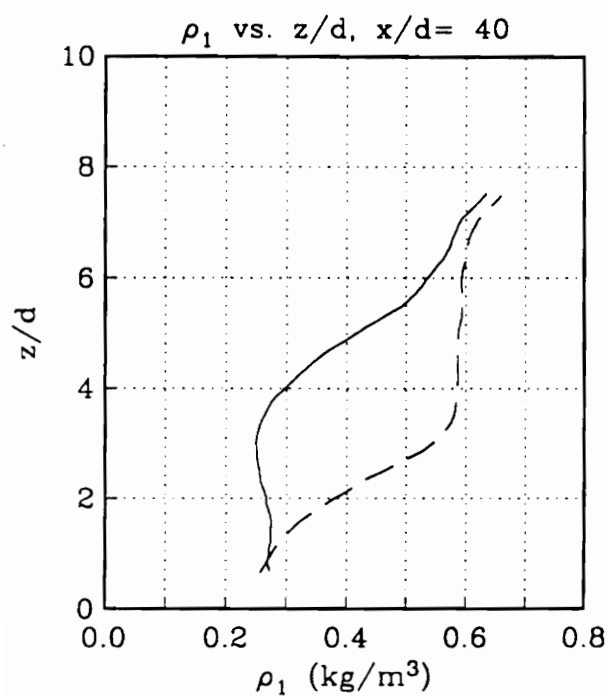
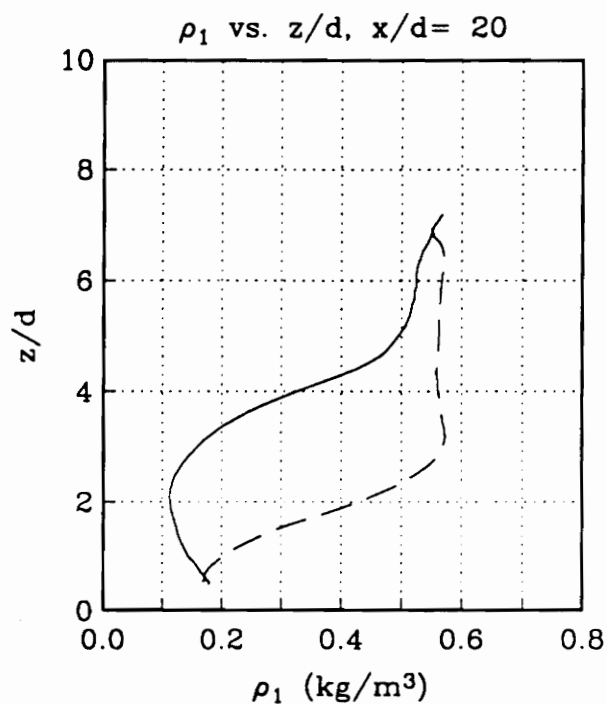
15° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure



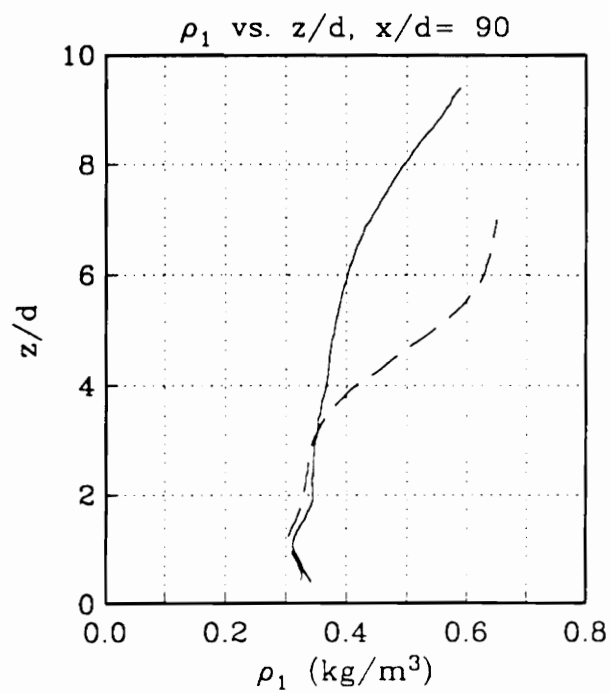
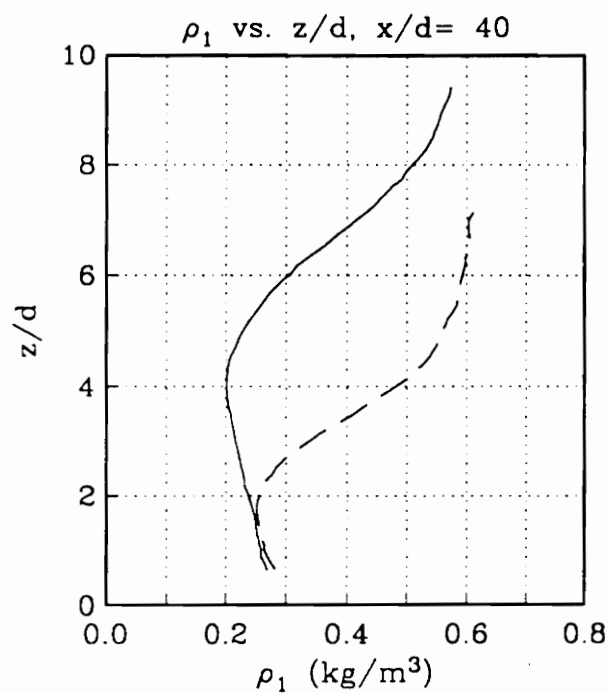
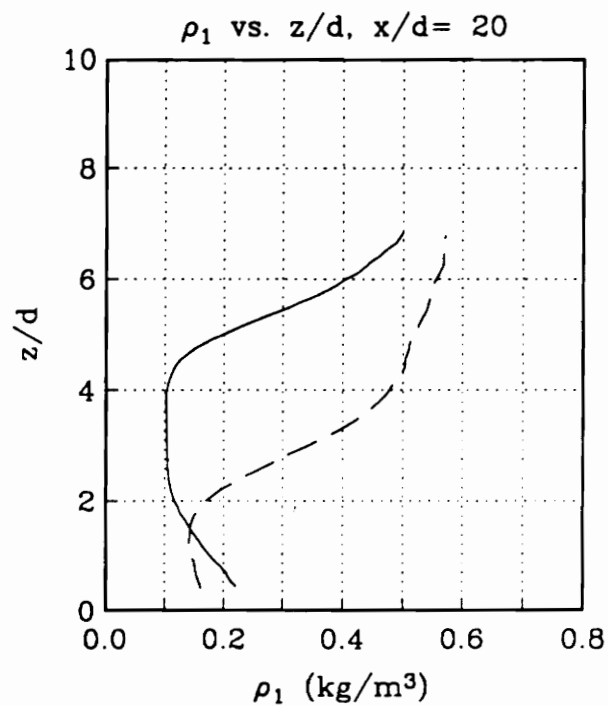




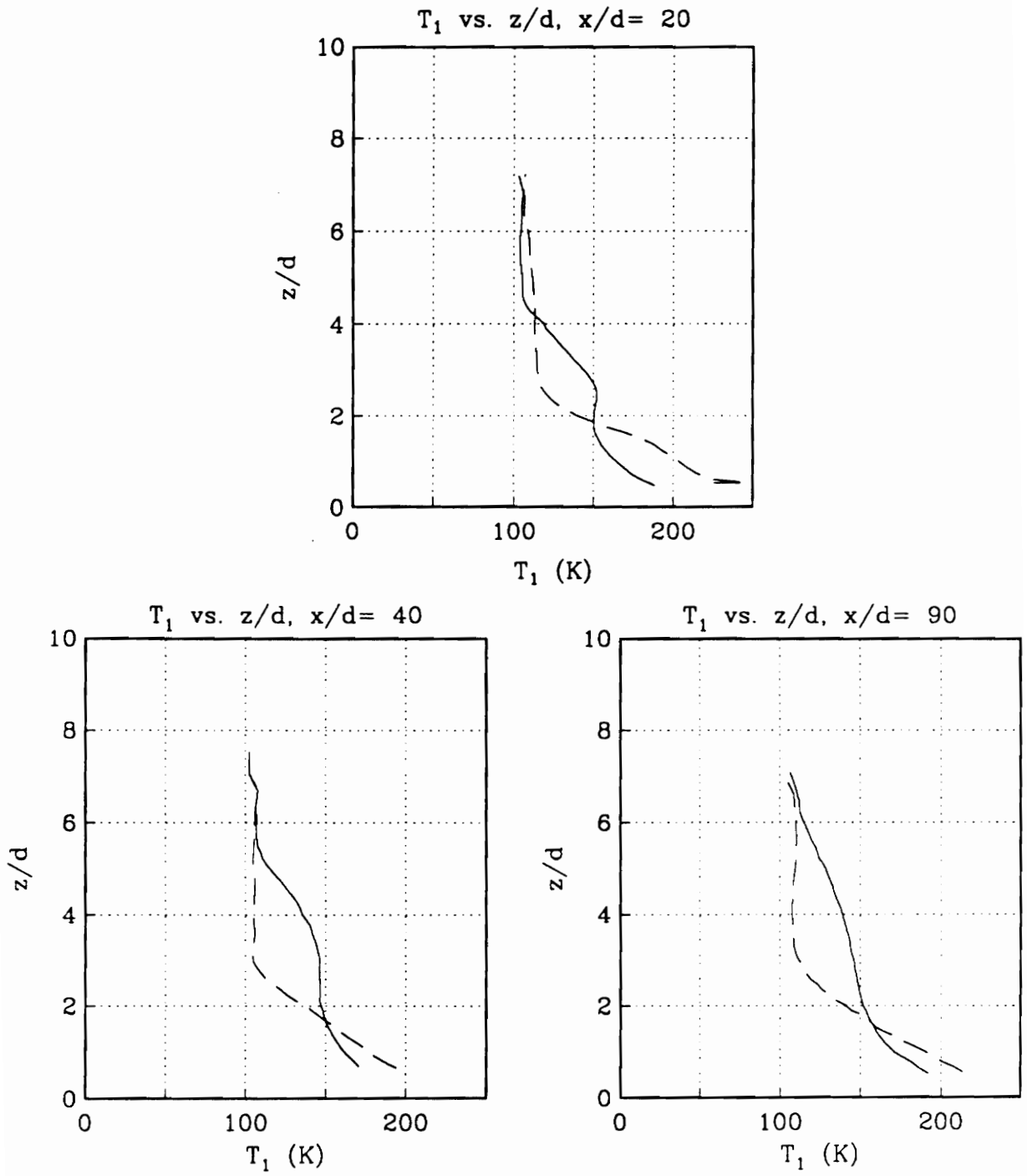
30° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure



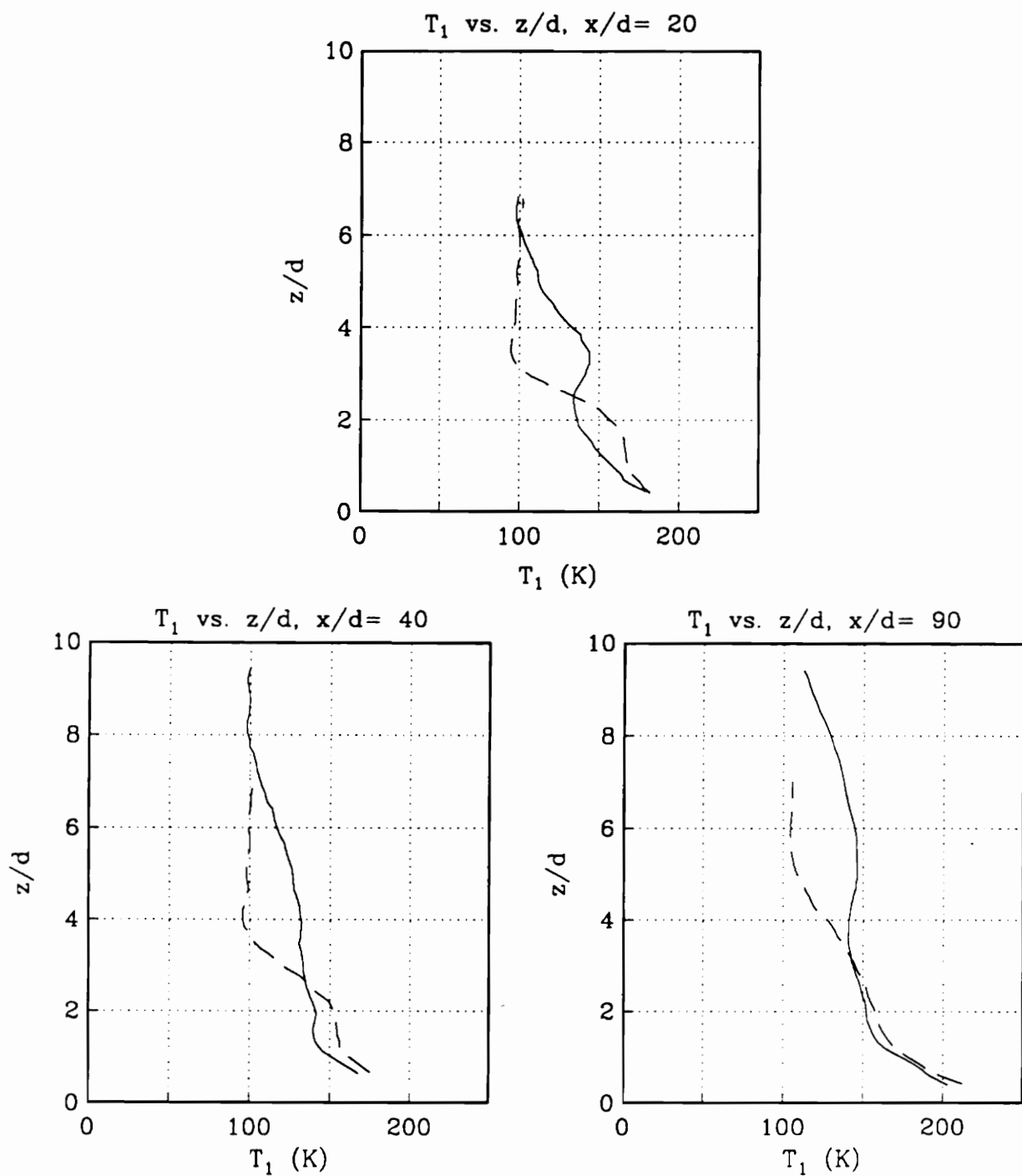
15° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure



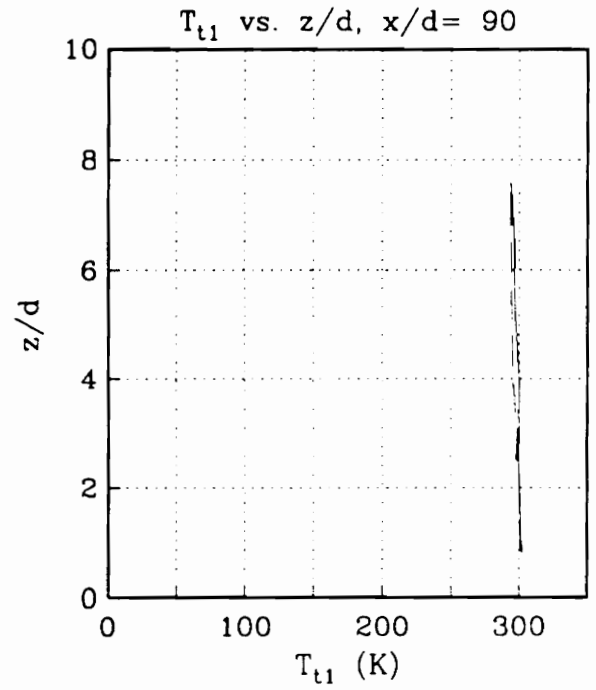
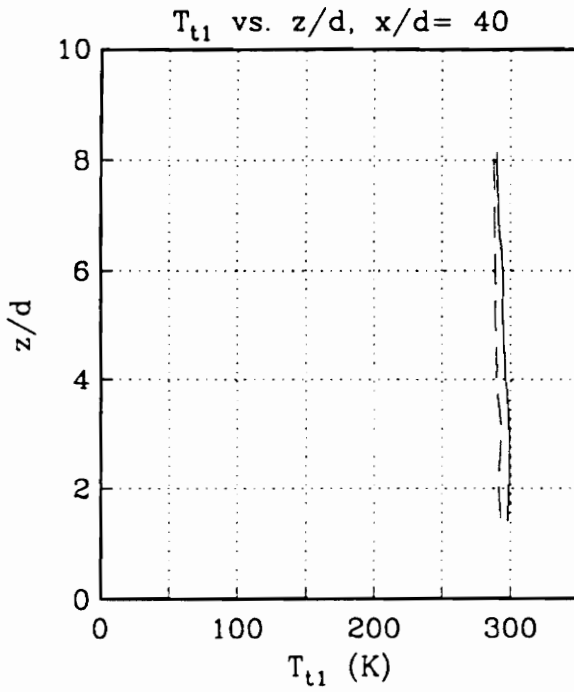
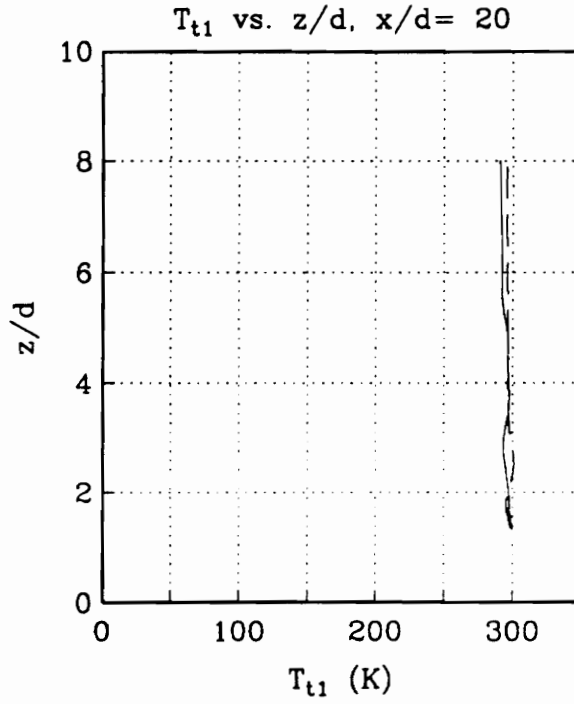
30° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure



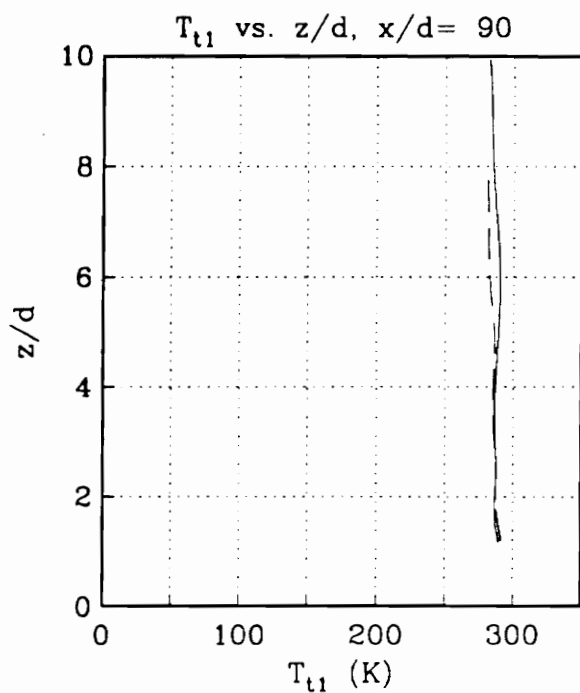
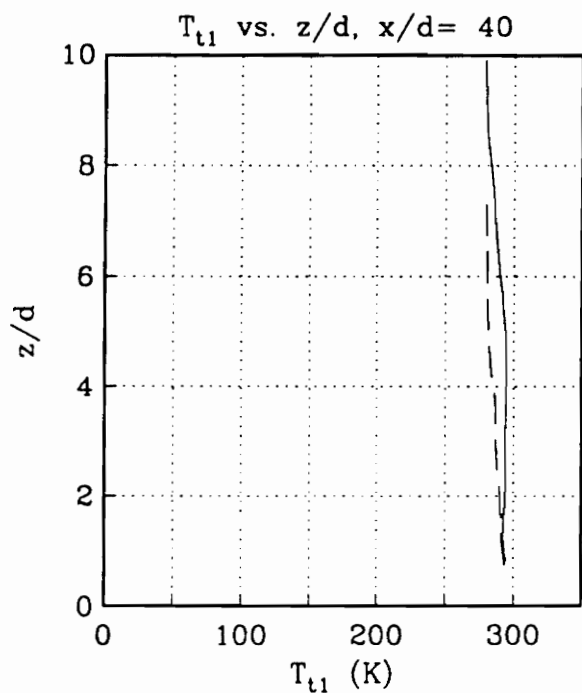
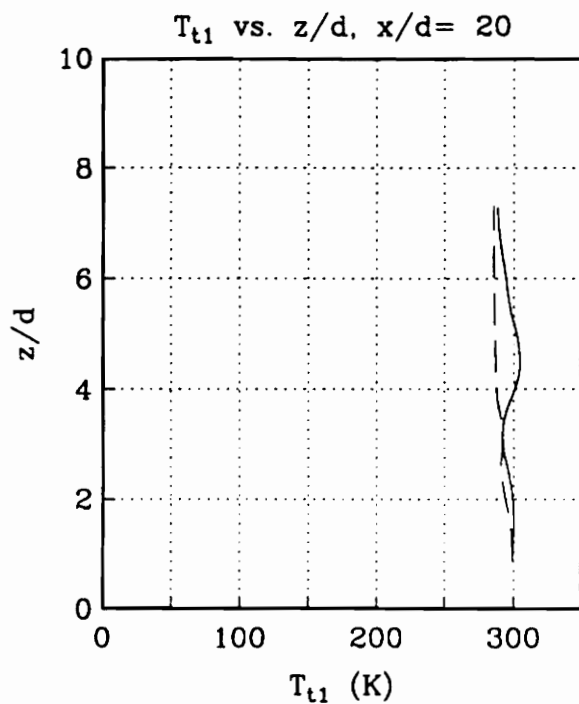
15° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure



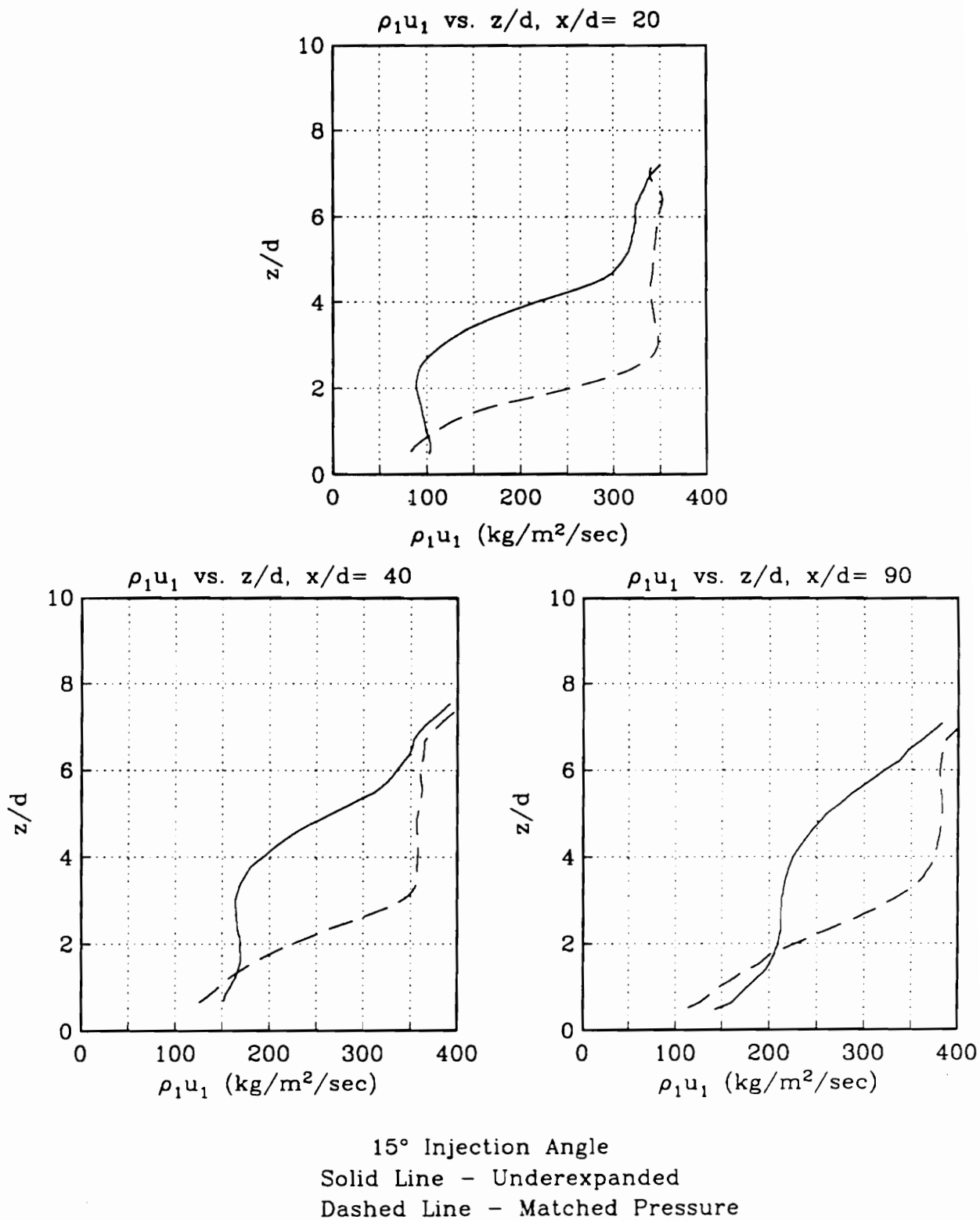
30° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure

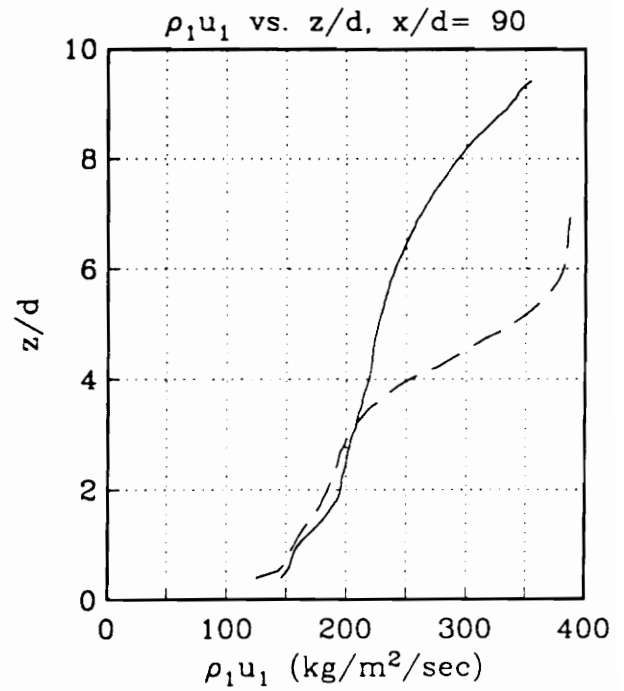
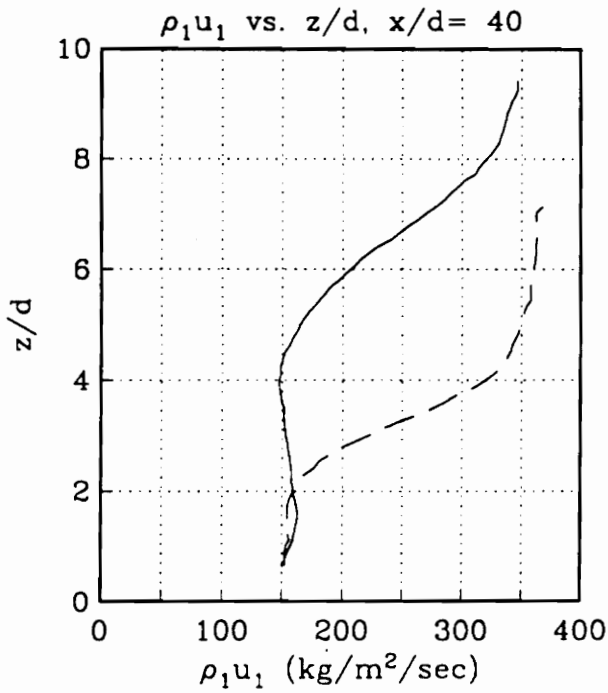
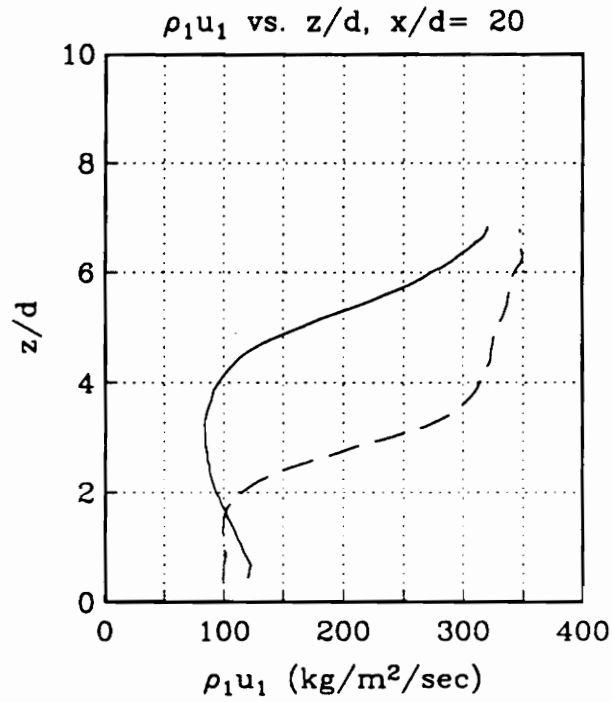


15° Injection Angle
Solid Line - Underexpanded
Dashed Line - Matched Pressure

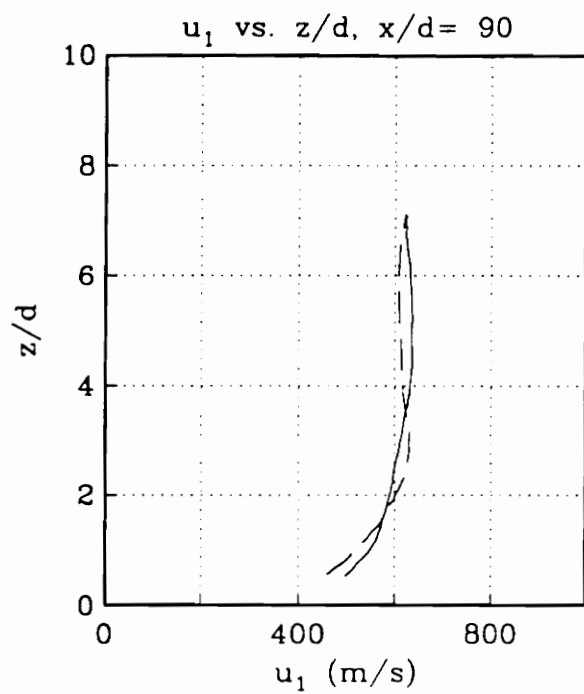
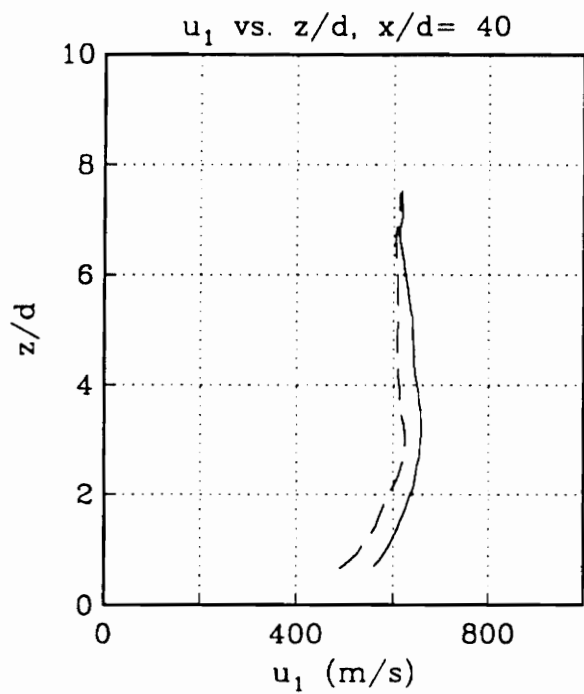
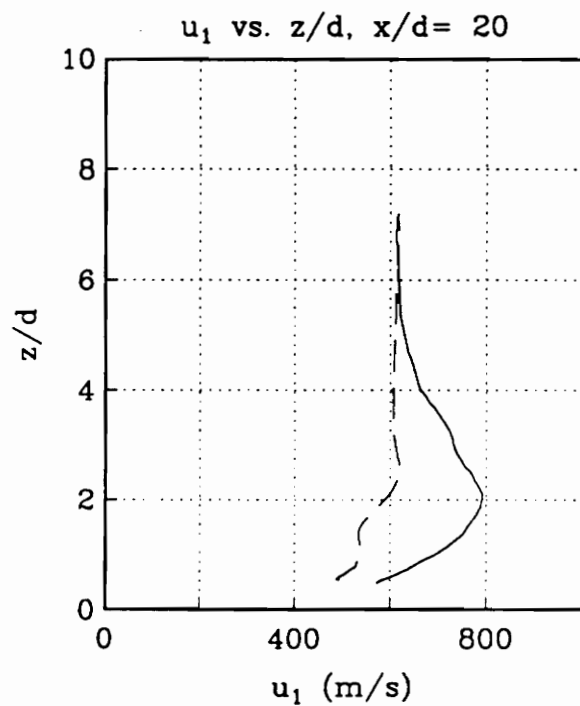


30° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure

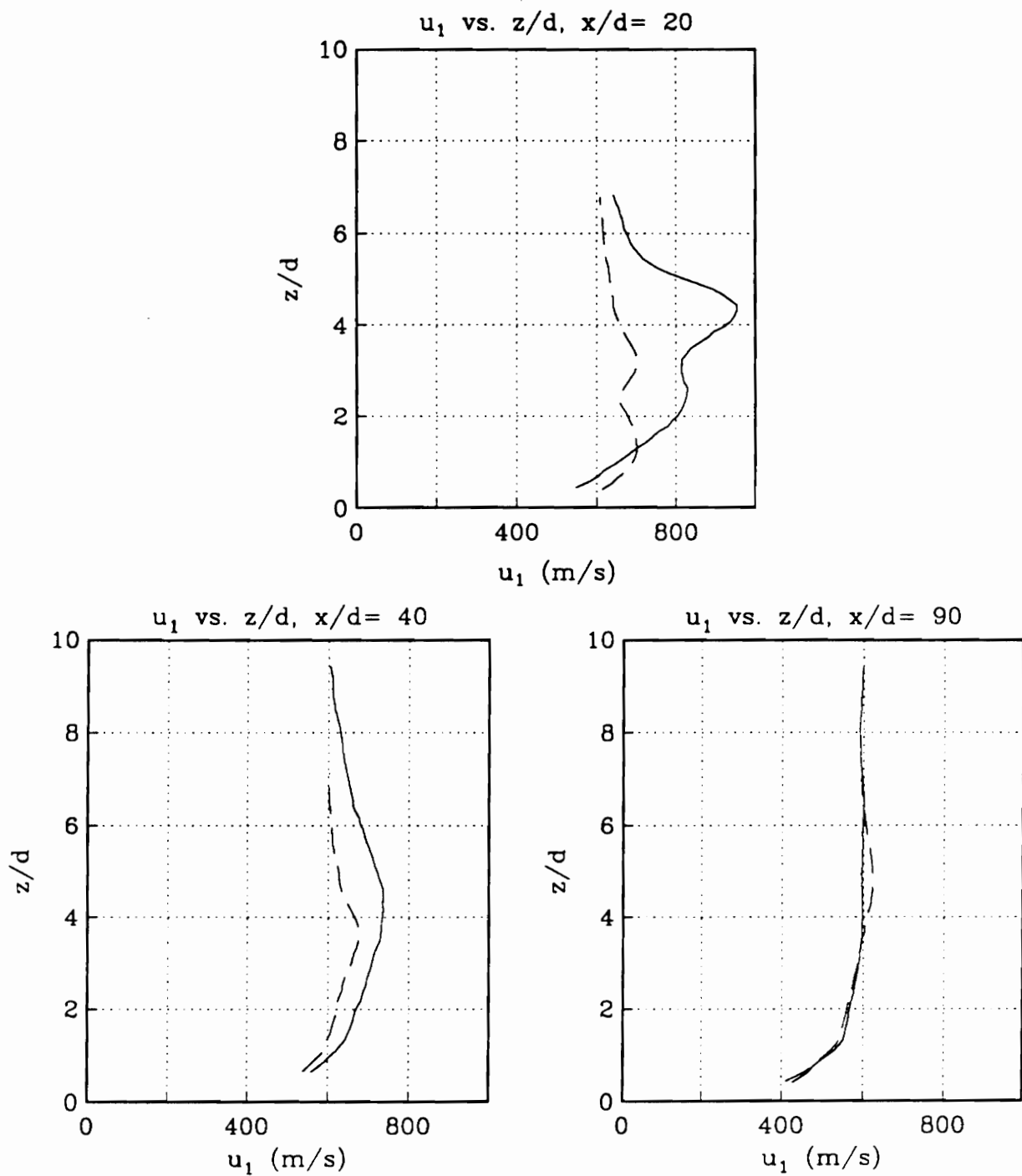




30° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure

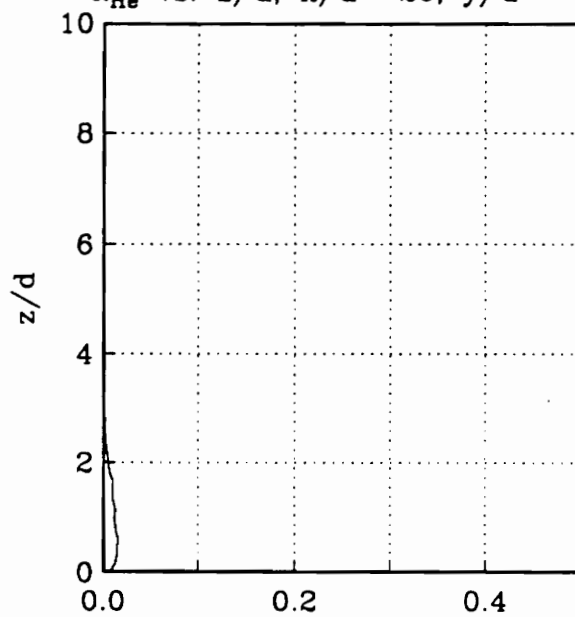


15° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure



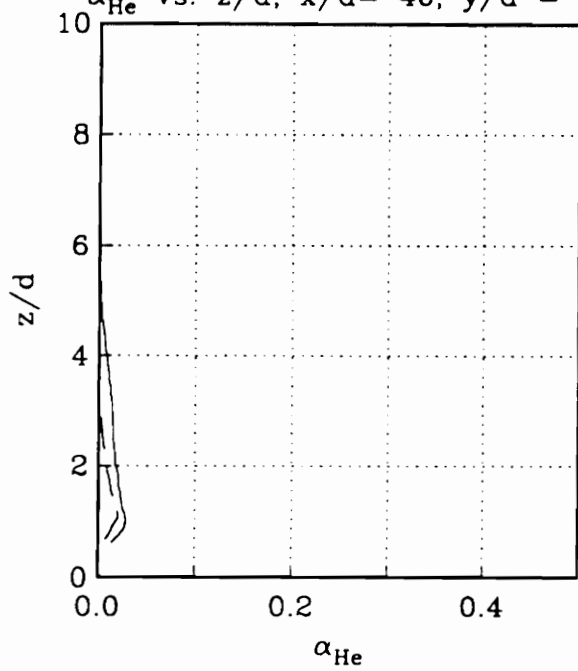
30° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure

α_{He} vs. z/d , $x/d = 20$, $y/d = 3$



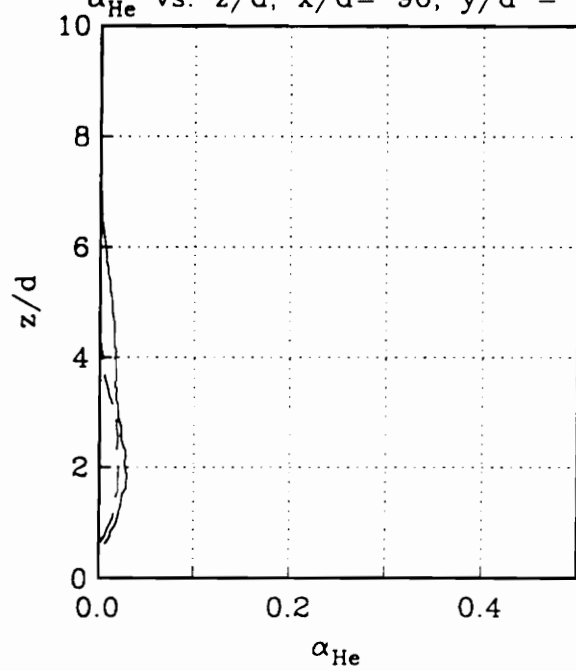
α_{He}

α_{He} vs. z/d , $x/d = 40$, $y/d = 3$



α_{He}

α_{He} vs. z/d , $x/d = 90$, $y/d = 3$



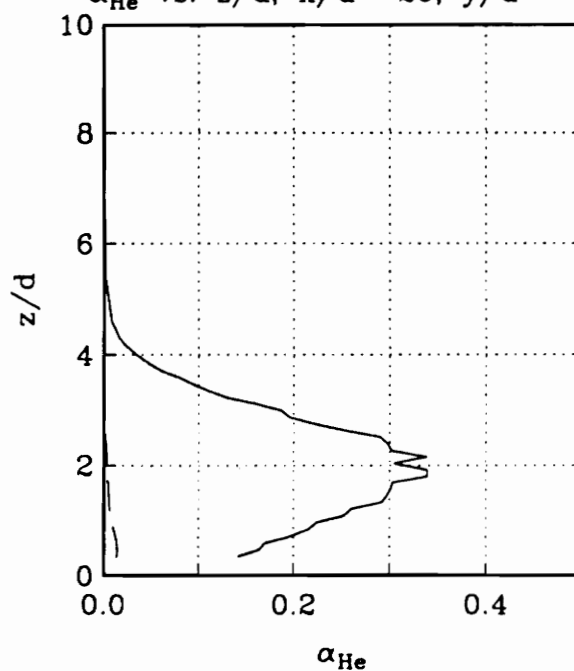
α_{He}

15° Injection Angle

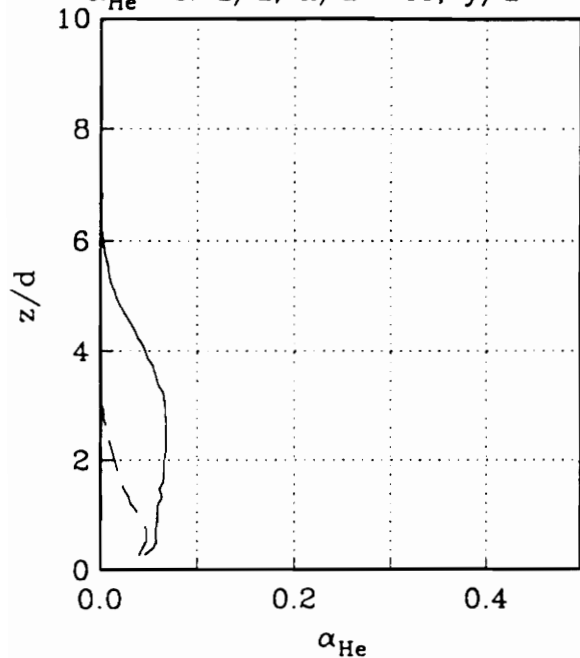
Solid Line - Underexpanded

Dashed Line - Matched Pressure

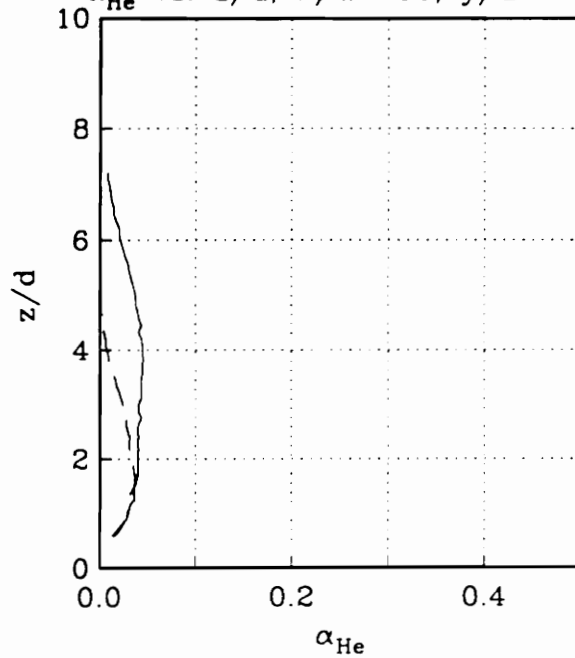
α_{He} vs. z/d , $x/d = 20$, $y/d = 2$



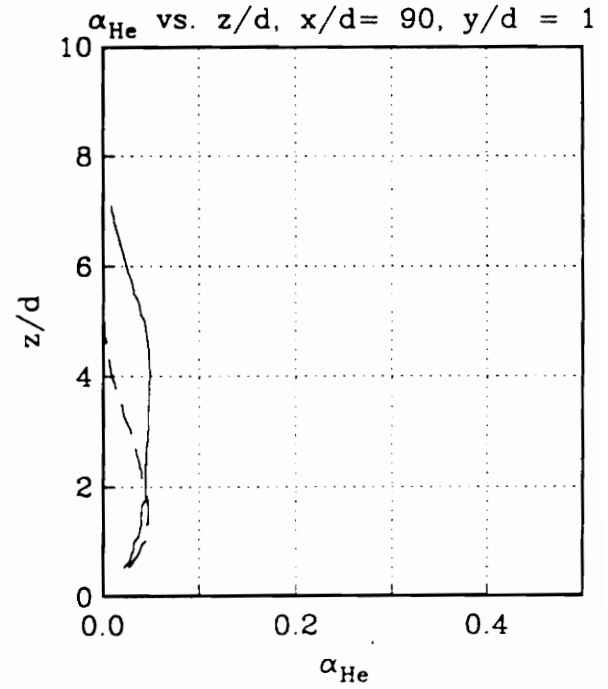
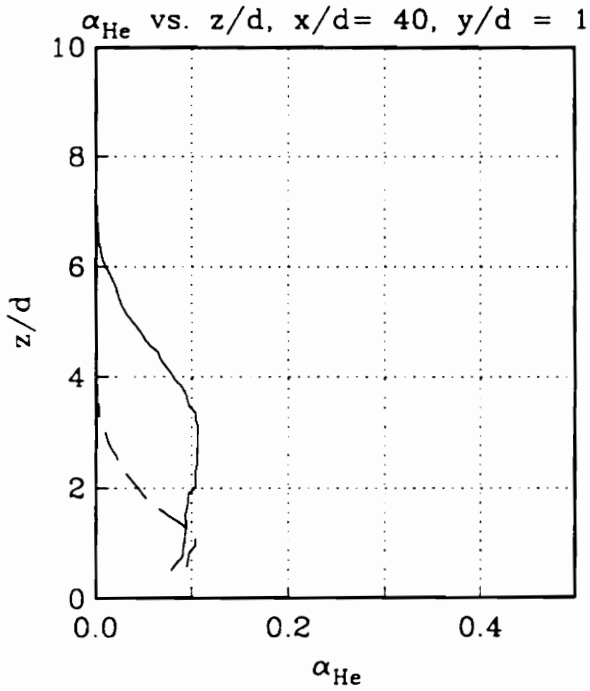
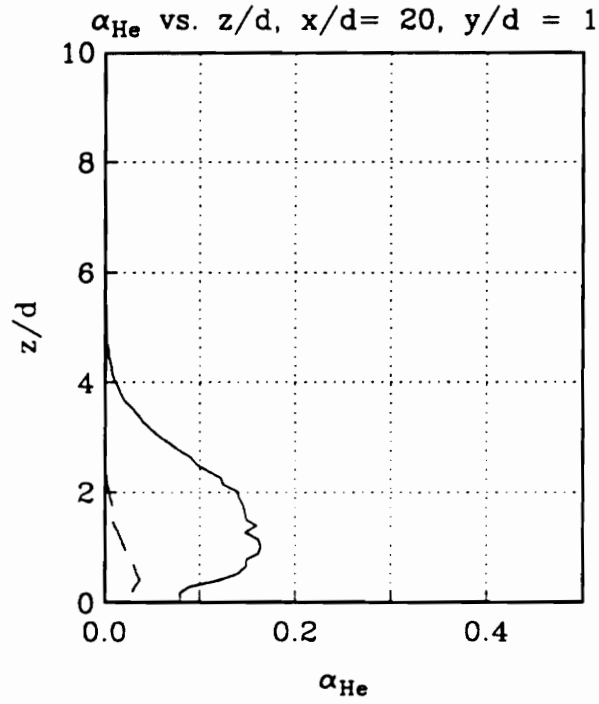
α_{He} vs. z/d , $x/d = 40$, $y/d = 2$



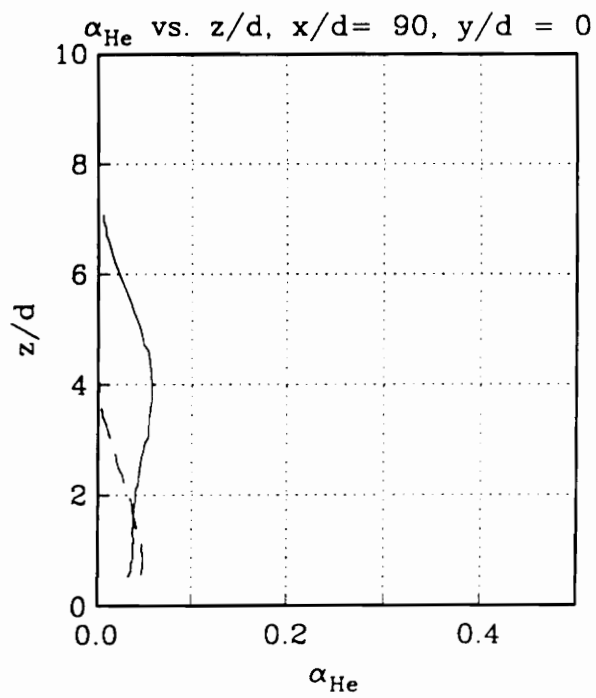
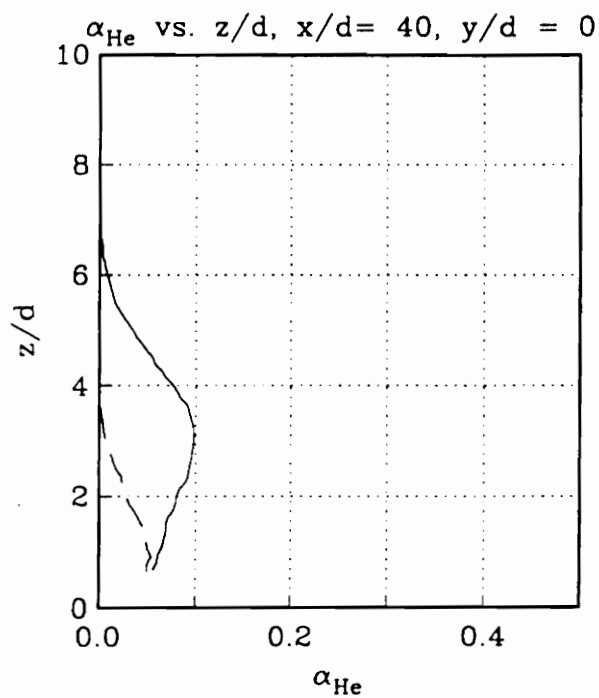
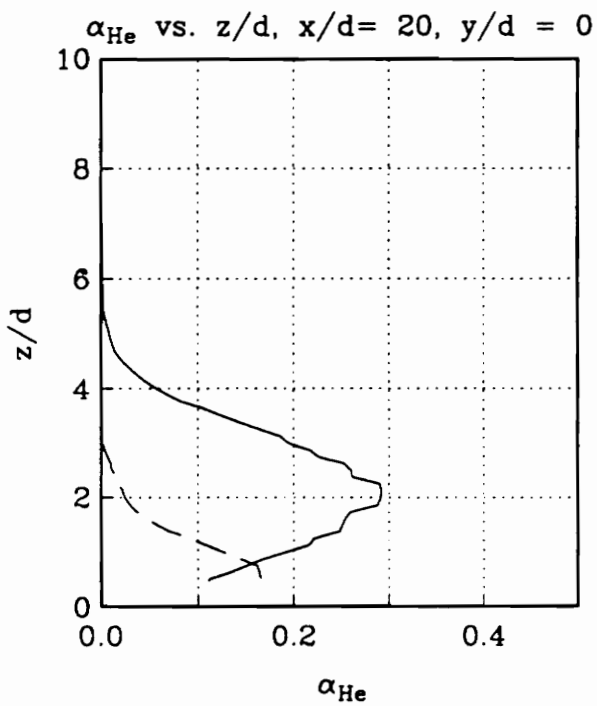
α_{He} vs. z/d , $x/d = 90$, $y/d = 2$



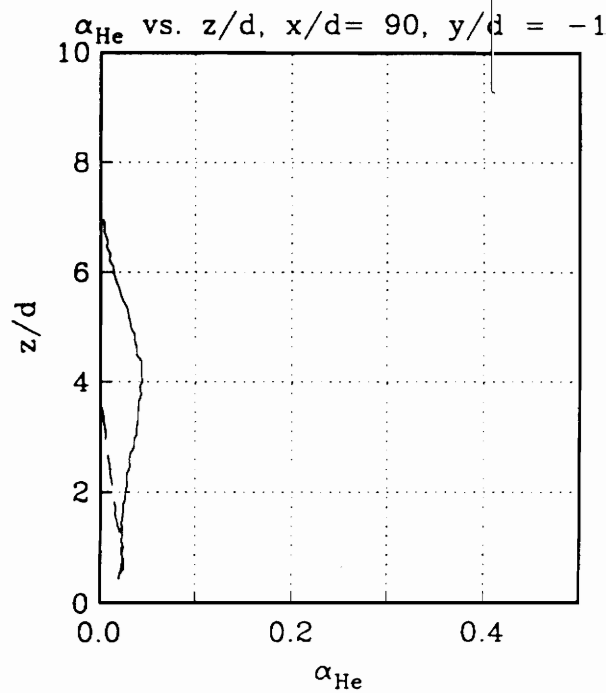
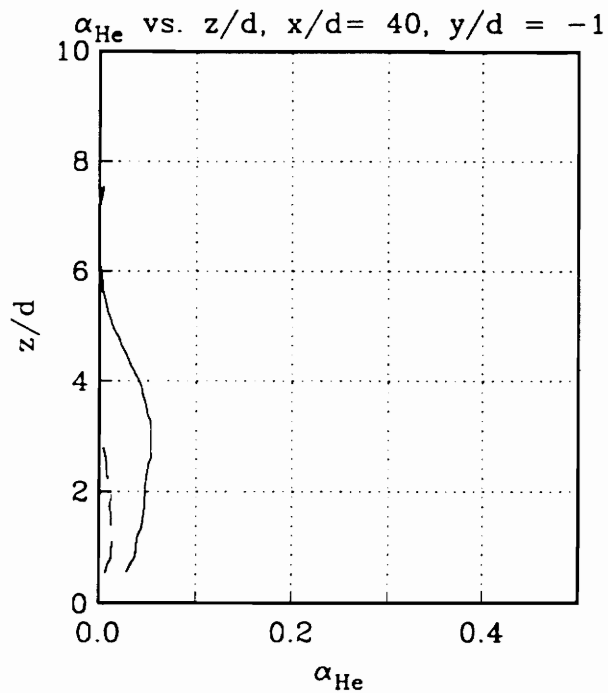
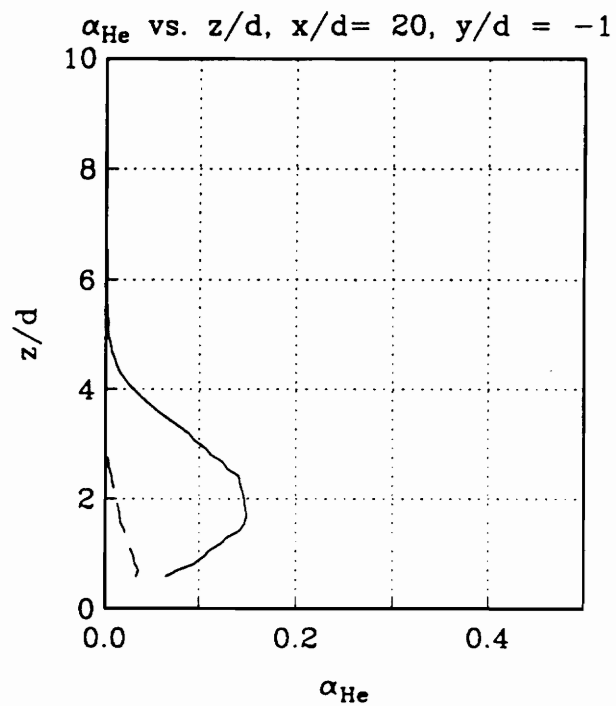
15° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure



15° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure

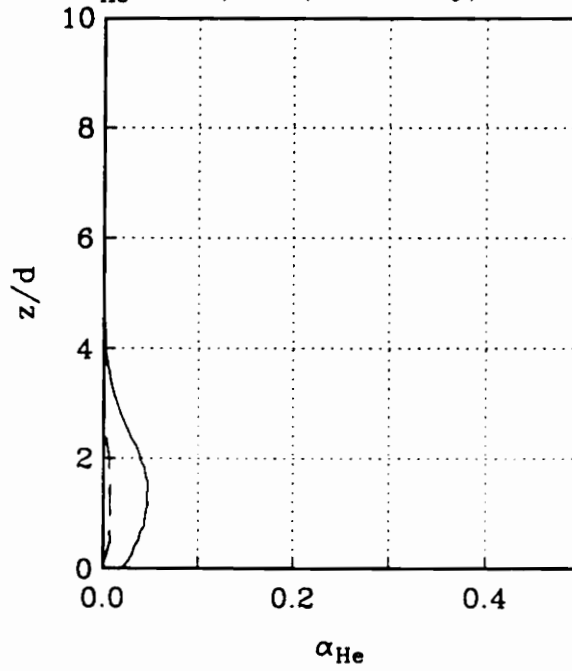


15° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure

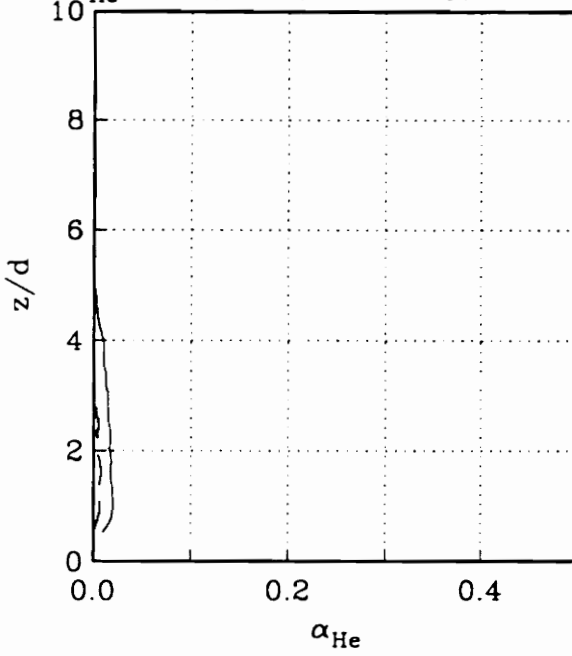


15° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure

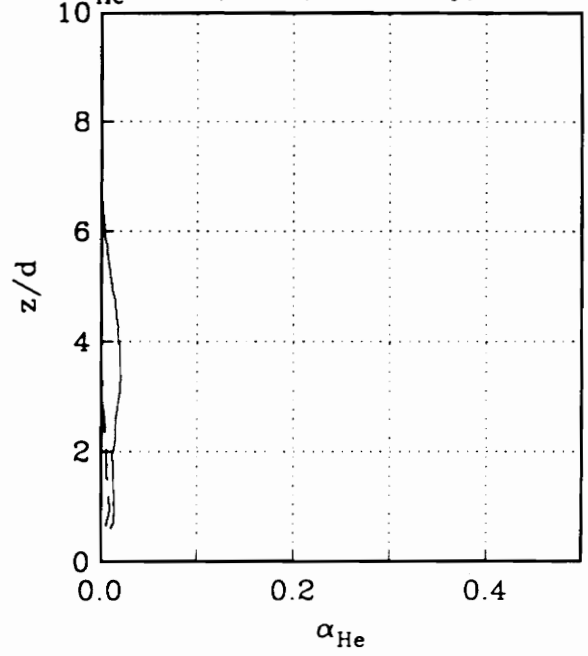
α_{He} vs. z/d , $x/d = 20$, $y/d = -2$



α_{He} vs. z/d , $x/d = 40$, $y/d = -2$



α_{He} vs. z/d , $x/d = 90$, $y/d = -2$

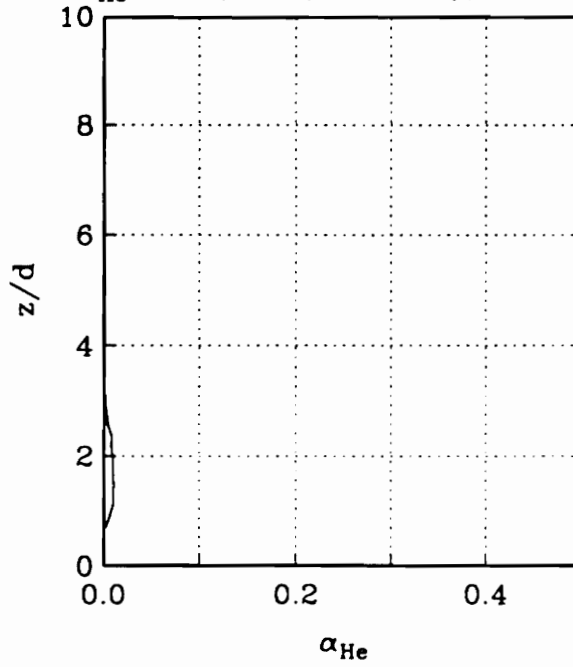


15° Injection Angle

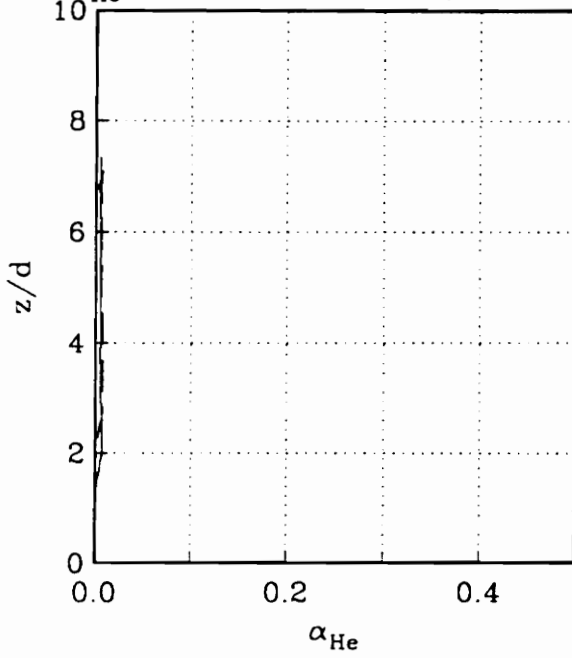
Solid Line - Underexpanded

Dashed Line - Matched Pressure

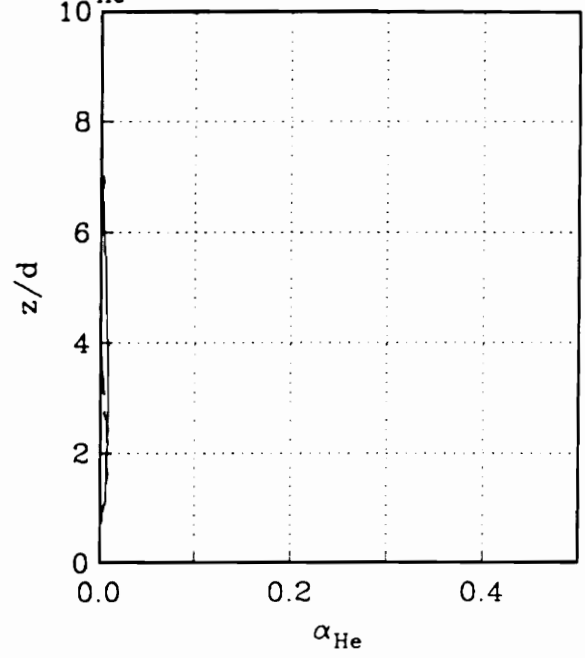
α_{He} vs. z/d , $x/d = 20$, $y/d = -3$



α_{He} vs. z/d , $x/d = 40$, $y/d = -3$



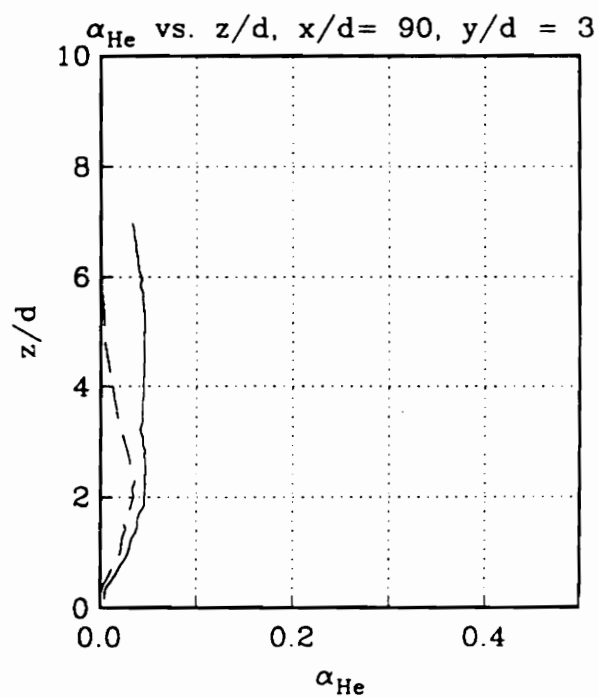
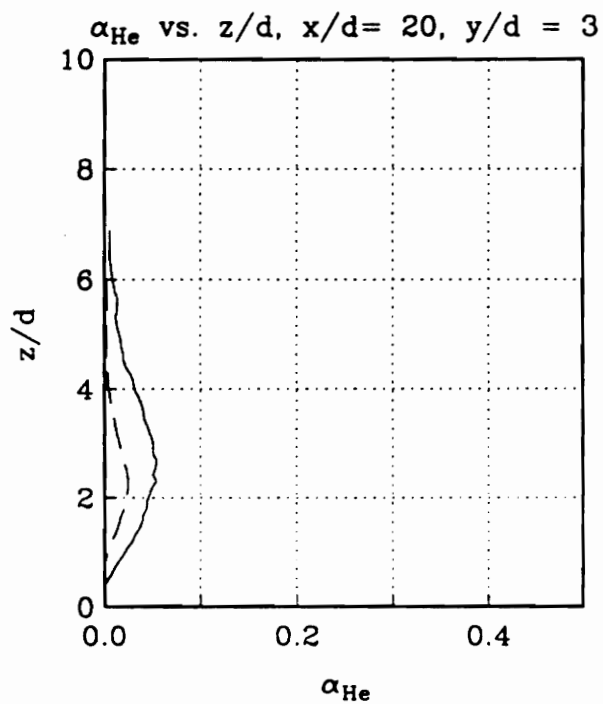
α_{He} vs. z/d , $x/d = 90$, $y/d = -3$



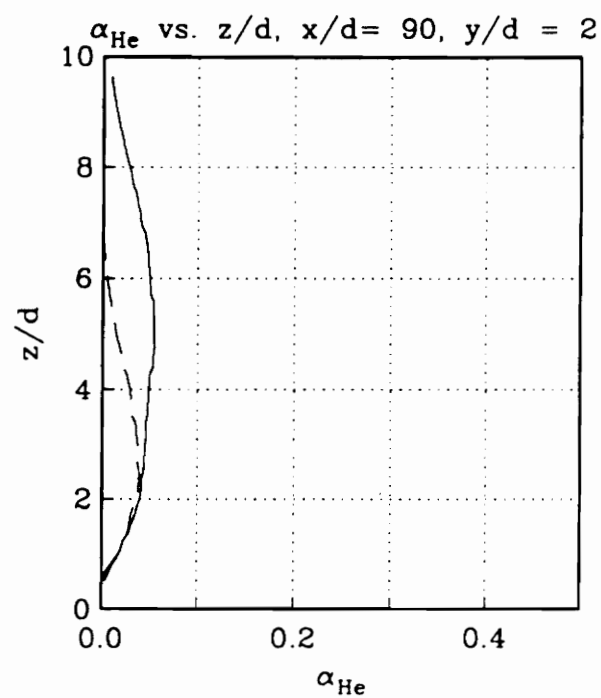
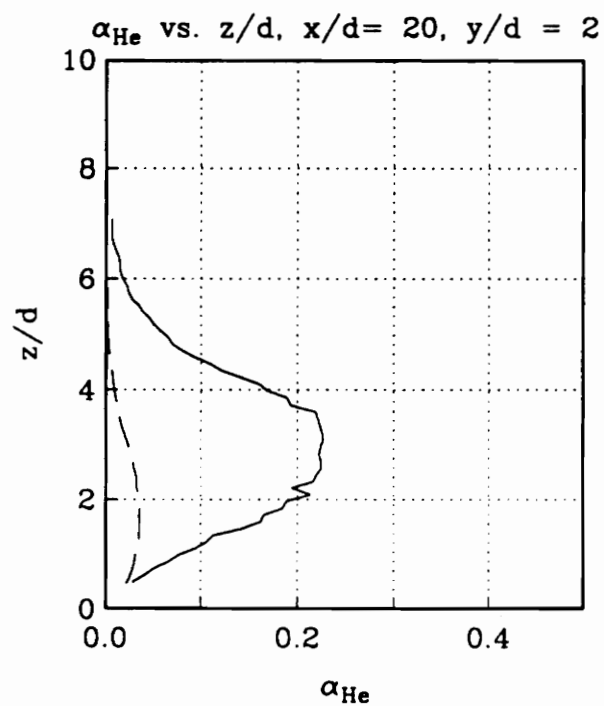
15° Injection Angle

Solid Line - Underexpanded

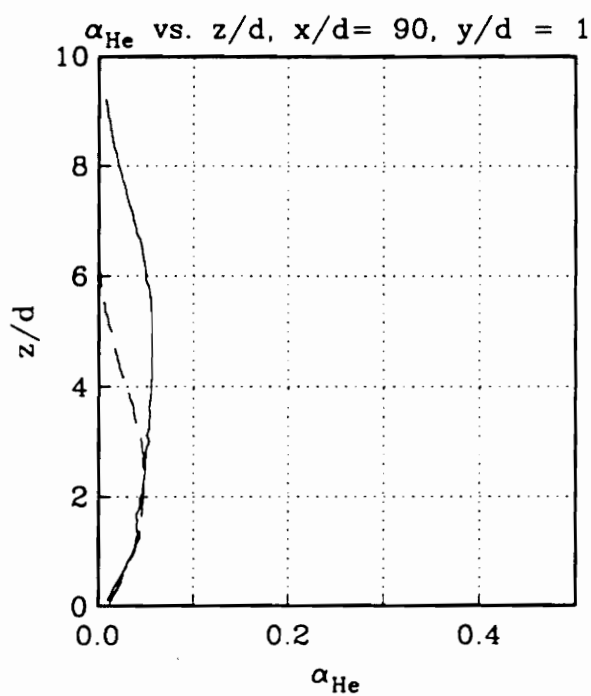
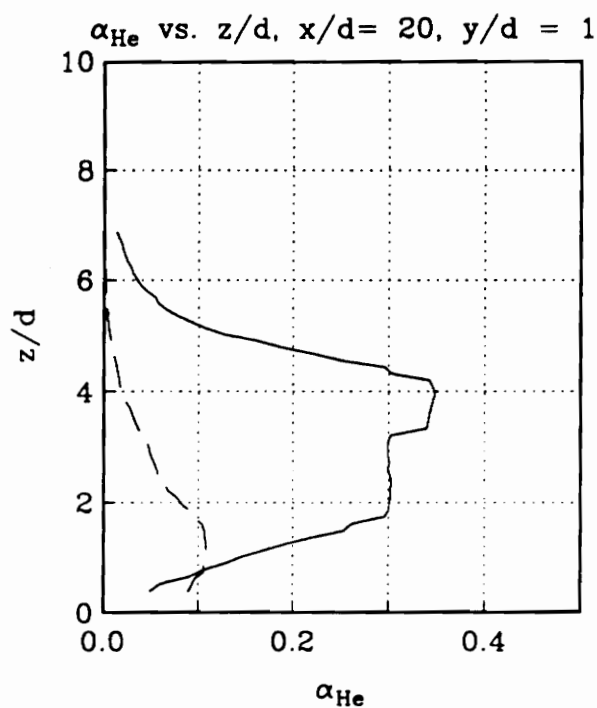
Dashed Line - Matched Pressure



30° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure

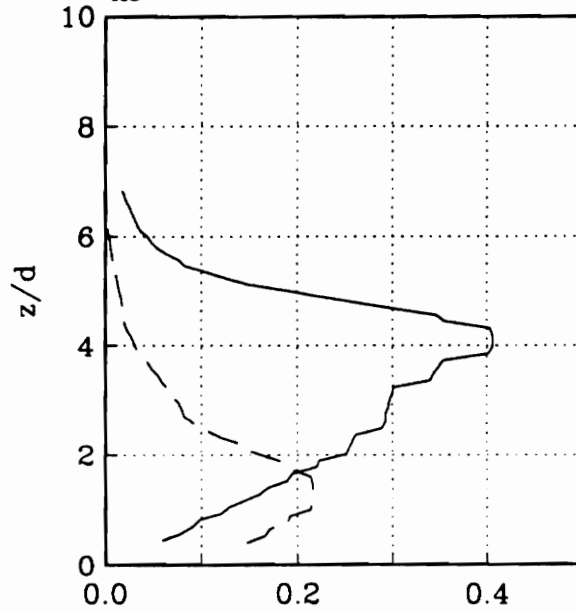


30° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure



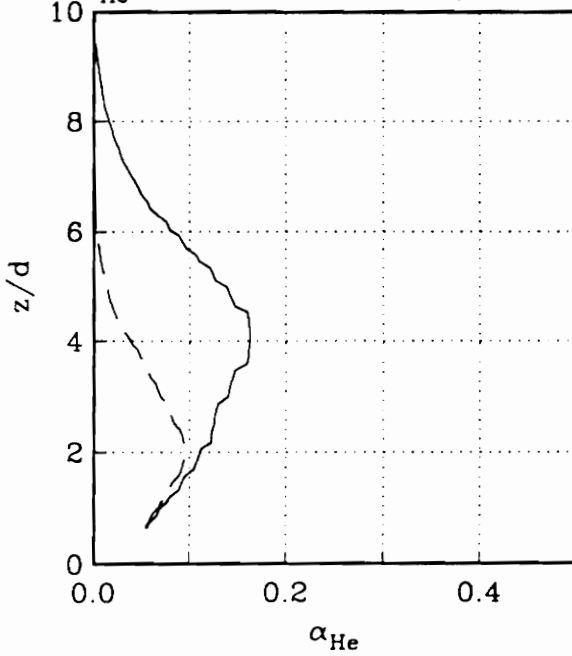
30° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure

α_{He} vs. z/d , $x/d = 20$, $y/d = 0$

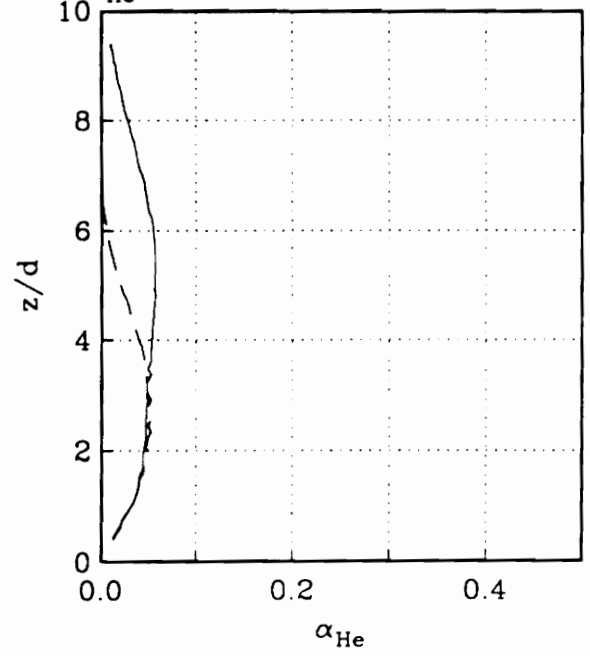


α_{He}

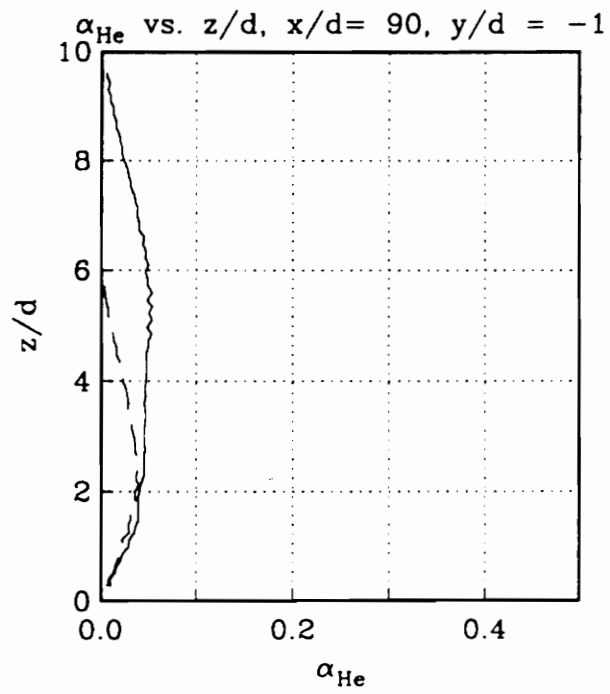
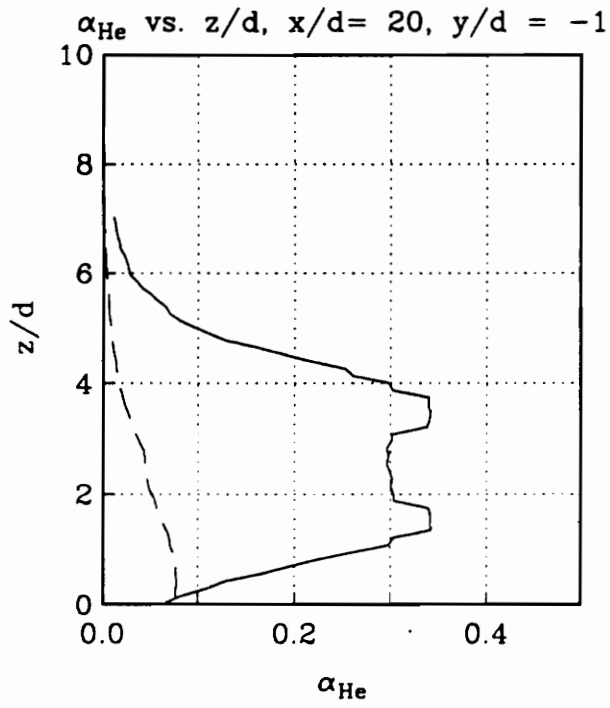
α_{He} vs. z/d , $x/d = 40$, $y/d = 0$



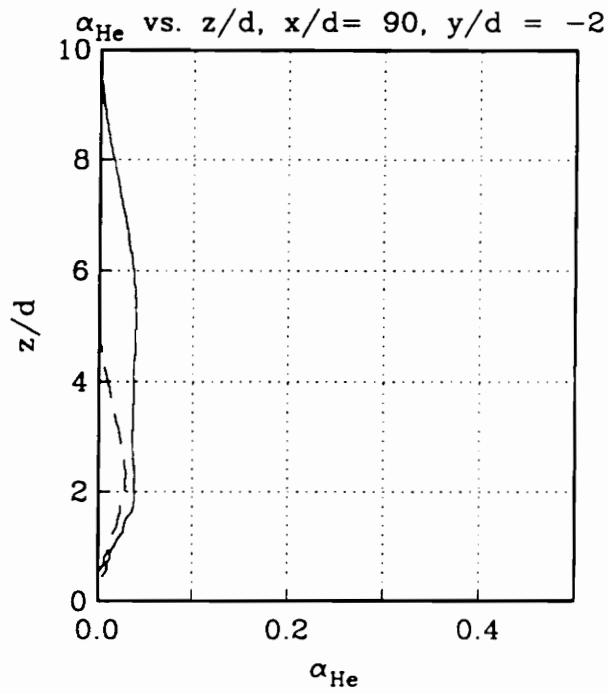
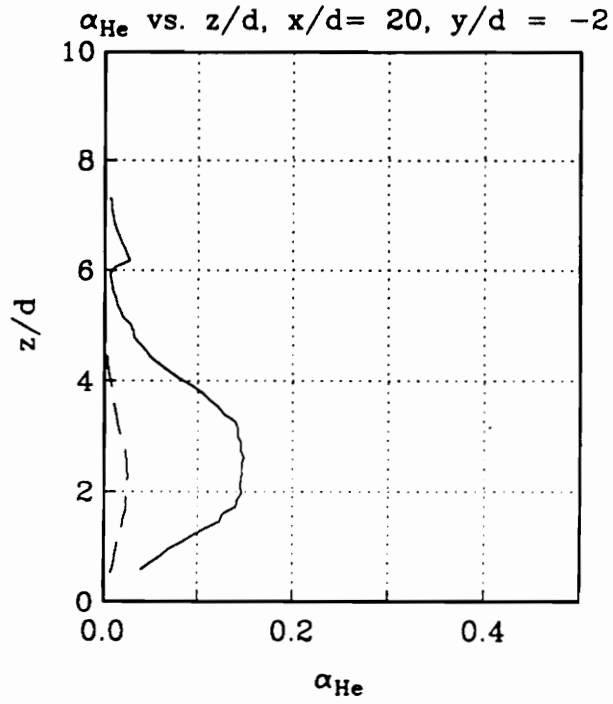
α_{He} vs. z/d , $x/d = 90$, $y/d = 0$



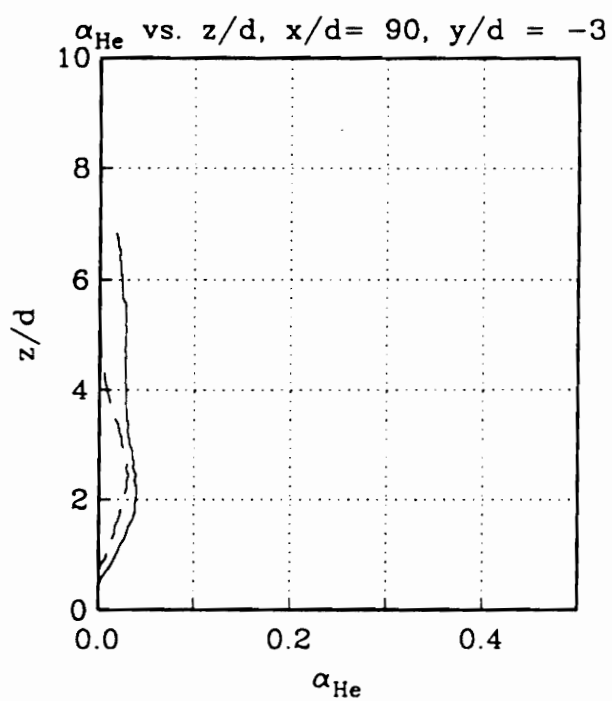
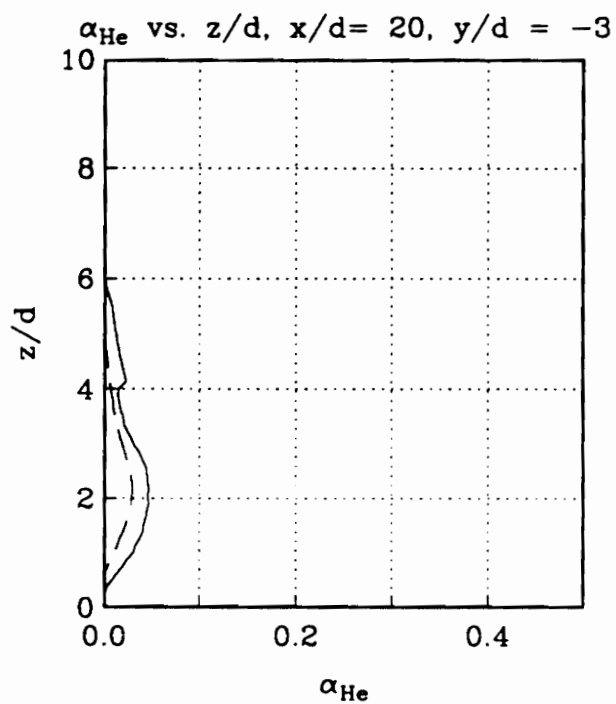
30° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure



30° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure



30° Injection Angle
Solid Line - Underexpanded
Dashed Line - Matched Pressure



30° Injection Angle
 Solid Line - Underexpanded
 Dashed Line - Matched Pressure

VITA

The author was born in Richmond, Virginia on June 16, 1964. He graduated from Patrick Henry High School in Ashland, Virginia in June of 1983. He received a Bachelor of Science degree in Aerospace and Ocean Engineering from Virginia Polytechnic Institute and State University in June of 1987, and entered the Aerospace Engineering graduate school at Virginia Tech that Fall. He completed this work in May of 1990.

Richard Mary