

Development of a Transonic Turbine Cascade Facility

by

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(ABSTRACT)

This thesis describes the design and initial testing of a transonic turbine cascade facility. It is specifically concerned with the best way to obtain flow periodicity and repeatability through the cascade by the use of tailboards at the cascade exit. The problem of how to achieve flow periodicity and repeatability has not been completely resolved. An examination of the literature available on transonic turbine cascade testing indicates some researchers use no tailboards, some use a solid tailboard, and still others use a porous tailboard. In this thesis, the flow through the turbine cascade is tested for three different cascade exit configurations; no tailboard, a solid tailboard, and a porous tailboard. The cascade is also tested with the tailboard at different angles, to see what effect the angle of the tailboard has on the flow through the cascade. The data acquisition and flow visualization systems are discussed and some preliminary results are given.

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Nomenclature

A	cross sectional area
c	speed of sound
h	height
M	Mach number
\dot{m}	mass flow rate
n	number of blade passages
p	pressure
R	gas constant
Re	Reynolds number
span	blade span
T	temperature
V	velocity
γ	specific heat ratio
μ	viscosity
ρ	density
$\frac{x}{c}$	percent axial chord

Subscripts

o	total conditions
th	throat

Chapter 1

Introduction

A transonic turbine has subsonic flow relative to the blades at the inlet and supersonic flow relative to the blades at the exit. In the past several years, their usage has greatly increased. Transonic gas turbines are found in jet engines. They are useful, since they have less turbine stages, higher specific work, and higher weight flow per unit frontal area than subsonic turbines [1]. They are also used in steam turbines of large power plants [2].

Two-dimensional cascade testing has been instrumental in the development of efficient turbomachinery blading. Lately, however, there has been some debate over its usefulness, since the cascade is just a two-dimensional model of the actual three-dimensional flow in turbomachinery. But two-dimensional cascade testing still has many uses. Gostelow [3] recommends it for the following reasons:

- It is the best method to obtain blade performance data.
- It is less expensive to test in a two-dimensional cascade than in a

full-scale test rig.

- A clearer picture of flow patterns and more precise measurements can be obtained with a cascade.
- Computational methods of flow through the blades need to be checked against experimental results to show they are correct.
- Observing cascade flows, especially with flow visualization, is very useful in getting a basic understanding of turbomachinery flows.

There are a number of problems associated with transonic turbine cascade testing. One problem is obtaining flow uniformity at the cascade inlet. Another is the best way to control the cascade exit Mach number. But the major problem associated with transonic turbine cascade testing is achieving flow periodicity through the cascade. Sieverding states that a very serious problem in transonic turbine cascade testing is the reflected shocks behind the cascade off the free shear layer or tailboard (a movable wall that connects to the trailing edge of the top blade), since these shocks cause the flow to be non-periodic [1]. Figure 1 is a sketch of a transonic turbine cascade with reflected shocks off a solid tailboard, and Fig. 2 is a similar sketch with reflected expansion waves off a free shear layer.

There is no general agreement on the best way to achieve flow periodicity. Some researchers use a free boundary downstream of the cascade. They believe the best way to obtain flow periodicity through the cascade is to use a high number of blades. Others employ a solid tailboard downstream of the cascade. Still others use a porous or slotted tailboard.

This thesis describes the design and initial testing of a wind tunnel used for the testing of transonic turbine blades. It is specifically concerned with the best way to achieve flow periodicity and repeatability through the cascade. Flow through the cascade is compared with three different exit configurations. The first is a free boundary at the cascade exit. The second is a solid tailboard at the cascade exit. The third is a porous tailboard downstream of the cascade. The cascade is also tested with the solid and porous tailboards at different angles, to see what effect the angle of the tailboard has on the backpressure and thus on the exit Mach number. A schlieren and shadowgraph system is used for flow visualization. Static pressure taps and total pressure probes, along with a data acquisition system, are used to obtain the static pressure distribution on the blade surface, the end wall static pressure distribution, and the total pressure distribution in the wakes behind the blades.

Chapter 2

Literature Review

There are a number of papers on the design and testing of a transonic turbine cascade tunnel. Baines, et al. [4] give an excellent description of their design for a cascade tunnel used for aerodynamic testing of transonic turbine blades. Their tunnel is a short-duration blowdown tunnel with an exit Reynolds number per meter of 3×10^5 to 6×10^7 at a Mach number of 1.0, and a maximum exit Mach number of 1.45. Another good description of a transonic turbine cascade tunnel is given by MacMartin and Norbury [5]. Their tunnel is also a blowdown tunnel with a cascade exit Mach number of 1.2 and a Reynolds number of 2×10^6 .

There is also much literature on the actual test section of transonic turbine cascades. There are differences, however, in the way flow periodicity is achieved. Some researchers do not use tailboards at the cascade exit; they have a free shear layer there. They believe the best way to obtain flow periodicity is by using a high number of blades so that the reflected shocks have time to disappear before they

reach the blades where the measurements are taken. A few researchers who do not use tailboards are Haller and Camus [6], Graham and Kost [7], Camus, et al. [8], and Curtis, Hutton and Wilkinson [9].

Others researchers feel the best way to achieve flow periodicity is by using a solid tailboard attached to the cascade exit. Sieverding [10] recommends using a solid tailboard for cascade exit Mach numbers greater than 1.1 to 1.3. He also gives two added advantages of using a solid tailboard over not using a tailboard. The first is the exit Mach number of the cascade and the Reynolds number can be varied independently of each other very easily with a solid tailboard [10]. The exit Mach number can be changed by varying the tailboard angle, and the Reynolds number is changed by varying the inlet total pressure. This is in contrast to the no tailboard case, in which by varying the inlet total pressure, the outlet Mach number and the Reynolds number both change. The second advantage is that the use of a solid tailboard causes the turbine cascade outlet flow to be more stable [11]. The tailboard eliminates the highly turbulent free shear layer which is a major source of instability. Additional transonic turbine cascade experiments that use a solid tailboard are Sieverding [12,13,14], Sieverding, Decuypere, and Hautot [2], Stubner, Case, and Blake [15], Cox, Forster, and Hobson [16], Chauvin [17], and Denton and Spurr [18].

Another way to obtain flow periodicity is to use a porous tailboard. Gostelow recommends the use of a porous tailboard to eliminate the reflected shocks and expansions [3]. Gostelow and Watson [19] have successfully used a porous tailboard to achieve flow periodicity.

The instrumentation used in transonic turbine cascade testing is also well documented. MacMartin and Norbury [5] give a detailed description of their pressure measuring instrumentation. They employ static pressure tapings in the blade surface, static pressure tapings in the end wall located $1/4$ axial chord length downstream of the blade trailing edge, and upstream and downstream traverse probes. Sieverding [12] mentions that the blockage effect of the probes at low supersonic Mach number outlet flow is a major problem. The blockage effect usually is caused by the probe stem and not the probe head. It is thus very important to minimize the probe stem diameter and place the probe as far back from the trailing edge plane of the blades as possible.

Gostelow [3] and Kodak [20] give excellent information on schlieren photography. Gostelow [3] also discusses shadowgraph photography. Curtis, Hutton, and Wilkinson [9] mount their blades in transparent plastic endwalls so that schlieren-shadowgraph photographs can be taken.

One of the problems of cascade testing is the influence of the tunnel construction on the test results. Kiock, et al. [21] provide some answers to this question. They report on the test of one plane transonic gas turbine rotor blade section in four different wind tunnels and compare the results. The tunnels used were at VKI Rhode-St.-Genese, Belgium, DFVLR Goettingen, West Germany, DFVLR Braunschweig, West Germany and Oxford University, UK. The blades were designed using Dejc's method [22] and were used as a test case for calculation at the VKI lecture series in 1973 [14], and also many authors have used this blade to check their numerical codes, e.g. [23]. The cascade has a design inlet flow angle

of 30 degrees, a critical exit Mach number range of 0.81 to 0.86, and a space/chord ratio of 0.71. The blades tested first (at VKI) were found to have an undesirable flat part on the front pressure side, which was subsequently modified for tests at the other three tunnels. No tailboard was used for these tunnels.

The surface Mach number distribution for the purely subsonic case lies close together over the blade surface, except at the rear half of the suction side where there is an average and maximum variation of about 0.1 (exit Mach number is approximately 0.8). The same holds true for the transonic case, except the average difference in Mach number on the rear half of the suction side is 0.1, with a maximum difference of 0.2 (exit Mach number of around 1.0). The total pressure losses in the individual tunnels "lie within a band which corresponds to the standard deviations of each tunnel over several pitches." This is only for an exit Mach number less than 0.95, however. Above a Mach number of 0.95, the losses increase greatly. The exit flow angle scatter is between 1 to 2 degrees (design exit flow angle is 67.8 degrees). Axial velocity density ratio, "which describes the area variation from inlet to exit of the cascade in the meridional plane" [24], is a measure of two-dimensionality of the flow and it varied from almost 1 (two-dimensional) to 0.9. Most of the deviations occurred for supersonic exit Mach numbers, which could be the result of not all the tunnels being designed for supersonic flow. An important conclusion that was drawn from this paper is that only a certain amount of accuracy can be expected with a given blade design, since the test results from each tunnel were not exactly the same.

Chapter 3

Design of the Cascade Tunnel

The cascade tunnel is an intermittent, blow-down type and uses the air supply for the already existing supersonic wind tunnel in the Aerospace and Ocean Engineering Wind Tunnel Lab. The air pumping system is made up of eight Ingersoll Rand, Model 90, reciprocating compressors, with a 600 kw capacity, which can pump up the storage system to a maximum of 10 atm. Sixteen tanks with a total volume of 75 cubic meters make up the air storage system. The drying and filtering system contains both drying by cooling and by absorption and the fully automated absorption drying system constructed by Kemp Co. uses molecular sieves and activated alumina as desiccant.

The tunnel control valve, a butterfly valve, opens and closes by means of a pneumatic system. The cascade tunnel valve control consists of an initial valve opening, which can be set, and then a slower ramp opening, which is controlled by a pressure regulating system, until the valve is completely open. The pressure

regulating system is composed of a pressure transducer that senses the pressure drop in the storage tanks, and opens the valve further as the pressure drops. The rate at which the valve opens can also be set.

The cascade tunnel is connected to the tunnel control valve, which branches off the pipe between the air supply and the supersonic tunnel. A shut-off valve is in place between the tunnel control valve and the supersonic tunnel. This valve is kept shut while the transonic wind tunnel is operating, so that no air will escape into the supersonic wind tunnel.

The cascade wind tunnel consists of a 14 inch (360 mm) diameter pipe which connects the tunnel control valve to the test section, and has a 90 degree bend 10 feet (3.0 m) upstream of the cascade test section. An overall view of the transonic cascade tunnel is shown in Fig. 3, and a sketch is shown in Fig. 4.

The test section is 6 inches x 15 inches (152 mm x 381 mm) with end walls made of transparent plastic. The end walls are supported in circular aluminum doors that can be rotated for different inlet flow angles. Figures 5 and 6 are photographs of the test section with the door on and off, respectively. A two-dimensional linear cascade of 11 turbine blades, shown in Fig. 7, is mounted in the test section. The blades are pin-supported between the plastic end walls, which are used to allow observation of the shock waves and flow through the blades by means of a shadowgraph and schlieren system. An adjustable tailboard at the exit of the cascade is used to control exit Mach number by changing the area ratio. Both a solid and a porous tailboard are used to determine which gives better flow periodicity, repeatability, and exit flow control. Static pressure taps

are on the suction surface of a blade and on the pressure surface of the adjacent blade. Ten static pressure taps are located 0.12 axial chord lengths downstream of the cascade exit plane and three static pressure taps are located 2.0 axial chord lengths downstream of the cascade exit. These static pressure taps are used to determine the periodicity of the exit flow since the top and bottom taps of both groups are one blade space apart. A movable total pressure probe is mounted in the top wall upstream of the cascade and is used to measure the uniformity in the vertical direction of the inlet flow. Another fixed total pressure probe is mounted on the side wall upstream of the cascade and is used to give the reference total pressure. Downstream of the cascade a total pressure probe is mounted in an automatic probe traversing mechanism and is used to measure blade wakes and losses. The probe tip has an outside diameter of 0.062 inches (1.60 mm) that is flattened to a 0.075 inch x 0.040 inch (1.91 mm x 1.02 mm) rectangle (measured on the outside), with the probe tip wall thickness of 0.0090 inches (0.23 mm). The downstream exit plane that the probe measures in can be varied from right at the cascade exit to about 2.0 axial chord lengths downstream of the cascade exit. The test section connects to a diffuser which discharges the air in the test section to the outside atmosphere.

Since this is a blowdown tunnel, and the run time will probably be less than 5 seconds (the actual run time is between 2 to 3 seconds), the response time for the instrumentation must be quick. As mentioned earlier, the test section has numerous static and total pressure taps. The static pressures and the total pressure at the cascade inlet are measured using a Pressure Systems Incorporated

(PSI) Model 780B electronically scanned pressure measurement system. This system contains Electronically Scanned Pressure (ESP) sensors and a microcomputer based data acquisition system. It can achieve high data rates for multipressure measurement applications, since it has a single transducer per port. The ESP sensor that is used has 32 pressure inputs and a range of ± 15 psig (± 100 kPa). The PSI system can measure pressures up to a rate of 20,000 measurements per second.

The total pressure downstream of the cascade on the traverse is measured using a differential pressure transducer that measures the difference between the total pressure downstream and the total pressure upstream of the cascade. The total pressure upstream of the cascade is also measured using a pressure transducer. The outputs to both these transducers are sent simultaneously to a strip chart.

A schlieren and shadowgraph system is set up to take pictures of the shock waves and flow patterns in the cascade. A shadowgraph system can only see very strong density gradients, like shock waves or very strong expansions, whereas a schlieren system can reveal weaker density gradients. A single mirror system is used along with a Polaroid camera that takes 3 inch x 5 inch (76.2 mm x 127 mm) pictures. The light source for the schlieren system is an air cooled high pressure mercury lamp, and the light source for the shadowgraph is 1 microsecond spark source from a nanopulser.

An IBM PC is the principal source for data acquisition. It controls both the PSI system and the MetraByte DASH-16 multifunction, high speed,

analog/digital, I/O expansion board that is mounted in the PC. The MetraByte A/D conversion board in turn controls the flow visualization system and the traverse. A computer program written for the IBM PC in BASIC, found in Appendix A, operates both the PSI system and the A/D conversion board so that the static pressure measurements, the total pressure measurements, the traverse, and the flow visualization can be done simultaneously.

Chapter 4

Results

Preliminary results were taken with the cascade wind tunnel to determine flow uniformity, flow periodicity, cascade exit back pressure control, Reynolds number range, and repeatability of the data.

The transonic turbine cascade test section for the initial tests consists of 11 blades with a blade spacing of 1.467 inches (37.3 mm) and a 0.517 inch (13.1 mm) throat. Each blade has a 6 inch (150 mm) span, a 1 1/2 inch (38 mm) axial chord, and a 0.038 inch (0.97 mm) trailing edge thickness. There is an axial inlet to the cascade and a design exit angle of approximately 68 degrees.

4.1 *Flow Uniformity*

An important condition for a cascade wind tunnel is uniform flow at the test section inlet. If the flow is not uniform at the inlet to the cascade, then the flow periodicity of the cascade will not be maintained.

The flow uniformity at the cascade inlet in the vertical direction was tested by comparing the reference total pressure at the cascade inlet (p_{o1}), with the total pressure measured at 1-inch (25.4 mm) intervals along the cascade inlet vertical center line (p_{o2}), from the top of the test section to the bottom. Figure 8 gives the difference in these two pressure measurements and shows that the flow uniformity at the inlet to the cascade in the vertical direction is excellent over the central part of the test section. (The least count in the transducer readout is as big as the smallest pressure measurement difference.) The reason the pressure differences near the top wall vary more than the pressure differences near the bottom wall is that the probe comes within a 1/2 inch of the top wall (and thus within the boundary layer of the wall), but only comes within 2 1/2 inches of the bottom wall.

4.2 *Flow Periodicity*

One of the main difficulties in transonic turbine cascade testing is achieving pitchwise periodicity of the flow. This is because the trailing edge shock waves are reflected back into the cascade exit by the tailboard, or the free shear layer if there is no tailboard.

One of the best ways to achieve flow periodicity is to have a high number of blades in the cascade, but what constitutes a high number of blades is debatable. Gostelow [3] believes that seven blades is enough, while Camus, et al. [8] feel that six blades are all that are needed. Based on these suggestions from the literature, eleven blades, which is the number of blades chosen for this cascade, should be enough.

The flow periodicity through the test section was tested with no tailboard. It was also tested with a solid tailboard at two different angles; the first with an angle of 67 degrees from the horizontal and the second with an angle of 66 degrees, and with a porous tailboard at the same two angles. The flow periodicity was determined by use of shadowgraph pictures (taken of blades 4, 5 and 6 from the top of the cascade), by comparing the end wall static pressures that are one blade space apart and located downstream of the central blades (the passage between the sixth and seventh blade from the top of the cascade), and by comparing the wakes of two adjacent blades. Figure 9 is a photograph of the test section that shows the relative location of the end wall static pressure taps, the tailboard, and the movable total pressure probe for wake measurements. The static pressures

one blade space apart will be the same for periodic flow. The flow periodicity cannot be found by comparing static pressures on the surface of two blades, since there are only static pressure taps on the suction surface of one blade and on the pressure surface of the adjacent blade.

Figure 10 is a shadowgraph picture taken with no tailboard, and table 1 is the corresponding static pressure data. (The streaks in the flow direction in all the shadowgraph pictures are due to oil buildup on the test section windows.) The reflected shock off the free shear layer is clearly visible in the picture. The reflected shock interferes with the exit flow of the cascade causing the flow not to be periodic at this point. But the static pressures one blade space apart only differ by 0.78 percent of total pressure for the taps located 2.0 axial chord lengths downstream of the cascade exit, and differ by 3.4 percent for the taps located 0.12 axial chord lengths downstream, which indicates that the flow is periodic where the taps are located. The shock reflection off the free shear layer only seems to affect the periodicity of the flow for the top 4 or 5 blades, while the central blades do not seem to be affected. This is good since the wake data will be taken downstream of the central three blades (blades 6, 7, and 8 from the top of the cascade). Wake data was not taken for this case.

Figures 11 and 12 are shadowgraph pictures taken for the solid tailboard at angles of 67 and 66 degrees, respectively. Tables 2 and 3 are the corresponding end wall static pressure data. Reflected shocks off the tailboard can be easily seen in the photographs. But the end wall static pressures one blade space apart located 2.0 axial chord lengths downstream of the cascade exit only differ by 1.1

percent of total pressure for the 67 degree angle and 0.82 percent of total pressure for the 66 degree angle, while the static pressures located 0.12 axial chord lengths downstream differ by 0.84 percent of total pressure for the 67 degree angle and 2.7 percent of total pressure for the 66 degree angle. Figures 13 and 14 show the wakes at 1.12 axial chord lengths downstream of the cascade exit for the solid tailboard at 67 and 66 degree angle, respectively. (The thin line that arcs across the wakes is the upstream reference total pressure.) The maximum total pressure loss ($p_{o, wake} - p_{o, ref}$) of the wakes of the two adjacent blades are nearly equal, differing by only 1.2 percent of total pressure for the 67 degree angle tailboard and 0.61 percent of total pressure for the 66 degree angle. Thus, just as for the no tailboard case, the flow is periodic for the central blades and not completely periodic for the blades at the top of the cascade.

The results of testing the cascade with a porous tailboard are similar to the results with a solid tailboard. Figures 15 and 16 are the shadowgraph pictures and tables 4 and 5 are the corresponding end wall static pressure data for the 67 and 66 degree angle, respectively. Figure 17 is the wake at 1.12 axial chord lengths downstream of the cascade exit for the 67 degree angle. (Wakes were not taken for the porous tailboard at a 66 degree angle.) The maximum difference in total pressure loss between the two wakes is 0.62 percent of total pressure. Just as for the other two cases, the shadowgraph pictures demonstrate that exit flow is not completely periodic for the top blades of the cascade, while the end wall static pressures and the wake measurements show the exit flow is periodic for the central blades of the cascade.

4.3 Repeatability

Another important criteria for a cascade wind tunnel is repeatability. Repeatability means that for a given tailboard angle (or for the free shear layer without a tailboard) the same non-dimensional pressure ratio (thus the same exit Mach number), and the same shock angle should be obtained for each run while the total pressure is varied. Repeatability is important for this cascade, for since the tunnel control is not very precise, it is not possible to run at the exact same total pressure from day to day.

The case without a tailboard gives no repeatability at all because the back pressure varies as the total pressure varies. Table 6 gives total pressure versus exit Mach number. The exit Mach number was calculated by averaging the ten static pressure taps located 0.12 axial chord lengths downstream of the cascade exit and dividing the average static pressure by the total pressure to obtain the non-dimensional pressure ratio. As the total pressure varies, the exit Mach number varies also, and is not constant over any range of total pressures.

A solid tailboard gives very good repeatability. Table 7 is a table of total pressure versus Mach number for the solid tailboard with a 67 degree angle, and table 8 is a similar table for the solid tailboard with a 66 degree angle. Table 7 demonstrates that the exit Mach number (and thus the non-dimensional pressure ratio) for the 67 degree angle tailboard is constant at 1.18 ± 0.01 for a total pressure greater than 20.86 psia (143.8 kPa), while table 8 shows that the exit Mach number for the 66 degree angle tailboard is constant at 1.27 ± 0.01 for a

total pressure greater than 21.51 psia (148.3 kPa). Figure 18 contains two shadowgraph pictures taken with a solid tailboard at a 67 degree angle. The picture on the top was taken at a total pressure of 20.86 psia (143.8 kPa) and the picture on the bottom was taken at a total pressure of 27.23 psia (187.7 kPa). By comparing the two pictures one can see that the shock angles are the same at both total pressures. Figure 19 contains two shadowgraph pictures taken with the solid tailboard at a 66 degree angle, for total pressures of 21.51 psia (148.3 kPa) and 27.76 psia (191.4 kPa), respectively. The shock angles are similar, also. Thus the solid tailboard gives good repeatability over a wide range of total pressures (from 21 psia (140 kPa) to 28 psia (190 kPa)).

The porous tailboard demonstrates repeatability, but not as good as with the solid tailboard. Tables 9 and 10 give total pressure versus exit Mach number for the porous tailboard with a 67 degree and 66 degree angle, respectively. For the 67 degree angle, repeatability occurs over a total pressure range of 26.46 psia (182.4 kPa) to 28.52 psia (196.6 kPa), for a constant exit Mach number of 1.22 ± 0.02 , while for the 66 degree angle it occurs from 26.77 psia (184.6 kPa) to 28.13 psia (193.9 kPa), for a constant exit Mach number of 1.18 ± 0.02 . Figure 20 compares two shadowgraph pictures taken at total pressures of 26.46 psia (182.4 kPa) and 28.52 psia (196.6 kPa) for the porous tailboard at a 67 degree angle. The shock angles are the same for the two pictures. Figure 21 is the same thing with a 66 degree angle for total pressures of 27.54 psia (189.9 kPa) and 28.03 psia (193.3 kPa). The shock angles here are similar, also. Thus, repeat-

ability occurs over a smaller range of total pressures for the porous tailboard as compared to the solid tailboard.

4.4 Exit Back Pressure Control

Another problem associated with cascade testing is controlling the exit Mach number of the cascade. This is done by varying the back pressure which in turn varies the Mach number.

There is no exit back pressure control for the case without a tailboard. This is because the back pressure cannot be varied in this case. A solid tailboard installed downstream of the cascade gives very good exit back pressure control. The back pressure can be varied by changing the tailboard angle. As mentioned previously, the cascade with a solid tailboard was tested at two different tailboard angles. The exit Mach number was only calculated over the repeatability range. The exit Mach number was approximately 1.18 for a 67 degree tailboard angle and approximately 1.27 for a 66 degree angle.

A porous tailboard downstream of the cascade gives some control, but not as good as with a solid tailboard, because there can be flow behind the tailboard. This flow might go out through the porous holes in some areas and back in through the holes in other areas. The exit Mach number was approximately 1.22 for a 67 degree angle tailboard and approximately 1.18 for a 66 degree angle.

4.5 Reynolds Number Range of Operation

The Reynolds number for the turbine cascade is defined as

$$Re = \frac{\frac{\dot{m}}{n} / span}{\mu} \quad [1]$$

where n = no. of blade passages

and μ is based on downstream static conditions

The mass flow rate is given by

$$\dot{m} = \rho VA \quad [2]$$

For a perfect gas, since $\rho = \frac{p}{RT}$ and $c = \sqrt{\gamma RT}$

$$\dot{m} = p \left(\frac{V}{c} \right) \sqrt{\frac{\gamma}{RT}} \quad [3]$$

And also for a perfect gas

$$\frac{T_o}{T} = 1 + \frac{\gamma - 1}{2} M^2 \quad [4]$$

$$\frac{p_o}{p} = \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{\gamma}{\gamma - 1}} \quad [5]$$

Substituting equations [4] and [5] into equation [3] for p and T and also substituting $M = V/c$ into equation [3] gives

$$\dot{m} = \frac{p_o}{\sqrt{T_o}} \sqrt{\frac{\gamma}{R}} A \frac{M}{\left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{(\gamma+1)}{2(\gamma-1)}}} \quad [6]$$

For supersonic exit flow, $M = 1$ at the throat. Substituting $M = 1$ into equation [6] yields

$$\dot{m} = \frac{p_o}{\sqrt{T_o}} \sqrt{\frac{\gamma}{R}} A_{th} \frac{1}{\left(1 + \frac{\gamma-1}{2}\right)^{\frac{(\gamma+1)}{2(\gamma-1)}}} \quad [7]$$

Assuming air is an ideal gas and substituting R and γ into equation [7] gives

$$\dot{m} = 0.5317 \frac{p_o}{\sqrt{T_o}} A_{th} \quad [8]$$

$$(\dot{m} = 0.04042 \frac{p_o}{\sqrt{T_o}} A_{th}) \text{ SI units}$$

Substituting equation [8] into equation [1] yields

$$Re = \frac{0.5317 p_o A_{th}}{\mu \cdot span \cdot \sqrt{T_o}} \quad [9]$$

$$(Re = \frac{0.04042 p_o A_{th}}{\mu \cdot span \sqrt{T_o}}) \text{ SI units}$$

and since

$$A = h_{th} \cdot span \cdot n \quad [10]$$

where h_{th} = height of throat

Thus substituting equation [10] into equation [9] gives

$$Re = \frac{0.5317 p_o h_{th}}{\mu \sqrt{T_o}} \quad [11]$$

$$(Re = \frac{0.04042 p_o h_{th}}{\mu \sqrt{T_o}}) \text{ SI units}$$

For this cascade

$$h_{th} = 0.04304 \text{ ft } (0.01312 \text{ m})$$

$$T_o = 530^\circ\text{R } (294^\circ\text{K})$$

Substituting these values into equation [11] gives

$$Re = 3.09 \times 10^{-5} \frac{P_o}{\mu} \quad [12]$$

which is the equation that was used to calculate the Reynolds' number for the cascade.

The absolute viscosity is based on static conditions at the cascade exit. The ten static pressure taps at the cascade exit are averaged and the exit Mach number is calculated from which the static temperature can be found. The absolute viscosity is a direct function of the static temperature. The Reynolds number is only calculated for the range of total pressures where there is repeatability. Since there is no repeatability for the no tailboard case, the Reynolds number is not calculated for it.

For the solid tailboard, the Reynolds number range is from 2.86×10^5 to 4.04×10^5 . The Reynolds number range for the cascade with the porous tailboard is from 3.07×10^5 to 4.19×10^5 .

4.6 Preliminary Test Results

Some preliminary test results were taken. These results consisted of pressure distributions over the blade surfaces and wakes. Figure 22 compares the blade surface distributions for the solid tailboard at a 66 degree angle at total pressures of 28.6 psia (197 kPa) and 21.5 psia (148 kPa). These two total pressures are at the opposite ends of the repeatability range. The agreement between the two pressure distributions is excellent. The only noticeable difference occurs on the suction side at a blade coordinate of 0.646 where it is only a 0.02 difference.

Figures 13 and 23 are wakes taken 0.12 and 2.0 axial chord lengths downstream of the cascade exit plane with a solid tailboard at a 67 degree angle. Figure 13 shows there is not much shock losses between the wakes. The total pressure loss is 4.2 percent for the wakes at 0.12 axial chord lengths and increases to 4.9 percent at 2.0 axial chord lengths downstream of the cascade exit. The increase in pressure losses is due primarily to mixing that occurs downstream of the cascade exit. The wakes are also reasonably periodic, with the difference in peak total pressure loss for the wakes of two adjacent blades being 1.2 percent of total pressure for the wakes at 0.12 axial chord lengths downstream, and being 0.80 percent of total pressure for the wakes at 2.0 axial chord lengths downstream of the cascade exit.

Chapter 5

Conclusions and Recommendations

A transonic turbine cascade facility has been built and tested. Flow uniformity upstream of the cascade was achieved. Flow periodicity was tested for three different cases; no tailboard, a solid tailboard, and a porous tailboard. It was found for all three cases that the exit flow of the cascade was periodic for the central blades, while the exit flow for the top 4 or 5 blades was not completely periodic, due to shock reflections off the free shear layer or tailboard.

Repeatability was determined using the same three cases as above. Repeatability is defined as keeping a constant Mach number or pressure distribution and exit shock angle for a given tailboard angle (or free shear layer), for repeated tests with different inlet total pressures. The case without a tailboard gave no repeatability because the back pressure varied as the total pressure varied. A porous tailboard demonstrated repeatability over a small range of total pressures (from

26.5 psia (180 kPa) to 28 psia (190 kPa)), while a solid tailboard yielded the greatest repeatability range (from 21 psia (140 kPa) to 28 psia (190 kPa)).

Control of the exit Mach number and flow angle for the cascade was also tested for the same three cases. There was no independent control of the exit pressure for the case without a tailboard. A porous tailboard gave some control, but the best exit flow control was achieved with a solid tailboard.

Thus since a solid tailboard gave the greatest repeatability range and the best flow control of the three cases, and the periodicity was the same for each case, it was determined that a solid tailboard was preferable for future testing.

The Reynolds number range for the cascade with a solid tailboard is 2.86×10^5 to 4.04×10^5 , which is an acceptable range for most tests.

Recommendations for the future are as follows:

- Better valve control. The pneumatic system used to control the valve gave poor valve control.
- Increase the field of view for the shadowgraph system.
- Digital wake data. The program in Appendix A can be modified to record the wake data (which is now only recorded on a strip chart) and store it in the computer.
- Reduce oil in supply air by replacing or repairing the main compressors.
(The test section viewing windows had to be cleaned after every 5 or 6 runs, because of excessive oil buildup.)
- Install silencer on discharge.

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Appendix A
Computer Program Listing

```

10 '*****
20 '*
30 '*           A/D Block Scan Mode and PSI Pressure Measurement
40 '* MetraByte Corp. & PSI                               Rev. 4.00   4-01-88
50 '* with Todd Bushlow, Fei T. Kwok, and R. L. Campbell
60 '* Edited by Pete King and Mike Zaccaria
70 '*****
80 '
90 CLEAR, 59000! 'reduce workspace to 48K
100 SCREEN 0,0,0 : CLS : KEY OFF : WIDTH 80
110 DIM A$(30),B$(30),TU$(30),TD$(30),TRAV(1000)
120 FALSE=0:TRUE=NOT FALSE:XOFF$=CHR$(19):XON$=CHR$(17)
130 CLOSE
140 DEF SEG:WIDTH "COM1:",255:DEF SEG
150 CM$="COM1:9600,N,8,1"
160 OPEN CM$ AS #1
170 PAUSE=FALSE
180 B$=CHR$(13):GOSUB 3980:GOSUB 3980
190 PRINT:PRINT "Reset PSI system"
200 PRINT "Hit any key when ready . . . ":PRINT
205 A$=INKEY$ : IF A$="" THEN 205
210 '
220 PRINT"-Data will be dumped under B:RAWDAT , B:PRES
230 'PRINT " and converted to files DAT0,DAT1,DAT2,DAT3,PRES1,PRES2"
240 PRINT
250 'INPUT "Enter traverse UP command";TU$
260 TU$="V100 D835 Z0 R1 Z1 R1"
270 'INPUT "Enter traverse DOWN command";TD$
280 B$=TU$+CHR$(13):GOSUB 3980 'send traverse up command
290 '
300 '----- STEP 1 -----
310 'First load DASH16.BIN routine by contracting BASIC to 48K workspace
320 'CLEAR, 59000! 'reduce workspace to 48K
330 DEF SEG = 0 'find BASIC's segment
340 SG = 256 * PEEK(&H511) + PEEK(&H510)
350 SG = SG + 49152!/16
360 DEF SEG = SG 'SG = load location
370 BLOAD "DASH16.BIN", 0 'for DASH16.BIN
380 '
390 '----- STEP 2 -----
400 '
410 DIM DIO%(4) 'declare data array
420 'Initialize using mode 0
430 DIO%(0) = &H300 'base I/O address
440 DIO%(1) = 2 'interrupt level
450 DIO%(2) = 3 'D.M.A. level
460 'Be sure that base address & DMA level correspond to switch settings
470 'on DASH-16!
480 MD% = 0 'initialize mode
490 FLAG% = 0 'declare error variable
500 DASH16 = 0 'CALL offset = 0

```

```

570 CALL DASH16 (MD%, DIO%(0),FLAG%)           'initialize
580 'Check if any initializing errors
590 '(try some dumb numbers for MD%, DIO%(0 thru 2))
600 IF FLAG%<>0 THEN PRINT"Initialization error # ";FLAG% : STOP
610 '
611 '
612 ' Make sure that on/off valve is closed
613 'MD% = 13
614 'DIO%(0) = 0
615 'CALL DASH16 (MD%, DIO%(0), FLAG%):PRINT:PRINT "Tunnel valve closed"
:PRINT
616 'IF FLAG%<>0 THEN PRINT "Error # ";FLAG%;" on digital output"
617 '
620 '----- STEP 3 -----
630 'Set programmable timer to output desired sample rate
640 'INPUT "Enter tunnel pressure";MAXPSI
650 'VOLT=MAXPSI/10
660 'DATOUT%=INT(VOLT/.00296)
670 '
680 PRINT"SAMPLE RATE = 1,000,000 / (N1 * N2)"
690 INPUT "Enter N1 & N2 :",F1%,F2%
700 SR%=1000000!/F1%/F2% :PRINT"Sampling Rate per channel = "SR%" Hz"
710 INPUT"Is sampling rate correct <y/n> ?:",B$
720 IF B$="y" OR B$="Y" THEN 730 ELSE 690
730 PRINT
740 DIO%(0) = F1%
750 DIO%(1) = F2%
760 MD% = 17                               'timer set mode
770 CALL DASH16 (MD%, DIO%(0),FLAG%)
780 IF FLAG%<>0 THEN PRINT "Error in setting timer. Error # ";FLAG%:STOP
790 '
800 '----- STEP 4 -----
810 'If you skip this step, scan limits will default to:-
820 '    0 to 7 for 8 channel differential input configuration
830 '    0 to 15 for 16 channel single ended input configuration
840 'Now find out what you want for scan limits:-
850 INPUT "Lower channel scan limit (0-7 diff., 0-15 s.e.)? : ",LL%
860 INPUT "Upper channel scan limit (0-7 diff., 0-15 s.e.)? : ",UL%
870 'Set the limits using mode 1
880 DIO%(0) = LL%                          'lower limit
890 DIO%(1) = UL%                          'upper limit
900 MD% = 1
910 CALL DASH16 (MD%, DIO%(0),FLAG%)
920 IF FLAG%<>0 THEN PRINT"Error in setting scan limits # ";FLAG% : STOP
930 PRINT
940 '
950 '----- STEP 5 -----
960 'Set conversions, delay parameters, PSI system
970 INPUT "Enter total number of A/D conversions :",N% : PRINT
980 INPUT "Enter time delay (sec) before starting tunnel";SEC

```

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990 LIM3=SEC*320
1000 INPUT "Enter time delay (sec) from valve open to traverse up ";SEC
1010 LIM = SEC * 320
1020 INPUT"Enter time (sec) for data collection";SEC
1030 LIM2 = SEC * 320
1040 '-----
1050 GOSUB 2590      ' setup psi system I1,C1,F1
1060 '
1070 PRINT:PRINT"Hit any key to begin..." 'start tunnel and take data
1080 IF INKEY$="" THEN 1080
1090 FOR ZZ=1 TO LIM3:NEXT ZZ 'delay tunnel start
1100 '
1110 '-----STEP 6 -----
1120 '
1130 ' Set control valve circuit for proper operating pressure
1140 'MD%=15
1150 'DIO%(0) = 1
1160 'DIO%(1) = DATOUT%
1170 'CALL DASH16 (MD%, DIO%(0), FLAG%)
1180 'IF FLAG%<>0 THEN PRINT "Error # ";FLAG%;" on digital output"
1190 '
1200 ' Write digital output using mode 13
1210 'MD% = 13
1220 'DIO%(0) = 1
1230 'CALL DASH16 (MD%, DIO%(0), FLAG%):PRINT:PRINT "Tunnel valve open"
:PRINT
1240 'IF FLAG%<>0 THEN PRINT "Error # ";FLAG%;" on digital output"
1250 FOR ZZ = 1 TO LIM: NEXT ZZ 'delays traverse to allow tunnel valve
1260 'to open before moving
1270 'DIO%(0) = 3
1280 'CALL DASH16 (MD%, DIO%(0), FLAG%)
1290 'IF FLAG%<>0 THEN PRINT "Error # ";FLAG%;" on digital output"
1300 '
1310 '
1320 '-----STEP 7 -----
1330 'Now set PSI measurement and the block scan operation going
1340 PRINT "PSI system reading . . ."
1350 'GOSUB 2680      ' set psi system going
1360 '
1370 PRINT:PRINT "A/D block scan reading . . ."
1380 DIO%(0) = N%      'Total number of conversions
1390 DIO%(1) = &H3000 'Memory segment to dump data-hope its clear
1400 '                at 192K. Change this to suit your system.
1410 DIO%(2) = 1      '1 = trigger from timer
1420 DIO%(3) = 0      '0 = One shot and finish
1430 MD%=20           'mode 20 - block scan on interrupt
1440 '
1450 '*****
1460 CALL DASH16 (MD%, DIO%(0), FLAG%) 'set it going
1470 GOSUB 3180      'set PSI system going D2

```

```

1480 'GOSUB 6030 'Check input buffer for characters
1490 B$="Y1":GOSUB 3980:PRINT:PRINT "Traverse up" 'Start traverse up
1500 '*****
1510 '
1520 IF FLAG%<>0 THEN PRINT"Error in block scan setup=";FLAG%:STOP
'any errors?
1530 'Take picture by tripping relay
1531 MD% = 15
1532 DIO%(0) = 1
1533 DIO%(1) = 4000
1534 CALL DASH16 (MD%, DIO%(0), FLAG%)
1535 IF FLAG%<>0 THEN PRINT "Error # ";FLAG%;" on digital output"
1536 'Stop sending voltage to open relay
1537 DIO%(1) = 0
1538 CALL DASH16 (MD%, DIO%(0), FLAG%)
1539 IF FLAG%<>0 THEN PRINT "Error # ";FLAG%;" on digital output"
1540 '----- STEP 7a -----
1550 'Block scan check -- optional procedure
1560 ' ** Note: Though this command is never executed, it is needed
1570 ' for proper program operation
1580 'PRINT:PRINT"( Check status of block scans <y/n>? ) ";
1590 A$="N": IF A$="" GOTO 1590
1600 IF A$ = "Y" OR A$ = "y" THEN GOTO 1610 ELSE GOTO 1690
1610 MD% = 8
1620 CALL DASH16 (MD%, DIO%(0), FLAG%)
1630 PRINT"Operation type - ";DIO%(0)
1640 PRINT"Status - ";DIO%(1)
1650 PRINT"Scan count - ";DIO%(2)
1660 PRINT
1670 GOTO 1580
1680 '
1690 PRINT:PRINT "Collecting . . ."
1700 '
1710 FOR ZZ = 1 TO LIM2 : NEXT ZZ 'delay to allow system to collect
1720 'data before writing to arrays and
1730 PRINT:PRINT"Traverse down"
1740 '
1750 FOR ZZ=1 TO 320 : NEXT ZZ 'Wait 1 sec before shutting off tunnel
1760 ' CLOSES TUNNEL VALVE
1770 'MD% = 13
1780 'DIO%(0) = 0
1790 'CALL DASH16 (MD%,DIO%(0),FLAG%):PRINT:PRINT "Tunnel valve closed"
1800 'IF FLAG%<>0 THEN PRINT "Error # ";FLAG%;" on digital output"
1810 CLOSE #1 'close COM1: file
1820 '
1830 '----- STEP 8 -----
1840 'Retrieve data to arrays DT%(*) and CH%(*) using mode 9
1850 DIM DT%(N%),CH%(N%) 'set up integer arrays for data/chanl #
1860 MD% = 9 'mode 9 - data transfer
1870 DIO%(0)=N% 'number of words to transfer

```

```

1880 DIO%(1) = &H3000           'memory segment to transfer from
1890 DIO%(2) = 0                'start transferring at conversion 0
1900 DIO%(3) = VARPTR(DT%(0))   'location of DT%(*) array
1910 DIO%(4) = VARPTR(CH%(0))   'location of CH%(*) array
1920 CALL DASH16 (MD%, DIO%(0), FLAG%) 'make transfer
1930 IF FLAG%<>0 THEN PRINT "Mode 9 data transfer error # ";FLAG%:STOP
1940 PRINT:PRINT "A/D block scan completed . . .":PRINT
1950 '
1960 '----- STEP 10 -----
1970 'Dump A/D data to drive B
1980 PRINT:PRINT "Writing A/D data into file . . ."
1990 OPEN "b:rawdatt" FOR OUTPUT AS #1
2000 FOR L%=0 TO N%-1
2010   WRITE #1,DT%(L%)
2020 NEXT L%
2030 CLOSE #1
2040 '
2050 '----- STEP 11 -----
2060 'End scan interrupts using mode 7 - strictly only needed in recycle
mode.
2070 'This step is not needed if in one shot (non-recycle) mode as the
2080 'interrupt will terminate automatically on completion of scans.
2090 MD% = 7
2100 DIO%(0) = N%
2110 CALL DASH16 (MD%, DIO%(0), FLAG%) 'do it
2120 '
2130 '----- STEP 12 -----
2140 'Receive pressure data from PSI system
2150 GOSUB 3830 ' service request SRQ
2160 GOSUB 3330 ' psi data reduction F2
2170 GOSUB 3400 ' write out psi data to file 06
2180 '
2190 END
2200 '----- STEP 13 -----
2210 '- Output data into organized files to be plotted
2220 '- #'s 1-4 OUTPUT correspond to CHANNELS 0-3 A/D signal input
2230 ' NOTE: Need to set BASIC to handle (5) files by BASICA/f:5 in DOS
2240 '
2250 CHANNEL% = UL% + 1
2260 PRINT:PRINT "Organizing all data into files for plotting . . ."
2270 OPEN "b:dat0" FOR OUTPUT AS #1
2280 OPEN "b:dat1" FOR OUTPUT AS #2
2290 OPEN "b:dat2" FOR OUTPUT AS #3
2300 OPEN "b:dat3" FOR OUTPUT AS #4
2310 OPEN "b:rawdatt" FOR INPUT AS #5
2320 FOR I%=1 TO N%/CHANNEL%
2330   INPUT #5,TRAV(I%)
2340   PRINT #1,I%,TRAV(I%)
2350 NEXT I%
2360 FOR I% = 2 TO CHANNEL%

```

```

2370   FOR II% = 1 TO N%/CHANNEL%
2380     INPUT #5, Y
2390     PRINT #I%, Y, TRAV(II%)
2400   NEXT II%
2410 NEXT I%
2420 FOR I% = 1 TO 5 : CLOSE #I% : NEXT I%
2430 '
2440 OPEN "b:pres" FOR INPUT AS #1
2450 OPEN "b:pres1" FOR OUTPUT AS #2
2460 'OPEN "b:pres2" FOR OUTPUT AS #3
2470 FOR I% = 1 TO NUMB*TIME
2480   T = 1 / NUMB * I%
2490   FOR II% = 2 TO 2
2500     INPUT #1, P
2510     PRINT #II%, P, T
2520   NEXT II%
2530 NEXT I%
2540 CLOSE #1: CLOSE #2 ' : CLOSE #3
2550 CLS : END
2560 '
2570 '===== PSI SUBROUTINES =====
2580 '
2590 IBINIT1 = 59000!
2600 IBINIT2 = 59003!
2610 BLOAD "BIB.M", IBINIT1
2620 CALL IBINIT1(IBFIND, IBTRG, IBCLR, IBPCT, IBSIC, IBLOC, IBPPC, IBNA,
  IBONL, IBRSC, IBSRE, IBRSV, IBPAD, IBSAD, IBIST, IBDMA, IBEOS, IBTMO,
  IBEOT, IBRDF, IBWRTF)
2630 CALL IBINIT2(IBGTS, IBCAC, IBWAIT, IBPOKE, IBWRT, IBWRTA, IBCMD, IBCMDA,
  IBRD, IBRDA, IBSTOP, IBRPP, IBRSP, IBDIAG, IBXTRC, IBRDI, IBWRTI, IBRDIA,
  IBWRTIA, IBSTA%, IBERR%, IBCNT%)
2640 DIM J(5), K(3), BYTE(3), CAL(3, 112), COEFF(3, 112), PARAMETER(21)
2650 DIM PERIOD(18), VOLTS(3, 112)
2660 DIM BUFFER$(40)
2670 A1%=32: A2%=0: A3%=0 : A4%=0 : A5%=0 : A6%=0
2680 B%=8
2690 C=.0001 : D%=25: E=.01: F%=3 : G%=32: H%=3
2700 CH=A1%+A2%+A3%+A4%+A5%+A6% : SEN=CH/G% : BITS%=14
2710 BOARD$="DACU" : CALL IBFIND(BOARD$, DACU%)
2720 CLS : PRINT "780B SYSTEM TEST" : PRINT
2730 INPUT "Number of data frames averaged per measurement set "; B%
2740 INPUT "Total time (sec)"; TIME
2750 INPUT "Number of measurement sets/sec/channel"; NUMB
2760 T1=A1%*.0001
2770 T2=.6/NUMB/B%
2780 MTIME=(T1+T2)*B%
2790 D% = INT(TIME*NUMB)
2800 E = 1/NUMB-MTIME
2810 C=T2 '(100/NUMB-INT(100*E))/B%
2820 IF D%>255 THEN 2720

```



```
4200 NEXT II
4210 IF LOC(1)>0 THEN 4230
4220 IF PAUSE THEN PAUSE=FALSE:PRINT#1,XON$;
4230 RETURN
```

Tables

Table 1. End Wall Static Pressures for No Tailboard ($p_o = 24.57$ psia)

End Wall Static Pressure Tap	$\frac{p}{p_o} \left(\frac{x}{c} = 1.12 \right)$	$\frac{p}{p_o} \left(\frac{x}{c} = 3.0 \right)$
1	0.2485	0.4903
2	0.2825	0.4981

Table 2. End Wall Static Pressures for Solid Tailboard at a 67 Degree Angle ($p_o = 27.59$ psia)

End Wall Static Pressure Tap	$\frac{p}{p_o}$ ($\frac{x}{c} = 1.12$)	$\frac{p}{p_o}$ ($\frac{x}{c} = 3.0$)
1	0.3902	0.4148
2	0.3817	0.4297

Table 3. End Wall Static Pressures for Solid Tailboard at a 66 Degree Angle ($p_o = 27.73$ psia)

End Wall Static Pressure Tap	$\frac{p}{p_o}$ ($\frac{x}{c} = 1.12$)	$\frac{p}{p_o}$ ($\frac{x}{c} = 3.0$)
1	0.3503	0.3939
2	0.3234	0.3856

Table 4. End Wall Static Pressures for Porous Tailboard at a 67 Degree Angle ($p_o = 28.19$ psia)

End Wall Static Pressure Tap	$\frac{p}{p_o}$ ($\frac{x}{c} = 1.12$)	$\frac{p}{p_o}$ ($\frac{x}{c} = 3.0$)
1	0.3695	0.4091
2	0.3657	0.3976

Table 5. End Wall Static Pressures for Porous Tailboard at a 66 Degree Angle ($p_o = 27.54$ psia)

End Wall Static Pressure Tap	$\frac{p}{p_o}$ ($\frac{x}{c} = 1.12$)	$\frac{p}{p_o}$ ($\frac{x}{c} = 3.0$)
1	0.3609	0.4342
2	0.4008	0.4160

Table 6. Exit Mach Number for No Tailboard

p_o (psia)	p_o (kPa)	M
19.38	133.6	0.93
19.40	133.8	0.93
20.60	142.0	1.01
20.77	143.2	1.03
21.23	146.4	1.12
21.42	147.7	1.12
23.47	161.8	1.29
24.57	169.4	1.37
25.70	177.2	1.50

Table 7. Exit Mach Number for Solid Tailboard at a 67 Degree Angle

p_o (psia)	p_o (kPa)	M
18.31	126.2	0.74
19.13	131.9	0.82
20.14	138.9	1.06
20.86	143.8	1.18
22.38	154.3	1.18
22.70	156.5	1.19
23.12	159.4	1.18
23.69	163.3	1.18
26.06	179.7	1.19
27.02	186.3	1.18
27.52	189.7	1.19
28.36	195.5	1.18

Table 8. Exit Mach Number for Solid Tailboard at a 66 Degree Angle

p_o (psia)	p_o (kPa)	M
19.15	132.0	0.86
21.51	148.3	1.27
23.19	159.9	1.27
23.32	160.8	1.27
25.49	175.7	1.26
27.73	191.2	1.27
27.76	191.4	1.27

Table 9. Exit Mach Number for Porous Tailboard at a 67 Degree Angle

p_o (psia)	p_o (kPa)	M
21.58	148.8	1.05
22.34	154.0	1.07
23.50	162.0	1.13
25.03	172.6	1.16
26.46	182.4	1.20
26.83	185.0	1.21
27.67	190.8	1.23
28.19	194.4	1.24
28.52	196.6	1.23

Table 10. Exit Mach Number for a Porous Tailboard at a 66 Degree Angle

p_o (psia)	p_o (kPa)	M
21.25	146.5	0.99
22.69	156.4	1.06
24.63	169.8	1.11
25.63	176.7	1.14
26.77	184.6	1.16
27.54	189.9	1.18
27.65	190.6	1.17
27.77	191.5	1.17
28.03	193.3	1.18
28.13	193.9	1.19

Figures

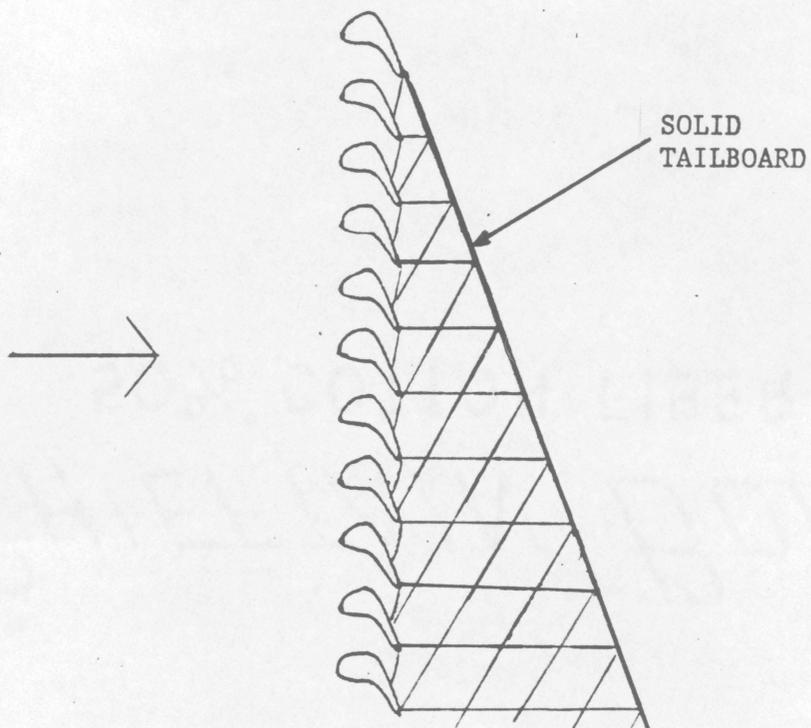


Figure 1. Reflected Shocks Off a Solid Tailboard

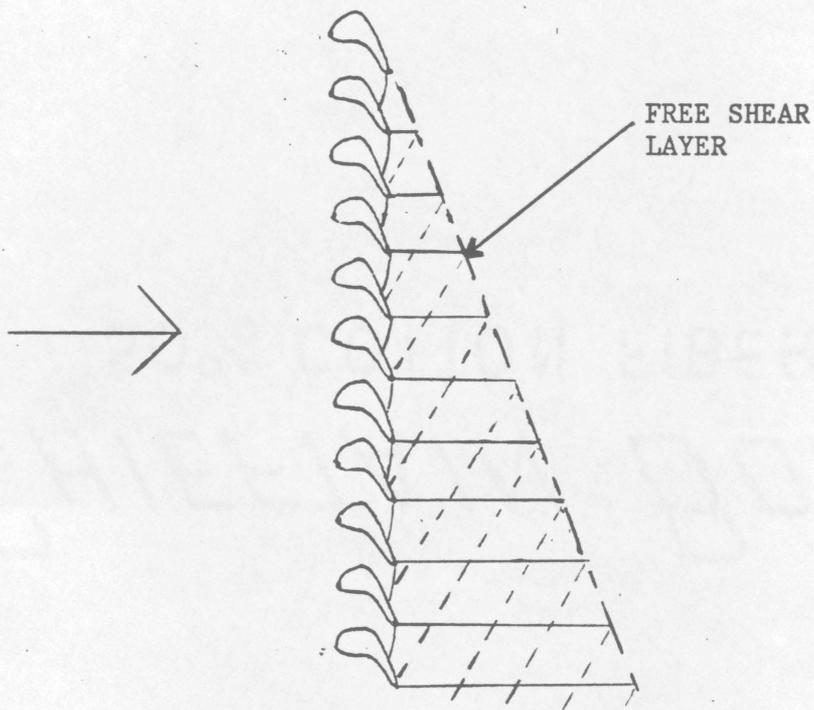


Figure 2. Reflected Expansion Waves Off a Free Shear Layer

CHIEFTAIN BRAND
50% COTTON FIBER

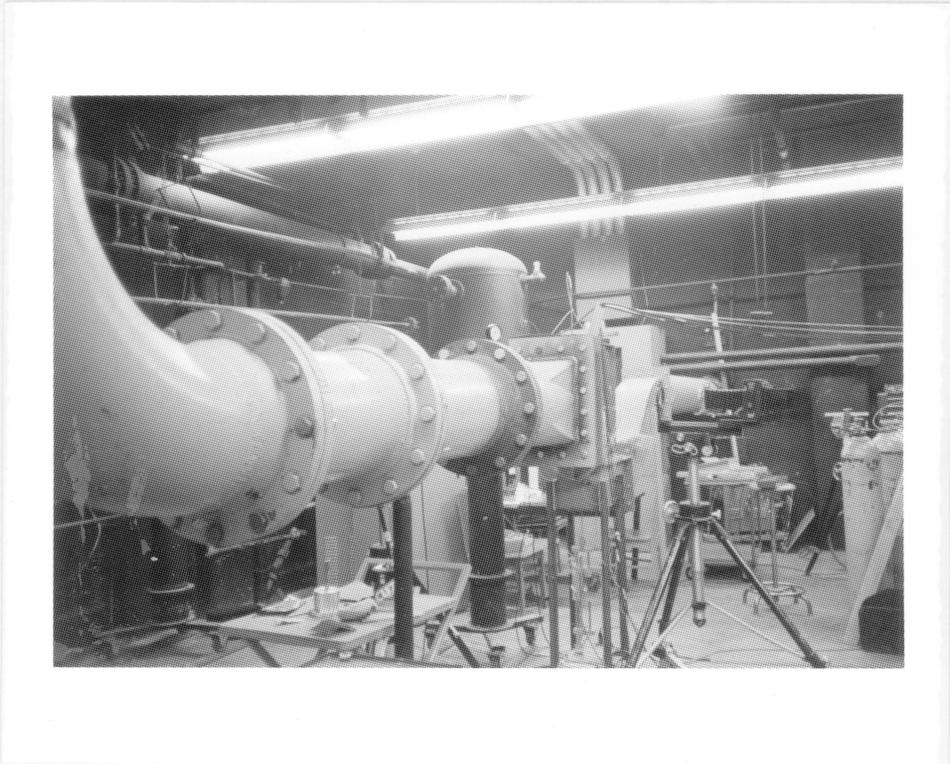


Figure 3. Transonic Wind Tunnel

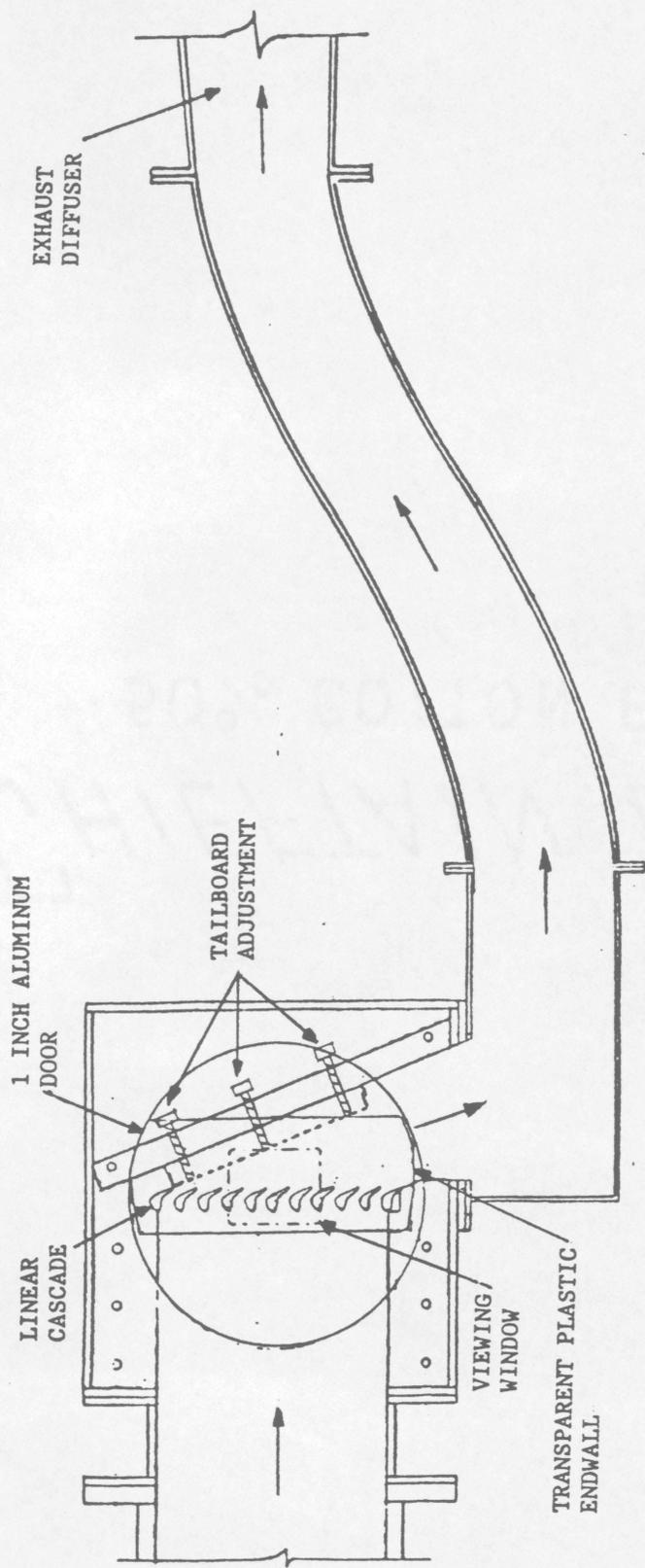


Figure 4. Transonic Wind Tunnel

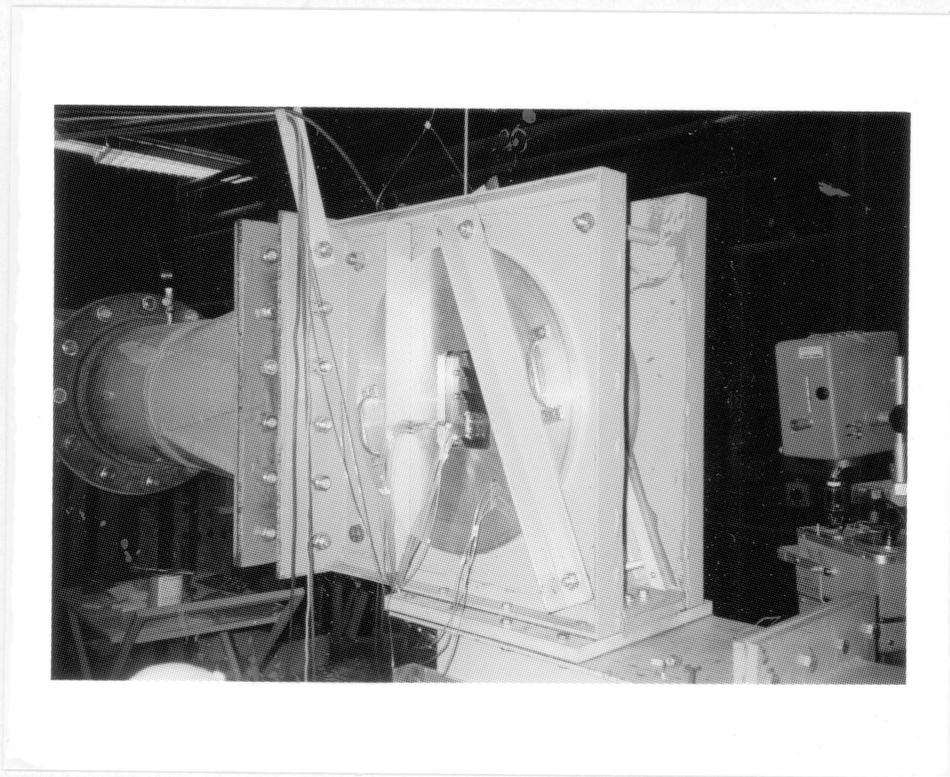


Figure 5. Test Section with Side Door On

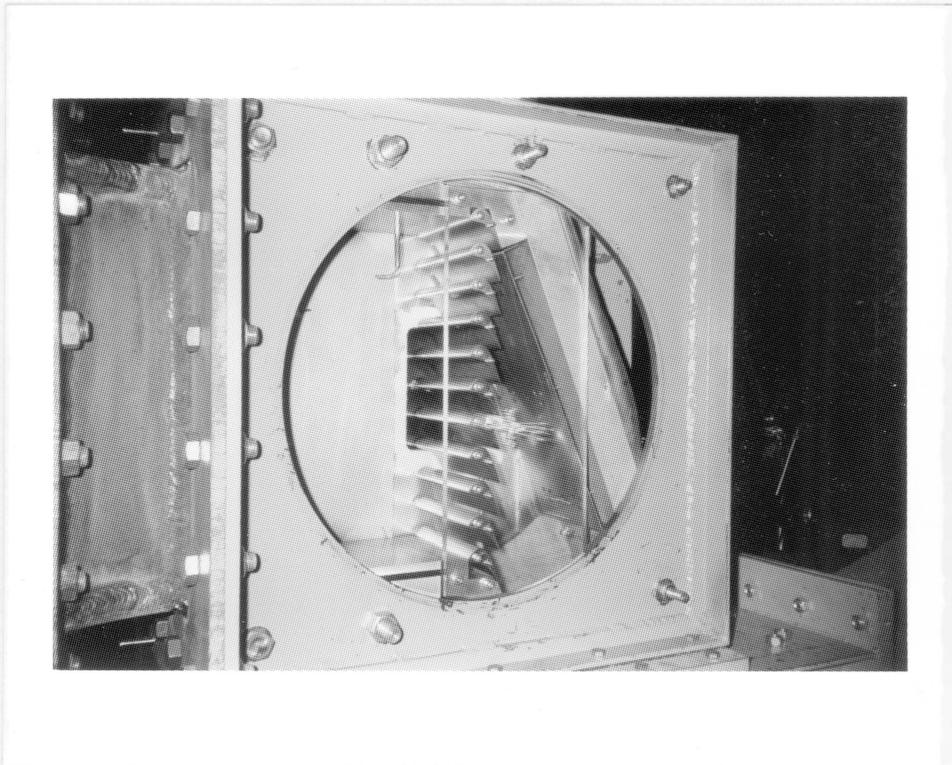


Figure 6. Test Section with Side Door Off

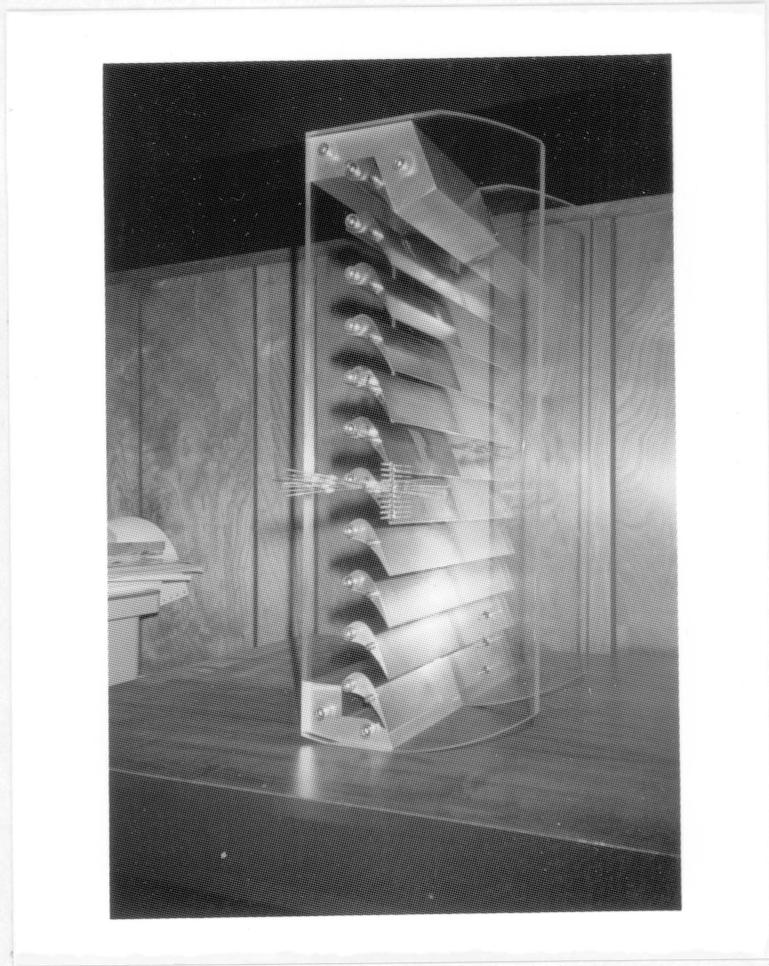


Figure 7. Transonic Turbine Cascade

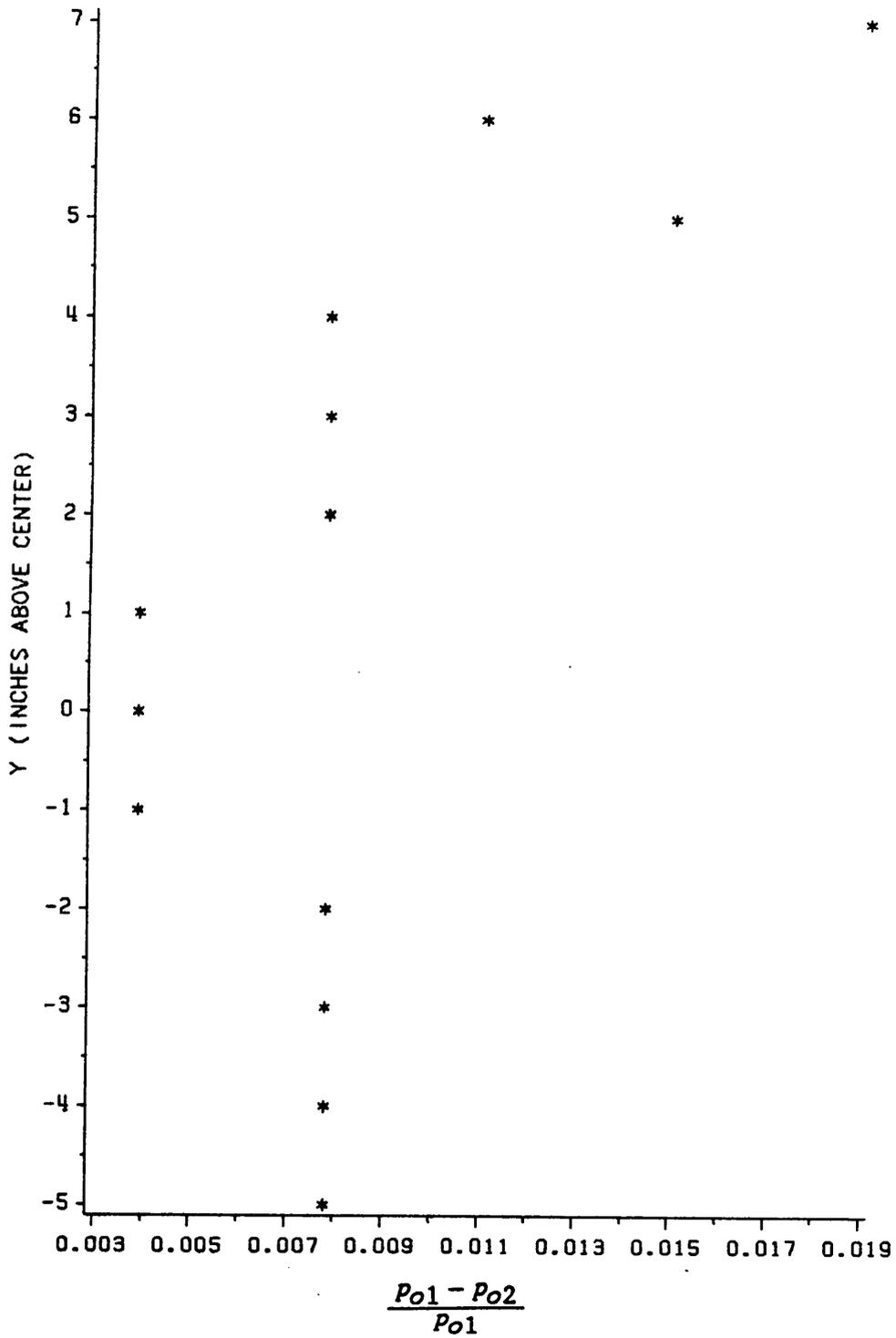


Figure 8. Flow Uniformity at Cascade Inlet: (1 inch = 25.4 mm) (p_{o1} is reference total pressure; p_{o2} is at 1 inch intervals along vertical center line)

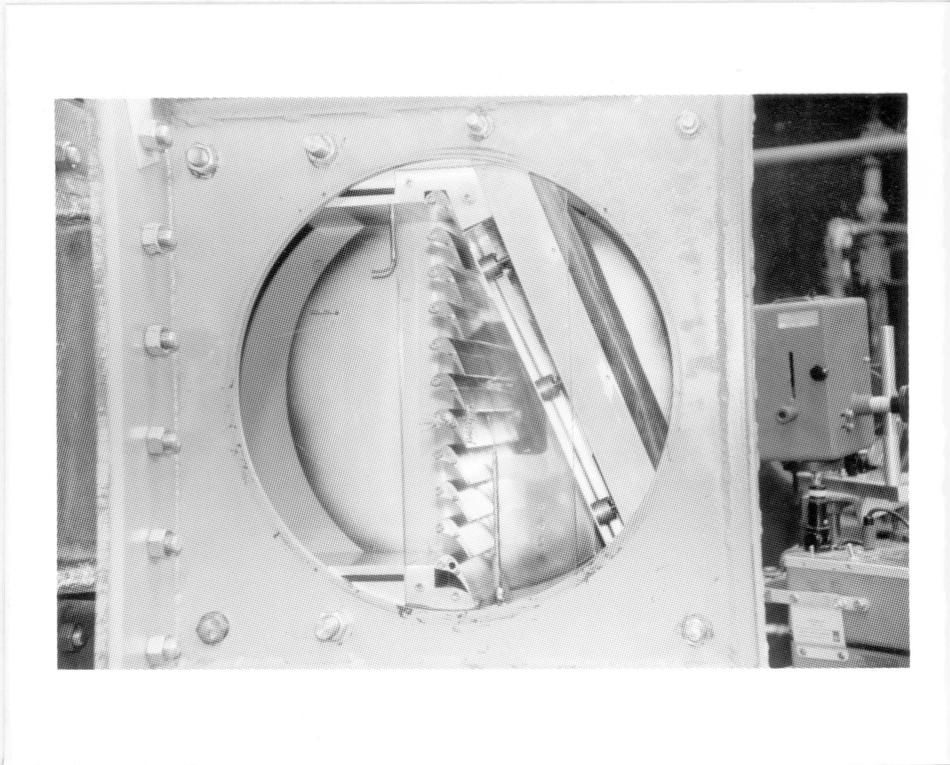


Figure 9. Test Section



Figure 10. Shadowgraph Picture for No Tailboard



Figure 11. Shadowgraph Picture for a Solid Tailboard at a 67 Degree Angle

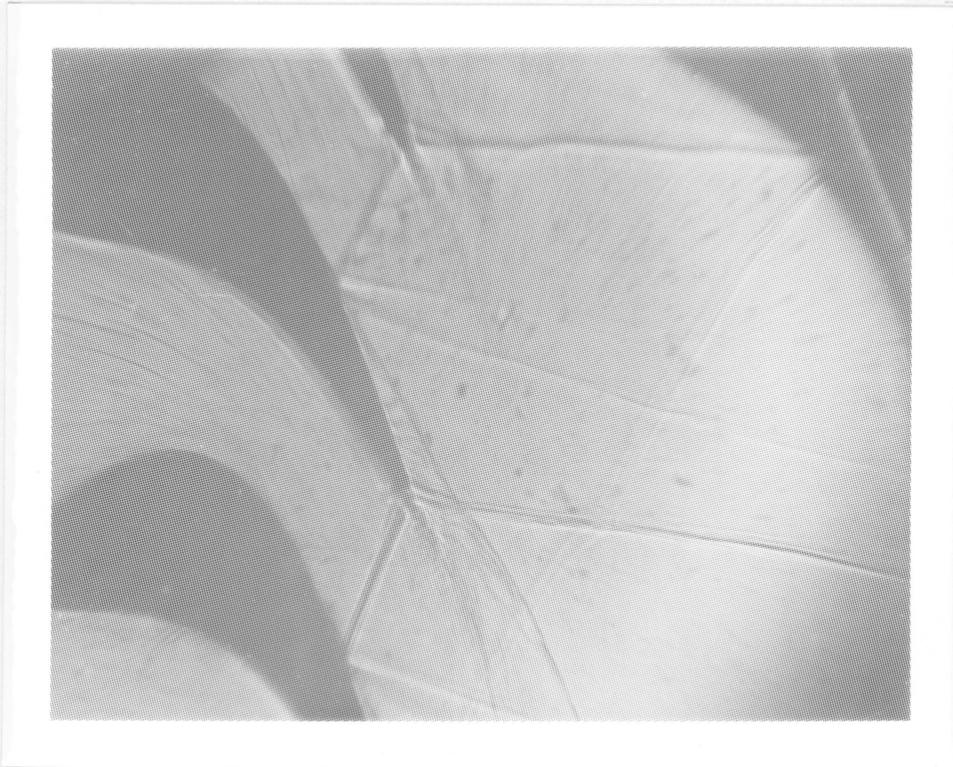


Figure 12. Shadowgraph Picture for a Solid Tailboard at a 66 Degree Angle

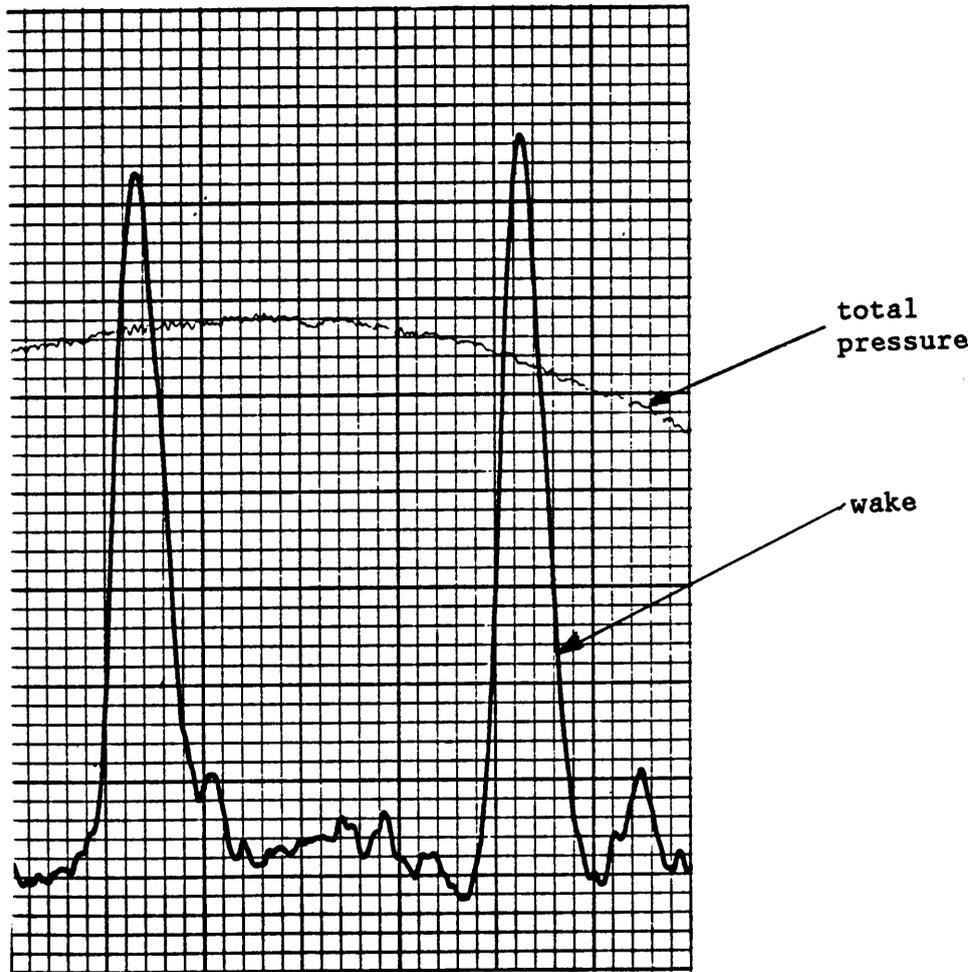


Figure 13. Transonic Cascade Wake for a Solid Tailboard at a 67 Degree Angle: (Taken 0.12 axial chord lengths downstream of cascade exit)
 (1 inch = 0.95 psig = 6.6 kPa for wake; 1 inch = 3.45 psig = 23.8 kPa for total pressure)

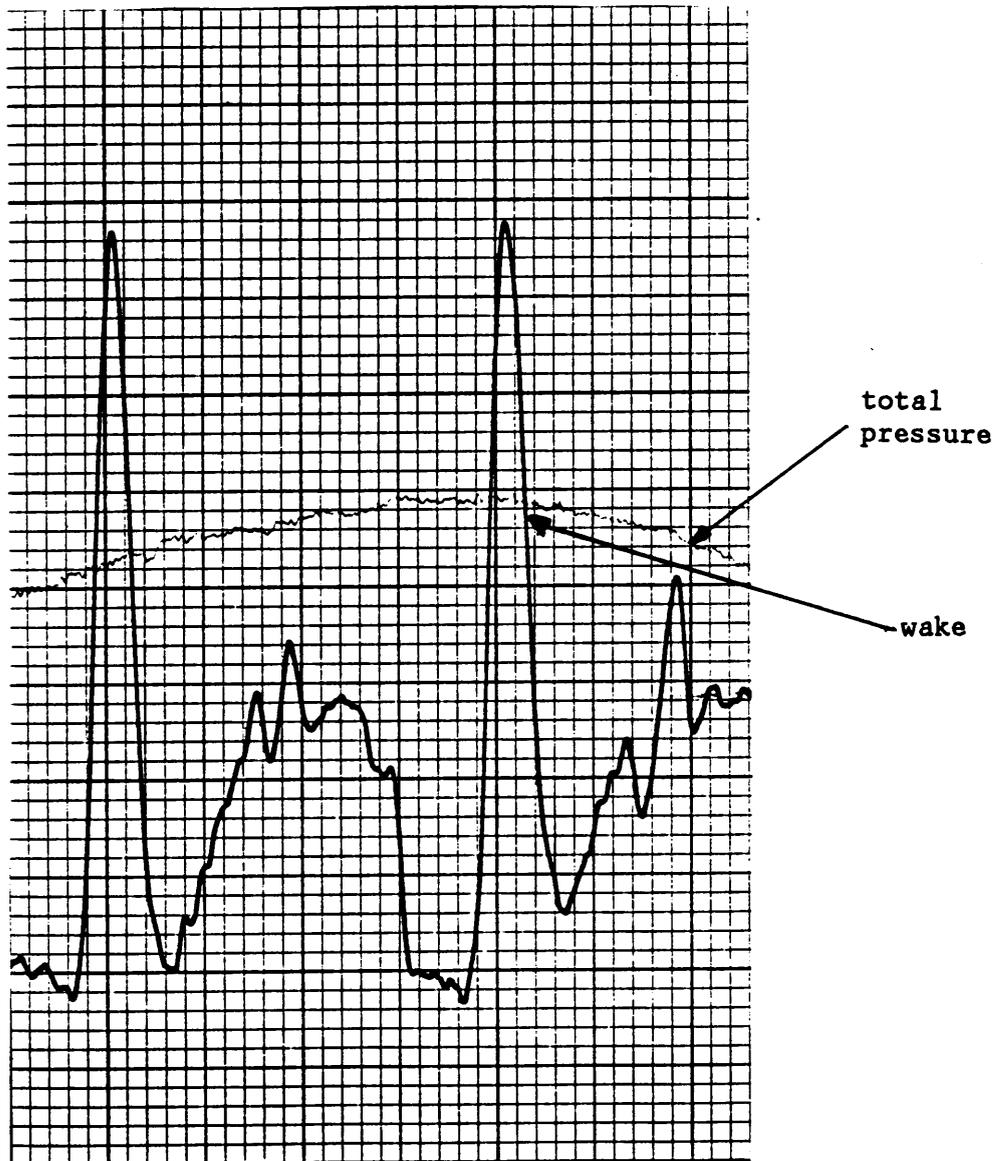


Figure 14. Transonic Cascade Wake for a Solid Tailboard at a 66 Degree Angle: (Taken 0.12 axial chord lengths downstream of cascade exit)
 (1 inch = 0.95 psig = 6.6 kPa for wake; 1 inch = 3.45 psig = 23.8 kPa for total pressure)

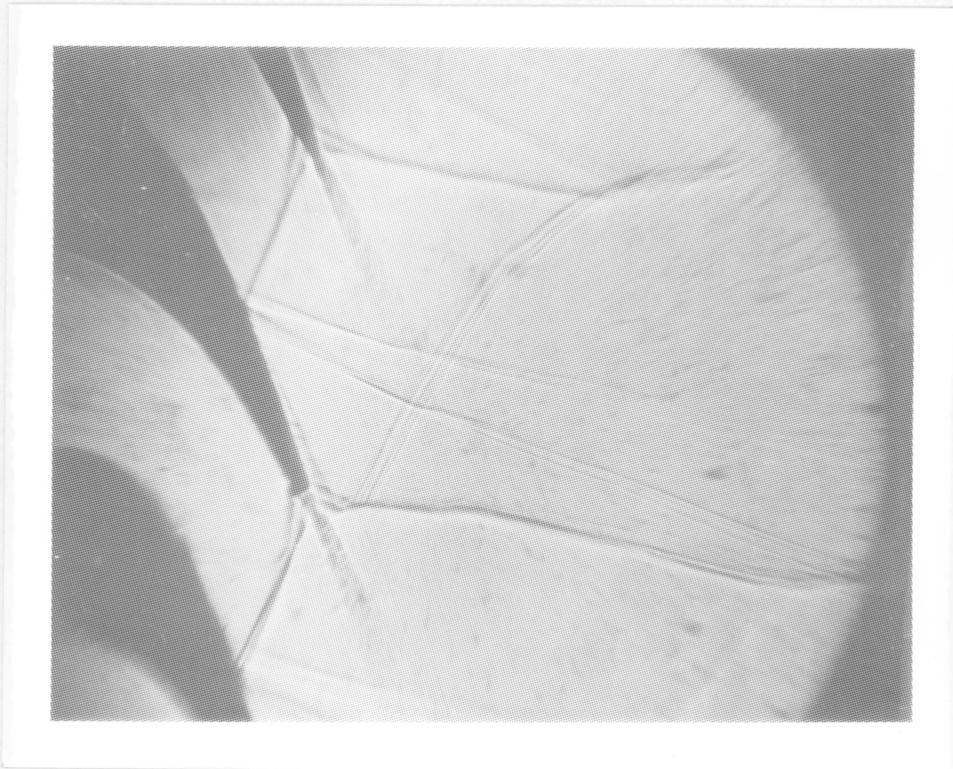


Figure 15. Shadowgraph Picture for a Porous Tailboard at a 67 Degree Angle

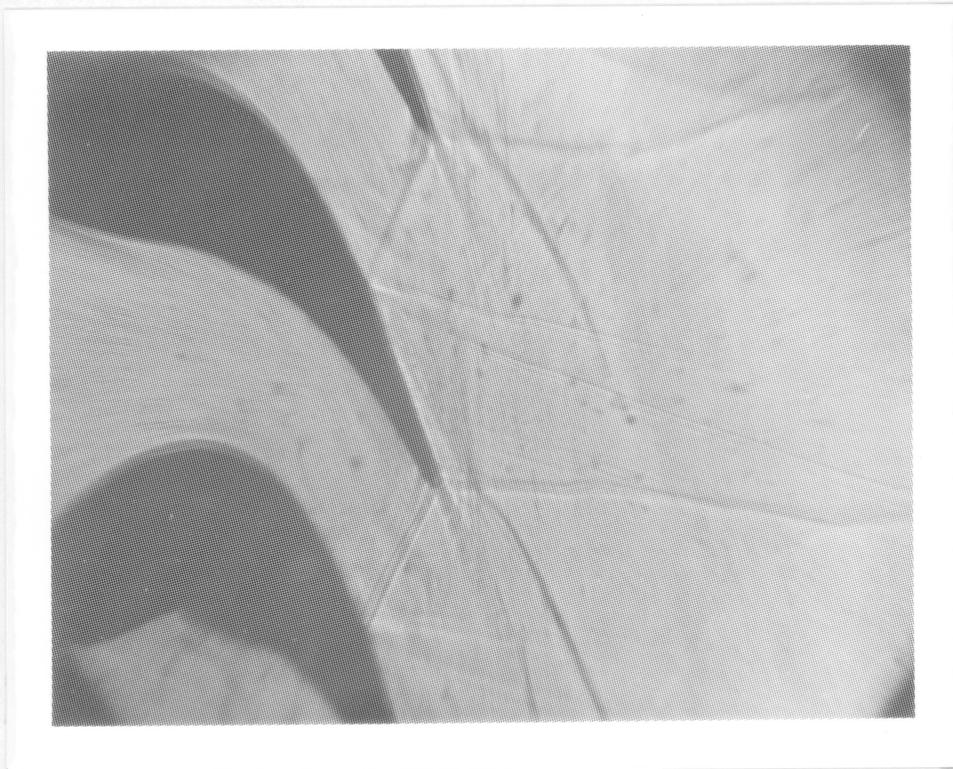


Figure 16. Shadowgraph Picture for a Porous Tailboard at a 66 Degree Angle

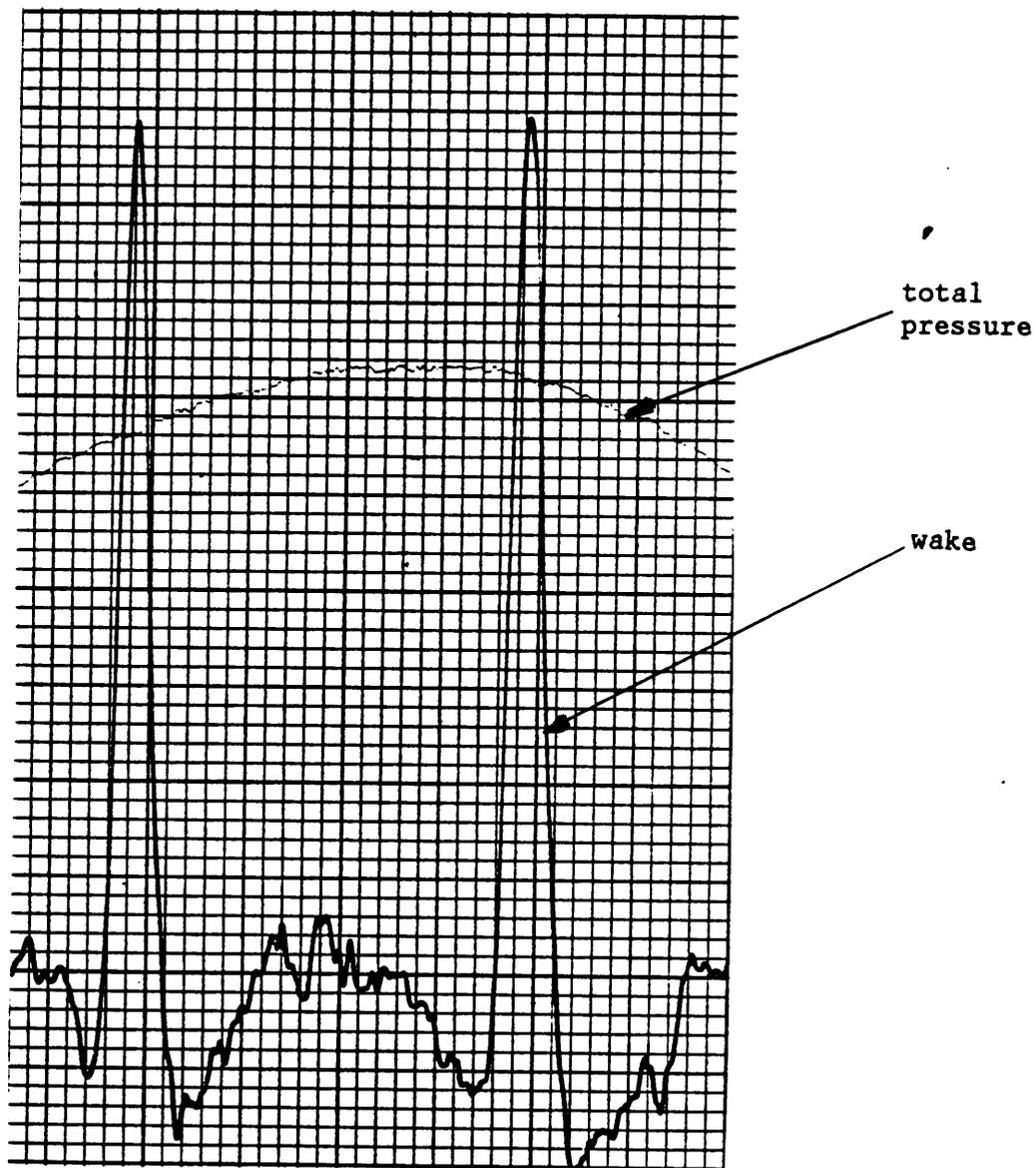


Figure 17. Transonic Cascade Wake for a Porous Tailboard at a 67 Degree Angle: (Taken 0.12 axial chord lengths downstream of cascade exit)
 (1 inch = 0.95 psig = 6.6 kPa for wake; 1 inch = 3.45 psig = 23.8 kPa for total pressure)

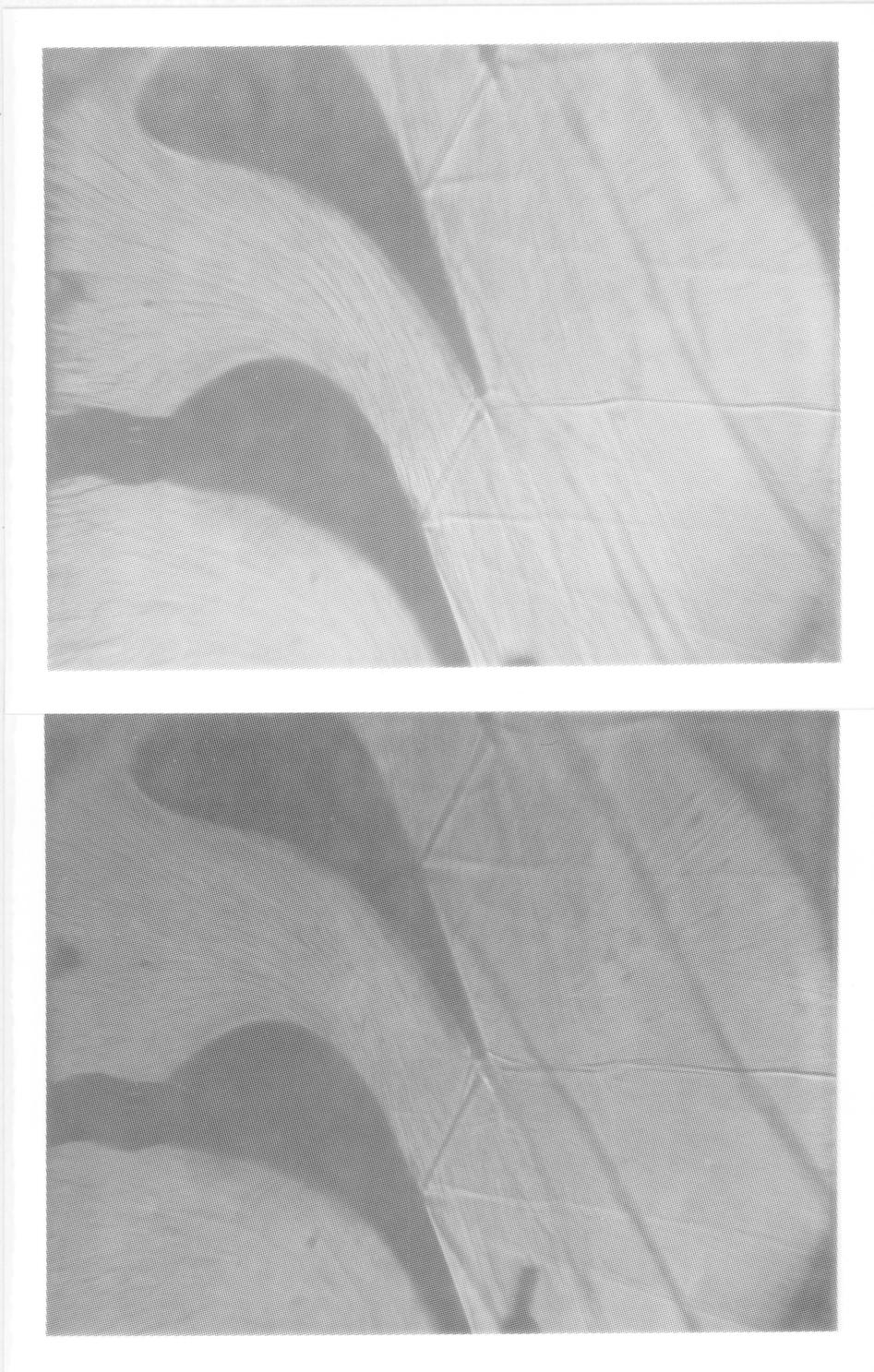


Figure 18. Shadowgraph Pictures for a Solid Tailboard at a 67 Degree Angle: (Top picture $p_o = 20.86$ psia = 189.9 kPa; bottom picture $p_o = 27.23$ psia = 187.7 kPa)

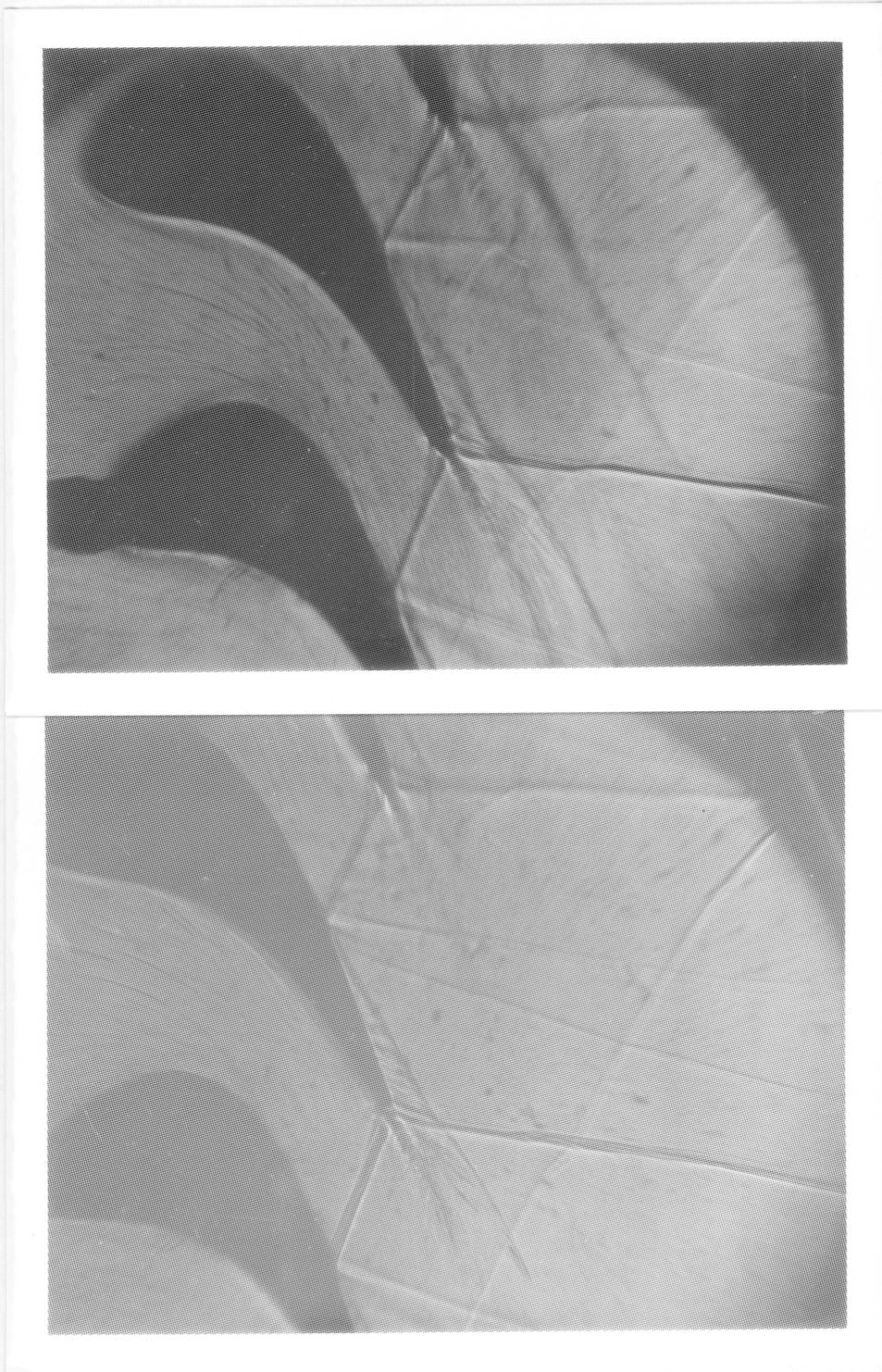


Figure 19. Shadowgraph Pictures for a Solid Tailboard at a 66 Degree Angle: (Top picture $p_o = 21.51$ psia = 148.3 kPa; bottom picture $p_o = 27.76$ psia = 191.4 kPa)

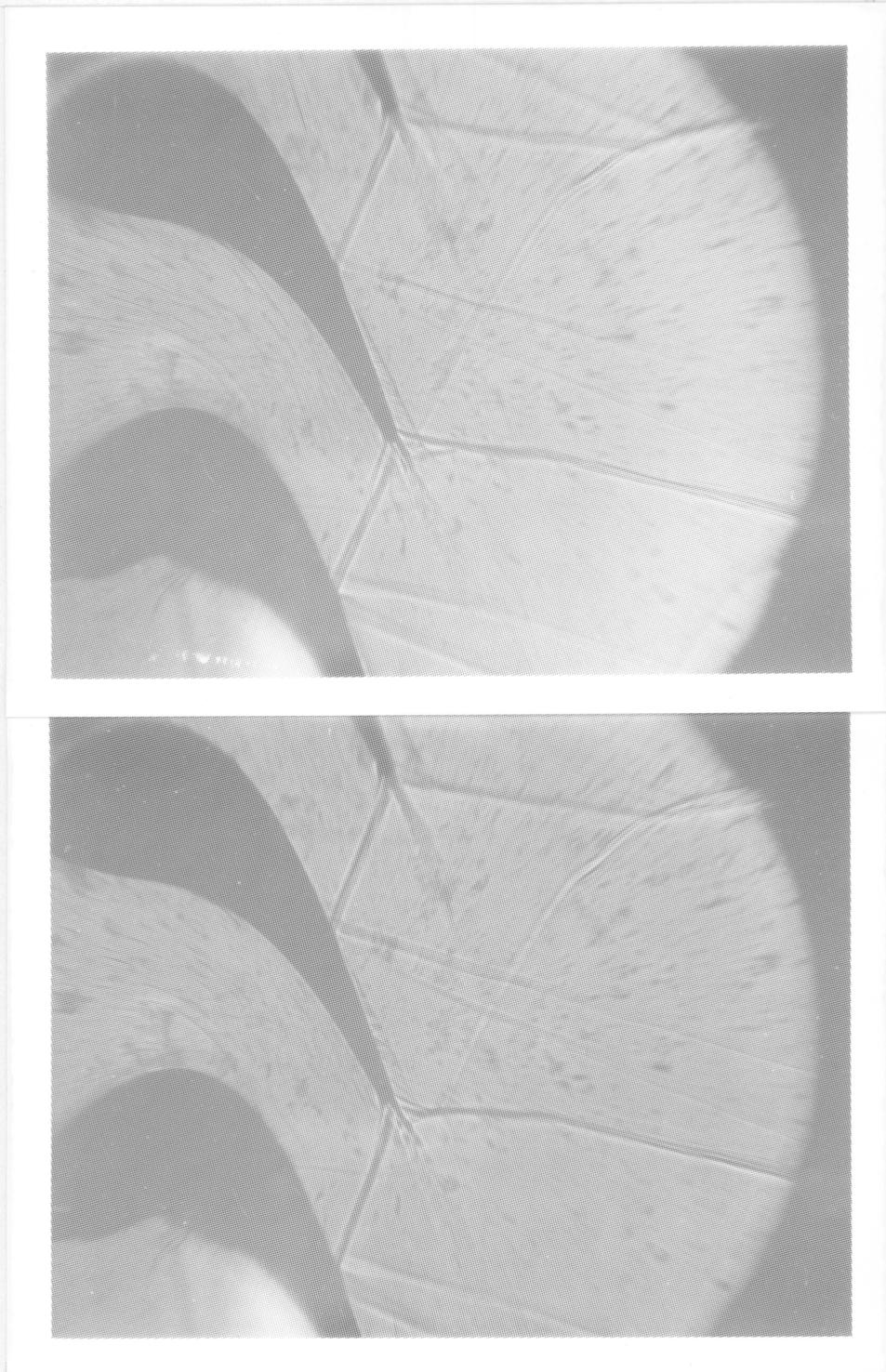


Figure 20. Shadowgraph Pictures for a Porous Tailboard at a 67 Degree Angle: (Top picture $p_o = 26.46$ psia = 182.4 kPa; bottom picture $p_o = 28.52$ psia = 196.6 kPa)

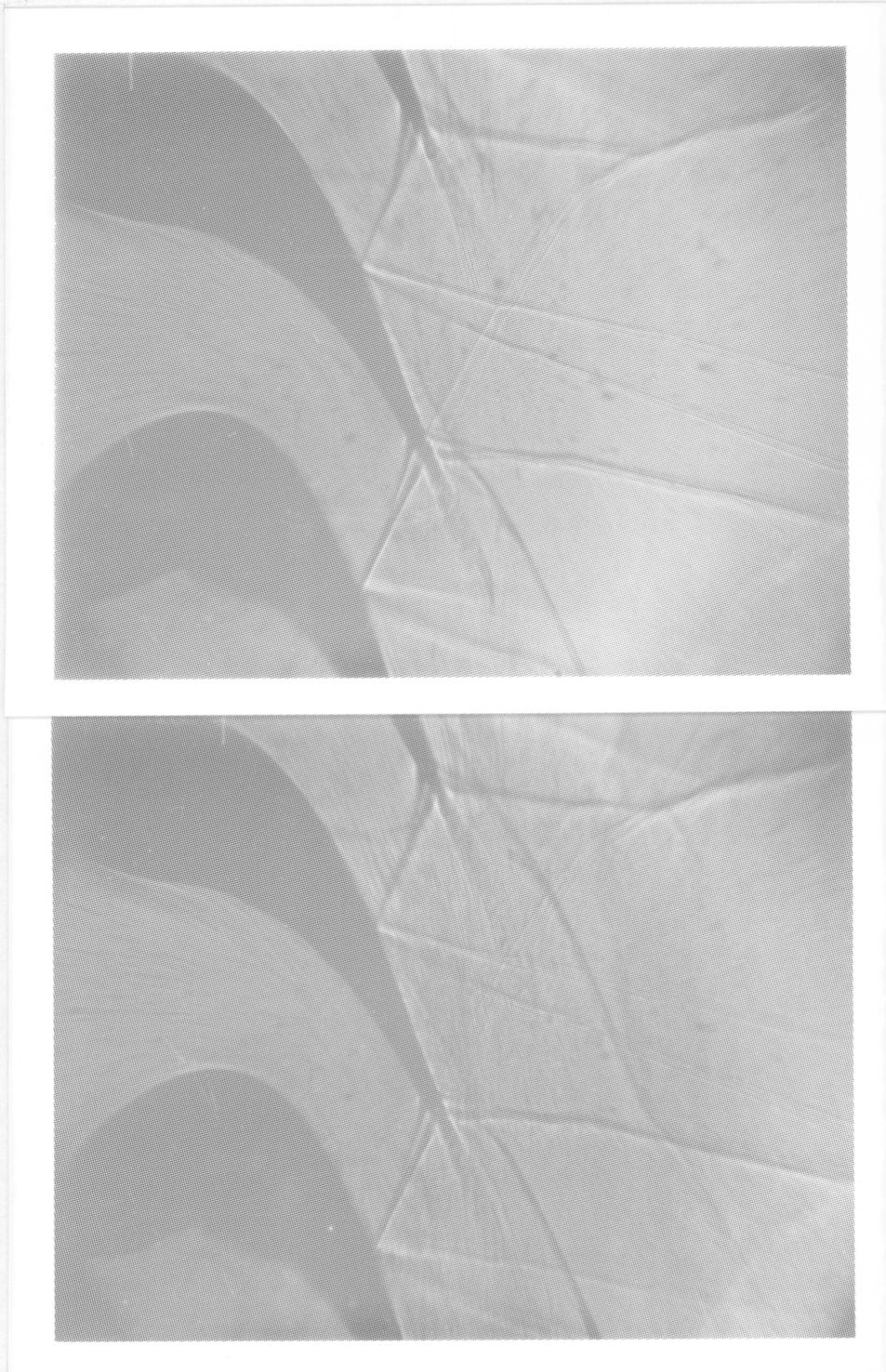


Figure 21. Shadowgraph Pictures for a Porous Tailboard at a 66 Degree Angle: (Top picture $p_o = 27.54$ psia = 189.9 kPa; bottom picture $p_o = 28.03$ psia = 193.3 kPa)

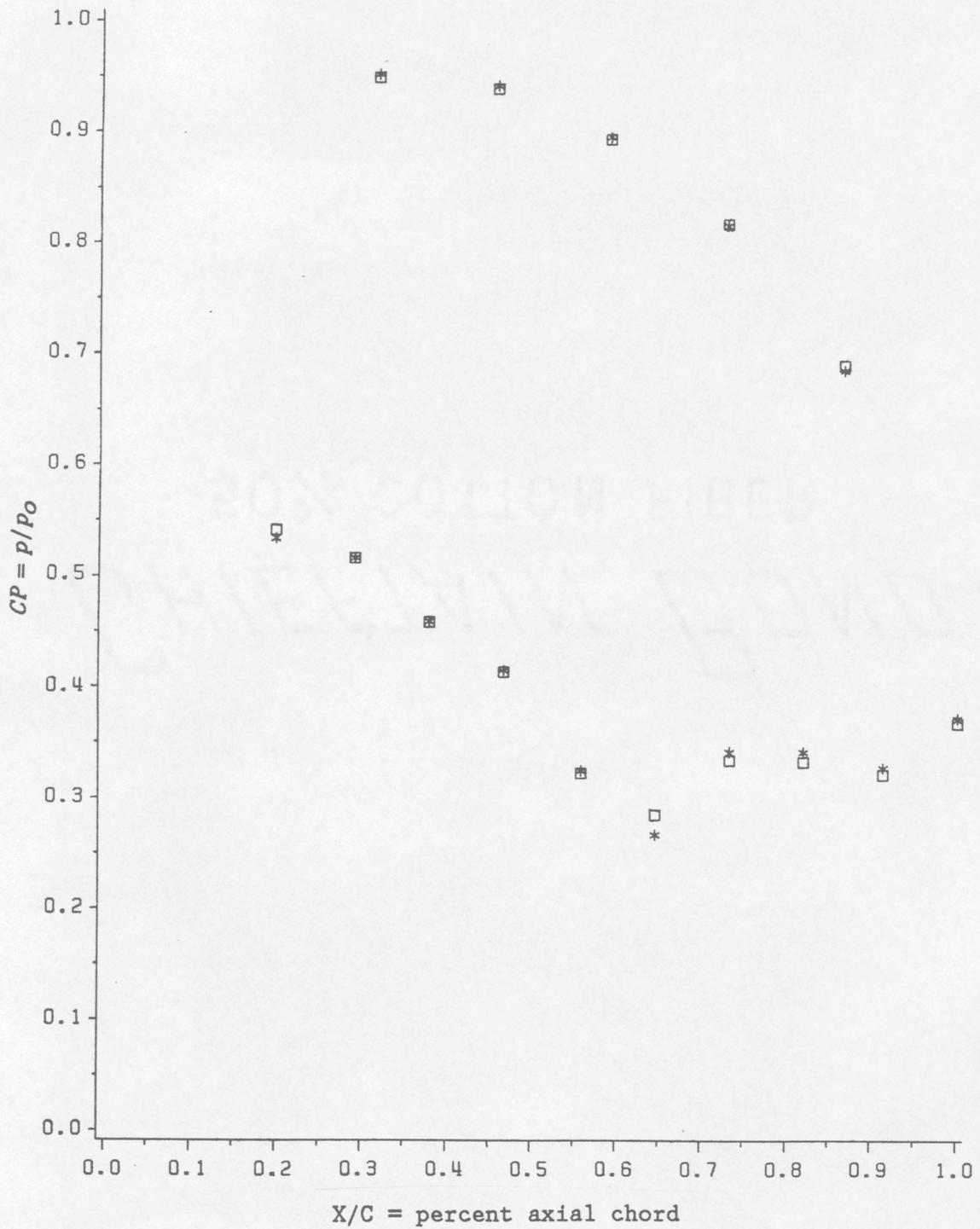


Figure 22. Blade Surface Pressure Distributions for a Solid Tailboard at a 66 Degree Angle: (Square $p_o = 21.5$ psia = 148 kPa; Star $p_o = 28.6$ psia = 197 kPa)

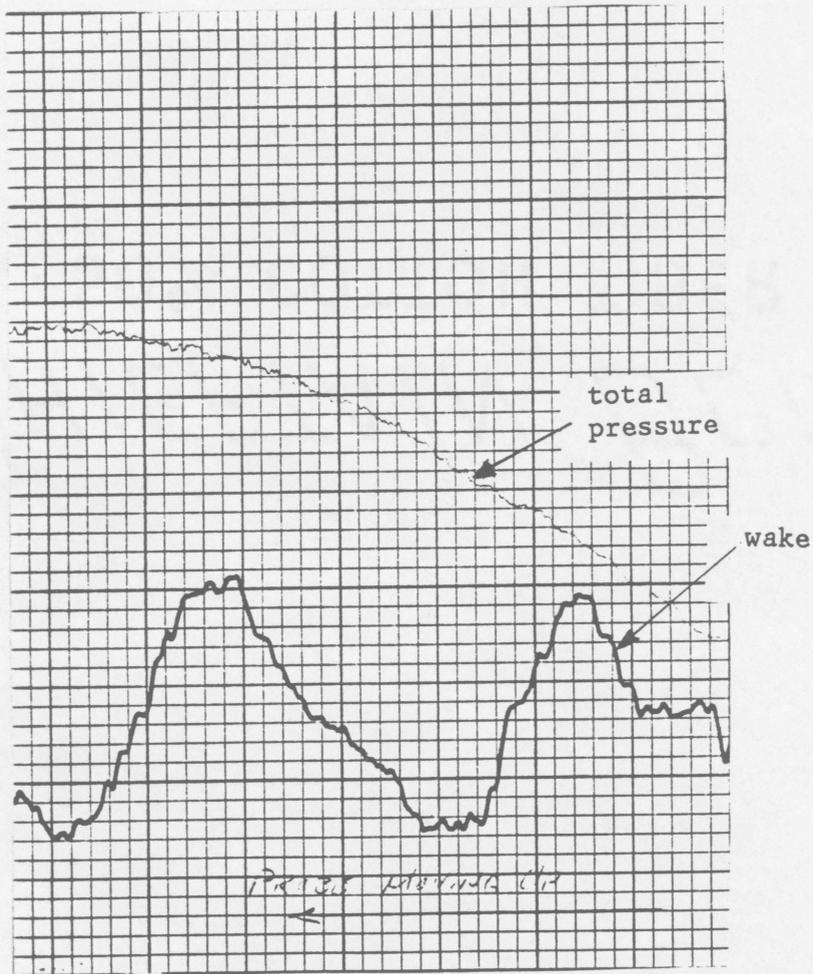


Figure 23. Transonic Cascade Wake for a Solid Tailboard at a 67 Degree Angle: (Taken 2.0 axial chord lengths downstream of cascade exit) (1 inch = 0.95 psig = 6.6 kPa for wake; 1 inch = 3.45 psig = 23.8 kPa for total pressure)

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