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UNITED STATES AIR FORCE

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WRIGHT-PATTERSON AIR FORCE BASE, OHIO

OPTICAL STUDY OF SUPERSONIC FLOW

OVER A REARWARD FACING STEP

THESIS

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OPTICAL STUDY OF SUPERSONIC FLOW

OVER A REARWARD FACING STEP

THESIS

Presented to the Faculty of the School of Engineering of

the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

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Captain USAF

Graduate Aerospace-Mechanical Engineering

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Preface

This study is the result of a suggestion by Dr. Max G. Scherberg of the Aerospace Research Laboratory. Dr. Scherberg has made several studies and written several articles on the behavior of the flow over a rearward facing step at high Mach numbers. This study was intended to investigate the flow at lower Mach numbers.

This study was conducted primarily with a schlieren system with some pressure data to correlate the optical findings. The emphasis throughout the study is on optical findings.

I wish to thank Dr. Max G. Scherberg for helping me get the study started; Dr. Andrew J. Shine for his assistance as thesis advisor; Mr. R. Wolfe and the employees of the AFIT School Shops for their help in the design, construction, and assembly of the test apparatus; Mr. J. Flahive, Mr. R. Brown, and Mr. W. Baker for their assistance in the laboratory; and my family for their support and understanding during the course of this study.

Albert L. Waters

Contents

List of Figures

Figure Page

List of Tables

Abstract

In this study, the supersonic flow field over a rearward facing step was studied with a schlieren system. The effect of Mach number variation, step height variation, and total pressure variation on the expansion fan angle, lip shock angle, flow turning angle, reattachment point, and reattachment shock angle was determined. Schlieren photographs of the flow at Mach number 2.7 to 3.1, step heights of 1/4 to 3/4 in, and total pressures of 60 to 95 psia are presented. It was found that the relatively small changes in Mach number had the smallest effect on the flow field and that changing the step height had the greatest effect on the flow field. The flow turning angle was sensitive to all three variables.

Optical Study of Supersonic Flow over a Rearward Facing Step

I. Introduction

An optical study of the flow over a rearward facing step was accomplished with a schlieren system. The effects of step height changes, small changes in Mach number, and changes in stagnation pressure were investigated. Measurements were made with regard to the expansion fan, the lip shock, the shear layer boundary, the reattachment point, and the reattachment shock. Schlieren photographs of the flow over a side mounted step were made. The tests were performed in the Air Force Institute of Technology blowdown wind tunnel with a test section 3 in high by 6 in long by 1 in wide.

Background

This study was performed to add to the knowledge of the flow field behind a rearward facing step. Although pressure studies have been made on the flow field at high Mach numbers (Ref 8:59) there is a lack of schlieren photographs in the literature. The use of a schlieren system cannot yield quantitative values of the field properties, but it does provide information about the location of shock waves, limits of expansion fans, and any other flow conditions that create a density variation. Supersonic flow over a rearward facing step causes a wide range of flow variations and the schlieren system can indicate the extent of these variations.

Objectives

The principal objective of this study was to investigate supersonic flow over a rearward facing step with a schlieren optical system. The specific objectives were:

1. To modify an existing blowdown wind tunnel to provide a low turbulence, two-dimensional, supersonic flow in the 2.5 to 3.5 Mach range.
2. To optically observe the basic flow structure behind a rearward facing step in supersonic flow and determine the effect on the flow structure of varying the step height, Mach number, and stagnation pressure.
3. To correlate the optical results with pressure data.

II. Apparatus

The wind tunnel, schlieren system, step models, and pressure instrumentation are discussed in this section.

Wind Tunnel

The wind tunnel was an intermittent operating blowdown type. It consisted of a high pressure compressor and storage tank, a calming or settling chamber, a convergent-divergent nozzle, a test section, three vacuum pumps and a vacuum tank, and necessary plumbing. High pressure air enters the calming chamber, flows through the test section and enters the evacuated vacuum tanks. The tunnel could provide supersonic flow for about 12 seconds. Additional description and operating characteristics of the wind tunnel are given in Appendix A.

Schlieren System

The schlieren system consisted of a spark light, a zirconium lamp, two 10 in parabolic mirrors, a knife edge and a camera. All knife edge positions were photographed, but the bottom horizontal position, parallel to the flow, gave the best overall detail of the flow. Polaroid Corporation type 47 film was used with the spark lamp light source for the schlieren photographs. Additional description of the schlieren system is given in Appendix B.

Step Models

The basic step model was 1 in wide, 2-3/4 in high, and 12 in long and had a 3/4 in step which was located behind a 2-1/4 in long flat surface. There was a reattachment surface 9-3/4 in long immediately behind the step. Step heights other than 3/4 in were obtained by attaching rectangular aluminum bars to the reattachment surface. Fig 1 is a schematic drawing of the basic model and the bars used to vary the step height and Fig 2 is a photograph of the 3/4 in step model installed in the test section.

Pressure Instrumentation

Pressure taps were drilled into a solid aluminum tunnel sidewall. The regular glass paneled sidewall was replaced by the pressure tapped sidewall to obtain pressure data. The pressure taps were 1/32 in holes in a 1/2 in pattern in the vicinity of the step; their location relative to the step is shown in Fig 3. The pressure taps were connected to a bank of twenty U-tube manometers. Since the wind tunnel only operated for approximately 12 seconds, the manometers were photographed and pressure data was obtained from the photograph.

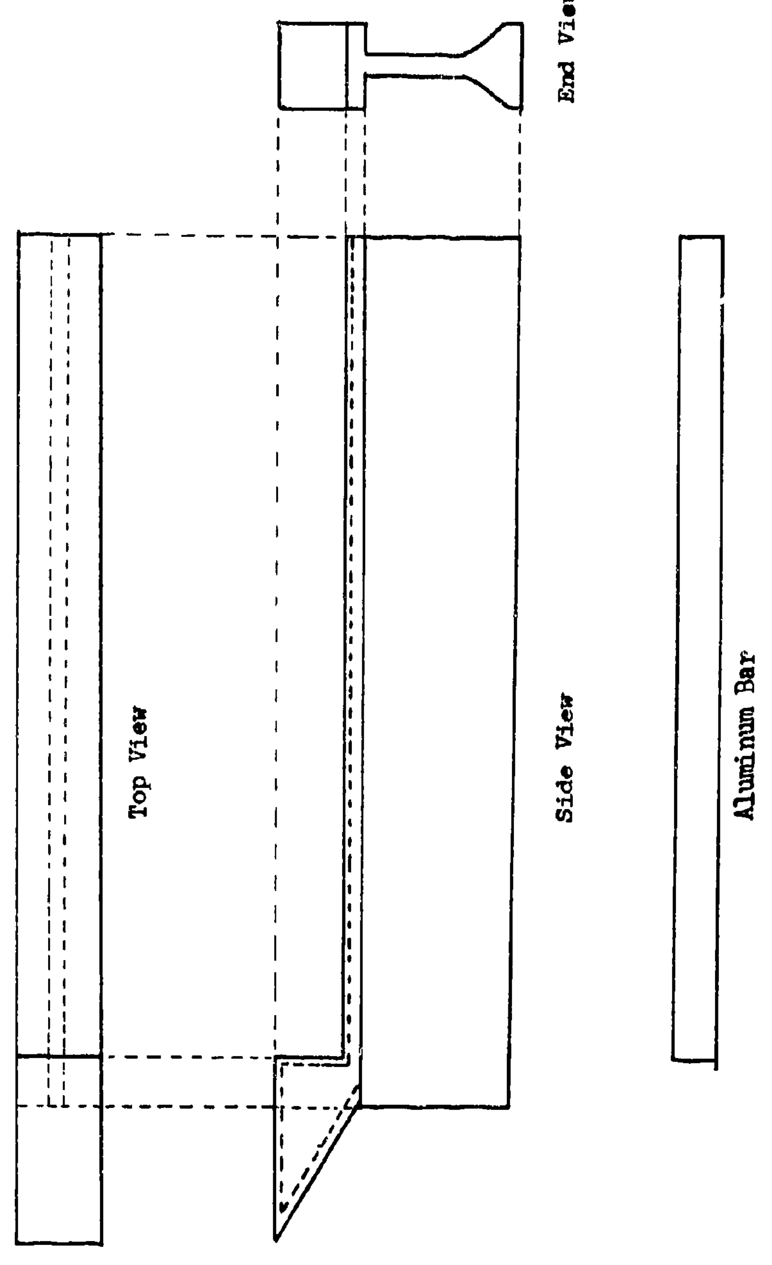


Fig. 1 Schematic Diagram of Step Model and Aluminum Bar (typical) Used to Vary Step Height. Dotted Lines on Side View Indicate "O" Ring Seal. Scale: 1 in = 2 in.

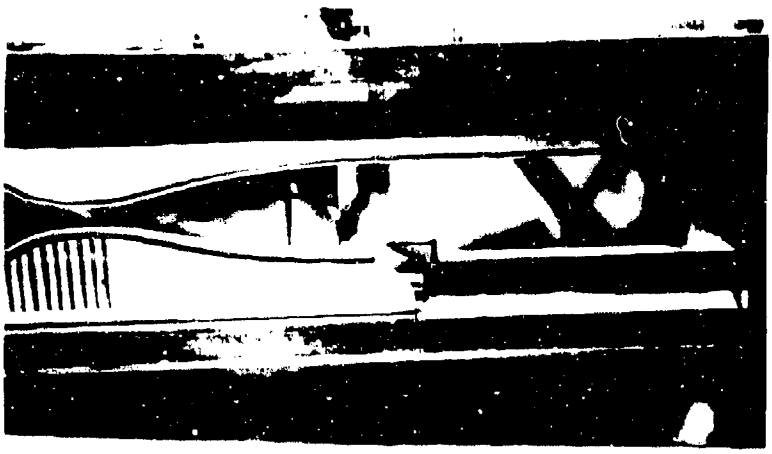


Fig. 2 Wind Tunnel Test Section With 3/4 in Step Model Installed.

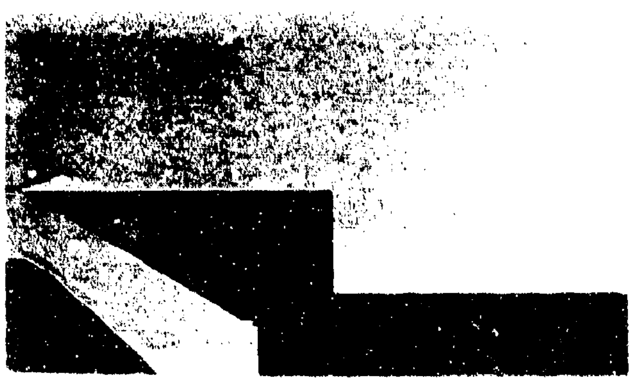


Fig. 3 Pressure Instrumentation Location Relativ to 3/4 in Step Model. White Dots Indicate Pressure Port Location.

III. Experimental Procedure

The basic procedure used to obtain the optical and pressure data is discussed in this section. First a general discussion of procedure pertaining to all experimental runs is given and then specific procedure for the various runs.

Prior to each run, the high pressure air compressor was operated for at least 30 minutes to allow temperatures to stabilize in the compressor, intercooler, and plumbing. The low pressure system was evacuated to approximately 0.5 psia. For the schlieren runs, the light source, mirrors, knife edge position, and camera position were adjusted to give the desired photograph. A bottom, horizontal knife edge was used for the data runs since all of the flow parameters of interest were visible with the knife edge in that position. The spark lamp was triggered manually after the desired flow conditions were established. For the pressure runs, one glass sidewall was replaced with the pressure tapped sidewall. A shutter operated camera was used to photograph the manometer board to record the pressure data.

The Mach number was varied by placing spacer washers under the nozzle blocks near the throat section to change the throat area and thus the area ratio of throat to test section. Three spacers of 1/8 in, 5/32 in, and 9/32 in height were used. To determine the four Mach numbers, a

10 degree wedge was installed in the test section and schlieren photographs were made of the flow for each of the nozzle area ratios. The Mach number was obtained by measuring the oblique shock angle from the wedge and using shock tables (Ref 4:180-183). Appendix C contains complete Mach number data.

After the Mach number was determined, the 10 degree wedge was removed from the test section and the basic step model was installed. Runs during which schlieren photographs were obtained were made at the four Mach numbers for each of the five step heights. Two runs were made at each step height and Mach number; one at approximately 50 psig and one at approximately 80 psig. The procedure used to photograph the side mounted step was the same as for the basic step.

The pressure runs were all made at Mach number 2.7. Chamber pressures of 50 and 70 psig were used for each step. The chamber pressure was set with the slide valve and the manometers were photographed approximately five seconds after the slide valve was opened.

IV. Results and Discussion

Chamber pressure, step height and Mach number are used as the independent parameters of this study. The chamber pressure is the total pressure of the flow entering the nozzle and was varied from 64 to 97 psia. Step height was varied from 3/4 in to 1/4 in in 1/8 in increments. The Mach number reported is the freestream Mach number at the beginning of the flat plate section of the model. Fig 4 is a composite schlieren photograph made by joining two photographs of the same flow conditions. It illustrates the flow phenomena that will be discussed and Fig 5 shows the nomenclature used for these phenomena in this report. Fig 8 is a series of schlieren photographs which illustrate the effect of step height change. Figs 6, 7, and 9-16 show the effects of step height change, Mach number change, and stagnation pressure change. The results of the optical study of a side mounted step are also presented.

Expansion Fan

The expansion fan is generated as the flow reaches the edge of the step. Assuming simple Prandtl-Meyer flow around the corner would indicate that the extent of the fan is dependent on Mach number, stagnation pressure and indirectly, on the step height (Ref 10:474). The step height changes the pressure at the base of the step which in turn determines how much expansion is necessary. In this study, the expansion fan was observed to terminate with a lip shock (Fig 4); the flow overexpands and then the lip shock returns the pressure to the base pressure.

The data indicate a general increase in expansion angle for an increase in Mach number (Fig 6). The increase in the expansion angle was 3 degrees for the 3/4 in step and 9 degrees for the 1/4 in step as the Mach number was increased from 2.7 to 3.1. Simple centered wave theory shows that the expansion angle is proportional to the Mach number (Ref 10:466). The result of the expansion fan angle measurements indicated that the expansion angle was directly proportional to the Mach number.

Increasing the stagnation pressure caused the expansion angle to decrease (Fig 6). The expansion angle for the 5/8 and 1/2 in step decreased 2 to 3 degrees at each Mach number as the pressure was increased from 65 to 95 psia. For the same increase in stagnation pressure, the expansion fan decrease was 0 to 2 degrees for the 3/4 in step. The data for the other two step heights, 3/8 and 1/4, do not exhibit the same decrease for increasing stagnation pressure.

Changing the step height at constant Mach number and pressure produced no discernible trend in the expansion angle (Fig 7). The total measured difference in expansion angle was 0 to 7 degrees as the step height was increased from 1/4 to 3/4 in, but no pattern to the changes could be established.

Fig. 4 Composite Schlieren Photograph of Flow Over 3/4 in Step. $P_o = 84$ psia, $M = 2.9$.

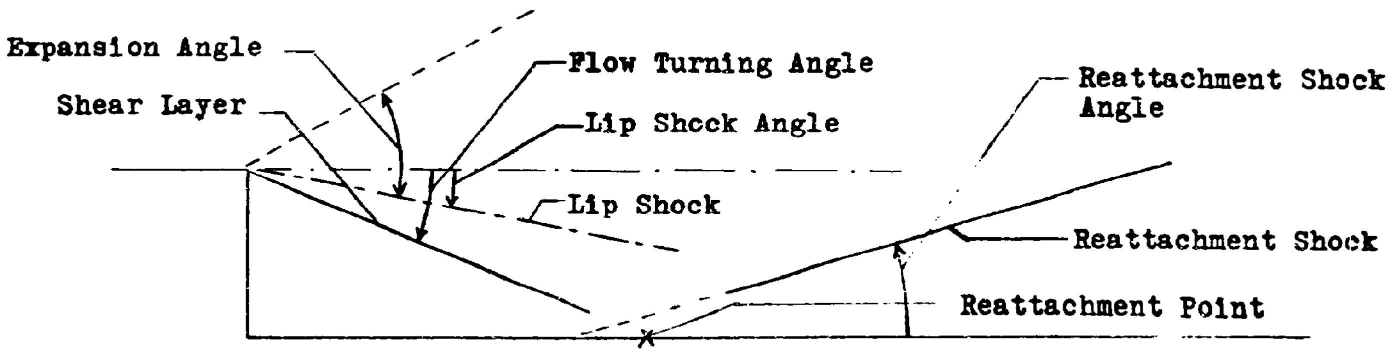


Fig. 5 Diagram of Flow Phenomena Investigated and Nomenclature Used in this Study.

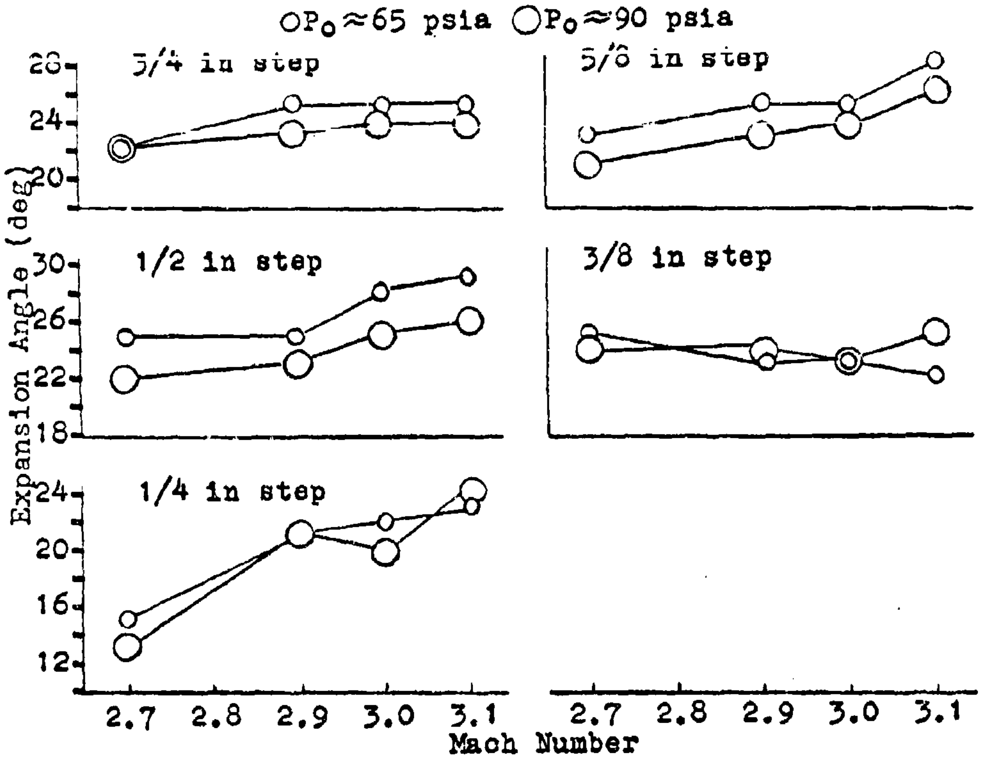


Fig. 6 Effect of Mach Number on Expansion Angle for Various Step Heights and Pressures.

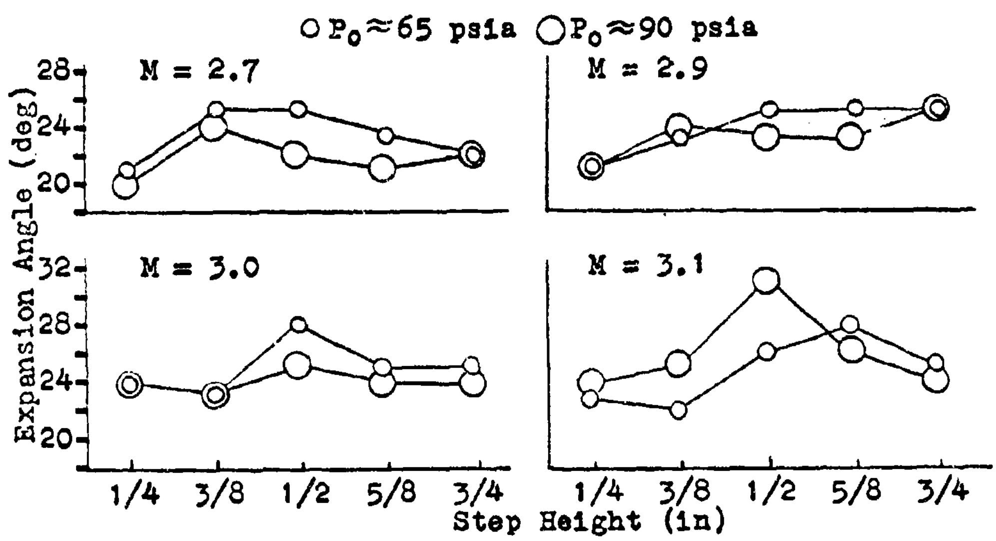


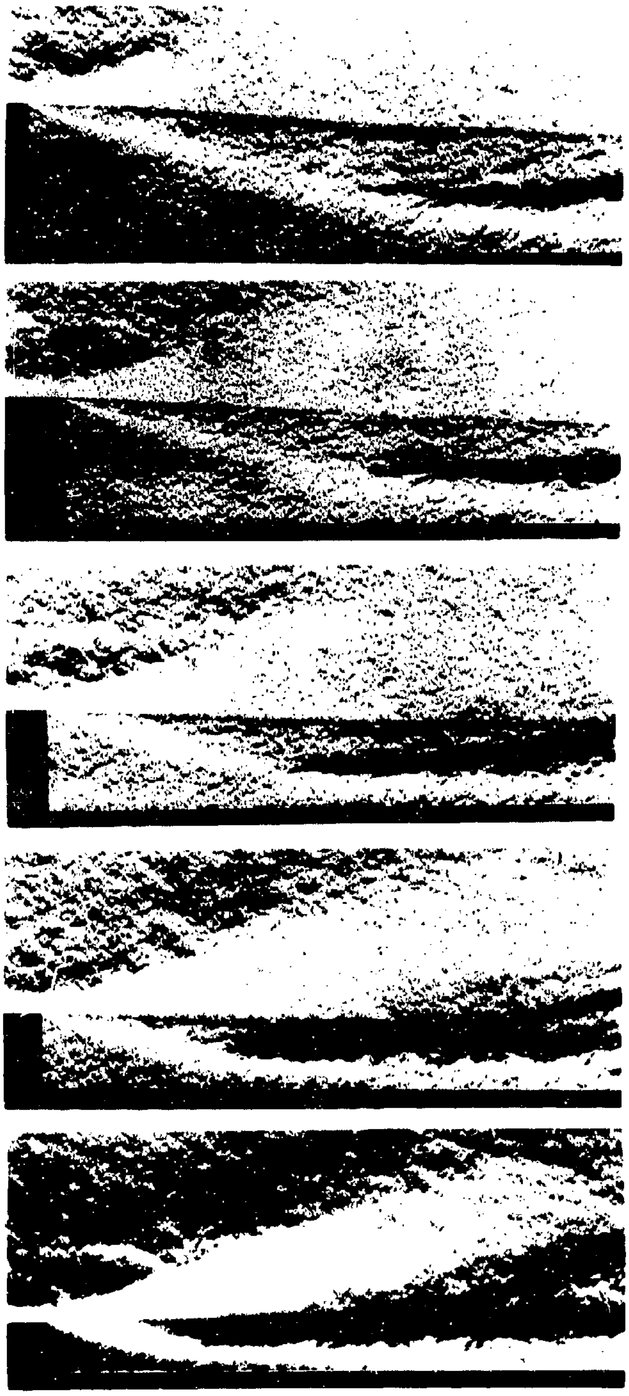
Fig. 7 Effect of Step Height on Expansion Angle for Various Mach Numbers and Pressures.

Lip Shock

The lip shock occurs at the end of the expansion fan. The flow overexpands in the expansion fan at the step and the lip shock is caused by the required pressure recovery (Ref 8:55). Scherberg and Smith (Ref 8) report that the lip shock does not extend to the step. Hama (Ref 3), however, reports that the lip shock does extend to the step. At the Mach numbers and pressures of this study, it was found that the lip shock does extend to the step (Fig 4), agreeing with the results of Hama. The lip shock appeared much weaker on the schlieren photographs than did the bow shock or the reattachment shock (Fig 4).

Increasing the step height from 1/4 in to 3/4 in in 1/8 in increments caused the lip shock to rotate downward (Figs 8,10). At the low step heights and low Mach numbers the lip shock was above the horizontal. As the step height was increased the lip shock angle rotated to 4 to 6 degrees below the horizontal. At the higher Mach numbers, the lip shock started out below horizontal and moved further below as the step height was increased.

Increasing the Mach number caused the lip shock to rotate clockwise and come closer to the shear layer (Fig 9). The rotation from the horizontal was approximately 5 degrees when the Mach number was increased from 2.7 to 3.1. From the schlieren photographs (Figs E-1 thru E-5) the lip shock strength did not appear to change as Mach number changed,



3/4 in step
P_0 = 90 psia

5/8 in step
P_0 = 91 psia

1/2 in step
P_0 = 93 psia

3/8 in step
P_0 = 89 psia

1/4 in step
P_0 = 96 psia

Fig. 8 Schlieren Photographs of Flow Over Various Step Heights at Mach Number 2.9.

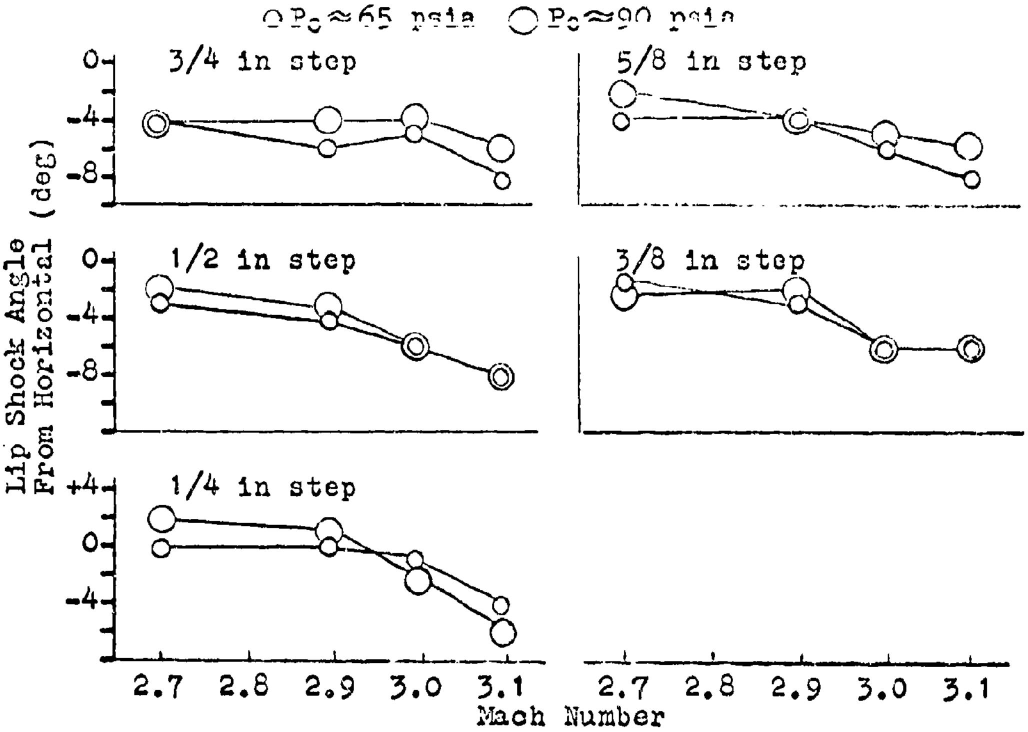


Fig. 9 Effect of Mach Number on Lip Shock Angle for Various Step Heights and Pressures.

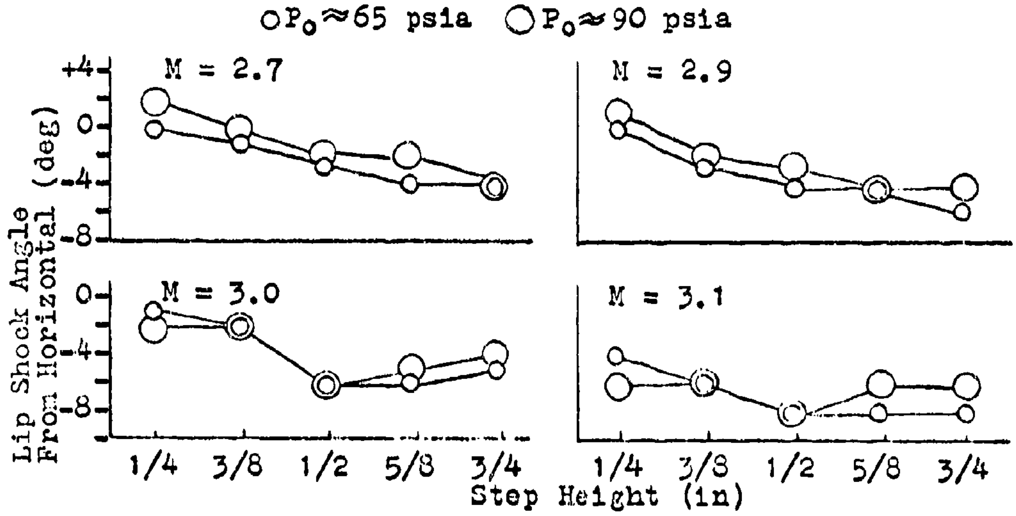


Fig. 10 Effect of Step Height on Lip Shock Angle for Various Mach Numbers and Pressures.

but no pressure measurements were made to support this finding.

The effect on the lip shock of changing the stagnation pressure was negligible (Figs 9,10). For fixed Mach number and step height, the maximum variation in lip shock angle was 2 degrees for a stagnation pressure change from 64 to 84 psia. Scherberg reported that the shock rotates clockwise with an increase in freestream pressure in the range 0.1 to 0.7 psi(a) at a Mach number of 3.5 (Ref 8:53). In the current report, freestream pressure varied from approximately 2.2 to 2.9 psia as the stagnation pressure was increased from 64 to 84 psia, and the change in the lip shock angle was negligible.

Flow Turning Angle

A shear layer forms between the region of low velocity air directly behind the step and the high velocity air which flows over the step. The shear layer represents the total turning angle of the flow which has passed over the step. The shear layer first appears as a very thin line about 1/16 in below the corner of the step (Fig 4). It grows in thickness as it approaches the reattachment point, contacts the floor of the step, and appears, on the schlieren photographs (Fig 8) to form a turbulent boundary layer. The angle that the shear layer makes with the horizontal, or flow turning angle, was measured to determine the effect of changes in the three independent parameters:

Mach number, stagnation pressure, and step height.

The change in step height caused the largest magnitude of change in the flow turning angle (Fig 12). At each Mach number, the flow turning angle reached a peak value at a particular step height. For Mach number 2.7, the maximum flow turning angle of 24 degrees was attained for the 3/8 in step. The higher Mach number flows resulted in a maximum shear layer angle of 22 to 30 degrees at the 1/2 in step.

The flow turning angle increased with an increase in Mach number for all step heights except the 3/8 in step (Fig 11). The 3/8 in step shows a decrease for the mid Mach numbers, but the overall trend was an increase in the flow turning angle of 3 to 8 degrees as the Mach number increased from 2.7 to 3.1.

As the stagnation pressure was increased from approximately 65 psia to 90 psia, the flow turning angle, at a given Mach number and step height, decreased 1 to 3 degrees in most instances. Some step heights showed no change or a 1 to 4 degree increase in shear layer angle. There was no trend to these variations.

Reattachment Point

The reattachment point is defined as that point where the angle that the shear layer forms with the horizontal first goes to zero. The shear layer makes a gradual turn as it approaches the floor of the step, and as a result,

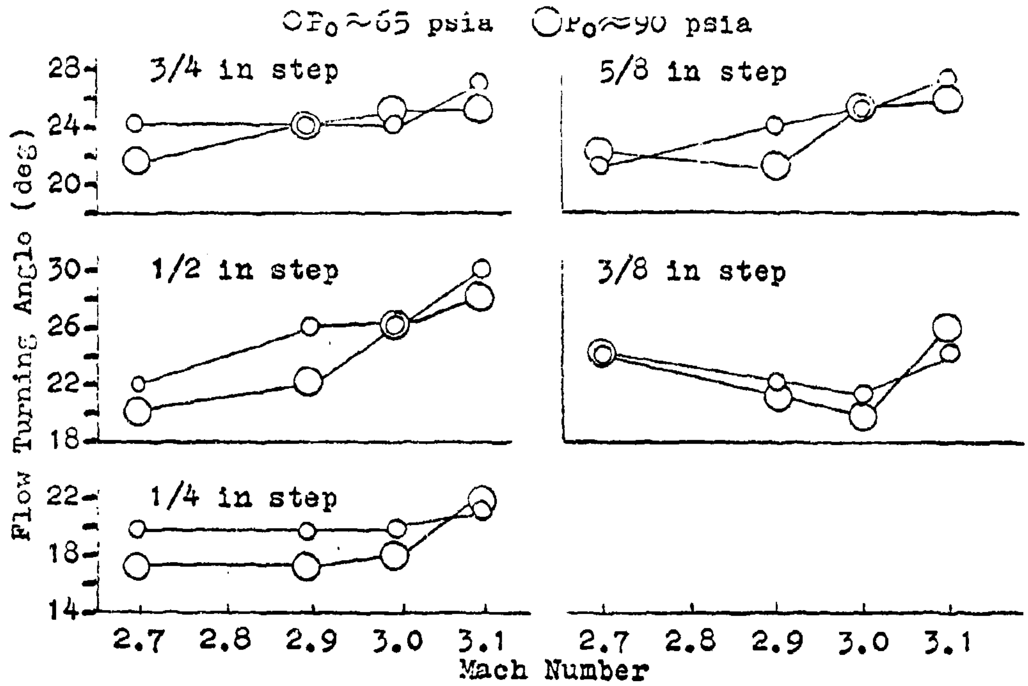


Fig. 11 Effect of Mach Number on Flow Turning Angle for Various Step Heights and Pressures.

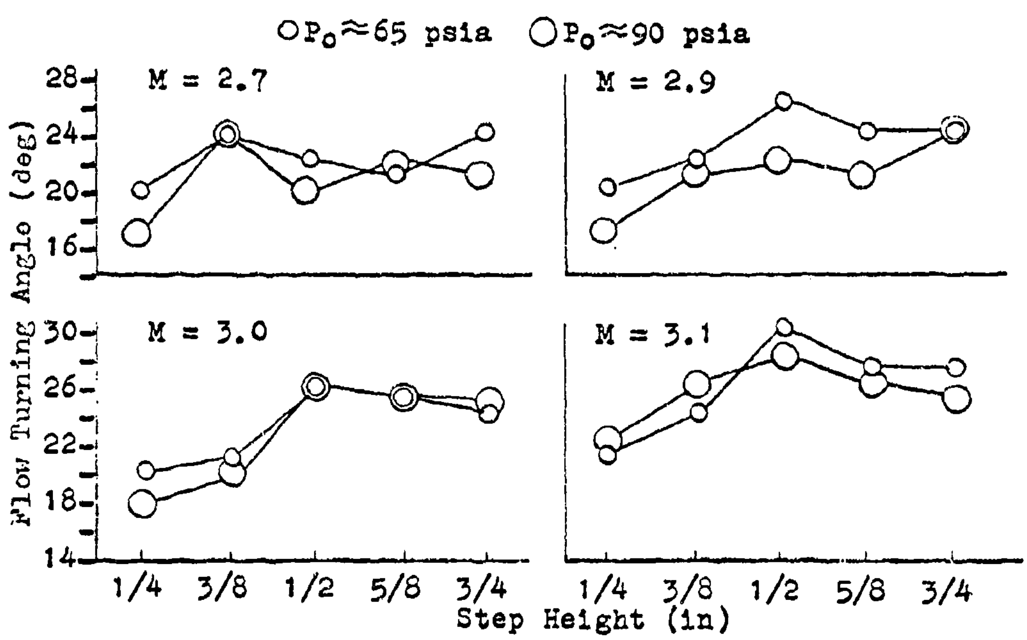


Fig. 12 Effect of Step Height on Flow Turning Angle for Various Mach Numbers and Pressures.

accurate determination of the reattachment point from schlieren photographs is difficult (Fig 4).

Increasing the step height caused the reattachment point to move away from the step. The location varied from approximately 0.8 in for the 1/4 in step to 2.8 in for the 3/4 in step (Fig 14). The peak noted in the flow turning angle for a particular step height did not occur in the location of the reattachment point.

The reattachment point moved very little for changes in Mach number and changes in stagnation pressure. The results for the 3/4 in step indicate a peak value occuring at a Mach number of 2.9 followed by a decrease (Fig 13). The other step heights do not exhibit this peak, so it is assumed to be caused by differences in knife edge position used for the schlieren photographs. The peak for the 3/4 in step was not checked for repeatability. Flow turning angle increased with increased Mach number, but the flow in the shear layer becomes horizontal at approximately the same point for all of the Mach numbers in this experiment (Fig 13). The reverse effect on the flow turning angle was noted for changes in stagnation pressure, but again the flow direction change to horizontal occured at approximately the same point for the low and high pressure runs (Fig 14).

The results of the reattachment point study compare favorably with those of Scherberg. For a 0.443 in step at Mach number 2.5, freestream pressure 1.124 psi(a) the edge shear layer is shown contacting the reattachment surface at

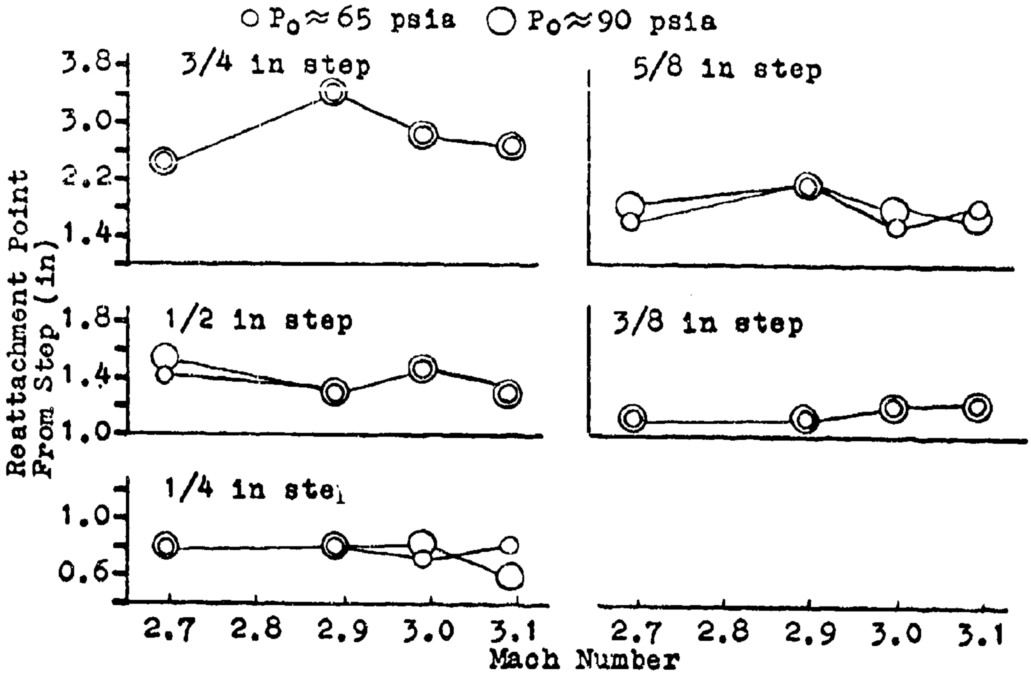


Fig. 13 Effect of Mach Number on Reattachment Point for Various Step Heights and Pressures.

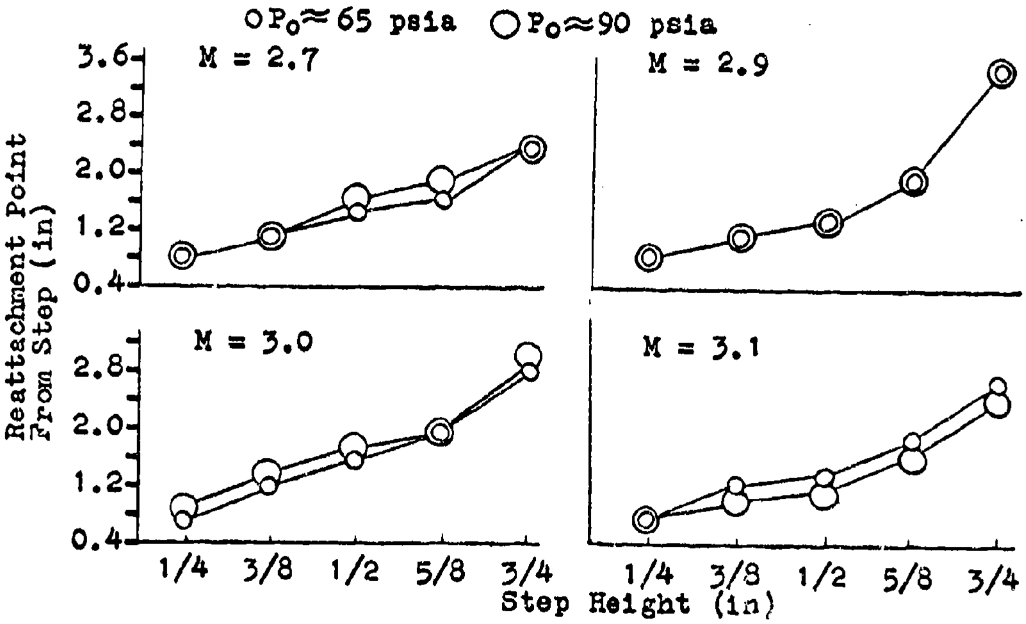


Fig. 14 Effect of Step Height on Reattachment Point for Various Mach Numbers and Pressures.

approximately 1 in (Ref 8:56). In the present experiment, at a Mach number of 2.7 and a freestream pressure of 2.0 psia, the reattachment point was at 1.4 in for the 1/2 in step and 0.9 in for the 3/8 in step (Fig 15).

Reattachment Shock

The reattachment shock forms as a result of the turning of the downward directed flow to horizontal. On the schlieren photographs (Fig 8), the reattachment shock is seen to be formed out of a series of smaller compression wavelets. The shock is concave upward in the formation area, but becomes almost straight when it is fully formed. The angle that the straight portion of the shock makes with the horizontal was measured for this study. On the 3/4, 5/8, and 1/2 in steps, an additional downstream photograph was made so that the reattachment shock angle could be measured.

The data for the reattachment shock angle indicate no definite change due to changes in the three independent parameters. The plots of the measured values of reattachment shock angle are essentially horizontal lines (Figs 15, 16). The reattachment shock was well defined on all schlieren photographs, but the shock, in most cases, is about 1/16 to 1/8 in wide. This, in addition to the initial curvature of the shock, makes it very difficult to accurately measure the reattachment shock angle.

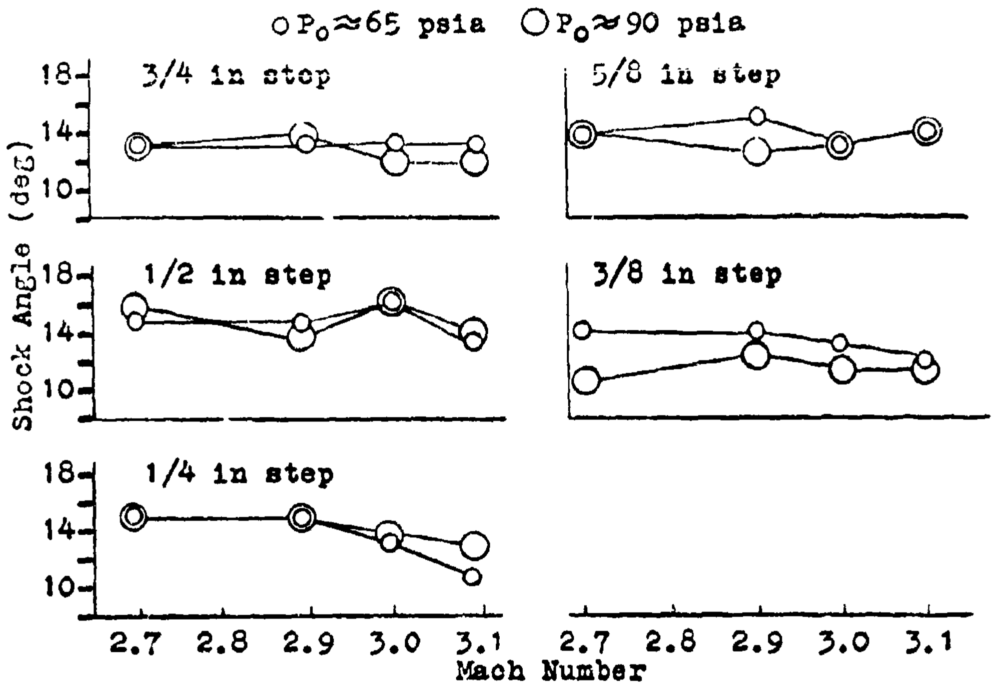


Fig. 15 Effect of Mach Number on Reattachment Shock for Various Step Heights and Pressures.

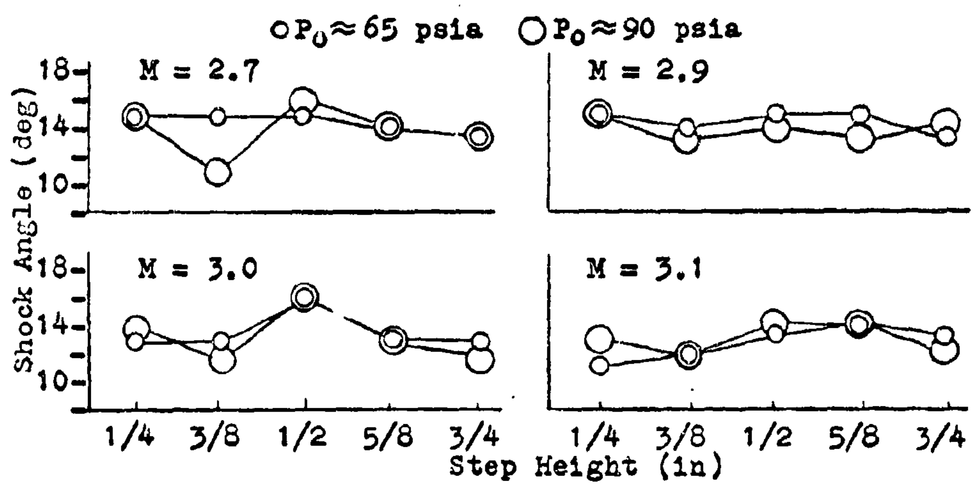
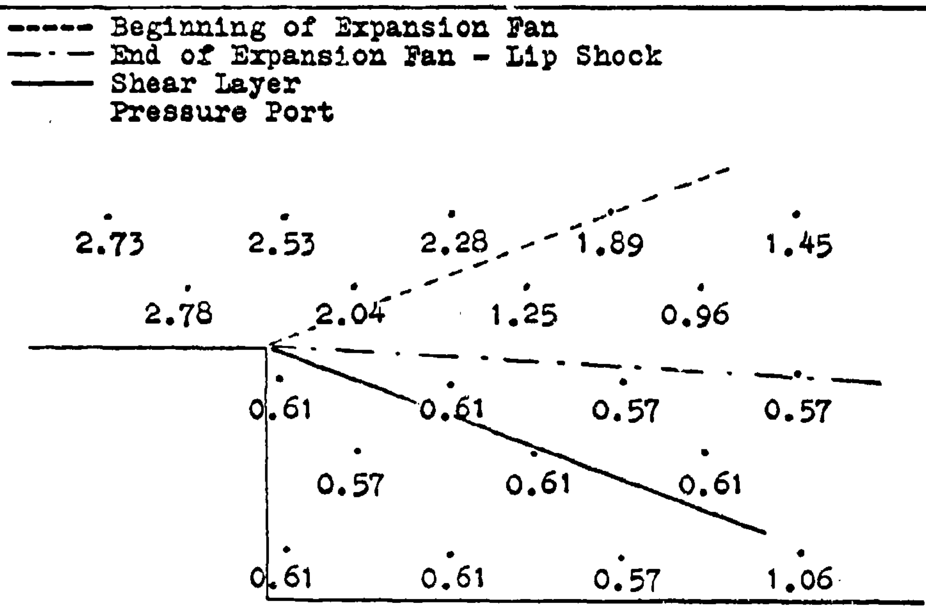


Fig. 16 Effect of Step Height on Reattachment Shock for Various Mach Numbers and Pressures.

Pressure Correlation

Pressure data was obtained to correlate with the results obtained from the schlieren photographs. Since a pressure traversing mechanism was not used, it was not possible to establish the exact limits of the expansion fan and shock systems. It was possible, however, to establish a range of pressure values in the flow field. All pressures were recorded for flows at Mach 2.7. Appendix G contains a complete comparison of schlieren and pressure data.

Fig 17 is a semigraphical comparison of schlieren data with pressure data. The freestream pressure was 2.78 psia at a Mach number of 2.7 and a stagnation pressure of 84 psia.



P_o = 84 psia, 3/4 in step.

Fig. 17 Comparison of Schlieren Data with Pressure Data.

The freestream pressure is seen to be decreasing along the flat plate section. The decrease becomes more rapid in the vicinity of the expansion fan position obtained from the schlieren photographs. The flow is expanded to cavity pressure at the lip shock position, since the cavity pressure is essentially constant below the lip shock. The formation area of the reattachment shock is noted by the increase in pressure (1.06 psia) at the aft pressure port in the bottom row.

The freestream pressure at the top of the step was approximately 2.2 psia when stagnation pressure was 64 psia. This value increased to 2.9 psia when stagnation pressure was increased to 84 psia. The pressure in the cavity below the shear layer was approximately 0.6 psia at a stagnation pressure of 64 psia and increased to 0.7 to 0.9 at a stagnation pressure of 84 psia. At a stagnation pressure of 64 psia the pressure in the cavity did not vary with change in step height, supporting the finding, discussed earlier, that the expansion angle did not change with change in step height.

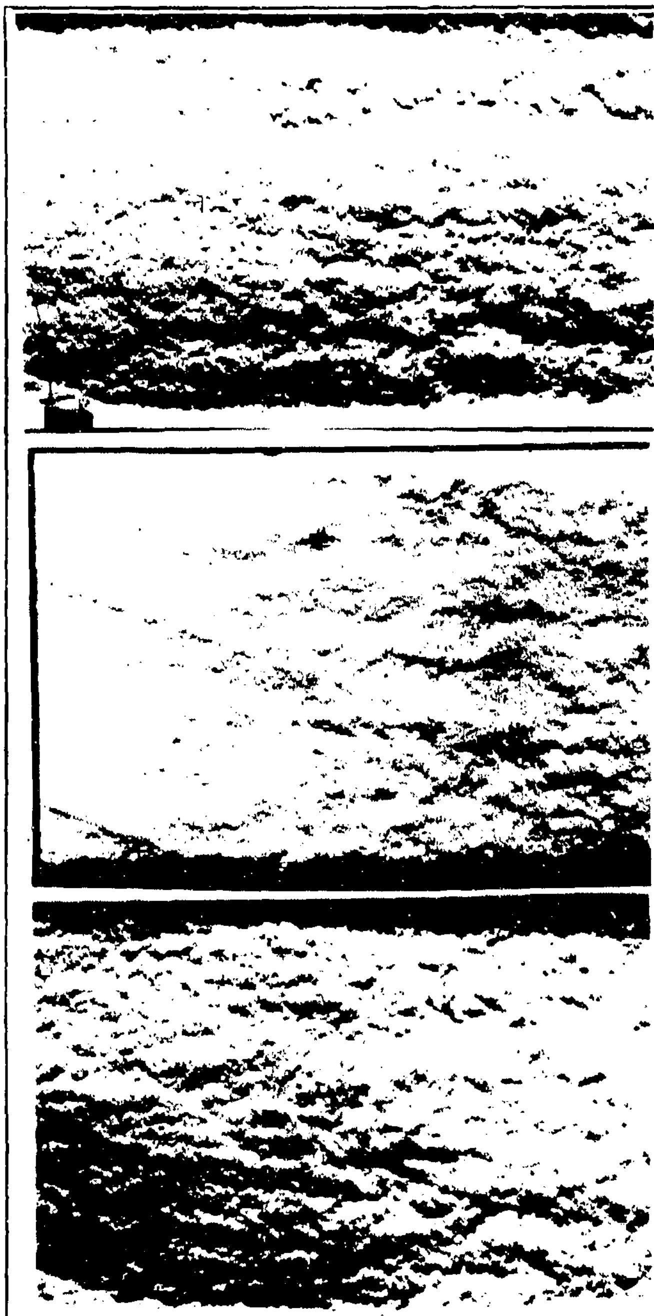
As expected, no pressure change was noted across the shear layer. The pressure mapping did not extend far enough to thoroughly investigate the shear layer in the area of the reattachment point. A large (0.5 to .75 psia) pressure increase was noted at a point corresponding roughly to the reattachment point. This pressure rise is attributed to the formation of the reattachment shock.

Side Mounted Step

A side mounted step was used to investigate the reattachment point and the areas upstream and downstream of the reattachment point. The side mounted step was placed at the same point in the flow as the basic step model. The side mounted step, in effect, permitted the area behind the step to be viewed vertically rather than horizontally as was done with the basic step.

Step heights of 3/4, 1/2, and 3/8 in were run in the side mounted position. The schlieren photographs of the 3/4 in step (not included in this report) show a very turbulent flow with no discernible flow characteristics. The 1/2 and 3/8 in steps, however, show a definite stratification of the flow both upstream and downstream of the reattachment point which is approximately in the middle of Fig 18. The stratification is more pronounced downstream of the reattachment point for both step heights. This stratification is interpreted as the vortexing of the flow caused by the shear layer contacting the reattachment surface.

Unfortunately, the effects of step height and stagnation pressure change could not be fully investigated because the side mounted step panel failed during a high pressure run. This side mounted step investigation did indicate, however, that it may be possible to obtain useful information from schlieren photographs of the flow field.



1/2 in step
P_o = 94 psia
knife edge
M = 2.7
Scale:
0.85 in = 1 in

3/8 in step
P_o = 84 psia
knife edge
M = 2.7
Scale:
0.88 in = 1 in

3/8 in step
P_o = 84 psia
knife edge
M = 2.7
Scale:
0.88 in = 1 in

Fig. 18 Schlieren Photographs of Flow Over Side Mounted Step. The Step is at the Left Edge of the Photographs, and Flow is from Left to Right.

V. Conclusions

The following conclusions are based on the results of this study.

1. The expansion fan increases with an increase in Mach number, decreases with increasing stagnation pressure, and varies erratically with increasing step height.
2. The lip shock rotates downward with an increase in step height and with an increase in Mach number. There is negligible variation in lip shock angle with increasing stagnation pressure.
3. The flow turning angle reaches a peak value for each Mach number at a particular step height. Increasing the Mach number causes the flow to turn through a greater angle. Increasing stagnation pressure, in general, causes the flow turning angle to decrease.
4. The reattachment point moves away from the step as the step height increases. Increasing the Mach number or the stagnation pressure causes small changes in the reattachment point.
5. The reattachment shock angle does not vary appreciably for changes in Mach number, step height, or stagnation pressure.

6. The step height has the greatest overall effect on the flow field, and the flow turning angle is the most sensitive, of the variables measured, to changes in the independent variables.

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Appendix A

Blowndown Wind Tunnel

The AFIT blowdown wind tunnel operation and description are contained in this section. A schematic diagram of the tunnel components is shown in Fig A-1 and a photograph in Fig A-2.

The high pressure air supply system consists of a high pressure air compressor, an air dryer, and a high pressure air storage tank. The air supply system can provide 0.5 lb_m/sec airflow at 95 psia. The relative humidity of the compressed air is normally 5 to 8% at 70 F.

The air supply line is connected to the calming chamber by a fast acting, manually operated, slide valve. The 2 in pipe coming out of the slide valve is expanded to 12 in by a 15 degree conical section approximately 15 in long. The conical section is welded to the 12 in diameter by 105 in long calming chamber. Inside the calming chamber there is a spreader cone which forces the air coming out of the 2 in pipe to fill the 12 in calming chamber. The spreader cone is constructed of 1/8 in steel and has a series of circular holes which increase in diameter from 1/4 in at the vertex of the cone to 1-1/4 in at the base of the cone. After the spreader cone there are 4 screens to help remove any turbulence caused by the flow spreader. Between the last two screens, a cloth filter (10 layers of cotton cloth) helps remove any dust particles. The pressure drop across the filter is nearly zero.

The test section is bolted to the calming chamber with a 12 in flange. The flow area is reduced from the 12 in calming chamber to a 1 by 6 in rectangular area leading to the nozzle blocks. The 1 by 6 in area is 6 in long and is the result of modifying a previous test section. The 1 by 6 in area is reduced to a 1 by 0.695 in throat by the nozzle blocks shown in Fig 2. Area ratio (area test section/area throat) of the nozzle blocks used for Mach number 2.7 was 4.56 to 1. The nozzle blocks have "O" ring seals around their edges, 1/16 in from the flow surface, to prevent high pressure, low velocity air from flowing between the test section sidewalls and the nozzle blocks and mixing with the low pressure, high velocity air in the test area. The two removeable tunnel sidewalls are machined from 1-1/4 in aluminum. Each sidewall has a 11-1/4 by 4-1/2 in optical quality window. The glass is 1-1/4 in thick in one sidewall and 3/4 in thick in the other.

The low pressure or vacuum system of the wind tunnel consists of three vacuum pumps and a vacuum storage tank. Two of the vacuum pumps are Lieman 5 hp models, and one is a Stokes 5 hp model. The vacuum storage tank has a volume of approximately 450 cu ft. The vacuum tank, test section, and calming chamber are all evacuated prior to wind tunnel operation.

The no flow operating pressure of the high pressure supply system is approximately 115 psia. The nominal operating temperature of the air in the calming chamber was 70 F. The vacuum pumps reduce the pressure in the low pressure system to approximately 0.3 psia in 15 minutes. The wind tunnel reaches stable operating conditions in approximately 1 second and will operate with supersonic flow in the test area for approximately 12 seconds.

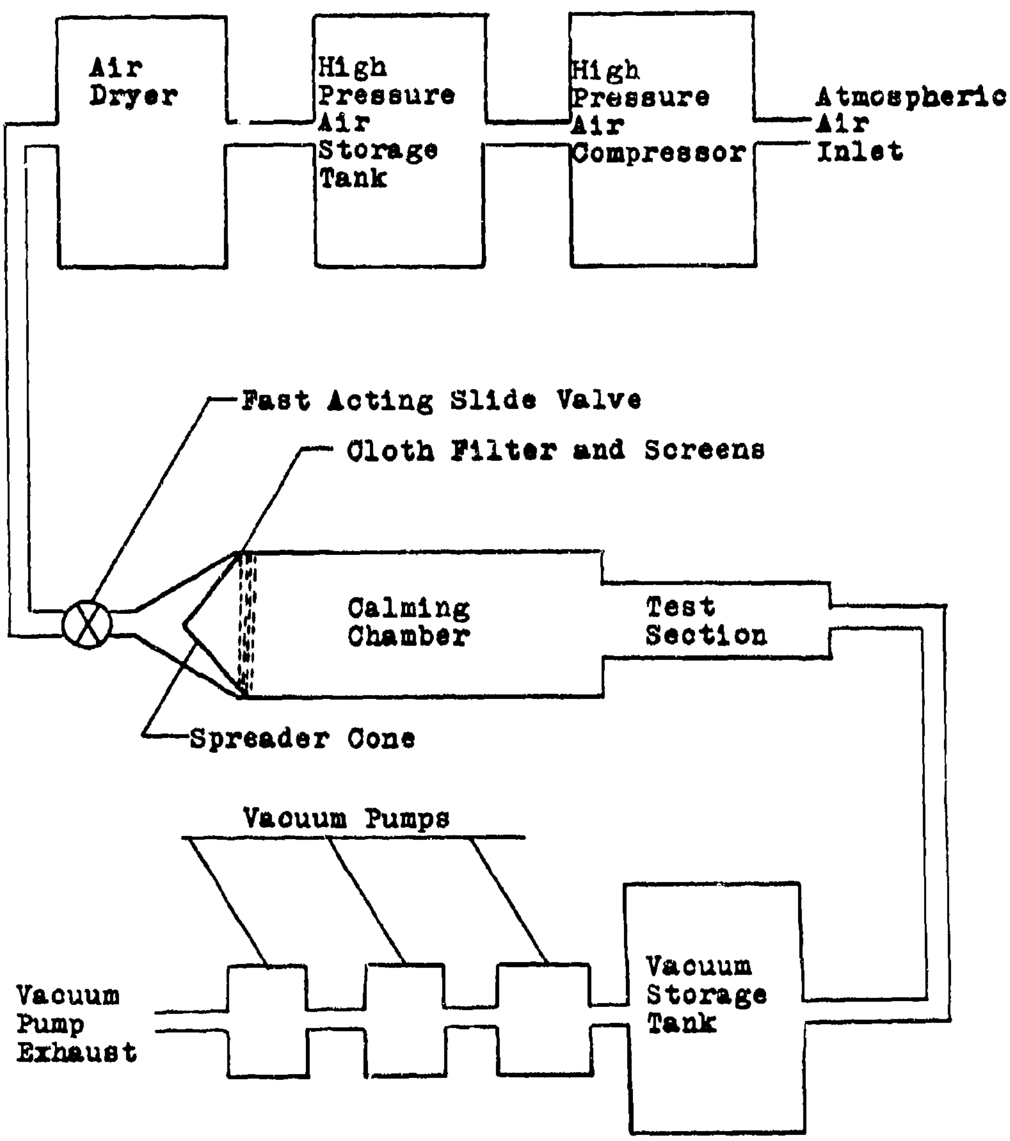


Fig. A-1 Schematic Drawing of the AFIT Blowdown Wind Tunnel.

(a) Fast Acting
Slide Valve

(b) Calming Chamber

(c) Test Section

(d) Lines to Vacuum
System

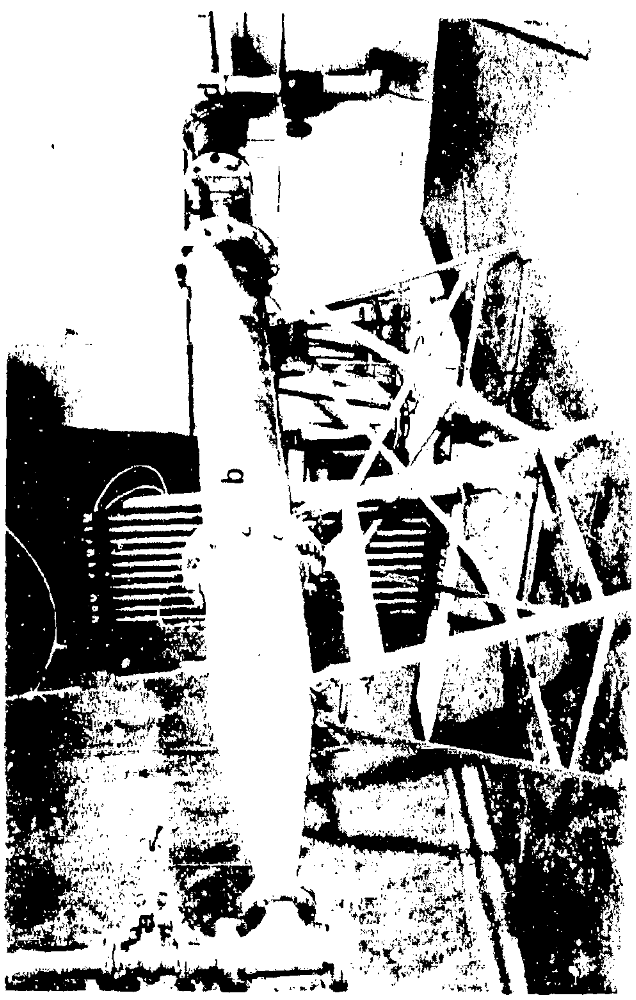


Fig. A-2 Overall View of Wind Tunnel

Appendix B

Schlieren System

The schlieren system consists of a steady light source, a spark light source, two parabolic mirrors, a knife edge, a ground glass viewing screen, a camera, and a moveable platform. Photographs of the equipment layout are shown in Figs B-1 and B-2.

The steady light source consists of a Sylvania K-300 bulb, a condensing lens, and a George W. Yates, Co. Type G-3000 power supply. The steady light is located at the focal length (approximately 45-1/4 in) from the first mirror. The light from the steady source is turned to fall on the first mirror by a plane mirror. This plane mirror is used to switch from this light source to the spark lamp.

The spark lamp source consists of a Cook Electric Co. 0 to 10,000 volt, high voltage chassis (Part #596-4267), a Cook Electric Co. spark lamp (Part #596-4116), and a triggering mechanism. The normal operating voltage is 8500 volts. The duration of the spark is reported to be about 1/6 microsecond.

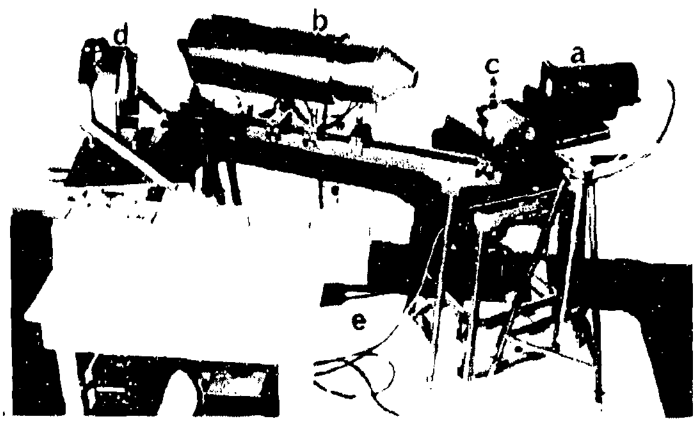
The parabolic mirror on the light source side is 10 in in diameter and has a focal length of 45-1/4 in. The center of the mirror is level with and 77-1/4 in from the test section.

The light sources, power supplies and mirrors are all mounted on a moveable platform. The platform is constructed of plywood and has four rollers which ride in tracks parallel to the test section. The platform can be moved 2 ft fore and aft to take pictures at all positions in the test section without realigning the light sources and mirrors.

The 10 in parabolic mirror on the camera side of the schlieren system has a focal length of 44-3/4 in. During the tests, this mirror was adjusted between 105 and 125 in from the model depending on the desired size of the image in the camera. The knife edge is located approximately at the focal length of the mirror. Immediately after the knife edge, a plane mirror turns the light beam approximately 90 degrees. The plane mirror permits the camera to be moved out of the work area adjacent to the test section. The camera is located at a distance from the knife edge which gives the sharpest focus of the test section. The camera can hold either a ground glass screen or a Graphic Polaroid Back.

The schlieren system is aligned with the steady light source. Then the spark light source is adjusted to the same apparent position as the steady light source. To change from steady light to spark light, the plane mirror in front of the steady light source is moved out of the path of the light from the spark lamp.

During operation, the steady light is used for adjusting the camera position and knife edge position and to observe flow patterns on the ground glass screen. After all adjustments are made, the spark light is used to photograph the flow field. Polaroid Corporation type 47 film, ASA 3000, is used for spark light pictures. No shutter is used with the spark light since it has a duration of 1/6 microsecond. The film is placed in the camera with the shutter open. When the spark light is triggered, the film is exposed. Since the operation is conducted with an open shutter, the room must be dark.



(a) Spark Lamp

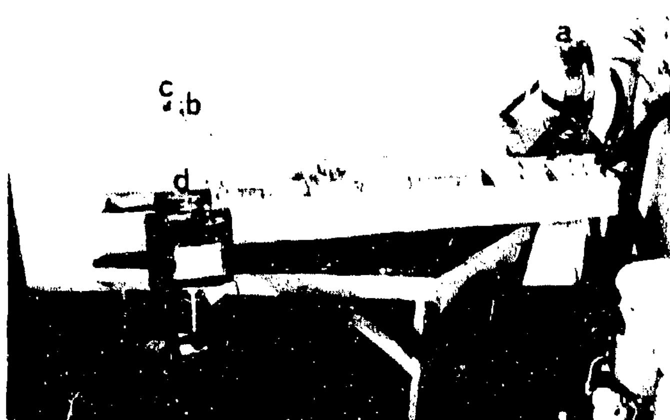
(b) Zirconium Lamp

(c) Plane Mirror

(d) Parabolic Mirror

(e) Moveable Platform

Fig. B-1 Light Source Side of Schlieren System



(a) Parabolic Mirror

(b) Knife Edge

(c) Plane Mirror

(d) Camera

Fig. B-2 Camera Side of Schlieren System

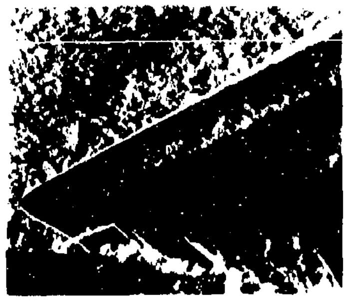
Appendix C

Mach Number Determination

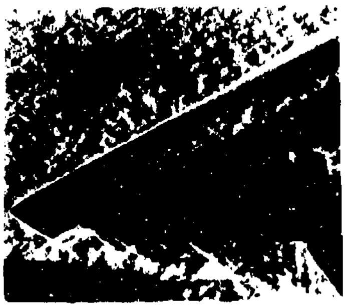
The Mach numbers reported for the four area ratios used in this experiment were computed by assuming two-dimensional flow. The shock wave angle on a 10 degree wedge was determined from schlieren photographs of the flow. The shock wave angle and wedge angle were used as entering arguments in two-dimensional shock charts (Ref 5:42) to determine the Mach number.

Fig C-1 shows the four schlieren photographs used to determine the Mach number. Table C-1 shows the shock wave angles measured from the photographs and the Mach numbers obtained from the two-dimensional shock tables.

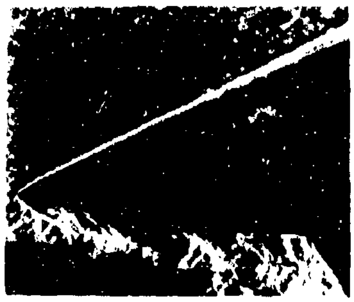
a. No Spacer



b. 1/8 in Spacer



c. 5/32 in Spacer



d. 9/32 in Spacer

Fig. C-1 Schlieren Photographs of the Flow Over a 10 Degree Wedge.

Table C-1
Mach Number Data

Picture No.	Spacer	Shock Angle (measured)	Mach No. (2-D tables)
a	none	29.5	2.72
b	1/8 in	28.5	2.89
c	5/32 in	27.5	3.00
d	9/32 in	27.0	3.10

Appendix D

Discussion of Schlieren Data

The data presented in Figs 6,7,9-16 were obtained from the schlieren photographs in Appendix E. The angles were measured with a protractor under a three power magnifying glass.

The expansion angle was measured from the first detectable change in flow conditions to the lip shock. The termination of the expansion fan was easy to detect on the schlieren photographs, but the beginning of the fan was less well defined.

The lip shock was well defined on the schlieren photographs. The lip shock angle corresponded to the termination of the expansion fan.

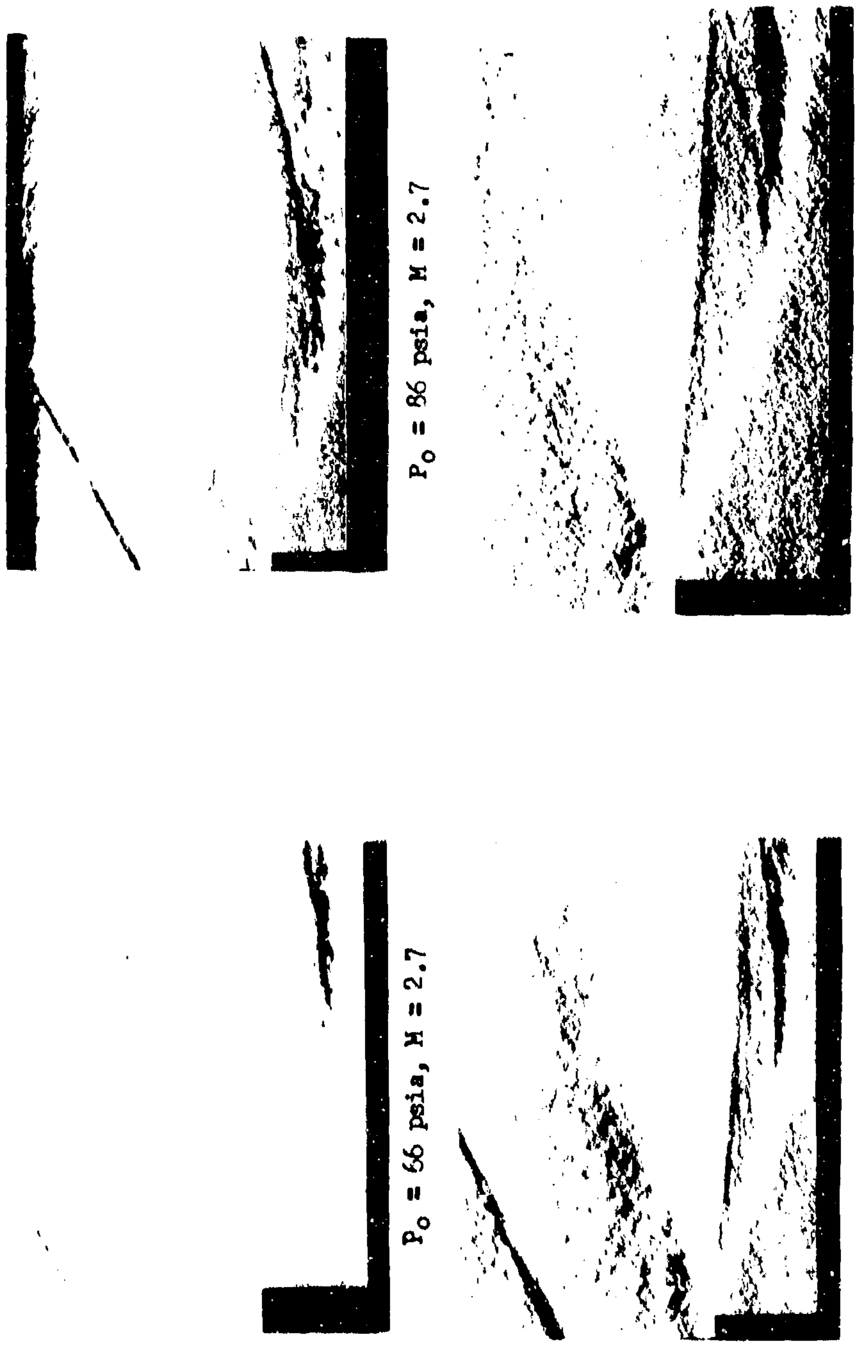
The shear layer was well defined on the schlieren photographs and the flow turning angle was measured at the middle portion of the straight part of the shear layer.

The reattachment point was not well defined due to the difficulty in determining when the flow turning angle was zero. In some photographs, the reattachment point could be determined as that point where the shear layer contacted the step floor (e.g., Fig E-2a, M = 2.7). On other photographs, the reattachment point had to be determined by the flow direction of the shear layer. The latter method was more difficult to apply.

The reattachment shock is curved for a portion of its length, and then straightens. The reattachment shock angle was measured after the shock was straight. The reattachment shock is well defined in all schlieren photographs. On the large step height, the reattachment shock was out of the field of view of the camera. An additional photograph (not included in this report) was made from which the reattachment shock angle was measured.

Appendix E

Schlieren Photographs



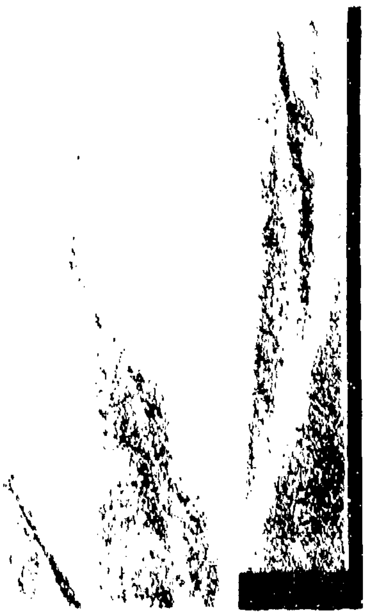
P_o = 86 psia, M = 2.7

P_o = 90 psia, M = 2.9

P_o = 66 psia, M = 2.7

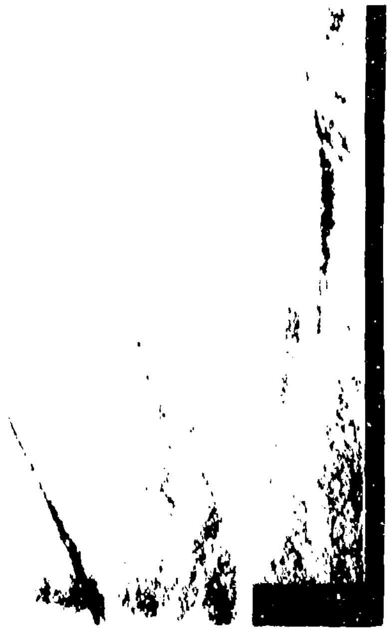
P_o = 56 psia, M = 2.9

Fig. [illegible]-1a Schlieren Photographs of Flow Over 3/4 in Step.



P_o = 57 psia, M = 3.0

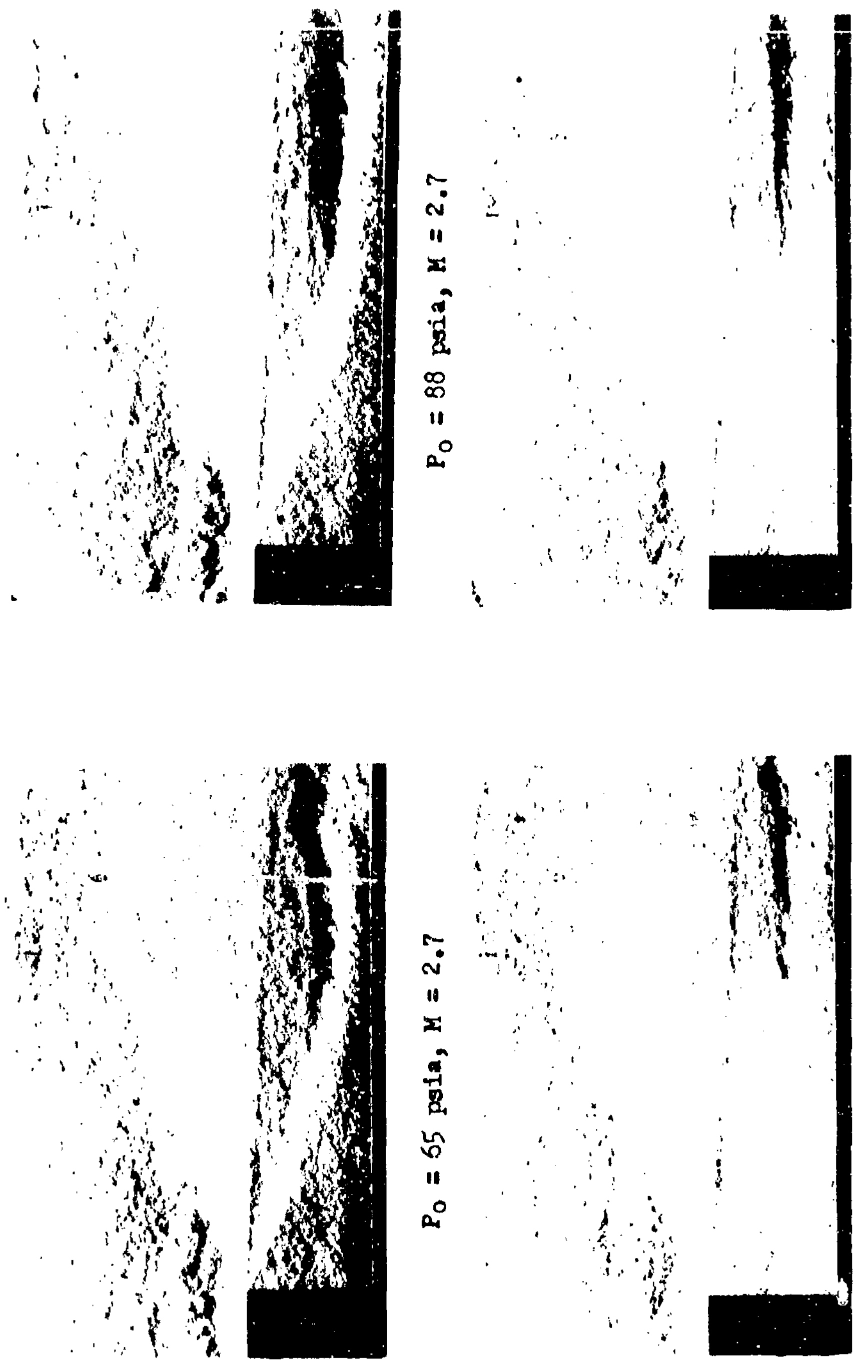
P_o = 96 psia, M = 3.0



P_o = 58 psia, M = 3.1

P_o = 96 psia, M = 3.1

Fig. E-1b Schlieren Photographs of Flow Over 3/4 in Step.



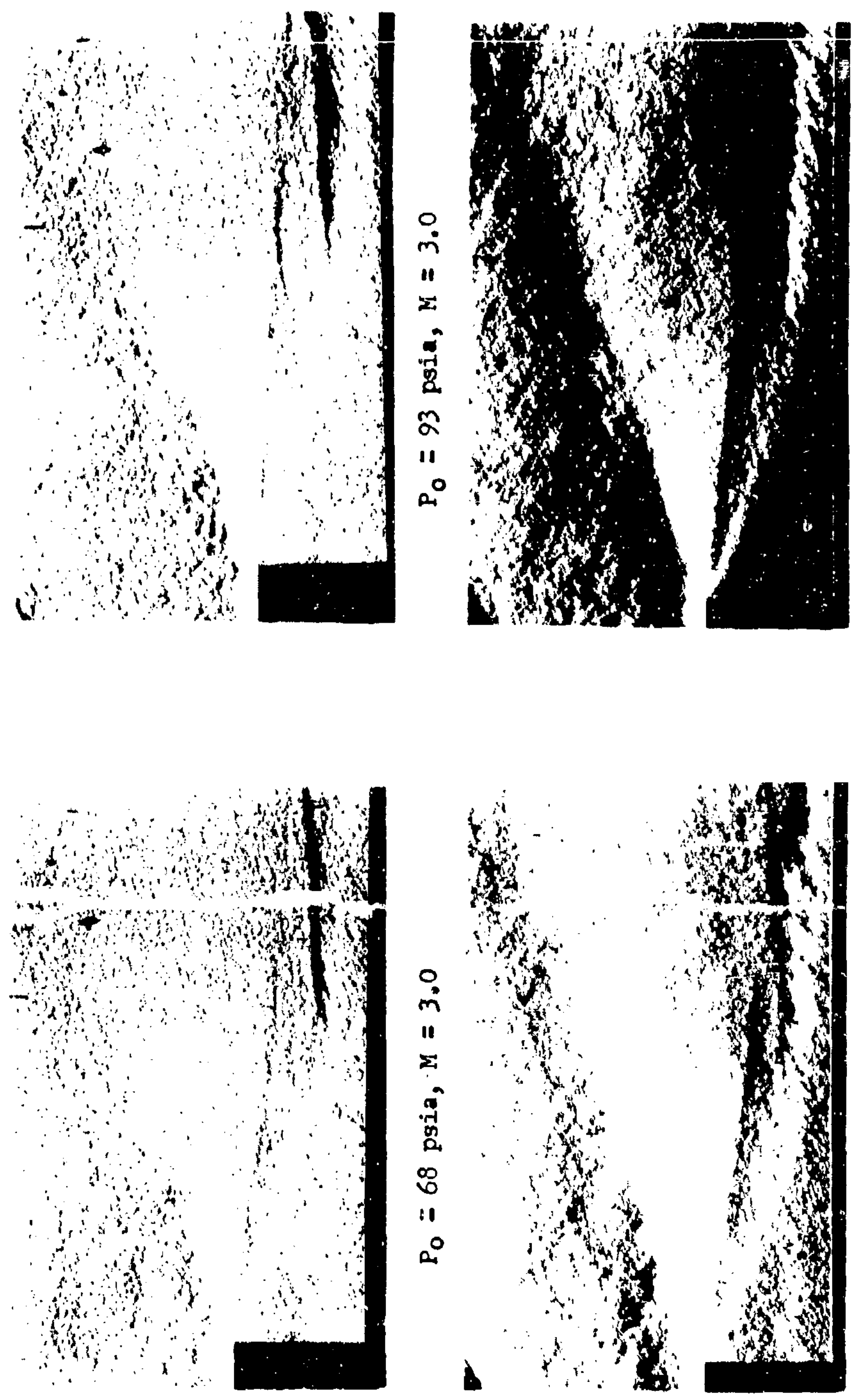
P_o = 55 psia, M = 2.7

P_o = 88 psia, M = 2.7

P_o = 66 psia, M = 2.9

P_o = 91 psia, M = 2.9

Fig. E-2a Schlieren Photographs of Flow Over 5/8 in Step.



P_o = 68 psia, M = 3.0

P_o = 93 psia, M = 3.0

P_o = 64 psia, M = 3.1

P_o = 96 psia, M = 3.1

Fig. E-2b Schlieren Photographs of Flow Over 5/8 in Step.

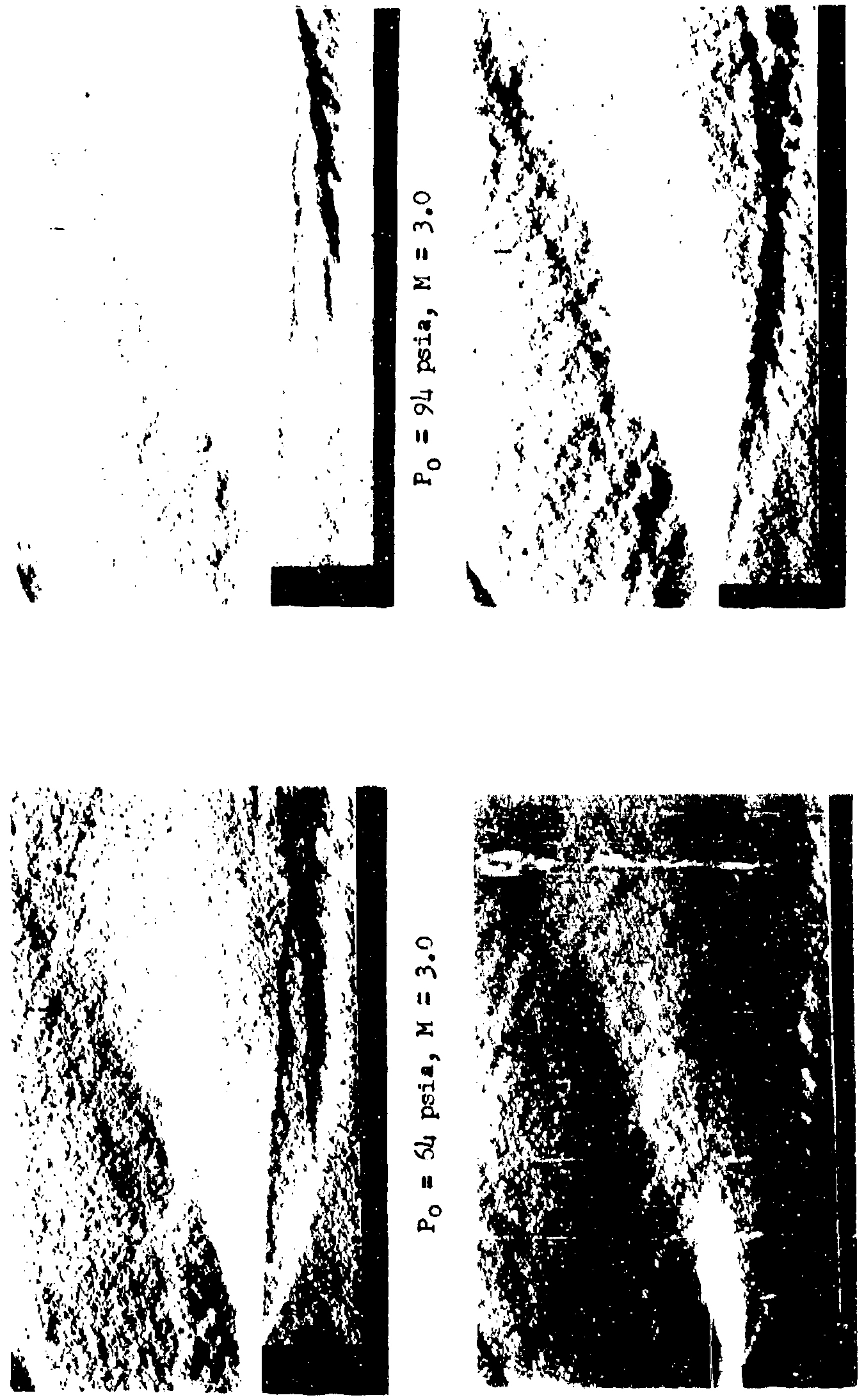
P_o = 64 psia, M = 2.7

P_o = 86 psia, M = 2.7

P_o = 65 psia, M = 2.9

P_o = 93 psia, M = 2.9

Fig. E-3a Schlieren Photographs of Flow Over 1/2 in Step.



P_o = 64 psia, M = 3.0

P_o = 94 psia, M = 3.0

P_o = 64 psia, M = 3.1

P_o = 97 psia, M = 3.1

Fig. E-3b Schlieren Photographs of Flow Over 1/2 in Step.

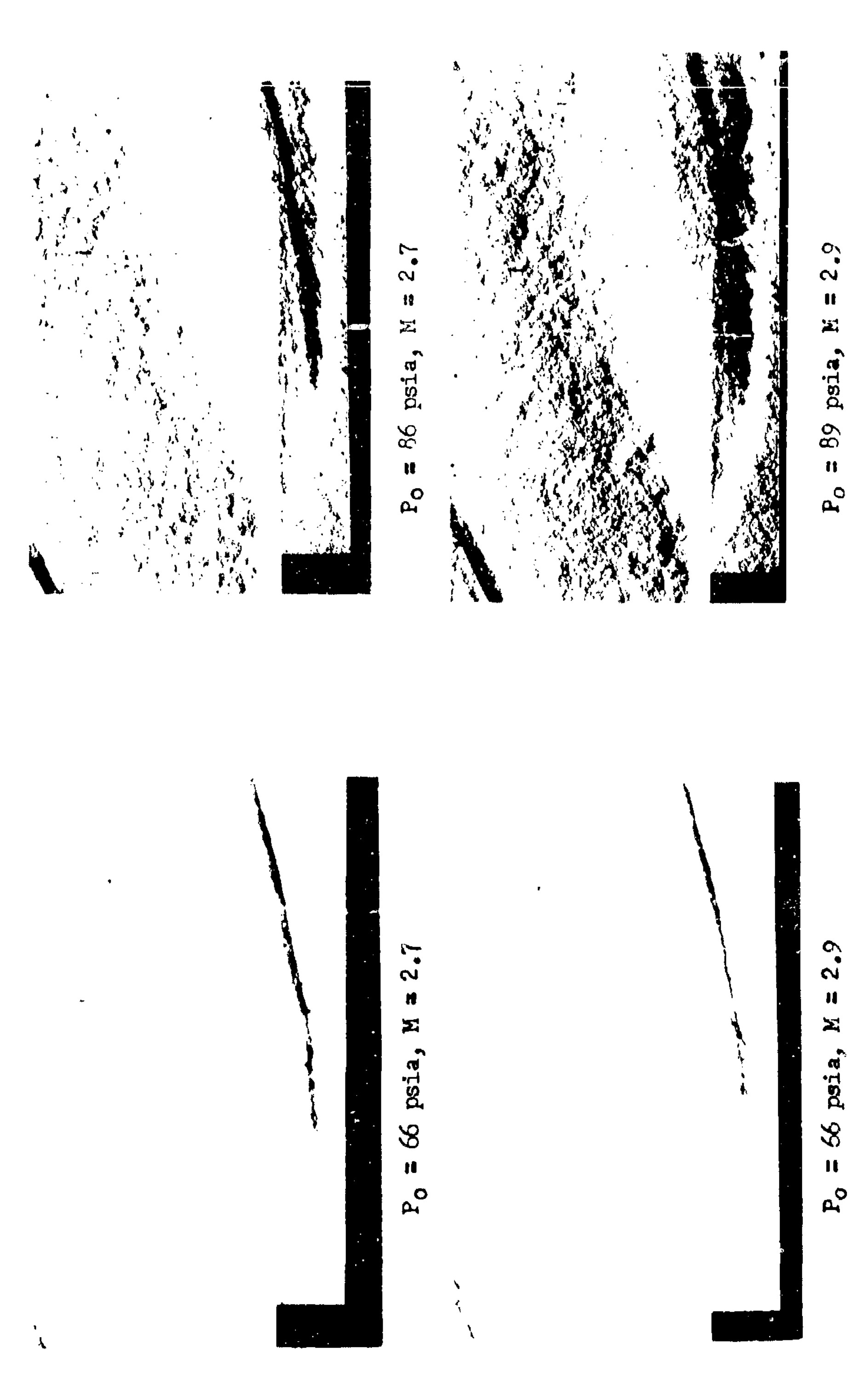


Fig. E-4a Schlieren Photographs of Flow Over 3/8 in Step.

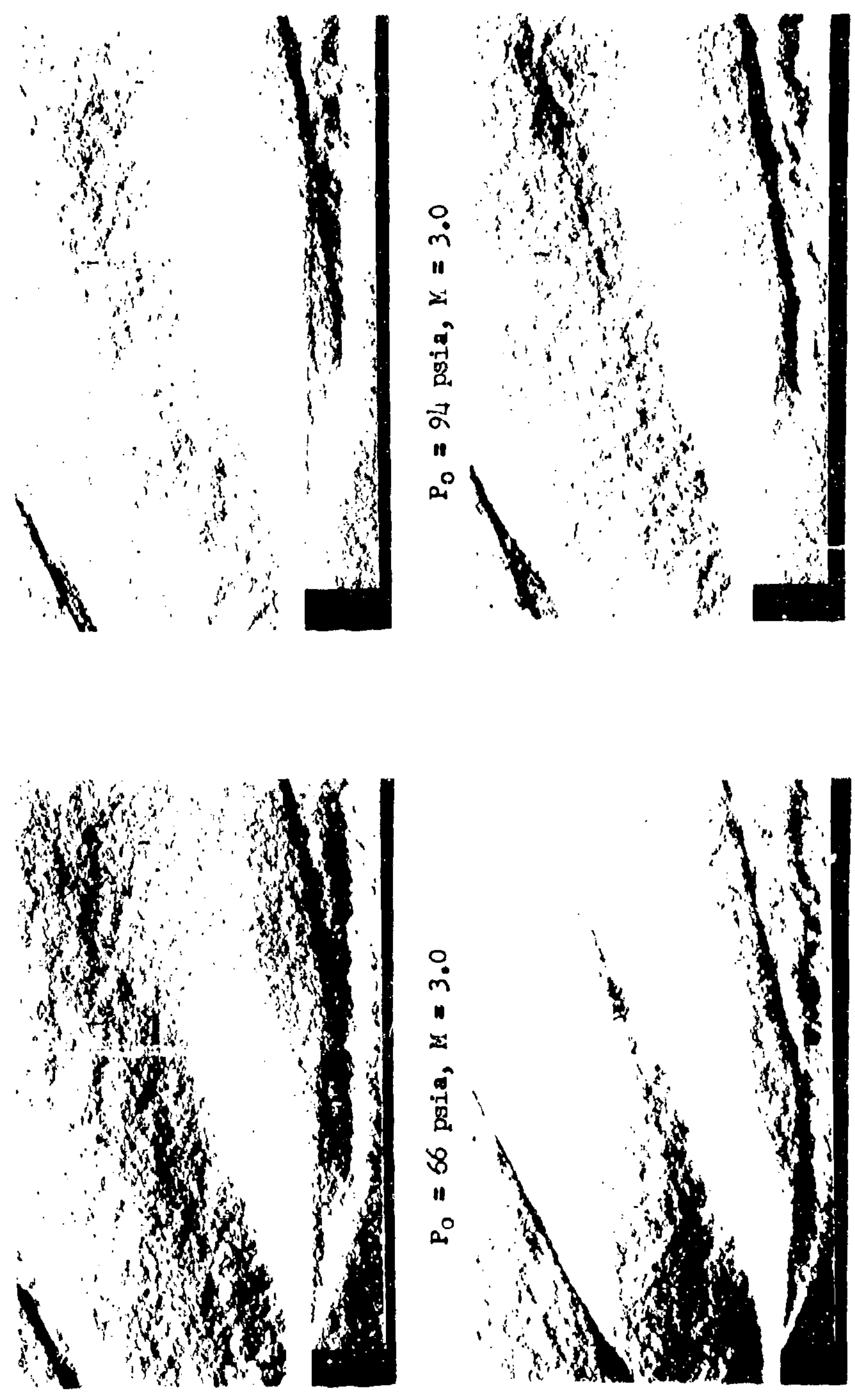


Fig. E-4b Schlieren Photographs of Flow Over 3/8 in Step.

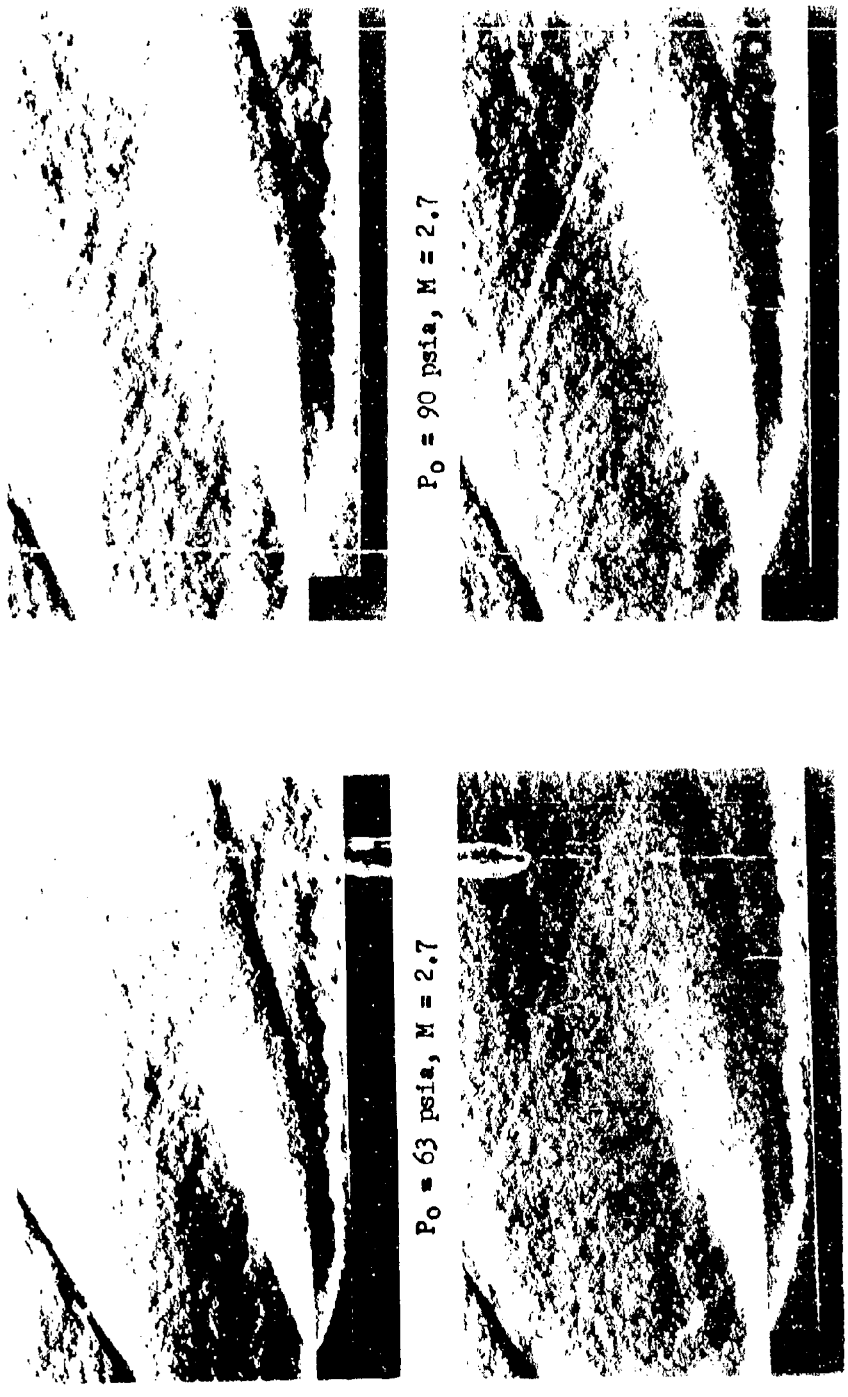


Fig. E-5a Schlieren Photographs of Flow Over 1/4 in Step.

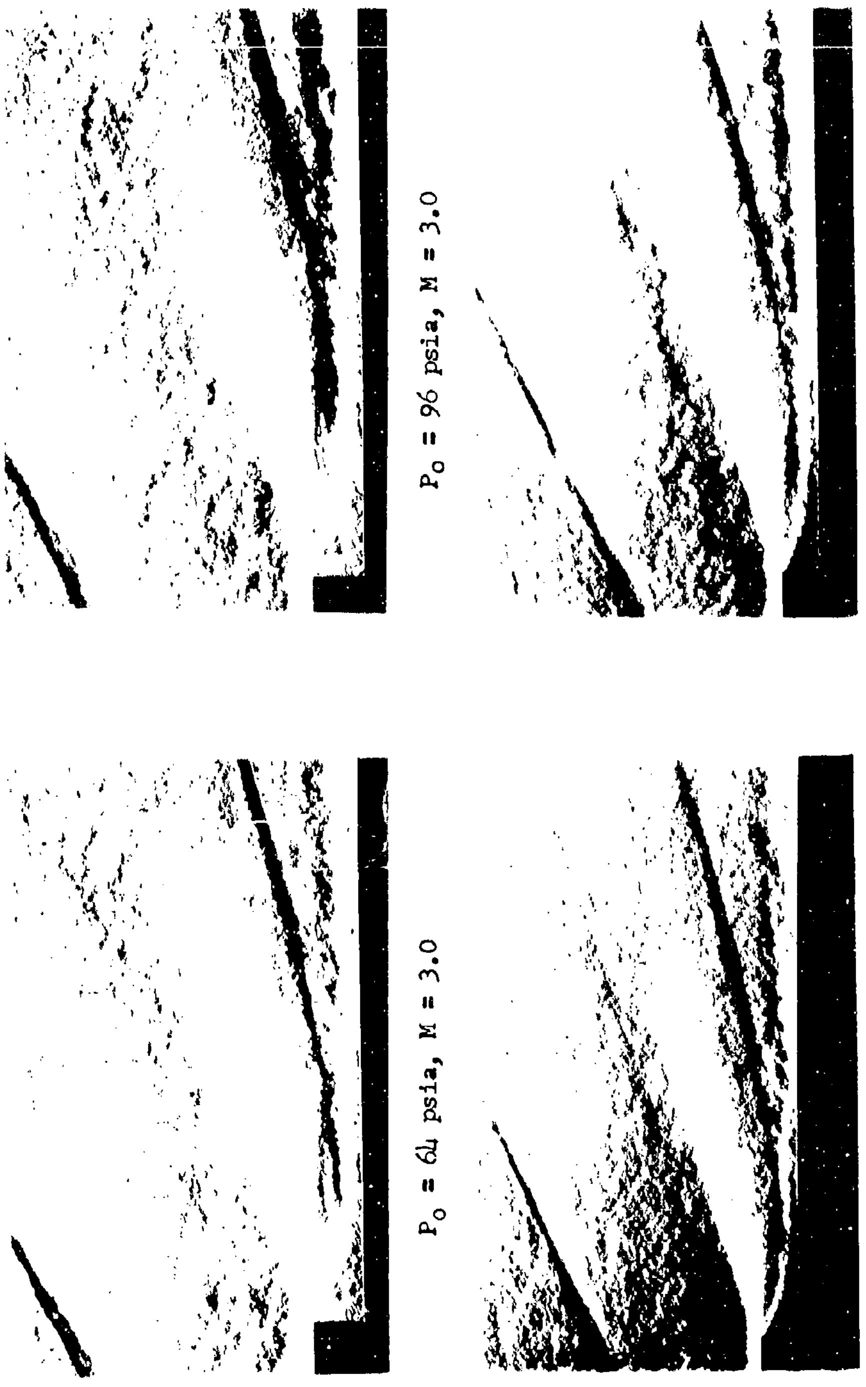


Fig. E-5b Schlieren Photographs of Flow Over 1/4 in Step.

Appendix F

Pressure Data

Pressure data are contained in this appendix. Fig F-1 shows the numbering system used to record the pressure data. Fig F-2 is a typical photograph of the manometer board used to record the raw pressure data. Tables F-1 and F-2 contain the pressure data for stagnation pressures of 64 psia and 84 psia respectively.

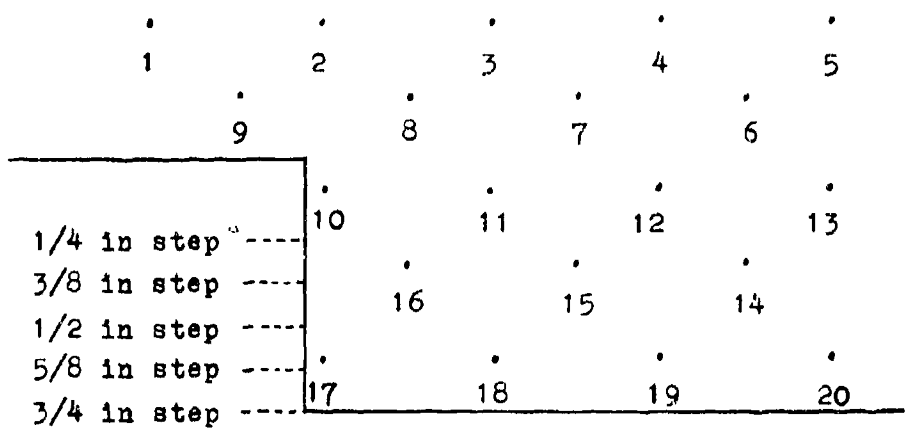


Fig. F-1 Diagram of Pressure Instrumentation Location and Numbering.

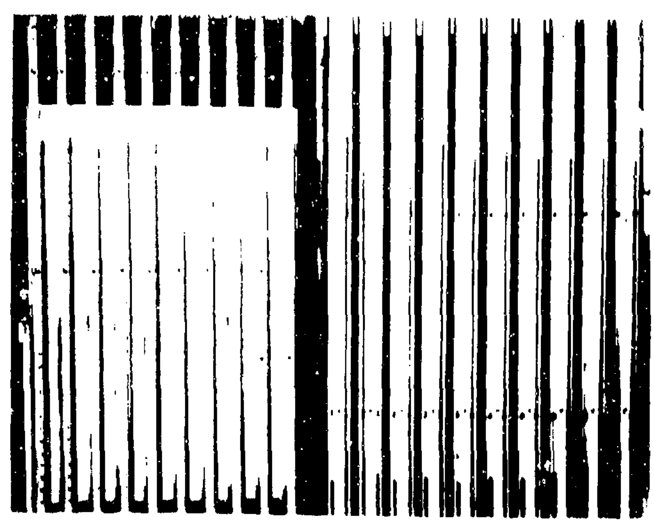


Fig. F-2 Typical Photograph of Manometer Board Used to Record Pressure Data. P = 64 psia, 3/4 in Step. Manometers are Numbered Consectively, Right to Left.

Table F-1

Measured Values of Pressure
(P_o = 64 psia, M = 2.7)

Position	Pressure (psia) Step Height (in) 3/4	5/8	1/2	3/8	1/4
1	2.09	2.04	2.14	2.14	2.14
2	1.99	1.99	2.04	2.04	2.14
3	1.74	1.70	1.80	1.75	1.90
4	1.45	1.45	1.50	1.45	1.65
5	1.20	1.15	1.15	1.20	1.15
6	0.76	0.76	0.66	0.76	0.81
7	0.96	0.96	0.96	0.96	0.96
8	1.55	1.45	1.55	1.50	1.65
9	2.24	2.19	2.28	2.24	2.58
10	0.57	0.51	0.61	0.57	0.61
11	0.47	0.51	0.51	0.61	1.15
12	0.47	0.57	0.57	1.01	1.65
13	0.42	0.51	0.57	0.61	0.61
14	0.47	0.57	0.81	1.50	*
15	0.47	0.51	0.57	0.71	*
16	0.47	0.51	0.51	0.61	*
17	0.47	0.51	*	*	*
18	0.51	0.51	*	*	*
19	0.42	0.57	*	*	*
20	0.57	0.91	*	*	*

* Pressure port covered by step floor.

Table F-2

Measured Values of Pressure
(P_0 = 84 psia, M = 2.7)

Position	Pressure (psia) Step Height (in) 3/4	5/8	1/2	3/8	1/4
1	2.73	2.73	2.83	2.83	2.83
2	2.53	2.58	2.68	2.78	2.63
3	2.28	2.29	2.39	2.44	2.53
4	1.89	1.94	1.94	1.99	2.09
5	1.45	1.50	1.45	1.55	1.45
6	0.96	1.01	0.96	1.06	0.96
7	1.25	1.25	1.30	1.35	1.35
8	2.04	1.99	1.99	2.14	2.19
9	2.78	2.92	2.92	3.03	2.93
10	0.61	0.61	0.71	0.86	0.91
11	0.61	0.71	0.76	0.81	1.40
12	0.57	0.66	0.66	1.35	2.04
13	0.57	0.61	0.71	0.86	0.91
14	0.61	0.71	1.01	1.75	*
15	0.61	0.66	0.61	0.96	*
16	0.57	0.66	0.71	0.86	*
17	0.61	0.66	*	*	*
18	0.61	0.71	*	*	*
19	0.57	0.66	*	*	*
20	1.06	1.15	*	*	*

* Pressure port covered by step floor.

Appendix G

Comparison of Schlieren and Pressure Results

This appendix contains a semigraphical comparison of some of the data obtained from the schlieren photographs and the pressure data. Measured values of the expansion fan, lip shock, and shear layer are plotted on scale drawings of the five step heights used in this study. The pressures reported are in psia and the location of each pressure point is indicated by a dot above the pressure.

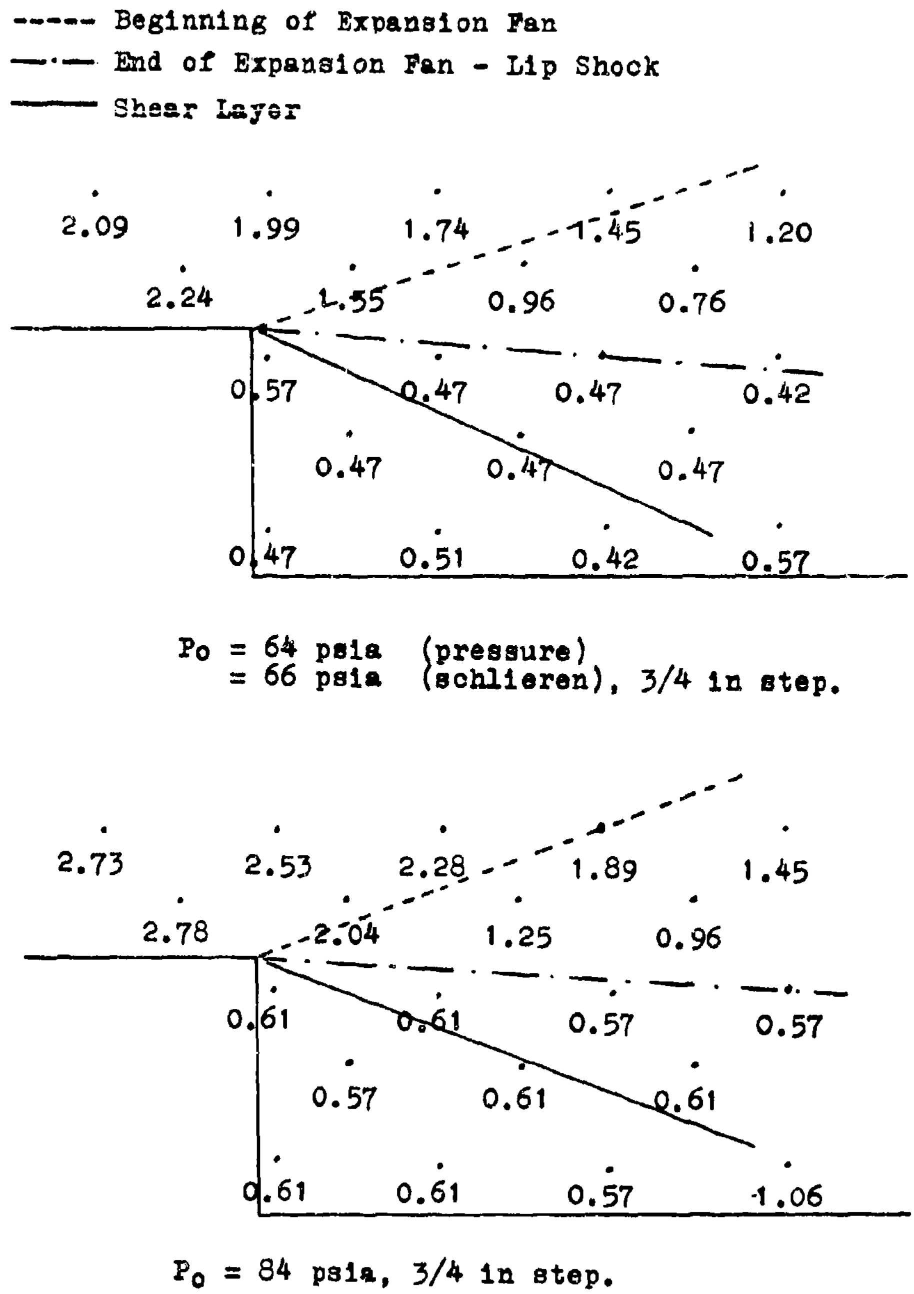


Fig. G-1 Location of Expansion Fan, Lip Shock, and Shear Layer Obtained from Schlieren Photographs Compared with Pressure Data. Scale: 2 in = 1 in.

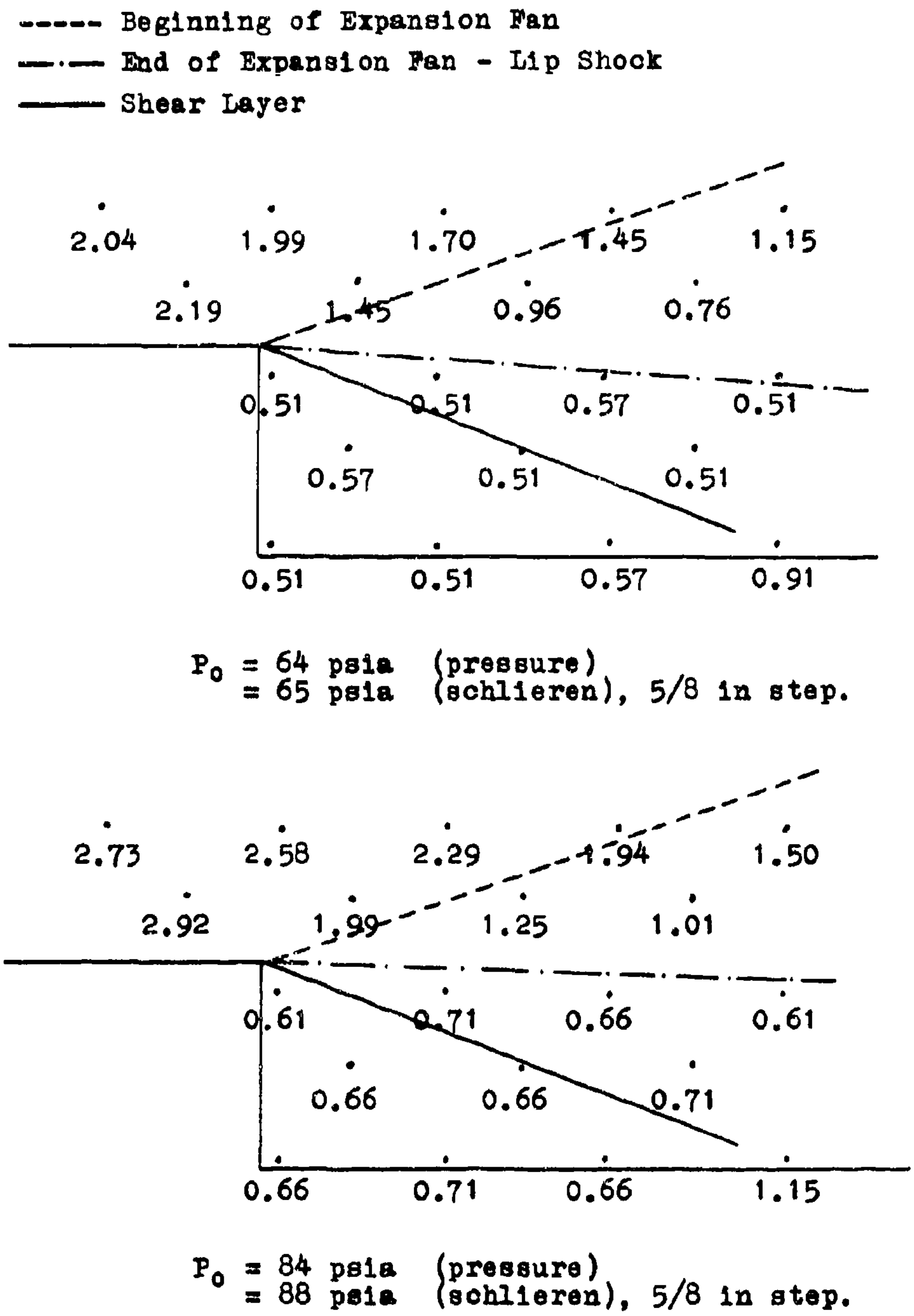
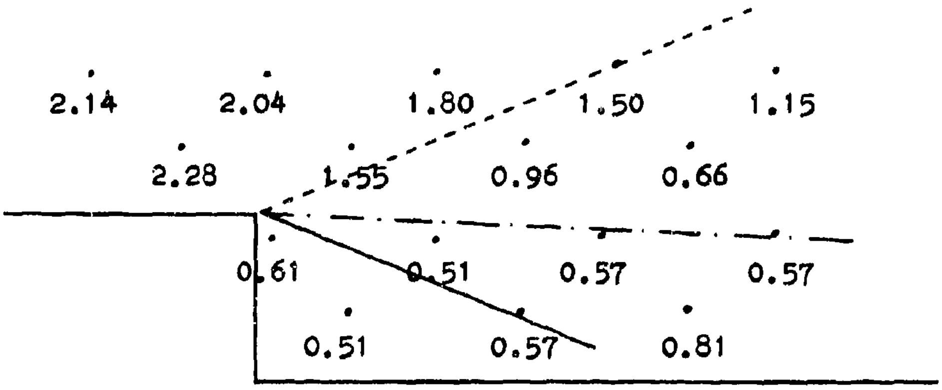


Fig. G-2 Location of Expansion Fan, Lip Shock, and Shear Layer Obtained from Schlieren Photographs Compared with Pressure Data. Scale: 2 in = 1 in.

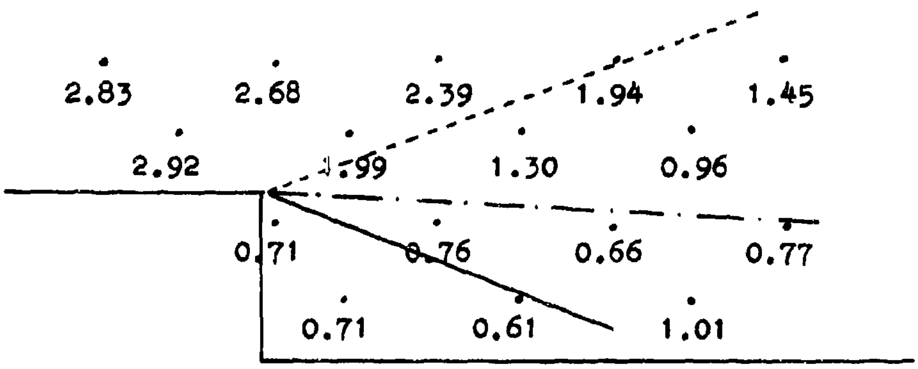
----- Beginning of Expansion Fan

—·— End of Expansion Fan - Lip Shock

——— Shear Layer



P_0 = 64 psia, 1/2 in step.



P_0 = 84 psia (pressure)
= 86 psia (schlieren), 1/2 in step.

Fig. G-3 Location of Expansion Fan, Lip Shock, and Shear Layer Obtained from Schlieren Photographs Compared with Pressure Data. Scale: 2 in = 1 in.

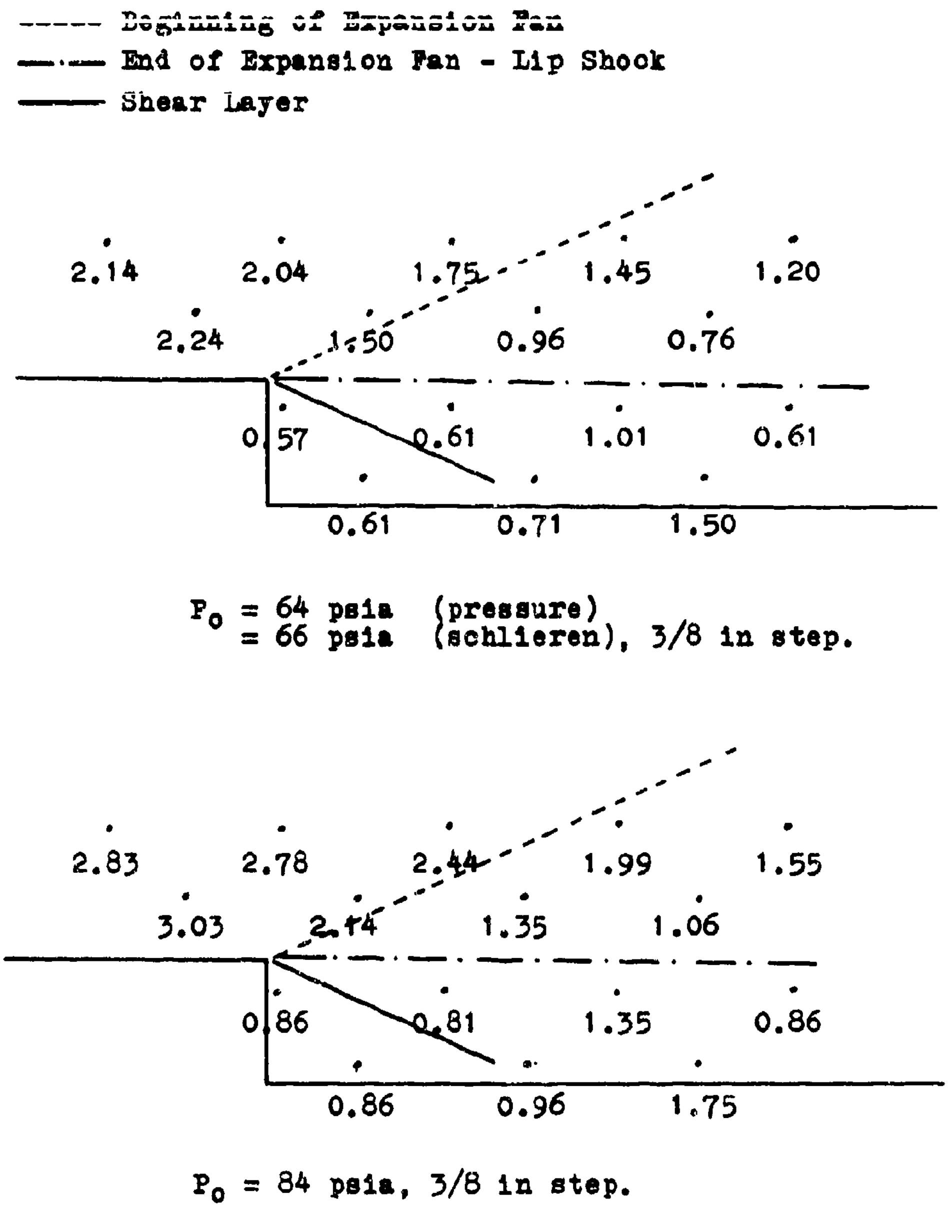
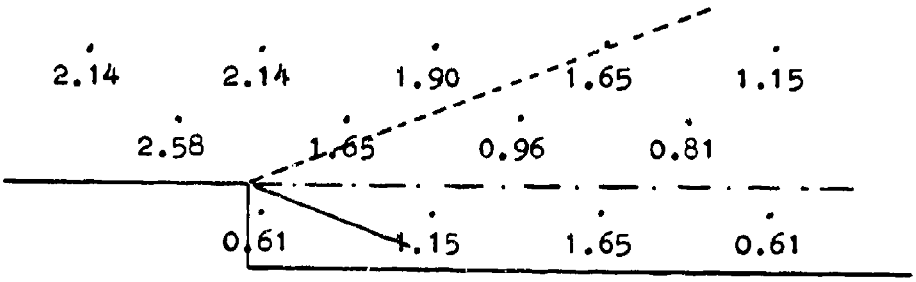
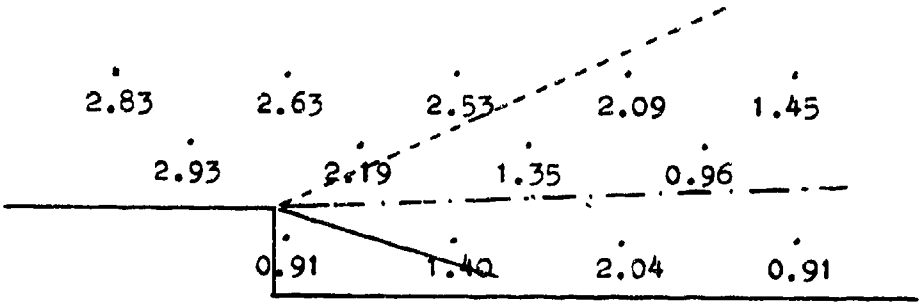


Fig. G-4 Location of Expansion Fan, Lip Shock, and Shear Layer Obtained from Schlieren Photographs Compared with Pressure Data. Scale: 2 in = 1 in.

- - - - Beginning of Expansion Fan
—·—— End of Expansion Fan - Lip Shock
——— Shear Layer



P_o = 64 psia (pressure)
= 66 psia (schlieren), 1/4 in step.



P_o = 84 psia (pressure)
= 90 psia (schlieren), 1/4 in step.

Fig. G-5 Location of Expansion Fan, Lip Shock, and Shear Layer Obtained from Schlieren Photographs Compared with Pressure Data. Scale: 2 in = 1 in.

Vita

Albert Lee Waters was born 6 July 1936 in Morganton, North Carolina, the son of J. Arthur and Gertrude E. Waters. His family moved to Bridgeville, Delaware in 1947 and he was graduated from Bridgeville High School in 1954. In June 1959 he was graduated from the USAF Academy with the degree of Bachelor of Science and was awarded a commission as a Second Lieutenant in the United States Air Force. He completed pilot training in September 1960. He served as an instructor pilot at Mather AFB, California prior to attending the Air Force Institute of Technology.

Permanent address: Bridgeville, Delaware

This thesis was typed by Mrs. Janet V. Waters.

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

In this study, the supersonic flow field over a rearward facing step was studied with a schlieren system. The effect of Mach number variation, step height variation, and total pressure variation on the expansion fan angle, lip shock angle, flow turning angle, reattachment point, and reattachment shock angle was determined. Schlieren photographs of the flow at Mach number 2.7 to 3.1, step heights of 1/4 to 3/4 in, and total pressures of 60 to 95 psia are presented. It was found that the relatively small changes in Mach number had the smallest effect on the flow field and that changing the step height had the greatest effect on the flow field. The flow turning angle was sensitive to all three variables.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Supersonic Flow						
Rearward Step						
Schlieren Photographs						