AN EXPERIMENTAL STUDY OF THRUST AUGMENTING EJECTORS

THESIS

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Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science

William D. Lewis, B.S. Engr

CPT U.S. Army

Graduate Aeronautical Engineering

December 1983

Acknowledgements

During the course of my experimental investigation many people have aided in accomplishing the final result. It required a great deal of teamwork to accomplish this task. It is these team members I would like to recognize:

- Dr. Franke, my thesis advisor for guidance and assistance.
- Capt Steve Reznick, my thesis sponsor for his time and assistance.
- Dr. Elrod and Capt Cox, members of the reading committee.
- Mr. Shortt, Mr. Brohaus and Mr. Tiffany of the AFIT fabrication shop for their suggestions, precise work and dedication to student support.
- Mr. Williams and Mr. Martin of the Flight Dynamics Lab for their cooperation and technical assistance.
- Mr. Yardich and Mr. Coates for their laboratory assistance.

A very special thank you goes to the next people for without their assistance, dedication and comradary I could not have completed my work:

- Mr. Ruley of the AFIT fabrication shop for his suggestions, tireless effort and willingness to assist in whatever manner possible.
- Mr. Linville for his tireless laboratory assistance.

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A	Area (in^2)
A_0	Cross Section Area of Primary Nozzle Exit(s) (in^2)
A_2	Cross Section Area of Mixing Chamber (in^2)
A_3	Cross Section Area of Diffuser Exit (in^2)
A_2/A_0	Inlet Area Ratio
A_3/A_2	Exit Area Ratio
F_i	Isentropic Thrust (lbf)
F_m	Measured Thrust (lbf)
h	Distance Between Primary Nozzles (Measured Along Perimeter) (in)
$\dot{m}_1$	Primary Mass Flow Rate (lbm/sec)
$\dot{m}_2$	Secondary Mass Flow Rate (lbm/sec)
$\dot{m}_3$	Total Mass Flow Rate (lbm/sec)
M	Mass Augmentation Ratio
P_a	Ambient Pressure (psia)
P_s	Static Pressure (psia)
P_t	Total Pressure (psia)
R	Gas Constant (lbf ft/slug R)
T	Temperature (R)
V	Velocity (fps)
θ	Primary Fluid Injection Angle (deg)
ρ	Density (slug/ft^3)
ϕ	Isentropic Thrust Augmentation Ratio
γ	Diffuser Wall Angle (deg)

Abstract

An automated thrust augmentation data acquisition facility was designed and constructed. The facility provides the capability of measuring thrust augmentation ratio and mass flow augmentation ratio. A three dimensional graphics plot of exit flow is provided for flow analysis.

Tests were conducted on a 4.4 in. diameter circular ejector, with eight primary nozzles mounted symmetrically along the perimeter of the inlet. A fixed ejector geometry was used. The ratio of mixing chamber area to diffuser exit area was 1.88. The fluid injection angle, measured from a line perpendicular to the ejector centerline, was varied and the thrust augmentation and mass flow augmentation ratios calculated. Both thrust augmentation and mass flow augmentation increased with fluid injection angle to the stall point where both decreased.

Axial flow symmetry of primary air was found to affect stall along diffuser walls.

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I. INTRODUCTION

Background

V/STOL aircraft have proven their effectiveness in the combat arena as evidenced by the Falkland Islands dispute in May 1982. The BAE Hawker Sea Harrier with its inherent short takeoff and landing requirements virtually eliminated the need for landing strips and large carriers. However, this capability is not attained without penalty. The large power requirements associated with takeoff, transition and landing greatly shorten the combat legs of these aircraft (Ref 1). Many methods have been employed to solve the traditional tradeoff of weight versus thrust. An increased efficiency of the generated thrust of a power system is a method of overcoming this problem. The utilization of a thrust augmenting ejector (TAE) would provide a smaller engine with increased thrust while simultaneously reducing the gross weight of the aircraft (Ref 2).

The need to examine the TAE to determine the configuration for optimum performance has been apparent since von Kármán published his classic paper on the subject in 1949 (Ref 3). The TAE is a device in which a secondary, or driven fluid is entrained by a primary or actuation fluid with subsequent transfer of energy through turbulent mixing in a mixing chamber. The primary fluid, which is originally at a higher stagnation pressure, is discharged with a high velocity into the mixing chamber of a specific shape. The entrained fluid causes a drop in static pressure. The secondary flow mixes turbulently with the primary jet in the mixing chamber and energy transfer occurs. The mixed flow then proceeds toward the exit end of the mixing chamber and finally discharges to some back pressure which may be atmospheric. If a diffuser is attached, the mixed flow produces some static pressure before reaching the exit. As a result of the pumping action described above, the total momentum of the mixed flow at the ejector exit is increased due to the entrainment of the secondary fluid, as compared with the momentum of the primary jet discharged directly into the atmosphere. Thrust augmentation is thus achieved (Ref 4). Campbell and von Ohain (Ref 5) designed and tested an ejector based upon the injection of primary fluid along the walls thereby energizing the boundary layer and optimizing the diffuser performance resulting in thrust augmentation ratios in excess of 2.5. Alperin and Wu (Ref 6) later developed an ejector with a curved inlet and nozzles at the inlet which produced ratios of 1.9 to 2.0. Reznick (Ref 7) pursued this concept utilizing eight nozzles symmetrically mounted around the throat of a circular ejector and reported ratios as high as 2.0. Quinn (Ref 2) and Fancher (Ref 8) found that varying the ejector diffuser section also affected the thrust augmentation ratios (TAR). Fancher determined that a properly designed ejector should give a TAR near $1.075 + 0.025\ (A_3/A_0)$, for $5 < A_3/A_0 < 14$. Unnever (Ref 9) followed Reznick and attained TAR of 1.0 to 1.7 while varying the configuration of the ejector. This research demonstrated that the efficiency of the thrust augmentation process depends on the ejector configuration, the geometry of these configurations, and aerodynamic operating conditions.

Purpose and Objectives

The basic objectives of this investigation are as follows:

(1) To design and construct an automated test facility which permits an examination of the effects of varying the numerous parameters associated with a thrust augmentation investigation.

(2) To confirm operation of the facility and check accuracy of results against redundant measurements.

(3) To compare the facility data with that attained by Reznick and Unnever (Ref 6,9).

(4) To determine the effect of various inlet nozzle configurations on thrust and mass flow augmentation.

(5) To investigate the effects of the exit velocity profiles on ejector performance.

Scope of Experimental Work

The approach employed was operation of a fixed ejector configuration in a steady state condition on a static test stand in a laboratory environment.

An automated data acquisitions system (DAS) was used to collect data for calculations of thrust augmentation ratio and mass flow augmentation ratio. The DAS employed a HP 9845B computer interfaced with 8 transducers and two stepper motors. A total pressure scan of the diffuser exit plane was conducted by traversing the total pressure probe across the exit plane. This collected data was used with the primary flow through an orifice plate to determine the mass flow augmentation ratio. The thrust augmentation ratio was determined by comparing the measured thrust from a cantilever beam load cell to the isentropic thrust of the primary inlet nozzles. This is a widely accepted approach for comparing thrust augmentation. The ambient room temperature varied from 60F to 90F. These measurements did not affect the TAR and were taken into consideration when calculating velocity. The primary to ambient pressure ratio was held constant at 1.14 for most calculations. The primary nozzle exit velocity was in the range of 500 fps.

II. FACILITY DESIGN

Due to the large number of parameters which affect the performance of a TAE, an automated approach to data collection was employed in order to reduce run time and eliminate random errors inherent when making several manometer readings. Automating the existing apparatus facilitated a rapid, accurate, and flexible means of gathering data. This approach also offered an enhanced method of data reduction and flow visualization by utilizing the data acquisition system (DAS) and its peripheral equipment. The thrust augmentation facility (TAF) is composed of four major components: (1) the test stand, (2) the air supply system, (3) the pendulum and ejector, and (4) the instrumentation and associated data acquisition system (Appendices C, B).

Test Stand

The apparatus required a test stand design which permitted maximum unobstructed flow through the ejector while possessing enough rigidity to insure operational vibration was minimized. Three large I beam uprights were anchored to the floor in a tripod arrangement (Fig 1). Atop the two base legs were mounted 2.5 in square tubing with aluminum clamp blocks at the apex. These blocks were used to secure the pendulum cross bar. The base legs were then connected front and rear with angle iron upon which was mounted a dove tailed horizontal slide. The slide included a vernier scale for proper positioning of the exit probe. This slide was centered between the uprights and mounted to the third I beam such that the slide was perpendicular to the plane formed by the uprights. The pendulum was suspended from the vertical arms allowing it to swing freely.

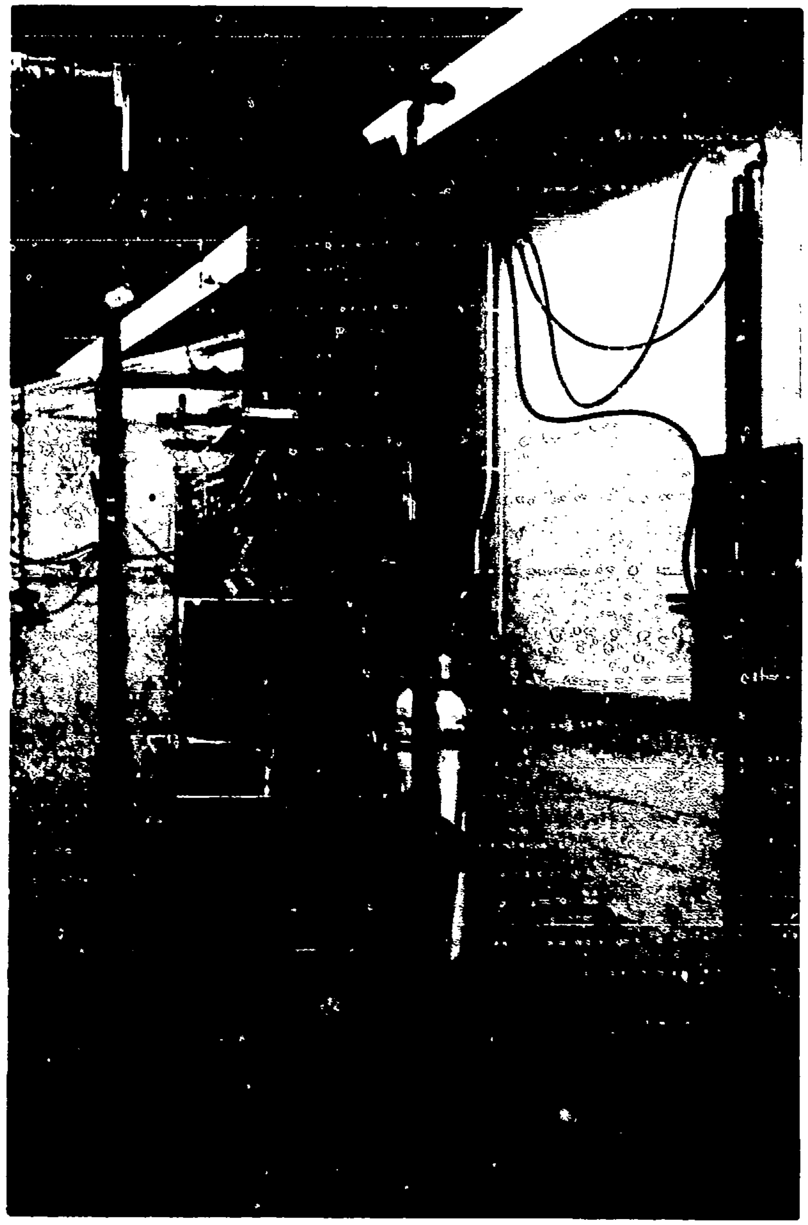


Figure 1. Thrust Augmentation Facility

The slide facilitated the positioning of the exit plane probe fore and aft (the z direction).

Air Supply

The primary air was obtained from the laboratory compressed air supply. the nominal maximum delivery from the system is approximately 1.0 lbm/sec at 55 psia. This mass flow exceeded the requirements of this investigation; therefore, a pneumatic controller was utilized to reduce and stabilize the pressure in the line. This controller was powered by compressed breathing air. It was necessary to use breathing air to avoid debris in the mechanism. A dome valve was installed upstream of the pendulum tee to allow a further reduction of the line pressure. The valve was opened and the flow allowed to stabilize prior to data collection.

Pendulum and Ejector

The pendulum and ejector (Fig 2) used on the facility were the same ones used by Reznick (Ref 7). The inlet tygon tubing, however, was replaced with hard plumbing and the variable position primary nozzle mounts (Ref 9) were placed on the inlet (Fig 3). Feeler gauges were used to determine the primary fluid injection angle (Appendix B).

Instrumentation

The mass flow calculations required the calculation of primary flow through an orifice plate and total flow at the exit plane. Two pressure transducers mounted on flange taps were required to determine the primary mass flow rate. With this data, standard ASME procedures were used to determine the flow through the orifice plate (Ref 10).

Figure 2. Thrust Augmenting Ejector with 8 Primary Nozzles.

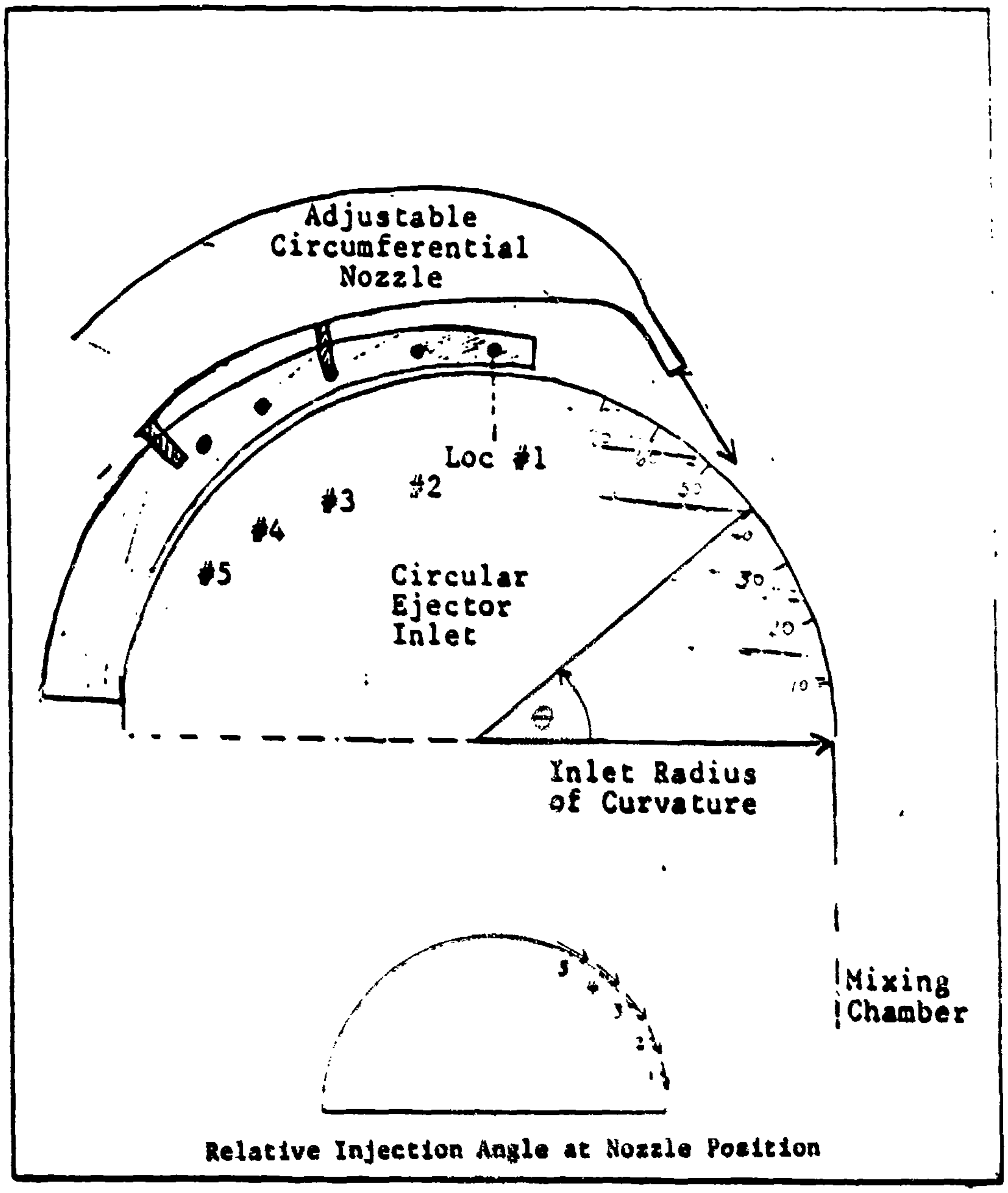


Figure 3. Variable Position Primary Nozzles

The exit flow required data from a total pressure transducer in conjection with ambient pressure transducer data to determine the exit velocity as the probe scans the exit plane. The DAS also possesses the capability of using a hot wire anemometer in lieu of the total pressure probe for determining the velocity at the exit plane of the diffuser. Presence of foreign matter in the air supply system forced the use of the pressure probe for most of the investigation.

The need to sample several nozzle pressures in approximately the same range suggested the employment of a scanivalve (Ref 11). The device used was a 48 port modal which,exceeded the requirements of this investigation, but added flexibility of data collection in the range of the included transducer (Fig 4). The scanivalve allowed sampling of discrete nozzle pressures using only one transducer. This method greatly simplified the calibration and reduces the demand of several I/O units for data collection. Calculation of the isentropic thrust augmentation ratio was accomplished via three transducers. The scanivalve was used for the primary nozzle pressures. The ambient pressure transducer data was again used for calculation. The measured thrust was determined via a cantilever beam load cell mounted on an angle iron support on the test stand uprights (Fig 5). The cantilever beam load cell was calibrated using a free weight attached to the ejector centerline by a flexible cable and suspended from a single pulley (Fig 6). The remainder of the transducers were calibrated using a known pressure source controlled by a pressure regulator located in the control room.

To conduct a complete scan of the exit plane under the control of the DAS with appropriate software, a traversing mechanism was designed which

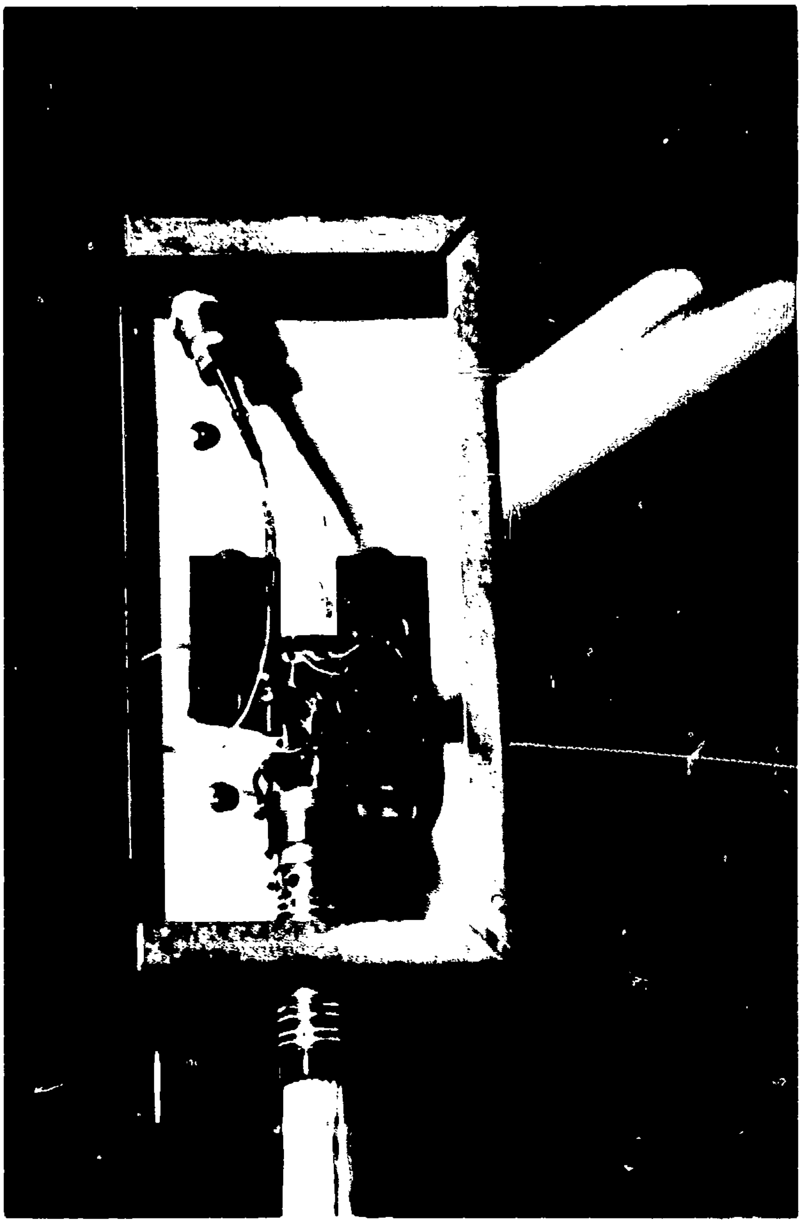


Figure 4. Scanivalve in Mounted Position

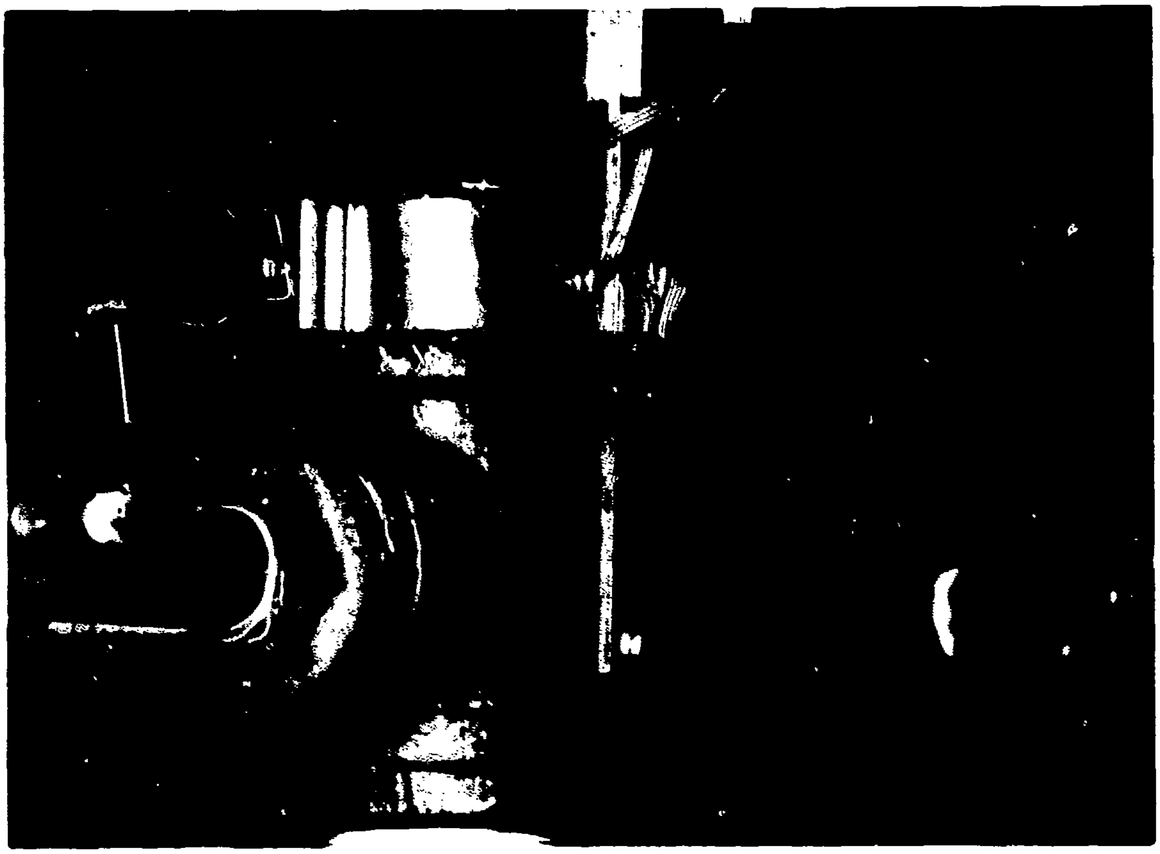


Figure 5. Cantilever Beam Load Cell

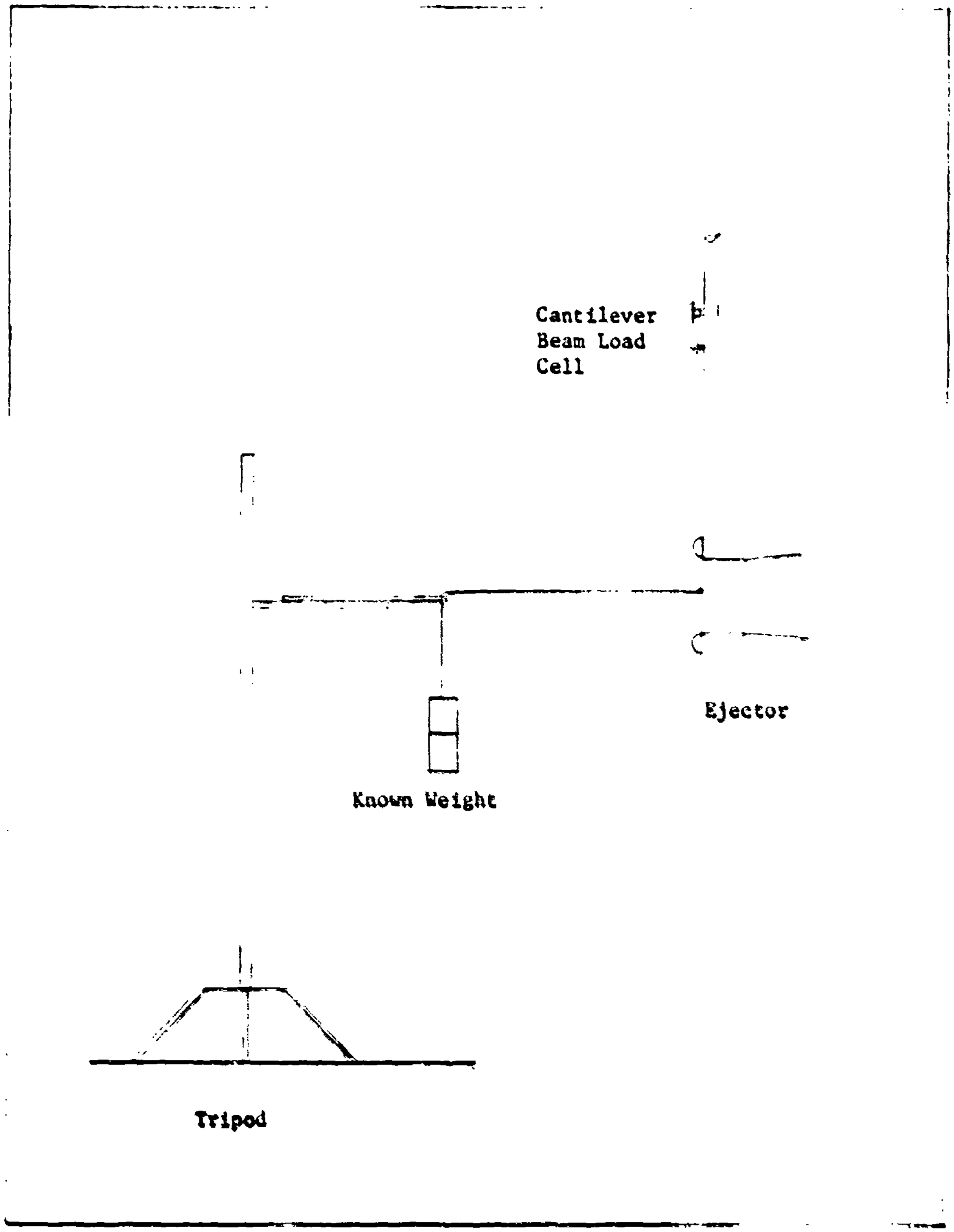


Figure 6. Cantilever Beam Calibration

would position the exit probe at discrete points in a rectangular grid. The traversing mechanism primary structure consisted of a 25 in square frame. Bi-polar stepper motors were used to drive horizontal and vertical screws for probe positioning. Position transducers were employed for position feedback (Fig 7).

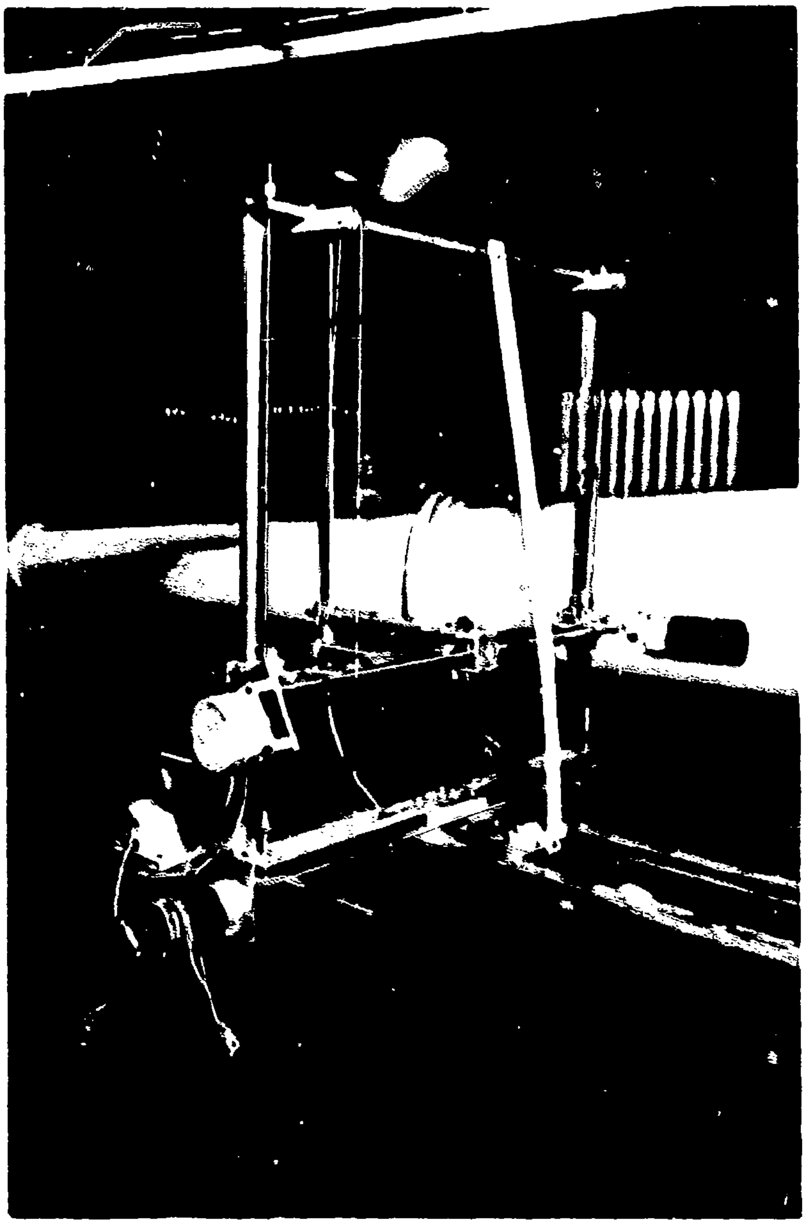


Figure 7. Traversing Mechanism

III. FACILITY PERFORMANCE

The performance of the test facility was analyzed in three phases: (1) air supply delivery, (2) mechanical operation, and (3) instrumentation.

Air Supply System

A steady state condition was desired for the investigation. Due to surges in the air supply from compressor operation, it became necessary to stabilize the pressure downstream of the pendulum tee. This stabilization was accomplished through the use of a pneumatic control valve. The pressure attained was steady while in its operating range. This range, however, was limited. The controller could operate properly within a pressure range of 7 psig. If the pressure limits were exceeded, the controller would begin an undamped hunting. This presented no problem unless an unexpected demand on system compressed air was created by an outside source on the compressor feed line.

Mechanical Operation

The mechanics of the facility operation are incorporated in the horizontal slide, the scanivalve, and the traversing mechanism. The vernier scale allows a precise positioning of the slide to within 0.05 in. The slide was positioned manually to correspond with the exit plane of the ejector. The scanivalve drive motor and positioner proved to be totally reliable. To insure continued reliability, it is necessary to maintain a backpressure greater than or equal to the maximum primary nozzle pressure to be sampled. This backpressure minimizes wear on internal components of the scanivalve.

The traversing mechanism is a bi-polar stepper motor driven gear and screw assembly. It is designed to delivery a 0.001 in traverse per step. The gears from the motor to the screw drives possess a small degree of backlash resulting in hysteresis of 0.002 in. This hysteresis results in an error of less than 0.5 percent for a spacing of 0.5 in. The slide permits axial positioning of the flow sensing probe and the traverser provides for horizontal and vertical positioning of the probe in a plane parallel to the TAE exit plane.

Instrumentation

The heart of the instrumentation is the HP 3025A automatic data acquisition system (DAS). This system has operated flawlessly in controlling system operation. The transducers were powered by a HP 6025C dual dc power supply, which fluctuated approximately 1 percent with temperature. Prior to input into the CEC dc bridge balance, type 8-108, the input voltage was passed through a locally fabricated voltage regulator of 17 volts input and 12 volts output. At this point the power unit fluctuations manifested a variation of less than one percent. The bridge balance proved to be a primary component of the instrumentation package (Fig 8) by controlling the excitation voltages and monitoring the output voltages of each transducer (Appendix A). The fluctuations in the input voltage directly affected the excitation voltages of the transducers, but the excitation voltage variation was less than 0.03 percent. This affected the output voltages correspondingly, and was manifested in the direction of the polarity setting of the bridge balance. The transducers used on the facility possessed a combined non-linearity and hysteresis of less

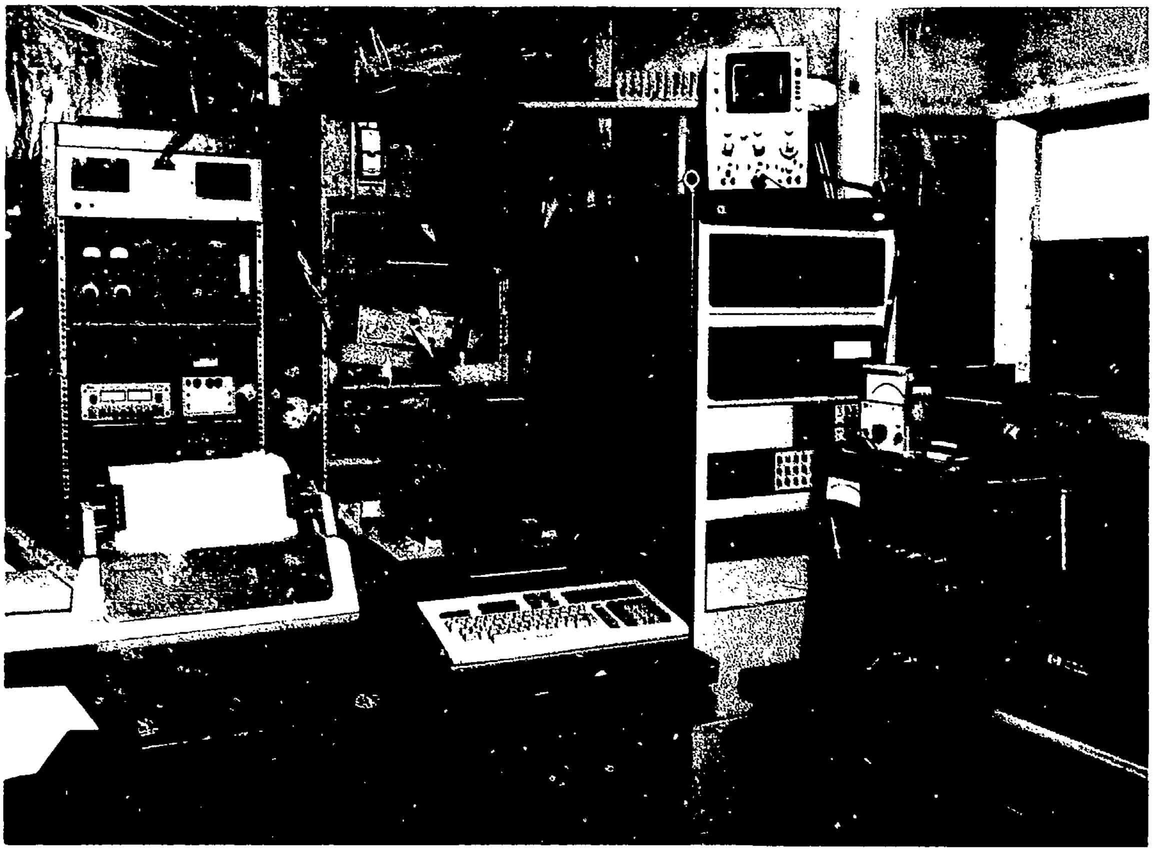


Figure 8. Control Room Instrumentation

than one percent. A source of error associated with the transducers was the readibility of the calibrating manometers. The readibility of the mercury manometer was 0.025 psi and 0.C02 psi respectively for the water manometer. The transducers experienced a slight zero drift during transition from the relaxed to the exercised positions. To compensate for this error, the calibration was conducted only after each transducer had been fully exercised. The total exit pressure transducer possessed a large interfering input dependant upon mounting position. This was due to the high degree of sensitivity compounded by the large diaphram of the transducer which was affected by gravitational forces. This was eliminated by mounting the transducer solidly to the frame of the facility. The position transducers demonstrated no observable error. Several errors were detected in the position encoder, but the problem areas were avoided (Appendix A) in order to operate the facility.

Flow Visualization

In order to visualize the flow of the facility, a tufted wire mesh grid was employed. This technique provided a method of detecting an area of disturbance in the exit plane. Once the location was determined, it could be further explored using a slender tufted rod throughout the diffuser. The final visualization technique utilized the DAS in conjunction with the HP 9872S plotter to present the collected data in such a manner as to deliver a three dimensional picture of the exit flow. This technique proved extremely useful when comparing high and low performance configurations.

IV. DATA REDUCTION

The two performance parameters used in this investigation were the isentropic thrust augmentation ratio and the mass flow augmentation ratio. The data necessary for these calculations was obtained from the TAF via the HP 3025A DAS.

Thrust Augmentation Ratio

The calculation of the measured thrust and of the isentropic thrust from the ejector was required to determine the TAR where:

$$\phi = F_m / F_i \qquad (1)$$

The measured thrust was obtained from the cantilever beam load cell. Using the calibration data, the thrust for a given data point was determined. The isentropic thrust of the ejector was computed using the equation:

$$F_i = 7\, A\, P_a \left((P_t / P_a)^{.286} - 1 \right) \qquad (2)$$

This is a measure of the ideal performance of the primary nozzles when allowed to discharge to ambient conditions in the absence of the ejector apparatus. The ambient pressure data was obtained through the DAS. The values of P_t were determined from the DAS by averaging the pressures of the primary nozzles for a given point. In all these cases the static pressure readings were assumed equivalent to the stagnation pressures and accurate within 1 percent. The primary slot nozzles and the exit dimensions varied approximately 2 percent (Ref 9). The average area for the nozzles was used to compute the isentropic thrust.

The values of measured thrust and isentropic thrust were then used to calculate the isentropic thrust augmentation ratio.

Mass Augmentation Ratio

The experimental apparatus permitted the mass flow and thrust measurements to be obtained simultaneously. The primary flow into the apparatus was measured using a 1 in orifice plate mounted in accordance with ASME procedures (Ref 10). An iterative solution for the discharge coefficient was calculated using a discharge coefficient versus Reynolds number curve derived from ASME tables. The primary mass flow value was checked using the nozzle exit values of the primary nozzles and found to agree within 2 percent. The total exit flow was calculated using a summation of incremental mass flow for discrete points using the expression:

$$\dot{m} = \Sigma \rho A_i V_i \qquad (3)$$

where A_i is the area of the exit increment, and ρ is calculated for room temperature and ambient pressure conditions. The velocity is computed for each data point. Since the exit velocity was less than 130 fps for all cases, the incompressible form of Bernoulli's equation was used:

$$V = \sqrt{2(P_t - P_a)/\rho} \qquad (4)$$

A total scan of the exit area was taken and the secondary mass flow determined from:

$$\dot{m}_2 = \dot{m}_3 - \dot{m}_1 \qquad (5)$$

The mass augmentation ratio was then computed from this combined ratio at the exit:

$$M = \dot{m}_2/\dot{m}_1 \qquad (6)$$

V. RESULTS AND DISCUSSION

Facility Performance

The facility was designed with a system of manometers for comparison with transducer results. Transducer measurements varied by less than 2 percent from the manometer measurements. The one exception was the differential transducer measuring the orifice pressure drop. It possessed a systemmatically high 4 - 5 percent error when compared to the manometer. A 0 - 20 psi transducer was used for this measurement. The pressure data were usually less than 2 psig. A transducer with more sensitivity and smaller range may eliminate this error.

Effects of Fluid Injection Angle on Thrust Augmentation

The thrust augmentation results (Fig 9) for the five discrete nozzle positions (Fig 3) indicate that the fluid injection angle is a primary parameter affecting thrust augmentation in this apparatus. The curve for position five is not presented due to its low values of thrust augmentation. Thrust augmentation increases with injection angle to the stall point where a rapid degradation of thrust occurs. The thrust augmentation is highly sensitive to small changes in injection angle. This sensitivity is especially critical near the stall point where a variation of one degree manifests a dramatic reduction in thrust. The optimum injection angle occured at 33 degrees. In addition, the optimum injection angle for each curve corresponded to a spacing between the primary nozzle exit and the inlet wall surface of approximately 0.25 in. The curves display the same trends as those of Alperin and Wu (Ref 6), Reznick (Ref 7), and Unnever (Ref 9). The results compare favorably with those of Unnever. The only

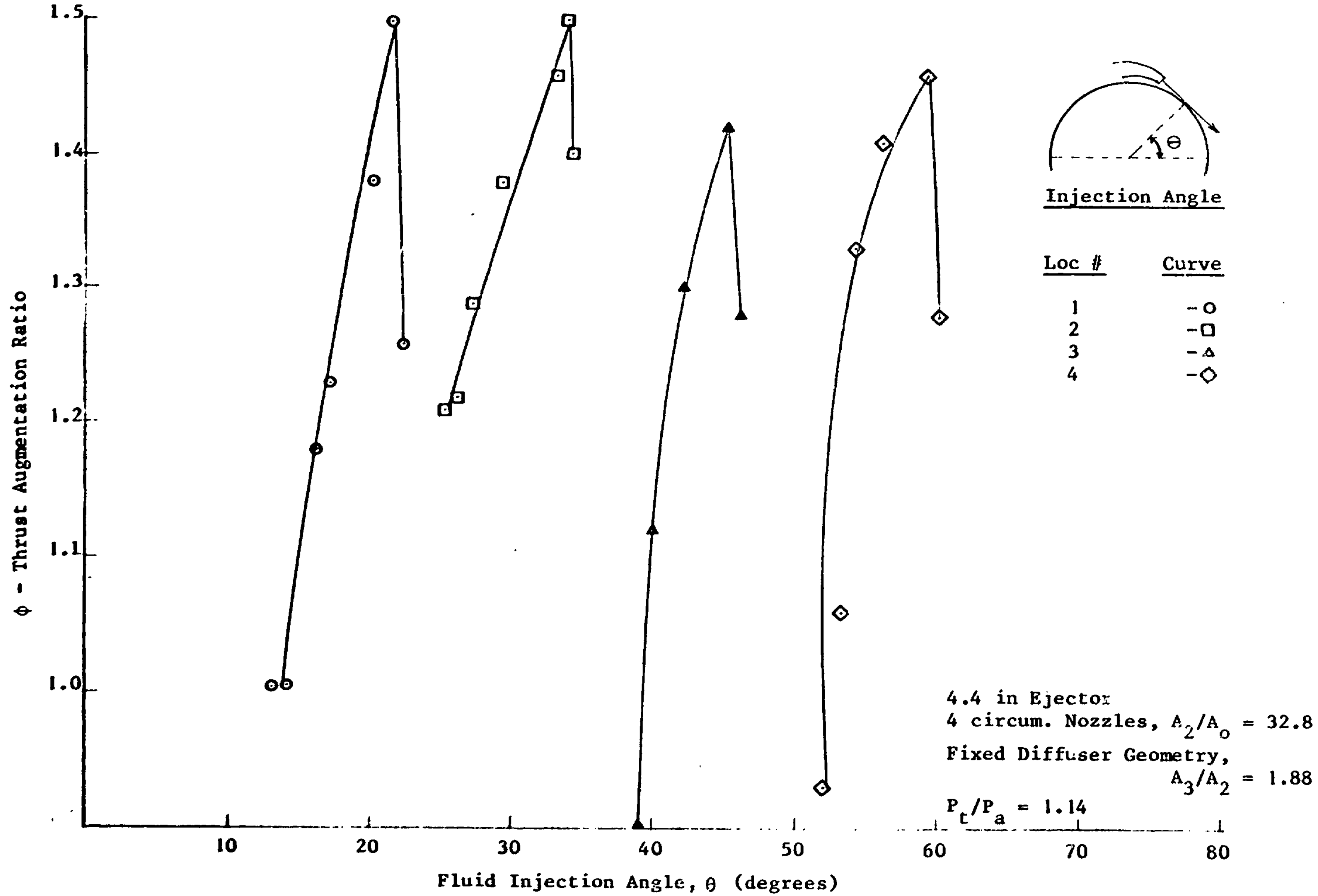
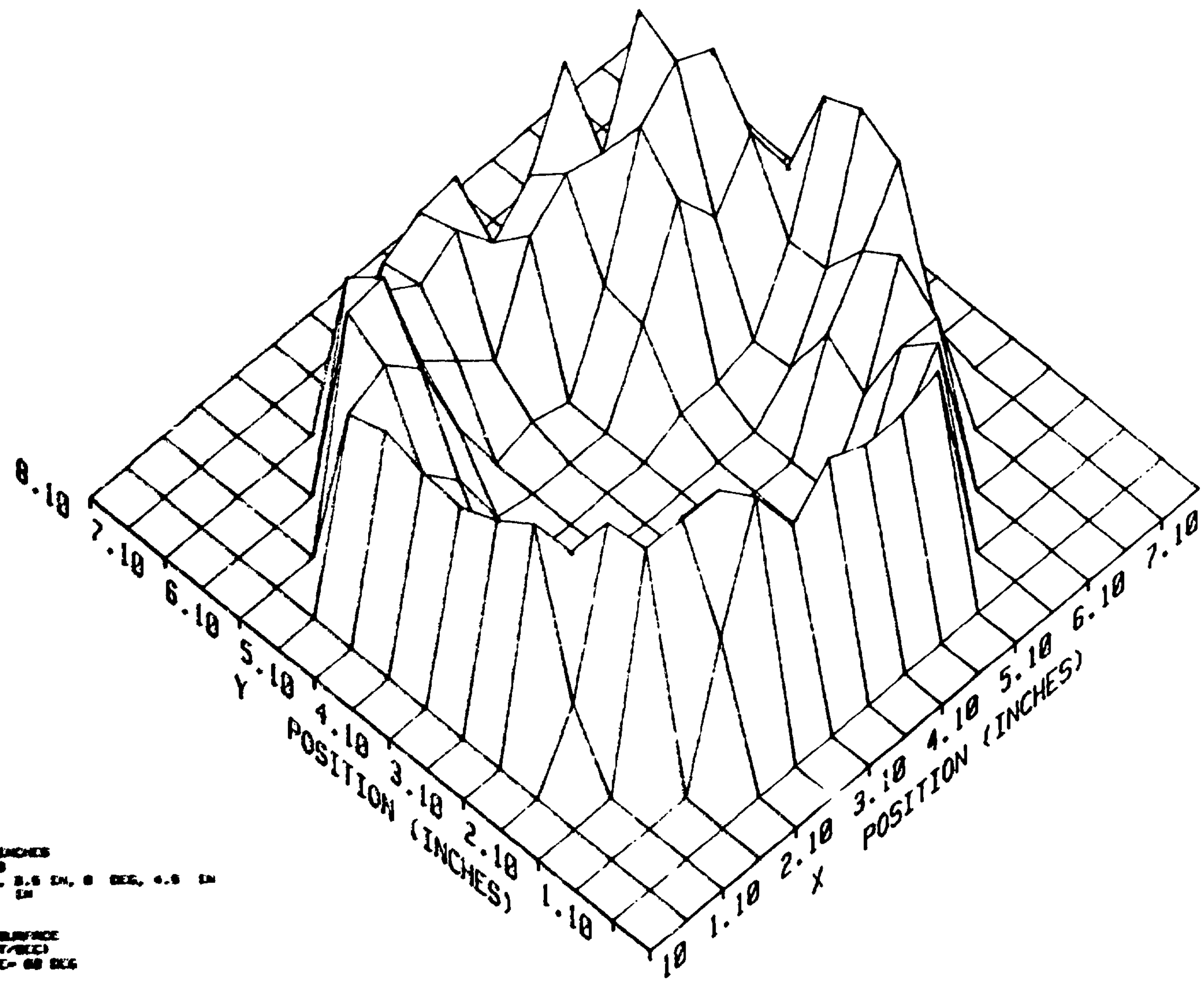


Figure 9. Effect of Primary Nozzle Position and Fluid Injection Angle on Thrust Augmentation

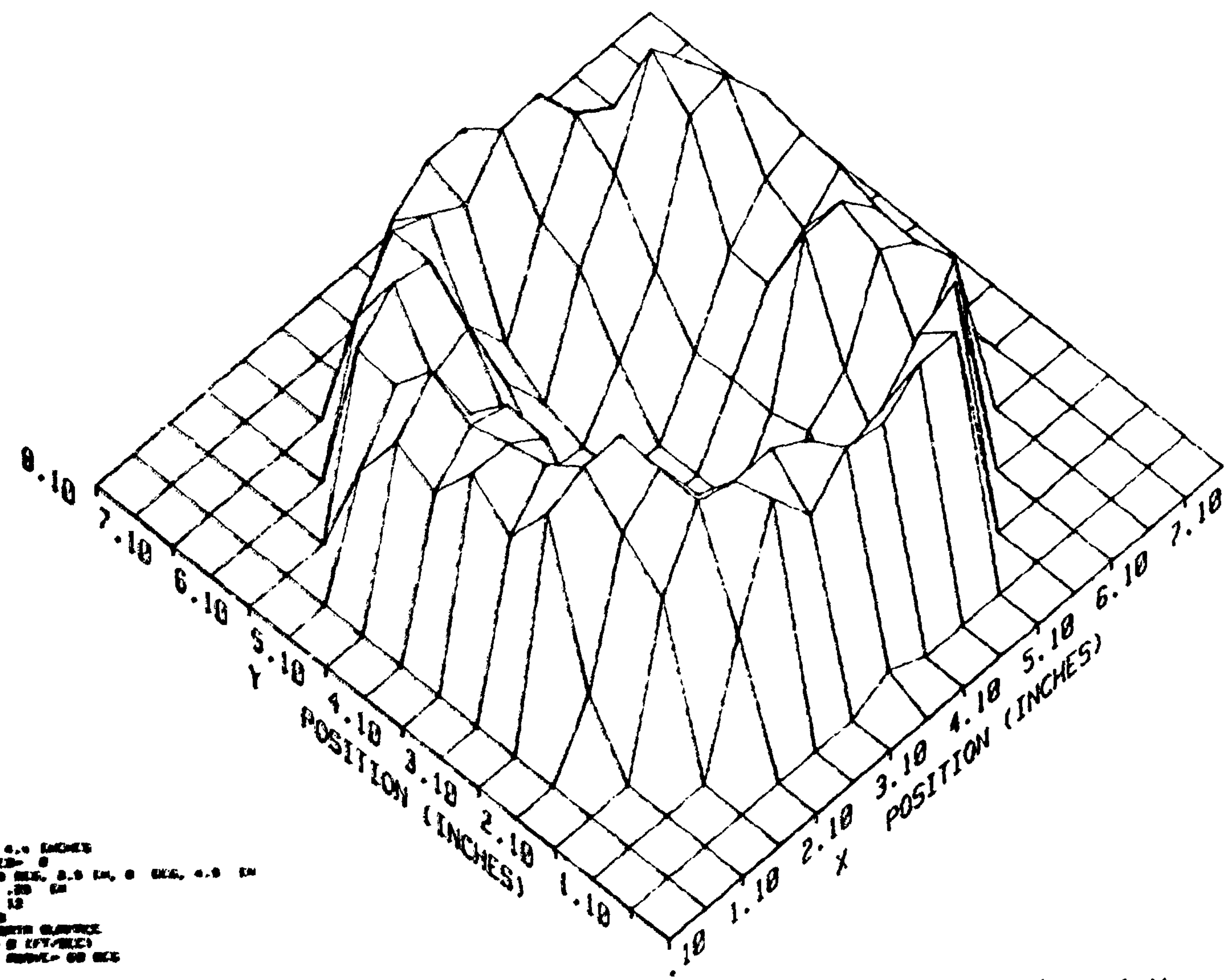
discrepancy found was a reduction of measured thrust. This parameter was systemmatically 8 to 11 percent lower than the Unnever results. This created a proportional decrease in thrust augmentation ratio. This discrepancy can be attributed to the different methods of thrust measurement. Reznick and Unnever used a single strain gauge in tension, whereas a cantilever beam load cell with 4 active gauges was employed throughout this investigation.

Three dimensional graphics were used to examine the exit velocity profiles. The fluid injection angle of 27° produced a thrust augmentation ratio of 1.29 (Fig 10). This configuration has a thin high velocity annular profile a g the side walls, due to Coanda flow effects, with a circular low velocity area in the center. At some points this low velocity area exhibited a reverse flow indicating incomplete mixing. A 33° configuration, the optimum injection angle for thrust augmentation with this apparatus, was examined (Fig 11). This configuration produced a thrust augmentation ratio of 1.51. The exit velocity was relatively constant near the walls, but this high velocity annulus was thicker than that at 27°. This increase in high velocity area caused a reduction of the centerline low velocity area. This indicates an increased mixing throughout the ejector. The velocity along the outer annulus displayed a higher degree of uniformity than the 27° configuration. Next, a 34° configuration, the stalled case (Fig 12) was examined and found to produce a thrust augmentation of 1.4. This configuration possessed several regions of low velocity along the diffuser walls. The overall exit profile displayed many step gradients across the surface. The centerline region has gained noticeable velocity, indicating mixing, however this is gained at the expense of stall at the walls. This trade-off is undesirable as a thurst augmentor due to the thrust loss.



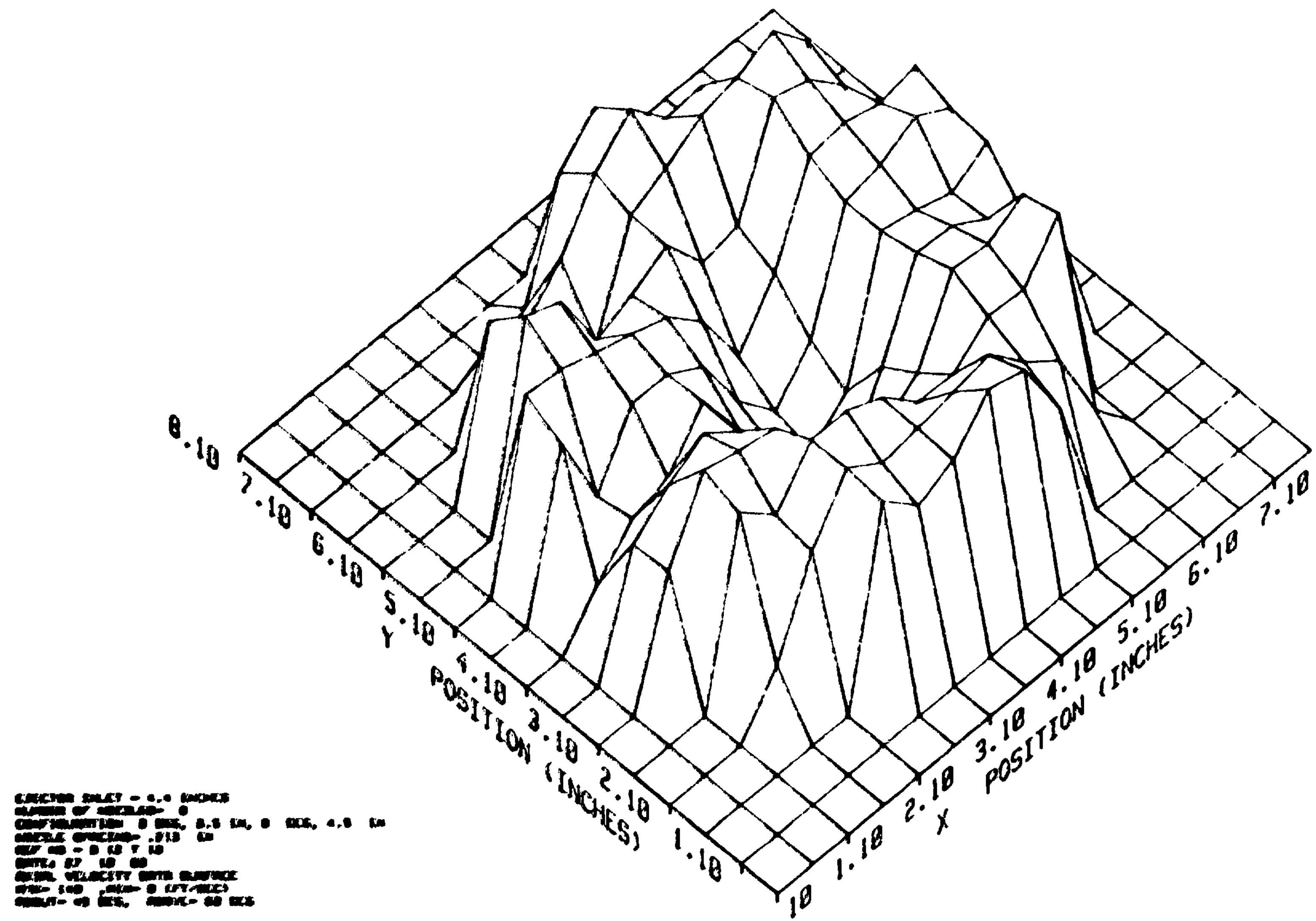
$P_t/P_a = 1.14$

Figure 10. Exit Velocity Profile at $\theta = 26^o$, Thrust Augmentation = 1.22



$P_t/P_a = 1.14$

Figure 11. Exit Velocity Profile at $\theta = 33^o$, Thrust Augmentation = 1.51



$P_t/P_a = 1.14$

Figure 12. Exit Velocity Profile at $\theta = 34^{\circ}$, Thrust Augmentation = 1.40

Effect of Injection Angle on Mass Flow Augmentation

The injection angle was examined to determine the effect on mass flow augmentation. Due to limited time, an approximation was employed to reduce experimental time and develop a trend for mass flow augmentation. An incremental area of the exit along the centerline was sampled (Fig 13). The exit plane was divided into 6 annuli. These corresponded to circular radii from the center of the ejector at 0.5 in increments. The two values of velocity corresponding to a particular annulus were averaged and assumed constant throughout that area. The mass flow through that annulus was then computed. This process was repeated for the remaining areas and then summed to obtain the total mass flow through the ejector. This total was compared to the primary mass flow to obtain the mass flow augmentation ratio. Because of the symmetry assumption, the approximate values are more reliable for configurations where the velocity is relatively uniform throughout the annulus. The curves of mass flow augmentation ratio (Fig 13) were formed with approximation data. Data points derived from a total exit scan are shown. This data agreed to within 6 percent for most points. One approximation was found to vary by 12 percent, but the distribution along the annulus was erratic (Fig 10). Subsequent retest of this configuration eliminated this 12 percent data due to scatter.

The mass flow augmentation results indicate an increase in mass flow augmentation corresponding to injection angle up to the stall point. The 27° configuration (Fig 10) displayed a mass flow augmentation ratio of 6.49. This relatively low flow is attributed to the low velocity centerline area. The 33° (Fig 11) configuration displayed a mass flow augmentation ratio of 9.87. The increase was attributed to the

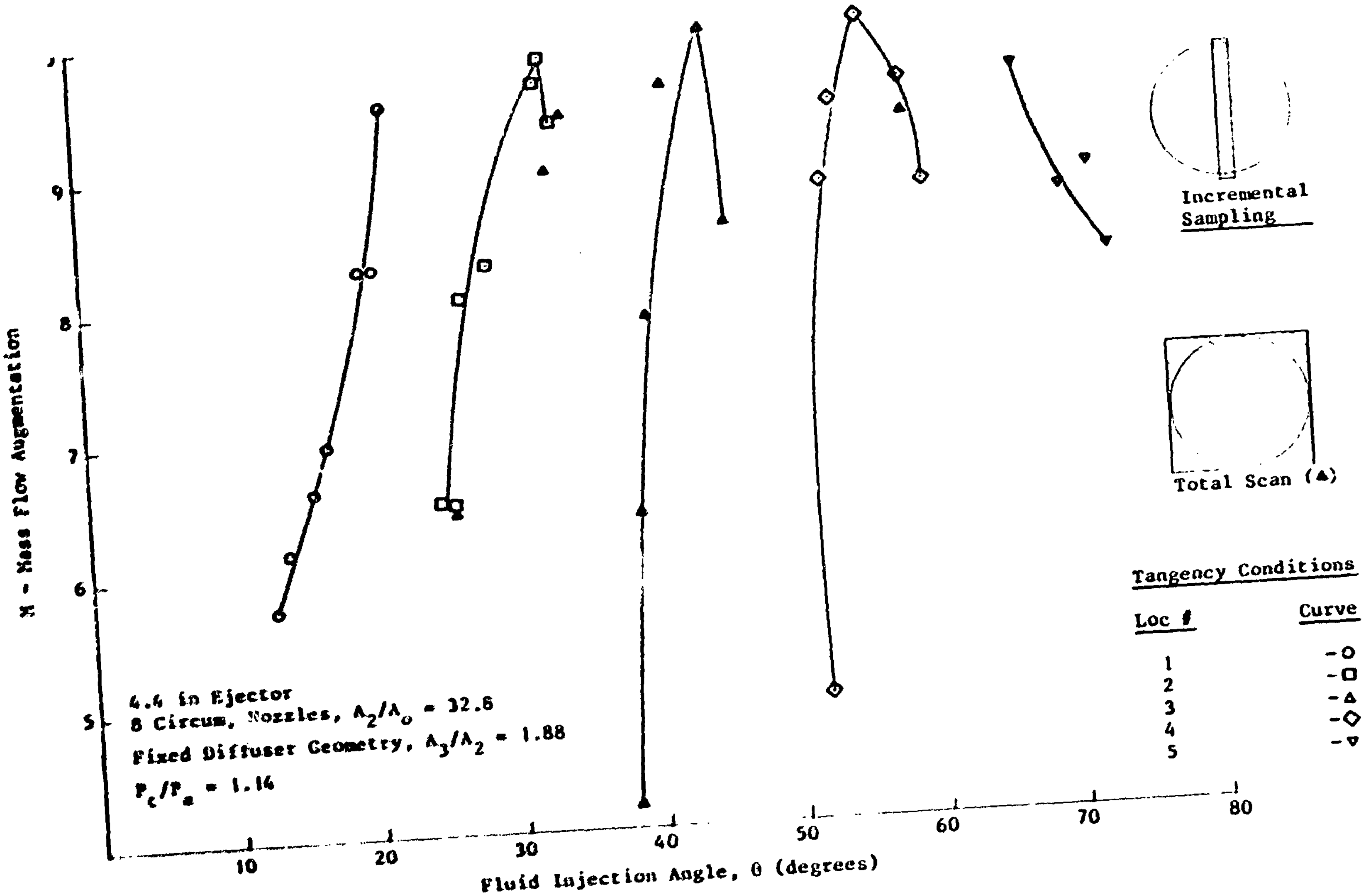


Figure 13. Effect of Primary Nozzle Position and Fluid Injection Angle on Mass Flow Augmentation

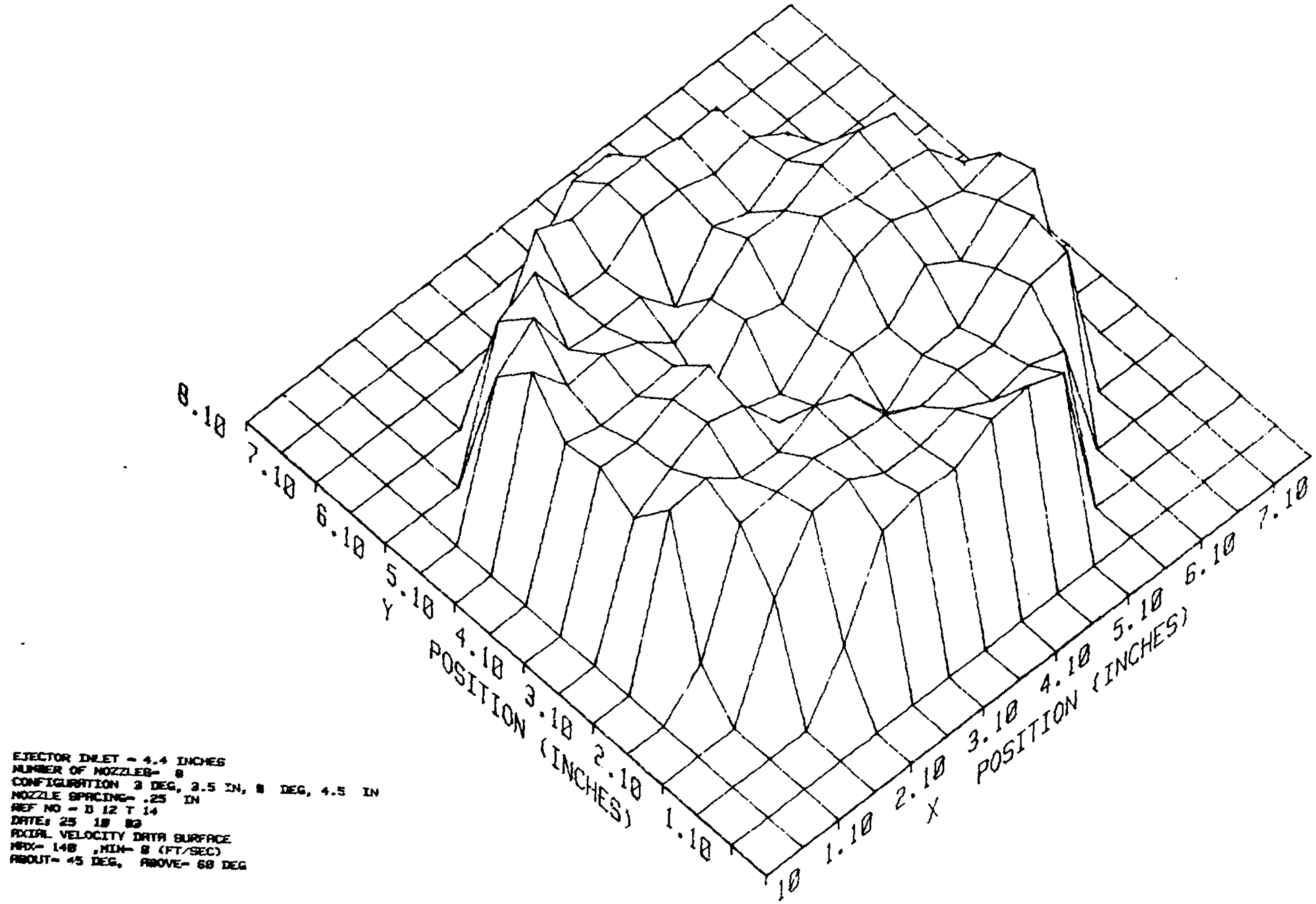
increased mixing in the ejector and the resulting reduction of the low velocity centerline area. The 34^0 configuration produced a mass flow augmentation ratio of 9.32 (Fig 12). This reduction of mass flow is attributed to the stall regions of flow along the side walls. An optimum configuration for mass flow augmentation was sampled (Fig 14). This configuration had a relatively constant exit velocity across the ejector. This total mixing produced a mass flow augmentation ratio of 9.65.

Comparison of Thrust Augmentation and Mass Flow Augmentation Ratios

Positions 1 and 2 (Fig 15) demonstrate an increase in mass flow augmentation with thrust augmentation to the stall point. At this point the thrust is significantly reduced while the mass flow augmentation continues to increase. Position 1 displayed a large range in both performance indicators. Positions 3 and 4 increase mass augmentation with thrust augmentation as did 1 and 2. At the stall point, however, the mass flow augmentation decreased. This trend indicates the possibility of a mass flow reversal point after stall. Curves 3 and 4 possess a wide range and produce high mass flows with thrust, but don't attain thrust equivalent to the first two positions. Position 5 produces high mass flows, but the thrust performance eliminates it as a thrust augmentor.

Axial Flow

In addition to the fluid injection angle, the axial flow of primary air has a dramatic effect upon both thrust augmentation and mass flow augmentation. A configuration, which allowed the flow of one primary nozzle to be skewed from a parallel with the axial flow, was examined (Fig 16). This exit flow displayed a large low velocity area, a stalled



$P_t/P_a = 1.14$

Figure 14. Exit Velocity Profile at $\theta = 59^o$, Thrust Augmentation Ratio = 1.46

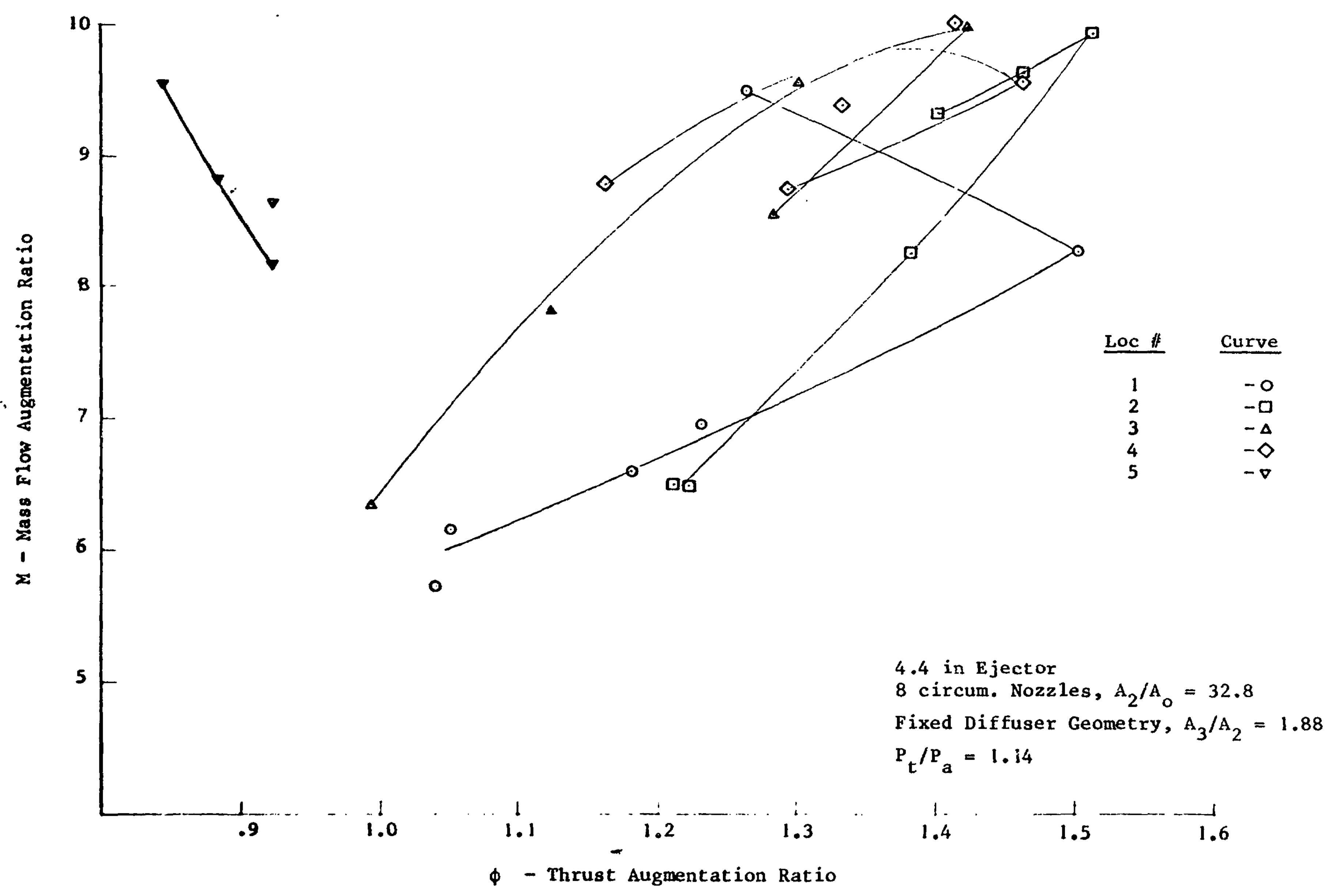
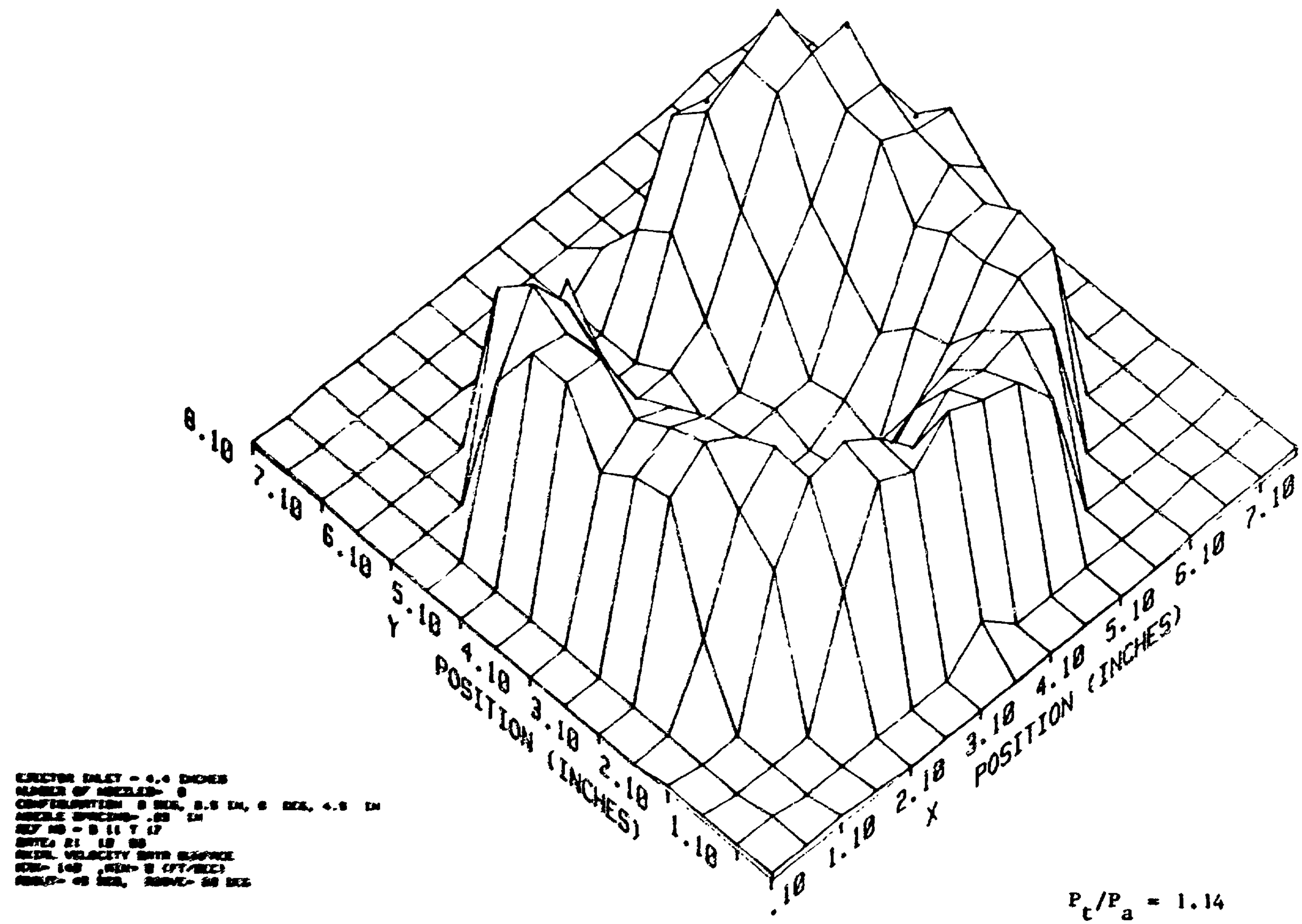


Figure 15. Thrust Augmentation Ratio versus Mass Flow Augmentation Ratio



$P_t/P_a = 1.14$

Figure 16. Stall Region in Exit Velocity Profile at $\theta = 33^o$

region, along the diffuser wall. This stalled region significantly reduced both the mass flow and the measured thrust. This evidences the importance, not only of nozzle spacing symmetry, but of nozzle axial flow symmetry. Reduction of these stall effects greatly stabilized the values of measured thrust from the cantilever beam load cell.

VI. CONCLUSIONS

The following conclusions are based upon the results derived from this investigation:

1. The thrust augmentation data acquisition facility design was adequate for this and further investigations.

2. Both thrust and mass flow augmentation increase with injection angle to the stall point where a marked decrease occurs due to stall effects.

3. Trends of thrust augmentation ratio versus injection angle compared favorably with previous work on the AFIT apparatus.

4. Maximum thrust for each position occured at an injection angle which corresponded to a spacing between nozzle exit and inlet wall of 0.25 in.

5. Axial flow symmetry of primary air is necessary to eliminate random regions of stall in the ejector.

6. Coanda flow and mixing have synergistic effects upon thrust and mass flow augmentation.

VII. RECOMMENDATIONS

The general design and flexibility of the data acquisition facility enables a more in depth look at flow phenomena. The results of this study suggest:

1. A thermocouple should be installed upstream of the orifice plate in order to obtain fluid temperature for computation of density.

2. Pressure taps should be installed in the diffuser and connected to the scanivalve. This information will allow a further investigation of flow separation.

3. Inlet nozzle configuration should be altered to include changing number of nozzles and varying injection angle of annular injection device.

4. Diffuser geometry should be varied to determine its effect on mass flow augmentation.

5. The total scan approximation for mass flow should be examined to determine the optimum spacing requirements for precision and speed.

6. Hypermixing nozzles should be employed to further investigate the effect of mixing upon performance indicators.

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APPENDIX A: Software Details

The collection transfer and control of the DAS is dictated by the utility software. There were four primary software programs incorporated in the investigation. These are:

(1) "PDUCER" - creates the calibration data for the transducers employed in the investigation.

(2) "DATACQ" - the data acquisition program.

(3) "DREDUC" - translates output voltages to engineering units then calculates and stores the desired values.

(4) "SURFAC" - plots a three dimensional picture of the exit flow.

Calibration

The output voltages from the transducers were calibrated using the "PDUCER" program. The program is designed to calibrate up to ten pressure transducers. For this investigation only six transducers were employed:

Transducer	Type	Serial #	Range	Ex Voltage
11	CEC 1000-02	8154	0-50 psi	10.000
12	STATHAM	62080	0-25 psid	5.000
13	STATHAM	6625	0-.7 psid	10.000
14	STATHAM	4852	0-15 psid	10.000
15	CANTILEVER	3	0-12 lb-f	10.000
16	CEC 4-326 0003	15666	0-15 psid	5.000

The interactive program allows for several variations. It initially reads the last calibration data stored in file "PData" and prints the data of the last calibration on the CRT. At this point one must decide to (1) calibrate all transducers, (2) select one or more to calibrate or (3) use old calibration data for any transducer not calibrated. The program then proceeds to permit calibration of the desired transducers. The transducer number and data are presented. The digital voltmeter is reconfigured internally and the channel scanner connects the bridge balance input channel for transducer excitation voltage confirmation. After instructions to adjust excitation voltage and set the reference pressure, exercise the transducer and set the balance voltage. A second reference pressure is requested. These pressures are then checked to insure that reference pressure is less than 0.5 psi from the suggested reference pressures. Because only two points are used to establish the calibration curves, a method to check linearity is unavailable. Due to this procedure, all transducers were manually checked for linearity throughout their range and were found to exhibit less than 1 percent error. The values entered for reference pressures are then converted into appropriate engineering units. Using these units, the slope, P intercept, and change in slope and P intercept are calculated. If there is a change of more than 2 percent in slope or P intercept an appropriate message is displayed warning of transducer instability. If no additional transducers are to be recalibrated, the calibration data is stored under file name PCal(x). If recalibration is desired, it is performed prior to storing in Pcal(x). Once all changes have been made, the calibration data is restored in PData. This terminates the program and prepares for the next execution.

Data Acquisition

The data acquisition program controls the facility operation; monitors, collects, and stores data; and requests parameters necessary for execution. It is the primary program for facility operation. The program is initiated by collecting input data from the user and storing this information in a file, DxxTxx. The number of data points and their locations are determined and stored. The traverse direction is determined and the program pauses to request confirmation of the availability of all required systems. This also allows the bridge balance input voltage to be checked. The digital voltmeter is internally triggered to the proper configuration. The exit plane probe is positioned at the first data point through a series of routines. The first routine calculates the required number of steps to properly position the probe. If this requires more than 100 steps, the motor enters continuous operation for the computed number of steps. The position is then sampled. If it is within 50 steps, the motor begins to drive toward that location. Once within 15 steps of the position, the position is adjusted one step at a time. This continues until the probe is within an allowable 0.002 in range. This range permits a rapid positioning of the probe. The position is then stored with the other data point information permitting an examination of the exact data point location.

With the probe in the proper position, the TAF begins collecting data for that point. For each calculation the digital voltmeter is reconfigured for proper data collection. Thrust data is first sampled for the point. Due to a fluctuating thrust derived from flow phenomena in the diffuser, it became necessary to obtain a time sampling of thrust data and calculate an average value. Determination of an acceptable sampling of data points was accomplished by varying the sampling population and comparing the results. A sampling population of fifty data points was determined adequate and used throughout this investigation.

Following the collection of thrust data, primary nozzle pressures were sampled. After DAS reconfiguration the scanivalve is placed in reference port (home) by the DAS. The scanivalve is then stepped through the range of nozzles. Pressure data is sampled at each of the ports. The scanivalve is then returned to home.

The DAS is again reconfigured. Both RMS and dc voltage readings are taken for hot wire calculation of diffuser exit velocity. Readings for orifice upstream and differential pressure, control room thermocouple, ambient pressure, exit total pressure and reference thermocouple are sampled respectively. The collected data is reorganized and stored in the appropriate array. The exit probe is then moved to the next point and repeats the sequence of data collection. The stored data is displayed on the CRT and placed in a file named TxxR. When the last data point has been sampled and the data stored, the program is complete and displayed as such on the CRT.

Data Reduction

The data collected in TxxR is of little use until it is converted into engineering units. This function, along with the calculation of required parameters for the investigation, is performed in the DReduc program. The program is initiated by reading the label file DxxTxx and the raw data file TxxR. The temperature data is calculated using a ninth order polynomial (Ref 12). This information is stored. The pressure data is calculated using the calibration curves from PDUCER. Following storage of this data, the program uses the converted values to determine the isentropic thrust augmentation and mass flow augmentation ratios. These values are stored appropriately. The operator may then choose the desired output. After output of data, the program is complete.

Graphical Presentation

A listing of the data provides all the required information of the ejector flow, however, a three dimensional sketch of the exit flow provides a valuable means of comparing velocity profiles. The SURFAC program provides such a tool to the user. The program is initiated by reading the label file, DxxTxx, and the engineering units file, TxxE, from the DReduc program. The operator must choose the desired output device. The graphics are organized for the selected device (Ref 13). The exit velocity is calculated and loaded into the U_x mean array. This array is reorganized into a two dimensional array labeled Z. These values are then processed through a direction cosine matrix employing user specified angles of rotation and viewing to present a desired perspective view. A hidden line elimination routine is employed to determine which lines should be plotted concurrent with the line segments being printed on the output device. The height of the output is scaled to insure plotting limits are not exceeded. Upon plot completion, a label is printed in the designated location using the information in the label file. The program is complete and is so displayed on the CRT.

Appendix B: Hardware

The basis of the hardware is the HP 3025A data acquisition system. It controls and monitors the various components of peripheral equipment. This equipment included the traversing mechanism, the scanivalve, and position encoder interface. Further capabilities on operation and capabilities of the DAS can be obtained from the operators manual (Ref 12).

Traversing Mechanism

The traversing mechanism was a major hardware design item. The basic construction is a 25 in square aluminum frame. A horizontal arm was mounted on screw drives to facilitate vertical positioning. Horizontal positioning was accomplished via a single screw drive parallel to the horizontal arm. The weight of the horizontal arm necessitated the employment of counter weights to enable the drive motors to function properly. The drive motors were 18 volt, 0.72 amp, bi-polar stepper motors (North American Phillips K8295-M1). The operation of the motors required an interface. The existing interface for the cascade test facility was utilized. This interface provided switching to four discrete polarity combinations providing a smooth continuous operation.

Position Encoder

A second interface component was the position encoder. A BCD interface cable provided connection to the DAS. The interface provided the DAS with position data via a binary code derived from the position transducers. Through use of this interface the DAS was able to monitor and control the position of the exit plane probe. This interface had been previously used on the cascade test facility.

Scanivalve

The scanivalve operated on a five volt dc power source (SOLA 85-05-210). The input was channeled through a SCANO solenoid controller, CTLR2/S2-S6, to the scanivalve. The solenoid controller was triggered through a small digital chip interface by the DAS. The signals for control were sent via a 16 bit I/O cable to the controller interface. The solenoid controller pulsed the scanivalve drive motor as demanded by the DAS.

Ejector

The ejector possesses many parameters which can be altered to affect performance. One of the variable parametrs which greatly affects the performance of the ejector is the flow injection angle. To establish a procedure which was consistent across the ejector and repeatable from one experimental run to another, required several modifications. The nozzles were modified to insure a uniform fit was attained when mounted on the ejector. A wooden jig of ejector inlet dimensions, was designed (2 in radius of curvature) (Fig 9). Angular scribe lines were placed on the jig. A nozzle mount and nozzle were installed on the jig. A machined guide was then placed in the exit of the nozzle to simulate flow. A feeler gauge was placed between the nozzle and the jig to establish the injection angle. The injection angle (Deg), relative to a line perpendicular to the ejector centerline, corresponding to each feeler spacing is:

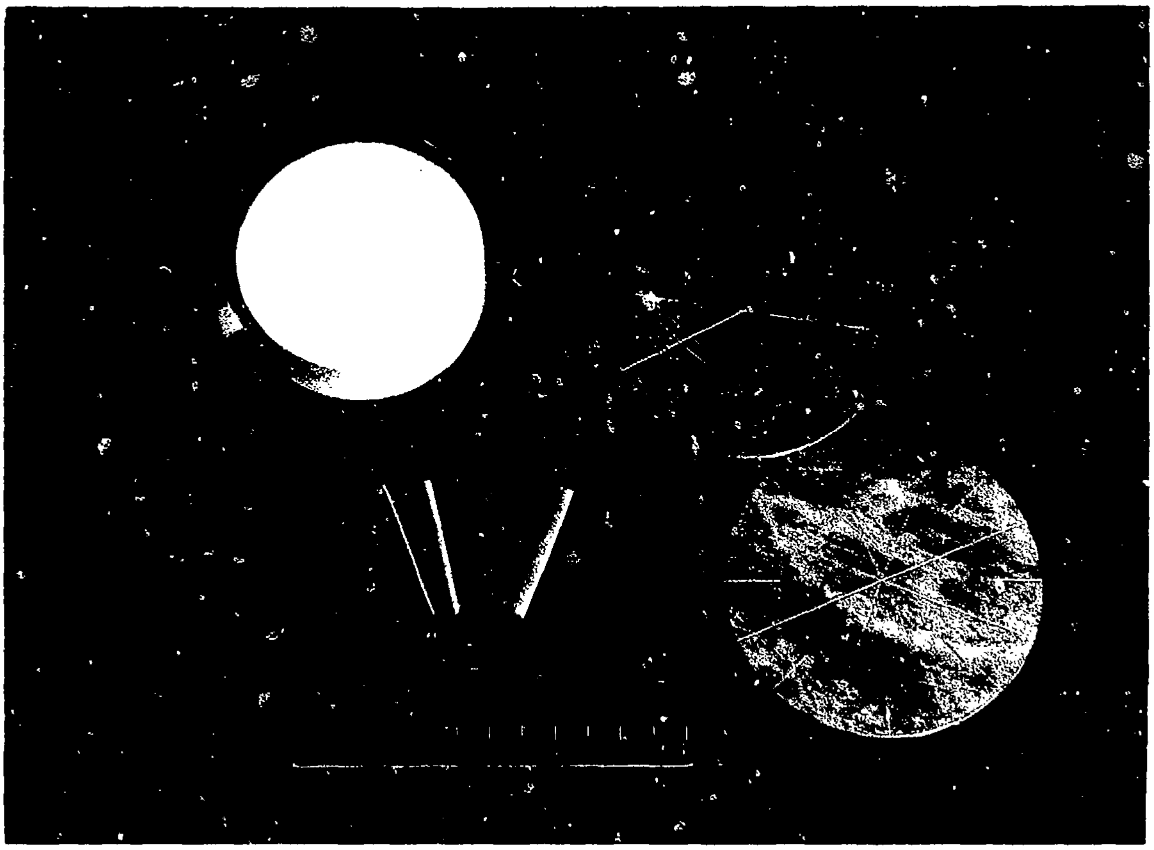

Figure 17. Injection Angle Measurement Device

L to R: Injection Angle Measurement jig with nozzle attached, feeler gauges spacing templates.

Spacing (in)	Posn 1	Posn 2	Posn 3	Posn 4	Posn 5
0.000	13	25	38	52	64
0.063	14	26	39	53	65
0.125	16	27	40	54	67
0.188	17	29	42	56	70
0.250	20	33	45	59	72
0.313	21	34	46	60	78

The projected angle of the flow to the jig was measured. This procedure provided a systemmatic approach for insuring symmetry and repeatability that had not been previously documented. To insure proper spacing of the nozzles around the inlet, aluminum templates with scribe lines were inserted inside the inlet and used to position the nozzles.

APPENDIX C: Instrumentation

The power source for the instrumentation system was the HP 6025C dual dc power supply. The output was passed through a 17 volt input/12 volt output voltage regulator into a CEC dc bridge balance, type 8-108. This bridge balance controlled the excitation voltage of each transducer and monitored their output voltages. For stable operation it was necessary to set the desired excitation voltages and balance the output allowing a 24 hour stabilization period. A second adjustment was required to correct for any temperature change. After this procedure the input power should be adjusted minimally, especially after calibration. Fine adjustments of balance are not possible without a destabilizing effect.

The transducers used were all purchased commercially with the exception of the cantilever beam load cell used for thrust measurement. The beam was constructed using four strain gauges (BLH Electronics FAE 25S-35-S6). These gauges were bonded to the beam in pairs on opposite sides. This arrangement provided four times the sensitivity of a single gauge, temperature compensation, and insensitivity to compression and lateral force if identical gauges and symmetry are assumed (Ref 11).

The aluminum beam dimensions were 0.25x1x5 in. When maximum output is desired for any strain gauge transducer, one should consider the use of low modulus materials (such as aluminum) to increase strain per unit force), however, these materials may have excessive hysteresis and low fatigue life (Ref 11). The beam was tested for nonlinearity and hysteresis and was found to display less than 0.2 percent from the combined effects.

It was necessary to calibrate the cantilever beam in its mounted position due to the effect of gravitational forces. A single pulley mounted on a portable tripod was employed. The calibration weight was attached to the ejector inlet via a flexible cable. The weight hung freely from the pulley. The cable was vibrated to eliminate any hysteresis in the pulley system. In order to calibrate the remaining transducers, a known pressure line was attached to the inlet of each transducer. The line pressure was controlled by a regulator located in the control room and monitored via manometers attached to the line. Caution should be exercised to insure the water manometer is off line while using the mercury manometer for higher pressures. The calibration is accomplished by following the interactive program PDUCER. After calibration and stabilization, the transducers displayed minimal drift. The exit pressure transducer exhibited a zero drift with position which was eliminated when solidly mounted. This transducer was also sensitive to ambient air circulation. The problem was eliminated by placing a foam insulator over the ambient port of the transducer.

The transducer output was delivered to the 3495A scanner of the DAS via the dc bridge balance. The scanner determined which transducer was to be monitored by the 3455A digital voltmeter. The voltmeter proved to be the workhorse of the DAS enabling precise data collection for each mode by internally reconfiguring as necessary (Ref 14).

VITA

William D. Lewis was born in Hillsboro, Ohio on 18 December 1952. After graduation from Hillsboro High School in 1970, he attended Ohio University. He then attended the United States Military Academy from 1971 - 1975 graduating with a B.S. in Engineering and receiving a regular commission in the United States Army. Following the completion of Airborne, Field Artillery Officers Basic and Defense Race Relations Institute, he was assigned to the 2d Infantry Division, Korea in a direct support battery. He was then assigned to the 7th Infantry Division, Ft Ord, California serving in varied artillery positions. In June 1978 he attended flight school at Ft Rucker, Alabama. Upon graduation he served as section leader, flight instructor, flight commander and Aide-de-camp to the Commanding General. In September 1981 he attended the Infantry Officers Advanced Course in Ft Benning, Georgia. In June 1982 he entered the Air Force Institute of Technology Graduate School.

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE:

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S): AFIT/GAE/AA/83D-13

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: School of Engineering

6b. OFFICE SYMBOL (If applicable): AFIT/EN

6c. ADDRESS (City, State and ZIP Code): Air Force Institute of Technology, Wright-Patterson AFB, Ohio 45433

7a. NAME OF MONITORING ORGANIZATION:

7b. ADDRESS (City, State and ZIP Code):

8a. NAME OF FUNDING/SPONSORING ORGANIZATION:

8b. OFFICE SYMBOL (If applicable):

8c. ADDRESS (City, State and ZIP Code):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.

11. TITLE (Include Security Classification): See Box 19

12. PERSONAL AUTHOR(S): William D. Lewis, B.S., CPT, U.S. Army

13a. TYPE OF REPORT: MS Thesis

13b. TIME COVERED: FROM ______ TO ______

14. DATE OF REPORT (Yr., Mo., Day): 1983 December

15. PAGE COUNT: 59

16. SUPPLEMENTARY NOTATION:

Approved for public release: IAW AFR 190-17.
LYNN E. WOLAVER
Dean for Research and Professional Development
Air Force Institute of Technology (ATC)
3 JAN 1984

17. COSATI CODES

FIELD	GROUP	SUB. GR.
21	05	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number):
Ejector
V/STOL
Thrust Augmentation
Mass Flow Augmentation

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

Title: An Experimental Study of Thrust Augmenting Ejectors

Thesis Advisor: Milton E. Franke, PhD

An automated thrust augmentation data acquisition facility was designed and constructed. The facility provides the capability of measuring thrust augmentation ratio and mass flow ratio. A three dimensional graphics plot of exit flow is provided for flow analysis.

Tests were conducted on a 4.4 in diameter circular ejector, with eight primary nozzles mounted symmetrically along the perimeter of the inlet. A fixed ejector geometry was used. The ratio of mixing chamber area to diffuser exit area was 1.88. The fluid injection angle measured from a line perpendicular to the ejector centerline, was varied and the thrust augmentation and mass flow augmentation ratios calculated. Both thrust augmentation and

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL: Milton E. Franke, PhD

22b. TELEPHONE NUMBER (Include Area Code): 513-255-2362

22c. OFFICE SYMBOL: AFIT/EN

Block #19

mass flow augmentation increased with fluid injection angle to the stall point where both decreased.

Axial flow symmetry of primary air was found to affect stall along diffuser walls.