A SIMPLE VENTILATED TRANSONIC NOZZLE FOR PROBE CALIBRATION IN WET STEAM

by

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Abstract

For some years CERL have been making pressure traverse measurements in high output operational L.P. steam turbines. It became necessary to extend the measurements to transonic and supersonic regimes so that accurate transonic calibrations of the CERL turbine probes became necessary. Tests in a transonic wind tunnel at R.A.E. Farnborough emphasized the need to construct a transonic test section for the CERL steam tunnel.

Because of the design of this tunnel it had been considered that provision of a transonic test section would involve major rebuilding of the tunnel with separate test sections for transonic and other regimes. However, a simpler solution was realized, in which the permeable walls were provided by simply-installed liners and the suction by self-induction. Calibrations obtained with this new test section, having suction on two walls only, showed excellent agreement with calibrations obtained in the much larger R.A.E. tunnel.

1. Introduction

For some years CERL have been making pressure traverse measurements in high output operational L.P. steam turbines (Moore et al., 1979). Whilst transonic flows were sometimes encountered in turbines, no true transonic calibration was available for the CERL turbine probes (Moore et al., 1973). Because of this, tests were arranged in a transonic wind tunnel at R.A.E., Farnborough (Langford, Keeley and Wood, 1980). These tests emphasized the need for a transonic test section to be constructed for the CERL steam tunnel. Although the need had been recognized previously, the likely size, complexity and cost of the tunnel conversion had caused plans for its implementation to be delayed.

The basic scheme for a transonic wind tunnel involves the use of vented walls, which have a dual purpose.

Firstly, tunnel blockage is avoided because the flow is able to divert around an object placed in it by passing through the permeable walls. Such blockage is severe at Mach numbers close to unity, since small changes in the cross-sectional area of the duct cause large changes in flow velocity. Thus, quite a small body placed in a stream flowing at a Mach number just above or below 1.0, in a channel with impermeable walls, will cause flow blockage in the plane of the body, inducing large scale perturbation of the flow throughout the channel, with possible shock-induced separation at the walls and a reduced nett flow rate.

Secondly, by varying the amount of bleed through the permeable walls, the flow Mach number may be varied, since an effective divergent nozzle is formed (Fig. 1).

It was realized that it might be possible to build a much simpler transonic test section than had originally been envisaged by utilizing the concept of permeable liners and self-induced suction.

Because of the design of the CERL Steam Tunnel, only two walls, the upper and lower, could readily be made permeable, and it was not known if this would be sufficient to control blockage. Further features which were in question were the effectiveness of the self-induction and the comparatively small size of the channel relative to the probes which were required to be calibrated.

2. Test Section Design Considerations

The basic configuration adopted is shown in Fig. 2 and Plate 1. The permeable walls for transonic wind tunnels have in the past mainly been made with either longitudinal slots or with perforated plates (Goethert, 1961). Longitudinal slots generally have been found adequate for high subsonic flow, but require careful shaping to achieve stable and longitudinally uniform supersonic flow. Perforated walls are less prone to give unstable or non-uniform flows and Goethert (1952) found that a perforated wall laid over slots was particularly well behaved.

Further features which can affect the flow uniformity are the open-area ratio or porosity of the walls and their setting angles.

At the time of building, the only ready-made perforated stainless steel sheet available commercially had 31.4% open area. By adopting the combination of perforated and slotted wall, the underlying longitudinal stringers forming the slots could be adjusted in size and spacing to give porosity of approximately 16% (7% if the area of the impermeable side windows is included). The optimum appeared from the literature to be between 5 and 12%, but the effect of having only two porous walls was again uncertain.

The cross-section dimensions of the CERL Steam Tunnel test section are 152 mm (6 ins) wide by a maximum of 305 mm (12 ins) high. Top and bottom liners may then be fitted within the 305 mm height, depending on the Reynolds and Mach numbers required. In deciding the positions of the permeable walls, a compromise had to be reached between maximum main flow area to reduce the likelihood of blockage problems and sufficiently large plenum cross-sectional area (Fig. 2) to give a wide Mach number range and adequate volume for alleviation of plenum blockage.

It was found that the "outer" liners bounding the 305 mm channel height could be moved outwards to give an additional 25 mm height, and the distance between the permeable liners was set to 203 mm, fed by a convergent approach nozzle. Therefore the overall cross-sectional area ratio

$$\frac{\text{main flow + plenum areas}}{\text{throat or main flow area}}$$

was 1.63. However, this is not equivalent to a Laval nozzle area ratio, since the bled flow is subject to high losses in passing through the permeable wall.

It was assumed that the open area of the permeable walls should be approximately equal to the plenum cross section, so that the outflow was not limited by plenum size, and the vertical distance between the permeable liners was determined by this criterion.

Figure 3 shows the influence of the wall setting angle on the mass removal requirements (Goethert, 1961). For the present application, where the performance might be limited by mass removal capacity, the minimizing of mass removal requirement by the use of divergent walls was considered desirable.

It was found in the A.R.A. transonic tunnel (Haines and Jones, 1958) that less mass flow removal was required and that a much smoother axial distribution of Mach number was obtained if, instead of beginning the porous section abruptly at the throat, the porosity was tapered in gradually over an axial distance equal to approximately 80% of the test section height. This was achieved in the CERL test section by attaching PVC tape over the perforated liner in the pattern shown in Fig. 4 and Plate 1.

The lengths of the perforated test sections in existing air tunnels tended to be two to three times the tunnel height. In the present tunnel the height was determined by criteria already mentioned. For the trials it was considered that it would be useful to have the control flaps mounted in the test section windows to facilitate flow visualization in this region, and this determined the length of the liners.

3. Investigation of Test Section Characteristics

The tests described here were run with wet steam entering the test section for two main reasons. The first was that the flow conditions appeared more stable when the flow was wet. Secondly, with superheated inlet conditions and a supersonic expansion there was a tendency for condensation to occur in the test section, leading to uncertainty about the test conditions. In one test, in which a wedge was mounted in the test section (§ 3.4), the tunnel was started dry and an unsteady bow shock was seen to appear ahead of the wedge. Immediately the speed of the conditioning turbine was increased to produce wet inlet conditions, the shock was seen to stabilize and become steady.

When quoting wet steam flow conditions it has been the practice to give the Mach number defined via the equilibrium sound speed $a_{eq} = (\gamma_{eq}\, p\, \bar{v})^{\frac{1}{2}}$ where $\bar{v}$ is the mixture specific volume and γ_{eq} is the equilibrium value of the specific heats ratio commonly taken as 1.12. However, when considering flows over bodies which are small compared with the relaxation lengths in wet steam, it is the gas or "frozen" Mach number of the flow which is more relevant, where the "frozen" sound speed is given by $a = (\gamma\, p\, v_g)^{\frac{1}{2}}$ where v_g is the gas specific volume and γ is the gas specific heats ratio (1.32 for L.P. steam conditions). Therefore, when, for example, turbine probe calibrations are being considered it is the frozen conditions which are thought to be most relevant.

3.1 Initial Trials

The first build of the test section was with parallel walls and uniform porosity over the whole length of the liners. The variation of Mach number with flap setting was measured using a supersonic pitot-static combination pressure probe mounted just upstream of the exit plane of the liners and close to the tunnel centre line. With the tunnel condenser operating normally and wet steam being produced by the conditioning turbine a frozen Mach number range of 0.89 to 1.01 (0.94 to 1.07 equilibrium) was obtained with flow from one boiler and 0.84 to 1.09 (0.90 to 1.15 equilibrium) with both boilers operating. The difference is assumed to result from the lower tunnel pressure ratio obtainable with a single boiler flow.

The CERL turbine pitch probe (Walters, Moore and Langford, 1971) was then mounted at +20° pitch, close to the exit plane of the liners (Plate 2) and the Mach number range was checked again. Little change was recorded in the maximum Mach number achieved, and there was no evidence in these tests of limitations caused by blockage.

Further tests were made with flaps closed (0° setting angle) to investigate the effect of varying condenser flow on the minimum Mach number range. As expected this was similar to the performance with a conventional subsonic nozzle fitted.

It was clear from Schlieren flow visualization that for transonic conditions the pitot-static probe was mounted too close to the test probe and that some better means of obtaining the flow reference conditions might be desirable. A further point which was noticed was that the pitot-static probe used, having separate needle-type static tube and pitot tube mounted side-by-side on a single support (Plate 2), might be unsuitable for flows with Mach numbers just above unity, since the nearly normal bow shock created by the pitot tube could fall across or close to the measuring holes on the static tube.

It was found that with the flaps closed or slightly open (up to approximately 15°) the flow tended to flow into the plenum chambers further upstream and then return to the main flow through the porous walls just upstream of the flaps. This might also mean that if the test body were mounted too close to the exit plane, the bleed flow which alleviates the blockage might be inhibited. Because of this, the flaps were reduced in height so that some outflow was still allowed when they were set at 0°. Subsequently this feature was discarded since it caused an undesirable flow distribution at the exit and it was thought to limit the achievement of subsonic Mach numbers.

Mounting the test body too close to the nozzle exit plane is undesirable in any case because of the possibility of interaction between the body wake and strong shock or expansion waves in the exit. For an axisymmetric body with blunt base, Goethert (1961) gives 2.5 times the base diameter as the recommended minimum axial distance from the exit plane.

Subsequently the test section was reassembled with ½° divergence on each wall and with tapered porosity over the first 102 mm (4 ins) of the liners, as lready mentioned in Section 2 and illustrated in Plate 1. A check on the performance showed that the maximum frozen Mach number achievable had risen to 1.25 (1.31 equilibrium). Fig. 5 shows the variation of Mach number with flap angle obtained from this test, showing a strongly non-linear relationship.

shadowgraph picture of Plate 3. In the case of near-sonic conditions the main decline of stagnation pressure occurred within the supersonic expansion at the end of the liners, so this may also have originated from the wavelets. At these near-sonic conditions the apparent fall in stagnation pressure upstream of this region was of the same order as the error band, so may not have been real.

3.3 Measurement of Flow Angle

To measure the flow angle in the vertical plane, a 10° semi-vertex angle wedge, spanning the width of the tunnel, was mounted in a window using a turbine probe protractor block for angle reference. This allowed the angle to be measured only to within approximately ±0.2°, although the discrimination in the pressure signals from the wedge would have given much greater accuracy had a more accurate scale been available.

The chord of the wedge was 22 mm and a pressure tapping was located on each windward surface at a distance of 16.7 mm from the leading edge and at a spanwise position to bring them on the tunnel centreline.

In the vertical plane, the tunnel centreline is set to fall 0.75° below horizontal in the streamwise direction to provide water drainage. At all flap settings, the wedge pressures became equal at flow angles between 0.5° and 1.0° below horizontal. Therefore, within the accuracy of the measurement, the flow was aligned with the tunnel centreline.

3.4 Flow Distribution with Body in Flow

It is customary in ventilated wall wind tunnels to use the plenum pressures as reference to give the flow conditions. Because of inequality and uneveness of the plenum pressures, it was decided not to calibrate the tunnel relative to these for the initial trials, but to measure the flow ahead of the 10° semi-vertex angle wedge with wall static tappings and retractable pitot probes.

Fig. 9 shows the static and stagnation pressures measured at stations 13 and 22, with the leading edge of the wedge positioned 47.5 mm downstream from station 22. It is probable that the wedge could have been mounted farther downstream without interacting with the exit flow, but a window was available with a mounting hole in the position shown and so this position was adopted.

In Fig. 9(a) ($M \cong 0.82$) it will be seen that there was a slight reduction in Mach number in the axial direction as the flow approached the wedge, and that as sonic conditions were approached (Fig. 9(b)) the fall in Mach number was accentuated. In both cases there was an associated rise in static pressure. This resulted from flow leakage ahead of the test body into the plenum chamber (Goethert, 1961) and it is recommended that the upstream conditions (station 13) are taken as the effective free stream flow for these settings.

In the case of supersonic flow (Fig. 9(c)) a bow shock formed ahead of the test body (Plate 3); the flow ahead of it was undisturbed and behaved in a similar manner to that in a closed wall divergent nozzle. In this case the reference conditions should be taken just upstream of the bow shock (station 22 in the figure). For $1.05 \lesssim M \lesssim 1.15$ the body-induced wall static pressure rise occurs between stations 13 and 22 and its position must be measured.

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7. Acknowledgement

The work was carried out at the Central Electricity Research Laboratories and is published by permission of the Central Electricity Generating Board.

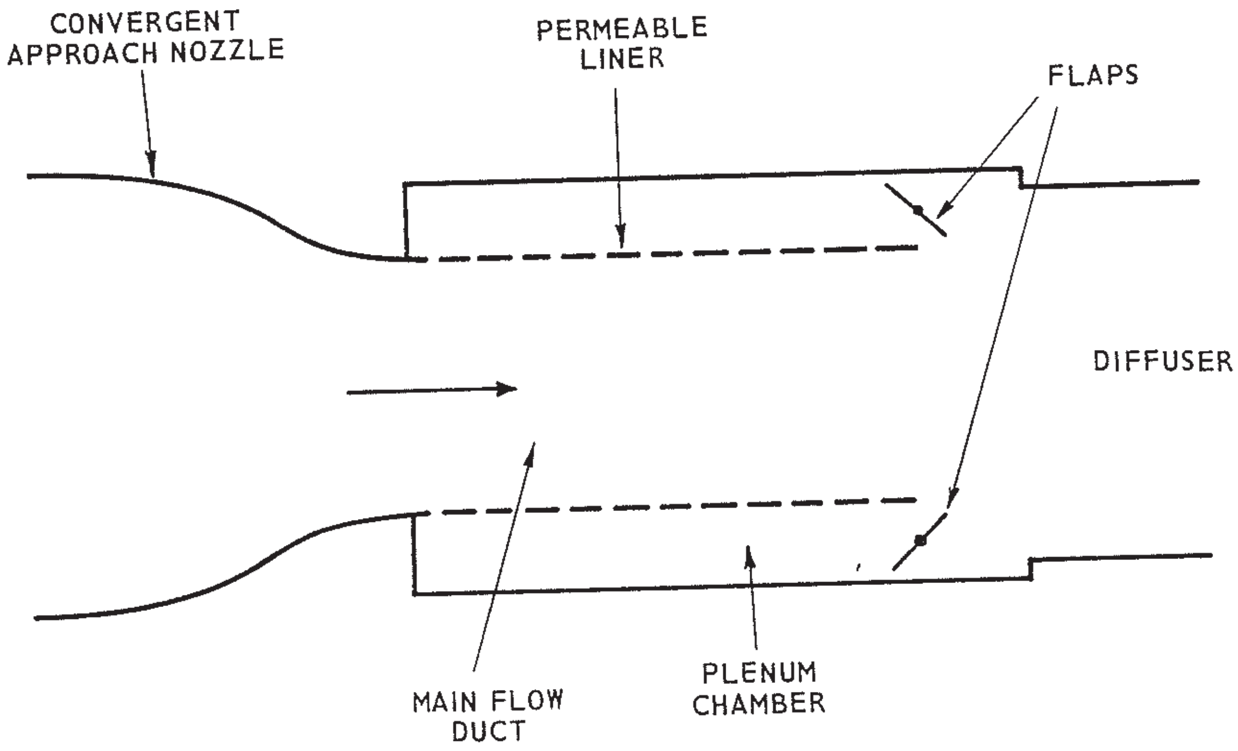
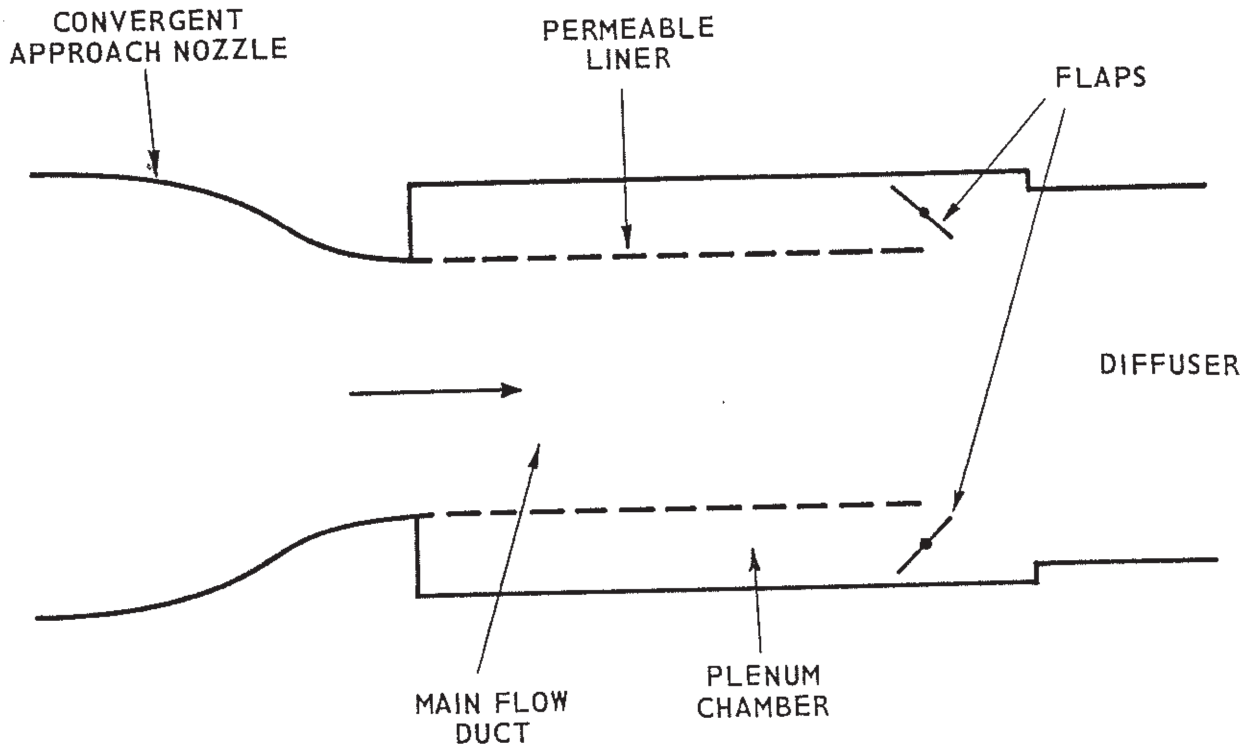


FIG. 2 CONFIGURATION OF CERL TRANSONIC TEST SECTION



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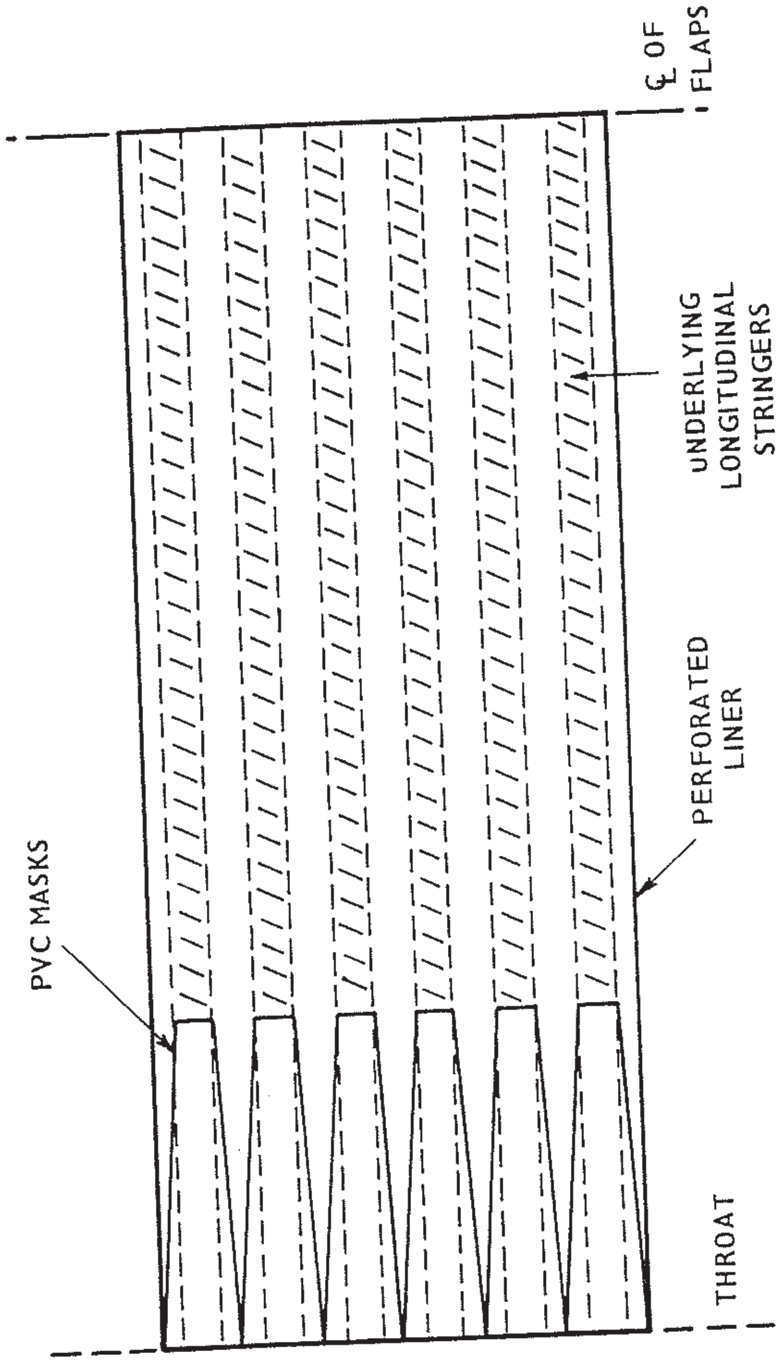
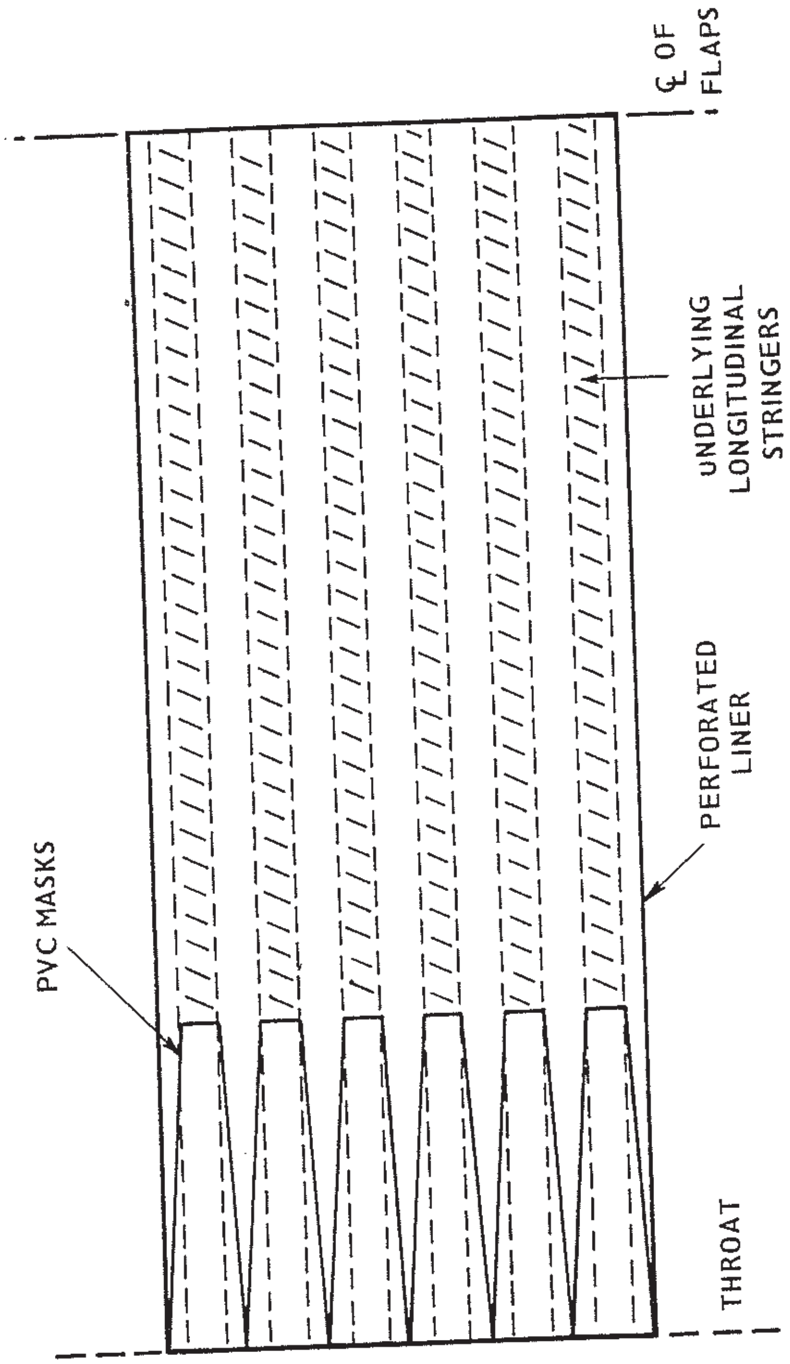


FIG. 4 MASKING TO PROVIDE TAPERED POROSITY AT ENTRANCE TO TEST SECTION



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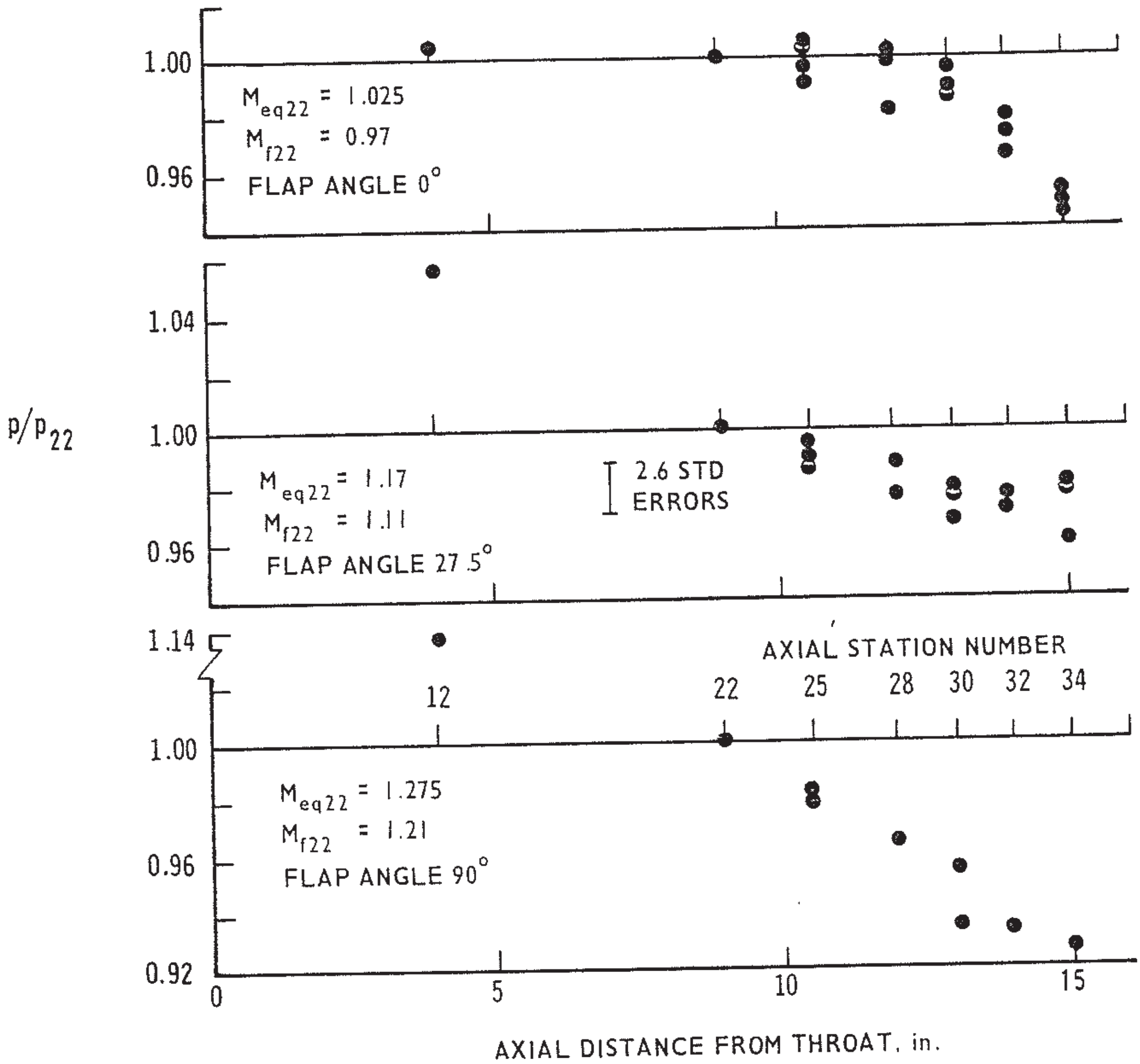
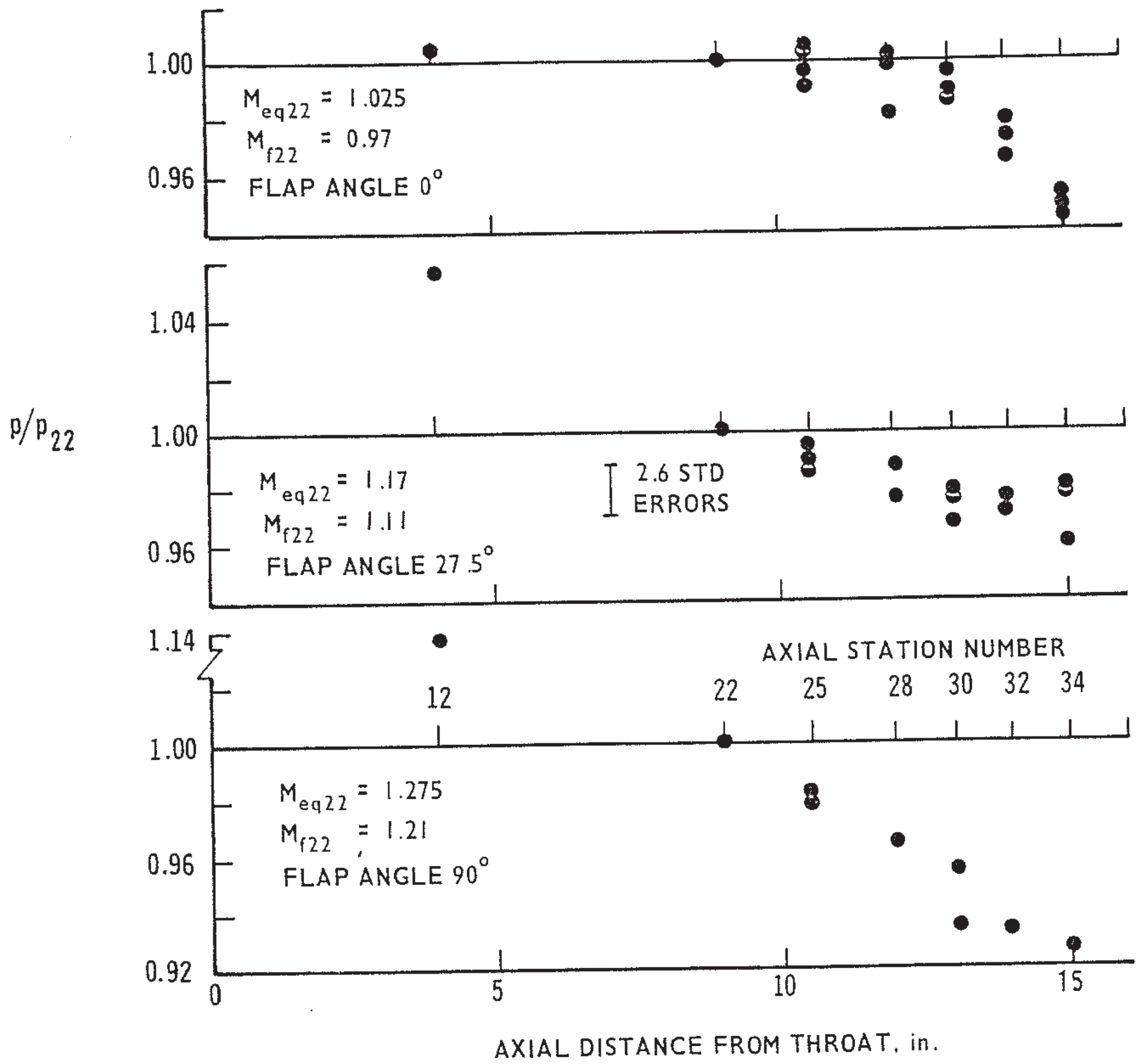


FIG. 6 STREAMWISE VARIATION OF STATIC PRESSURE



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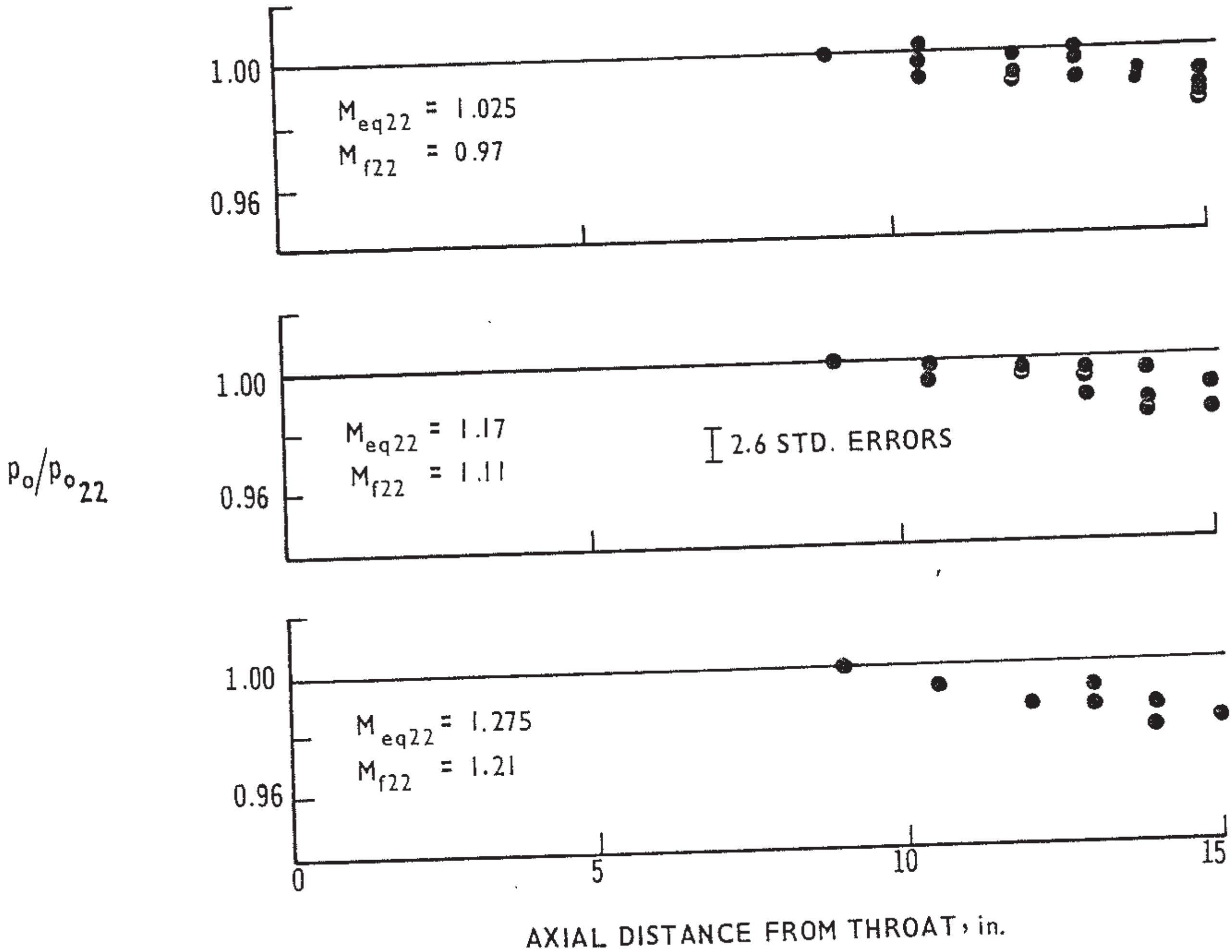
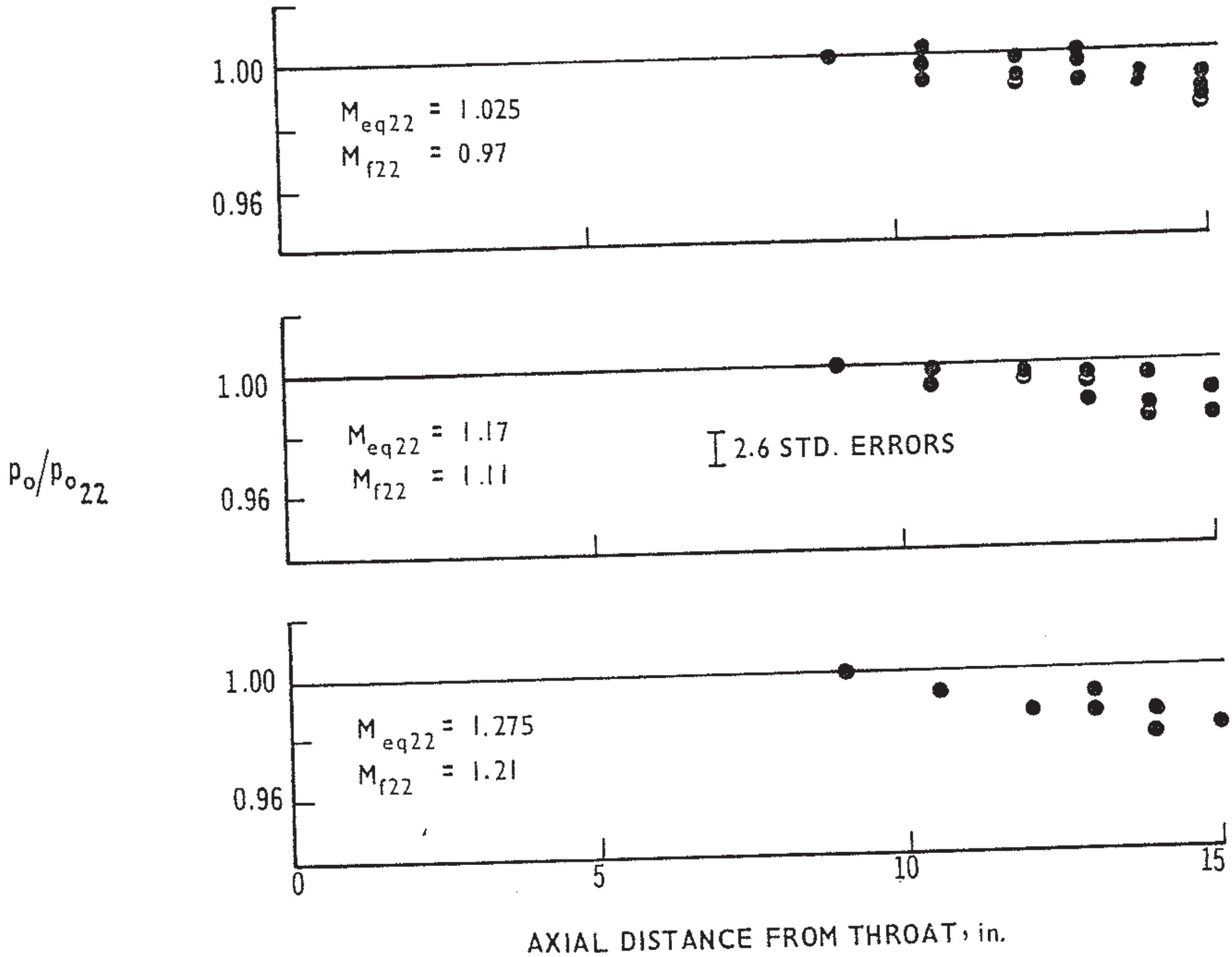


FIG. 8 STREAMWISE VARIATION OF STAGNATION PRESSURE



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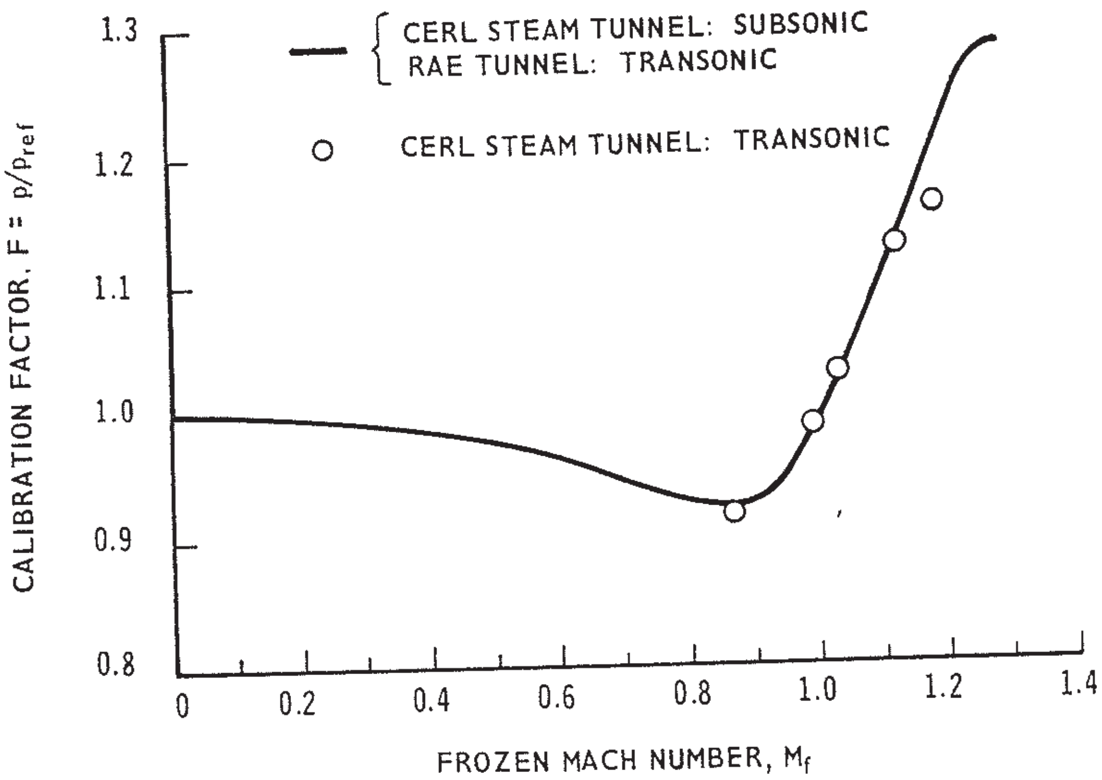
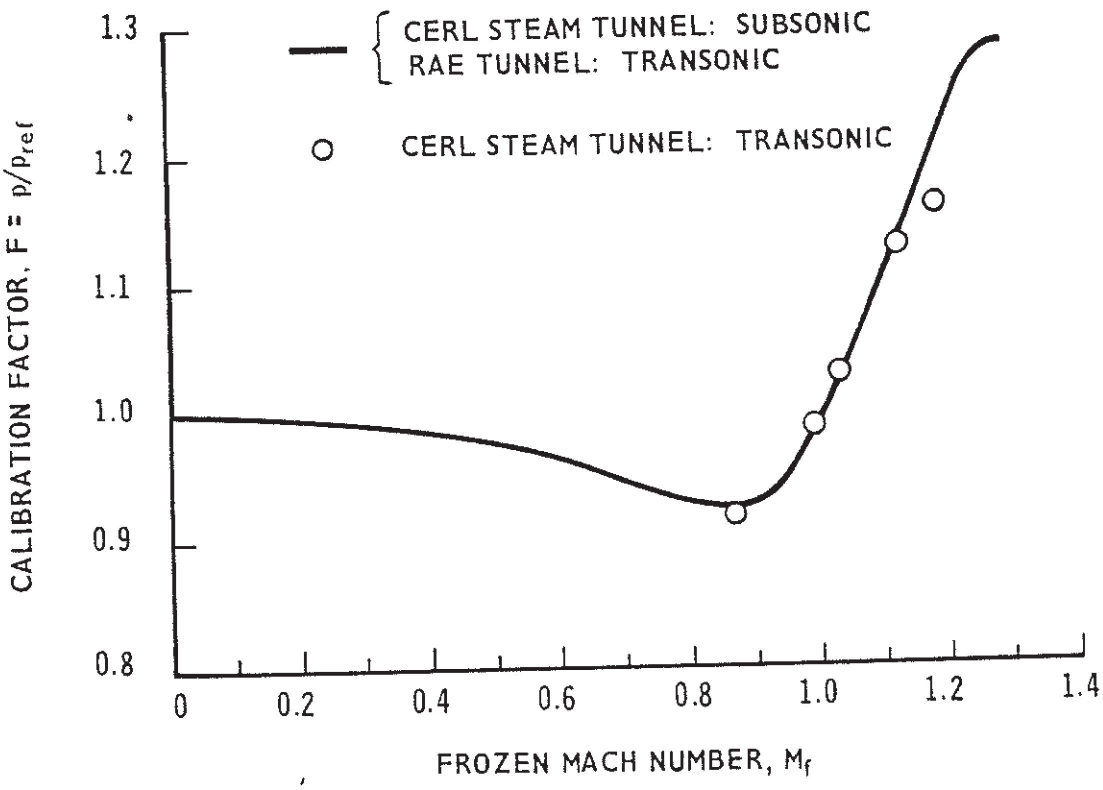


FIG. 10 CALIBRATIONS FOR PITCH ANGLE Ø = 0



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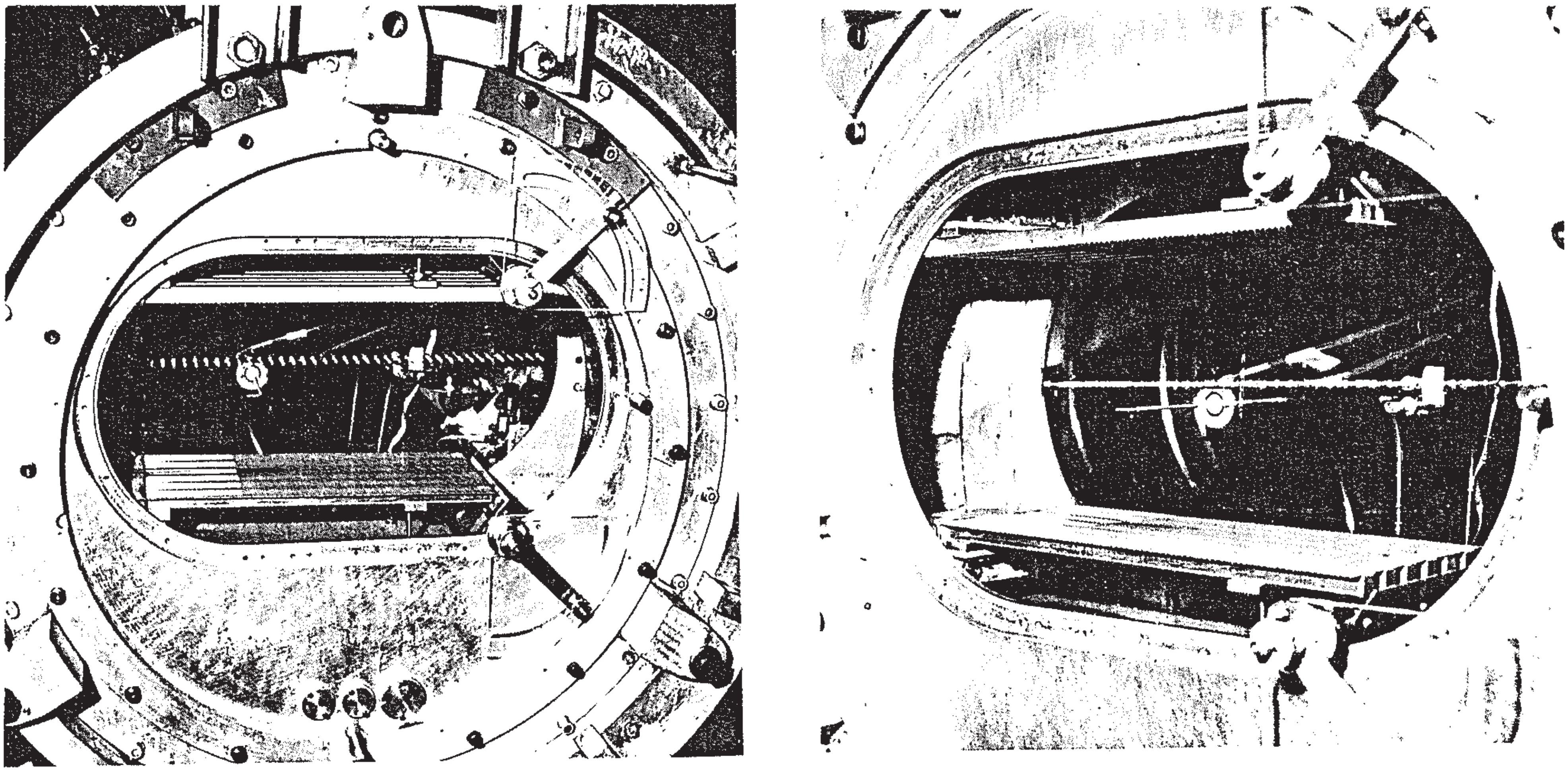

PLATE 1 TEST SECTION SHOWING PERMEABLE LINERS WITH UNDERLYING LONGITUDINAL STRINGERS, TAPERED POROSITY, FLAPS AND FLAP CALIBRATION QUADRANTS

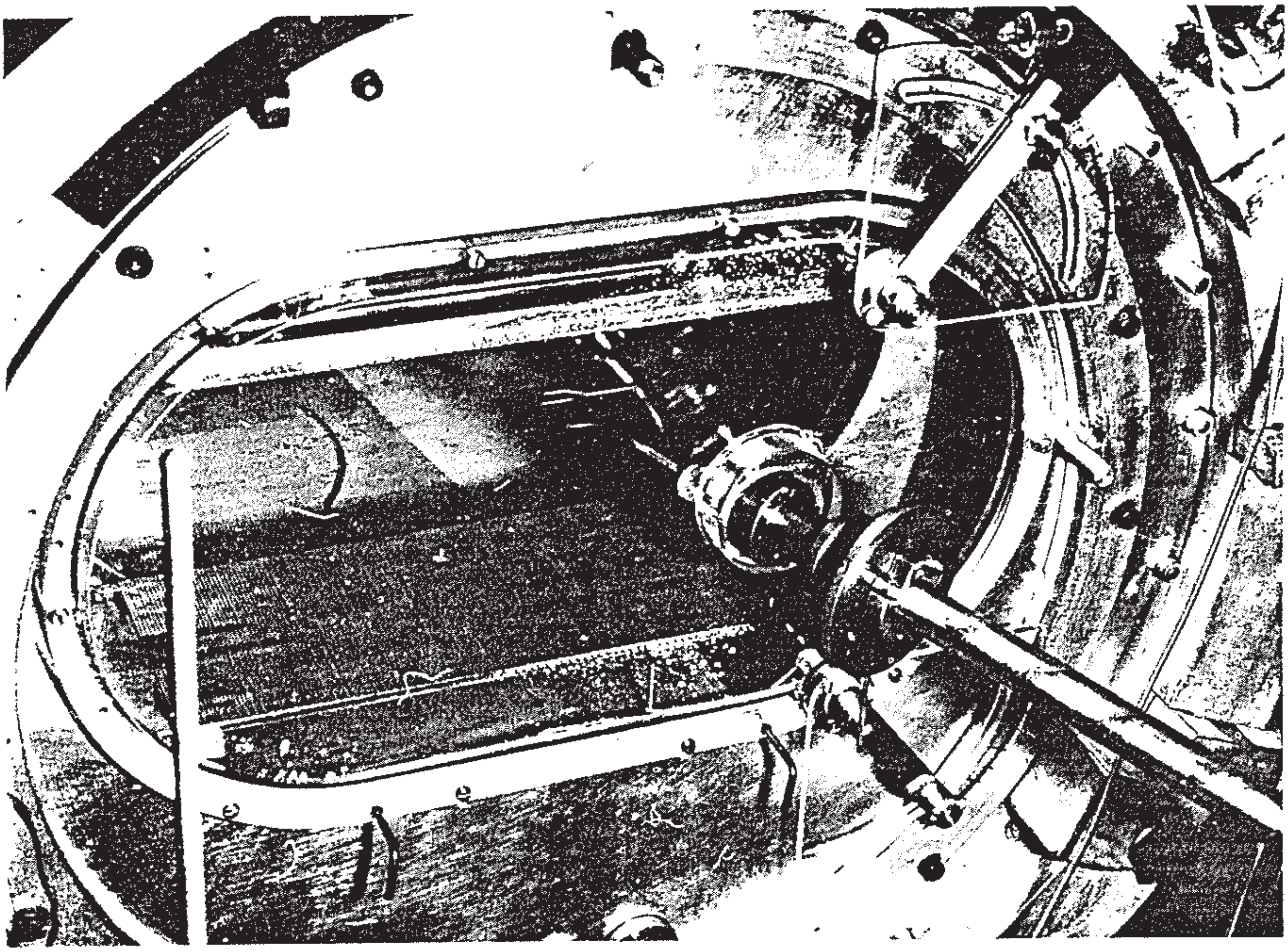

PLATE 2 TEST SECTION WITH ORIGINAL BUILD OF LINERS, SHOWING COMBINED PITOT-STATIC PROBE AND TURBINE PITCH PROBE

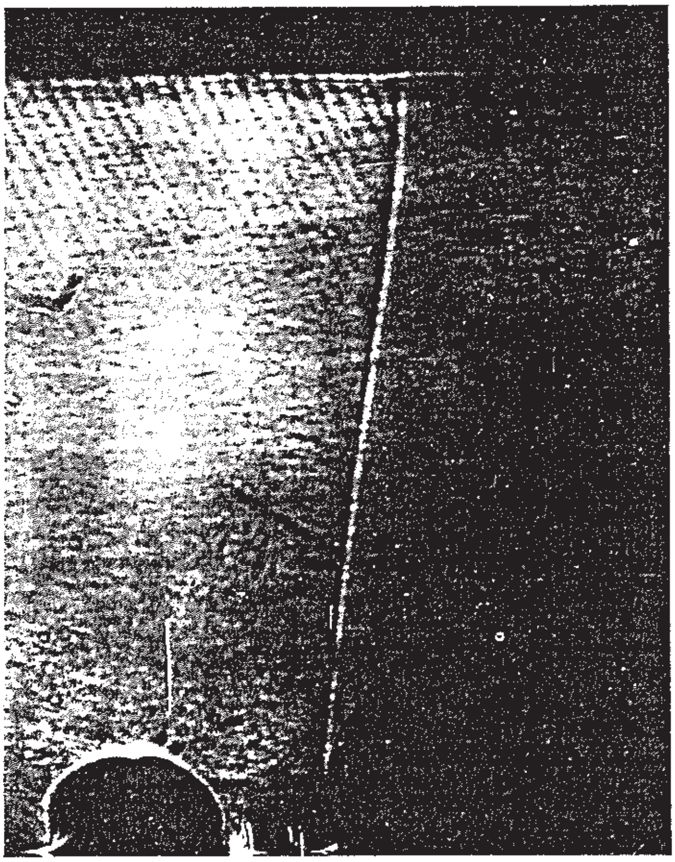

PLATE 3 SHADOWGRAPH SHOWING SHOCK WAVE UPSTREAM OF 20° WEDGE, CANCELLATION AT WALL AND WAVELETS CREATED BY PERFORATIONS