AN INVESTIGATION OF THE SHOCK WAVE STRUCTURE IN A CONDENSING WET STEAM CASCADE

- by -

S.A. Skillings

Central Electricity Research Laboratories,
Central Electricity Generating Board,
Leatherhead,
Surrey,
UK

Paper presented at the 9th Symposium on Measuring Techniques for
Transonic and Supersonic Flow in Cascades and Turbomachines,
Oxford, March 1988.

ABSTRACT

Some experiments have been performed to investigate condensing flow in a cascade of turbine blades. Certain aspects of the test section design are described and some results presented. Particular attention is paid towards the problems experienced during the experiment and the paper is concluded with some queries concerning the periodic flow fluctuations observed in the cascade.

1. INTRODUCTION

The thermodynamic cycles adopted for the generation of electrical power generally demand that the last few stages of low pressure steam turbines operate under wet steam conditions. In addition, when steam is raised using water-cooled reactors, the entire high pressure expansion will also lie in the two-phase regime. The performance of turbine blades in wet steam is therefore an important consideration, although one which has received all too little attention. Turbine designers tend to address only the erosion properties of wet steam and simply assume that it's presence will unavoidably degrade the efficiency of a machine by an arbitrary amount.

Recent evidence (**1**) has suggested that such treatments are inadequate and the appearance of water droplets in LP cylinders may be associated with a particularly high stage loss. However, the level of knowledge concerning condensation in turbines is such that no explanations have been forthcoming as to the cause of this reduced efficiency.

As an important step towards resolving the turbine condensation problem, droplet nucleation phenomena must be explored and understood in the two-dimensional cascade situation and several studies of this nature have been reported at previous meetings of this Symposium (**2,3**). However, wet steam cascade work presents a number of very individual problems (as will become apparent through the course of this paper) which have probably contributed towards the dearth of detailed experimental data in this field. Indeed, to the authors knowledge, no published work explains the shock wave structure which will be encountered in a condensing cascade, or describes how it will change when parameters such as inlet superheat or outlet Mach number are varied.

A cascade of turbine blades was designed and installed in the steam tunnel at the Central Electricity Research Laboratories (CERL) of the CEGB with the aim of clarifying the phenomena associated with condensation in a blade passage. The design, execution and results of the experiment are described in detail elsewhere (**4**). However, it is the purpose of this paper to highlight some of the problems encountered during the experiment and to discuss the periodic flow fluctuations observed in the cascade.

2. DESIGN OF TEST SECTION

2.1 Experimental Objectives

As a prerequisite to designing a test section, it was necessary to clearly define the aims of the experiment. The primary objective was not to produce a detailed quantitative analysis of the performance of the particular blade under investigation but rather to establish qualitatively the phenomena associated with condensation in a two-dimensional cascade. Consequently, the following basic goals were determined:

1. To create flow conditions representative of those occurring in the stator passage of the nucleating stage in an LP turbine. This did not demand that flow periodicity was rigorously sought, but simply that the flow accelerated to sonic conditions in a blade passage and exhausted into an environment where the flow was confined by steam emerging from similar passages on either side.

2. To install instrumentation capable of analysing unsteady flow regimes. Periodically fluctuating conditions are known to arise in nucleating straight nozzle flows (see **5**,**6**) but the existence of any analogous regime in cascades has not been reported.

3. To obtain schlieren pictures of the trailing edge shock structure for various values of outlet Mach number and inlet superheat.

4. To perform outlet plane total/static pressure traverses in order that values for mean outlet Mach number could be obtained and preliminary loss calculations be attempted.

5. To provide measurements of the mean droplet size produced by nucleation within the cascade.

2.2 The CERL Steam Tunnel

The steam tunnel test facility is described in detail by Moore *et al.* (**7**). The exhaust flow from a small impulse turbine is passed through a test section and on to a condenser via an adjustable outflow duct. The removal of various sections from this duct can produce turning angles at 4.5° increments between 0-90°. A steam supply of up to 0.9kgs^{-1} is available and by altering the work extracted at the turbine, the steam will either be wet equilibrium or dry superheated at inlet to the test section. Also, selective closure of cold water condenser passes can produce a wide variety of back pressures (and consequently outlet Mach numbers). In order to confirm that the steam tunnel is capable of producing the correct transonic conditions within a test section, design considerations similar to those described in (**2**) must be addressed.

2.3 Cascade Test Section

Blade profiles were selected which are typical of a quarter blade height stator passage in the nucleating stage of a 500MW LP turbine. Bearing in mind the experimental objectives discussed above and in the light of the test section choking requirements, the cascade was designed to comprise four half scale blades producing three blade passages. Instrumentation was incorporated to analyse phenomena in the central passage and the flow exhausted into a plenum, unconfined by tailboards. Fig 1 provides a schematic view of the test section.

The blade inclination angle (and hence that of the outflow duct) was determined such that the inlet flow would enter the cascade at zero incidence angle. The flow was directed towards the blades using intake nozzles and sufficient length of parallel liners to ensure that the flow onto the cascade was reasonably uniform. The ends of these liners were rounded at the corners creating a small bleed, thus diminishing the effect of the boundary layer which would thicken along the liners.

One of the principal aims of the experiment was to produce a clear photographic record of the shock wave structure using the schlieren technique. Successful schlieren photography in wet steam is often difficult due to the large quantities of coarse water running across the sidewalls and producing considerable deterioration in image quality. In an attempt to alleviate this problem, brass plates were attached to the duct upsteam of the intake nozzle (see Fig 1). These plates were constructed in order that water on the sidewalls would be channelled to positions on the intake nozzles which were connected by small bores to the downstream plenum. The pressure gradient would tend to bleed the water through these bores thus preventing it from contaminating the schlieren windows.

The blades were attached to brass plates which were in turn set into the dural windows. In order to facilitate schlieren analysis of the trailing edge shock system in the central passage, a window port was positioned just downstream of the brass plate. This enabled the interchangeable installation of schlieren windows with Perspex windows which could contain additional instrumentation. The windows were fixed in place by means of a dural clamp (Fig 2), glass to metal contacts being avoided to prevent window failures resulting from differential expansion rates as the rig approached operating temperatures.

3. INSTRUMENTATION

The positions of all probes and tappings are given in Fig 3 and much of this instrumentation can be seen in the photograph shown in Fig 4. No traverse of inlet conditions was attempted, relevant information being obtained from centrally mounted total pressure and temperature probes. Measurements of blade surface pressures were made using surface tappings connected to a transducer and air purge system by steel tubing which passed through the upper and lower blade passages. This arrangement would disturb the flow in the outer passages to a certain extent, however, it was considered extremely unlikely to interfere with the condensation phenomena in the central passage and facilitated very quick 'purge-down' times for these tappings. The probe used to measure total and static pressure at the downstream traverse plane was that described in (2), the alignment of the disc probe being achieved using the beam from a small He-Ne laser.

In order to study any fluctuating conditions which might arise, two high sensitivity absolute piezoresistive transducers (Endevco Model 8515B-15) were flush mounted in the blades and two similar transducers (Kulite Model XCS-093-15) were mounted in brass holders which could be fitted in the Perspex windows. These transducers were positioned to provide information concerning the transient behaviour and absolute values of pressure at the wall and on the blade surface at locations just downstream from the throat and near the trailing edge. Bridge excitation and output wires were fed out of the test section contained in steel and plastic tubing. It was suspected that these transducers would only remain operational for a short time in a hostile wet steam environment and despite coatings of parylene or RTV on their diaphragms the blade transducer nearest the trailing edge failed due to an open circuit in the bridge shortly after the commencement of testing. The remaining blade transducer and one of the wall transducers also ceased to function before the experiments were completed. The output from these transducers was transmitted via an amplifier (System 2300 Signal Conditioning, Welwyn Strain Gauge) to a tape recorder (Store 4DS, Racal) and a switching box from where the output could be directed to a DVM, spectrum analyser or oscilloscope. All conditions of interest were recorded on tape although a polaroid camera was available to provide a convenient reminder of typical scope traces.

The schlieren set-up is shown schematically in Fig 5 and photographic views of this system can be seen from both sides of the test section in Fig 6. It was necessary to wrap the optical path due to limited space although angles were kept to a minimum in order to reduce aberration effects. A 500 watt Varian Lamp light source was used and the high intensity beam produced was directed through the test section by means of an eight foot focal length concave reflector. Positioning a screen in front of the second schlieren mirror facilitated continuous observation of the shock system (i.e. operating in shadowgraph mode). A 35mm Nikon camera was installed to photograph shock systems which were essentially steady. It was found that greater information could often be obtained from a colour schlieren arrangement and this option was employed by incorporating the relevant modifications (see Fig 5). For the analysis of high frequency oscillating shock systems a high speed Hycam camera was introduced which is capable of recording up to 10000 frames per second.

Droplet sizing measurements were performed using light extinction techniques as described in (6). Ports to accommodate the steam tunnel optical system were mounted in the Perspex windows (see Fig 4).

4. CHARACTERISTIC SHOCK WAVE STRUCTURE

The flow pattern encountered in single phase transonic cascades is described in standard texts (e.g. 8) and a schematic representation is given in Fig 7. The shock system will principally consist of two trailing edge shocks, S_1 and S_2, where edge shock S_1 will generally lie within the passage and give rise to a reflected shock S'_1 . As the pressure ratio across the cascade is altered the position of this reflection point will move along the suction surface between the trailing edge and the blade throat.

For flows of wet steam, the pattern was found to be somewhat more complicated. With outlet Mach numbers $M_2 > 1.25$ a third shock, S_3 , appeared near the blade throat as can be seen from the schlieren photograph shown in Fig 8. This shock is the result of condensation heat release following spontaneous droplet nucleation and was clearly observed for both wet equilibrium or dry superheated inflow (conditions of inlet superheat $\Delta T > 15°C$ were not investigated). At higher back pressures shocks S_1 and S_3 merged to produce a pattern similar to that associated with a single phase expansion.

5. PERIODIC FLOW FLUCTUATIONS

5.1 High Outlet Mach Number

At conditions of high mean outlet Mach number ($M_2 > 1.4$) where trailing edge shock S_1 was positioned approximately along the line joining the blade trailing edges, a strong periodic fluctuation was detected by the downstream transducer (a piercing whistle was also clearly audible). Fig 9 shows the power spectral density at one such condition and it indicates a strong peak at 1604.5Hz. This oscillation produced pressure fluctuations with an amplitude of 10% inlet total pressure.

This oscillation is not suspected to be a wet steam phenomenon but rather a characteristic of the test section. The flow was clearly separating from the blade back near the reflection point of shock S_1. Also, possible influences of the turbulent shear boundary cannot be discounted.

5.2 Low Outlet Mach Number

With mean outlet Mach numbers in the range $0.75 < M_2 < 0.95$, a clear sequence of oscillating modes were encountered (Figs 10-12). As the Mach number decreased, an oscillation of 3200Hz was initially detected on the blade, Fig 10. This fluctuation was not detected by the wall transducers which continued to register turbulent noise outputs. As the back pressure increased, an oscillation of 3040Hz was recorded on the blade, with a peak at 2820Hz occasionally emerging and temporarily replacing the higher frequency mode, Fig 11. Concurrently, the wall transducer was detecting oscillations with frequencies equally shared between 3010Hz and 2820Hz with a peak occasionally appearing at 2750Hz. Upon further reduction in Mach number the blade transducer detected discrete frequencies of 2750Hz and 2350Hz until finally registering 1880Hz, Fig 12. By this stage the oscillations were actually stronger at the wall. As the mean outlet Mach number dropped below $M_2 \simeq 0.75$ the flow field became entirely subsonic and the turbulent noise spectrum returned.

Schlieren photography revealed that this oscillation sequence arose when trailing edge shock S_1 lay virtually across the throat of the blade passage. A similar occurrence was observed in a transonic cascade by Deich *et al.* **(9)** for both dry and condensing steam flows. They attributed these oscillations to a shock wave/boundary layer interaction. However, droplet sizing measurements revealed that the shock wave fluctuations were also interacting strongly with the droplet nucleation process since the measured mean size was much larger than at steady but otherwise similar conditions.

These observations have emphasised that the cascade flow, is ,in fact, three-dimensional, with significant variations in flow behaviour across the blade row. Indeed, it is possible that the various discrete frequencies represent standing wave oscillatory modes in a transverse direction across the blade passage and this must question the direct relevance of this phenomenon for turbine flows.

6. DISCUSSION OF RESULTS

6.1 Problems Experienced During Cascade Testing

A number of problems associated with the instrumentation of wet steam flows (purging of pressure tappings, temperature measurement in regions of supersaturation, measurement of mean droplet size and wetness fraction, etc.) have been widely discussed (e.g. **10**). Two further aspects have received little attention but were found to present particular difficulties during these experiments.

6.1.1 Schlieren Analysis

As mentioned earlier, there have been very few good quality schlieren photographs of wet steam flows published in the literature. The difficulty of wet steam schlieren analysis was recognised and a number of problems envisaged. Points 1 and 2 are examples of problems successfully overcome at the design stage. Point 3 represents an additional complication which was not anticipated at the outset.

1. The thermal transients involved in bringing large steam rigs to operating conditions potentially exert considerable stress on the schlieren windows. Failures are not uncommon and due to the time and expense involved in producing the optical quality glass, suitable design precautions were included (see Fig 2).

2. Schlieren photographs are often ruined by rivulets of water running across the windows. The installation of water traps as described in Section 2.3 proved a particularly simple

and successful remedy with good quality photographs being produced at inlet wetness fractions as high as 7.5%.

3. A particular property of large high temperature rigs is the need to remove thermal inertia effects. The time required to produce a good stable condition was found to be greater when the inlet conditions were dry than when they were wet. During this warm-up period a thin film formed on the schlieren windows and consequently when the desired condition was produced, the image quality had been degraded. Fig 13 illustrates a particularly bad example of this image degradation, showing some high speed photographs of the oscillating throat shock when the inlet superheat was $\Delta T \simeq 15°C$. The poor image quality is evident, thus demonstrating the surprising result that schlieren analysis of dry inlet flows was often rather less successful than for wet inlet flows.

6.1.2 Measurement of Unsteady Flows

In order to provide quantitative information concerning the unsteady behaviour of the cascade, a number of high sensitivity absolute piezoresistive pressure transducers were incorporated into the test section. The transducers had not been designed for use in a wet steam environment and the manufacturers suggested coating the diaphragms with parylene (Endevco) and RTV (Kulite) to improve operational integrity. The useful lifetime of the transducers was variable, lasting from only a few days to several months. Absolute piezoresistive transducers were selected to provide absolute values of pressure in addition to the unsteady characteristics. Performance in this respect was poor and even allowing for thermal shift effects, absolute values of pressure were extremely unreliable. However, whilst they remained in operation, the transducers consistently produced good transient data.

It is to be hoped that further wet steam cascade testing will involve analysis of unsteady phenomena. The use of pressure transducers of this type should be carefully reviewed and the associated problems recognised. A number of turbine probes are currently under development which employ similar transducers (e.g. **11**). Their applicability to the wet steam regime is at present somewhat dubious.

6.2 Unsteady Flow Regimes

Periodically unsteady flows were detected over two regimes of outlet Mach number. One of these regimes was associated with near limit load conditions (shock S_1 joining the blade trailing edges) and one with shock S_1 lying across the blade throat. Of these, the latter is potentially extremely interesting, since if it were found to arise in turbines, it would almost certainly interact with the droplet nucleation process and alter the mean droplet size produced. A number of important questions must be asked before firm conclusions are drawn:

1. Are these observations common in transonic dry steam or air cascades (or indeed in other condensing steam cascades)?

2. Is it possible that the oscillations have been produced by interactions with the turbulent shear layer and are similar phenomena encountered in cascades using tailboards?

3. The variations in transducer responses at the wall and on the blade (and the results of high speed schlieren) suggest a three-dimensional flow field. Is this a common observation?

4. The discrete oscillation frequencies detected possibly indicate the establishment of transverse standing waves across the blade row. Is this event likely and if so, how do the cascade results relate to the turbine situation?

7. ACKNOWLEDGEMENTS

The work was carried out at the Central Electricity Research Laboratories of the Technology Planning and Research Division and the paper is published with permission of the Central Electricity Generating Board. The author would also like to thank Dr. M.J. Moore who supervised the PhD project of which this experiment constitutes a part and Mr. P.T. Walters who made many helpful suggestions concerning cascade design and performed the droplet sizing measurements.

8. REFERENCES

1. Walters, P.T., Wetness and Efficiency Measurements in LP Turbines with an Optical Probe as an Aid to Improving Performance, ASME, 85-JPGC-GT-9, 1985

2. Jackson, R. and Walters, P.T., Design Considerations for the CERL Wet Steam Tip Section Cascade and First Test Results, Proc. of 5th Symp. 'Measuring Techniques for Transonic and Supersonic Flow in Cascades and Turbomachines', Leatherhead, UK, 1979

3. Trucco Martinengo, A., Benvenuto, G. and Campor'a, U., Observation of Condensation Shock in a High Deviation Blade Cascade by Means of the Schlieren Technique, Proc. of 8th Symp. 'Measuring Techniques for Transonic and Supersonic Flow in Cascades and Turbomachines', Genoa, Italy, 1985

4. Skillings, S.A., An Analysis of the Condensation Phenomena Occurring in Wet Steam Turbines, PhD Thesis, CNAA, CERL, 1987

5. Skillings, S.A. and Jackson, R., A Robust Time-Marching Solver for One-Dimensional Nucleating Steam Flows, 1987, Int. J. of Heat and Fluid Flow, Vol. 8, No. 2, 139-144

6. Skillings, S.A., Walters, P.T. and Moore, M.J., A Study of Supercritical Heat Addition as a Potential Loss Mechanism in Condensing Steam Turbines, Instn. of Mech. Eng., Int. Conf. on Turbomachinery, Paper C259/87, Cambridge, 1987

7. Moore, M.J., Walters, P.T., Crane, R.I. and Davidson, B.J., Predicting the Fog Drop Size in Wet-Steam Turbines, Instn. of Mech. Eng. Conf., Wet Steam 4, Paper C37/73, Warwick, 1973

8. Gostelow, J.P., Cascade Aerodynamics, 1984, Pergamon Press

9. Deich, M.E., Laukhin, Yu.A., Saltanov, G.A., Investigation of Unsteady Wave Structure in Turbine Nozzle Blade Cascades, Thermal Eng., 1975, Vol. 22, No. 8, 30-32

10. Moore, M.J., Chapter 4, Two-Phase Steam Flow in Turbines and Separators, Eds. Moore M.J. and Sieverding C.H., Hemisphere Pub. Corp., 1976

11. Kerrebrock, J.L., Epstein, A.H. and Thompkins, W.T., A Miniature High Frequency Sphere Probe, 1980, Measurement Methods in Rotating Components of Turbomachnery, ASME, (Ed. B. Lakshminarayana)

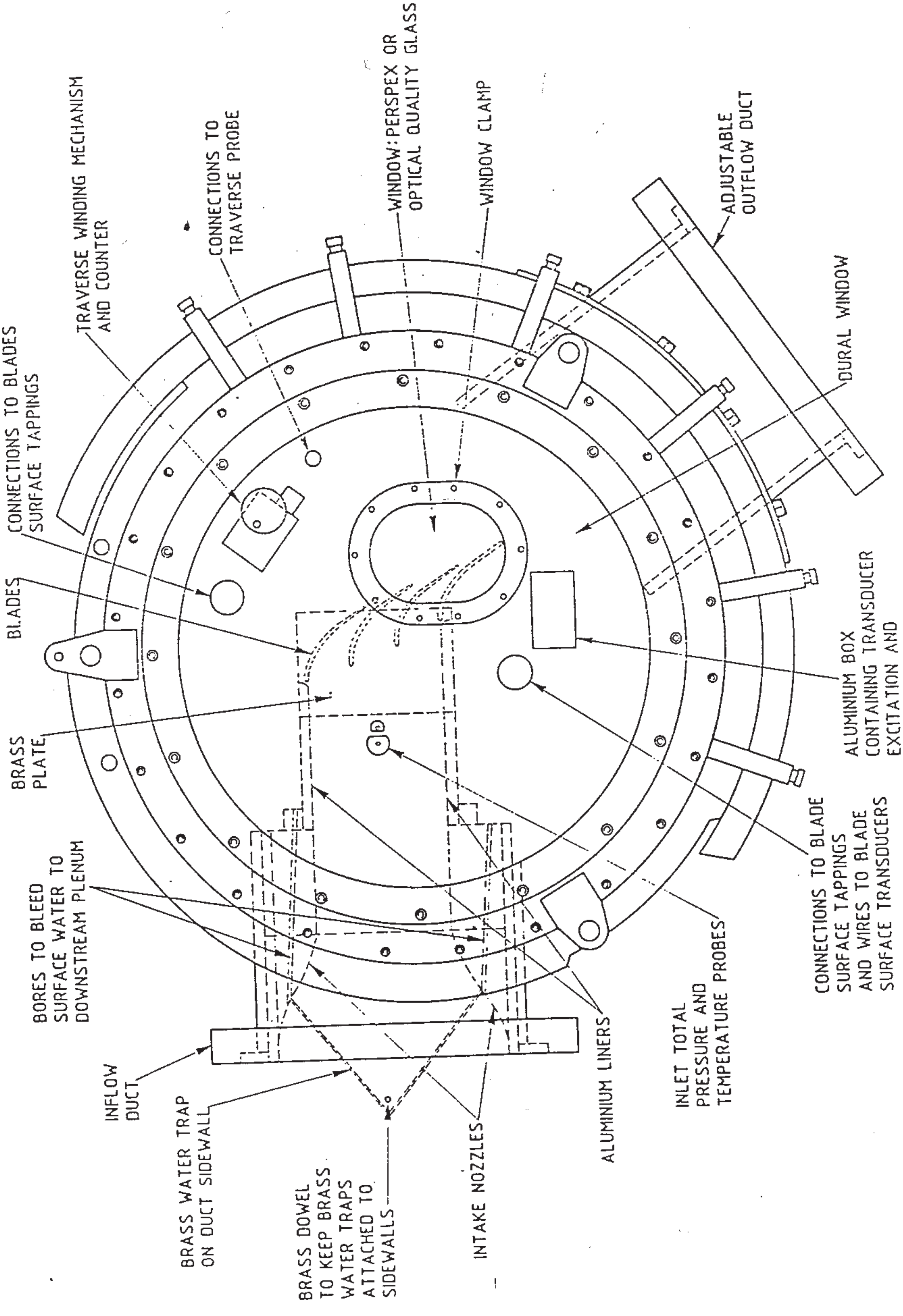
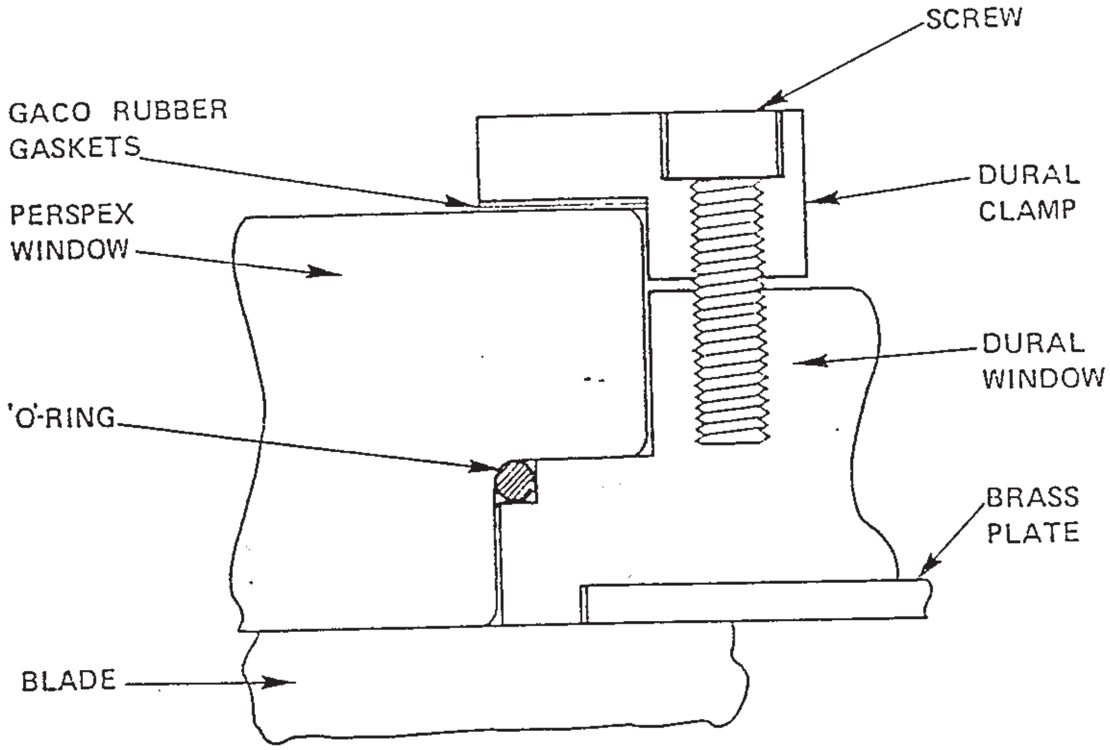
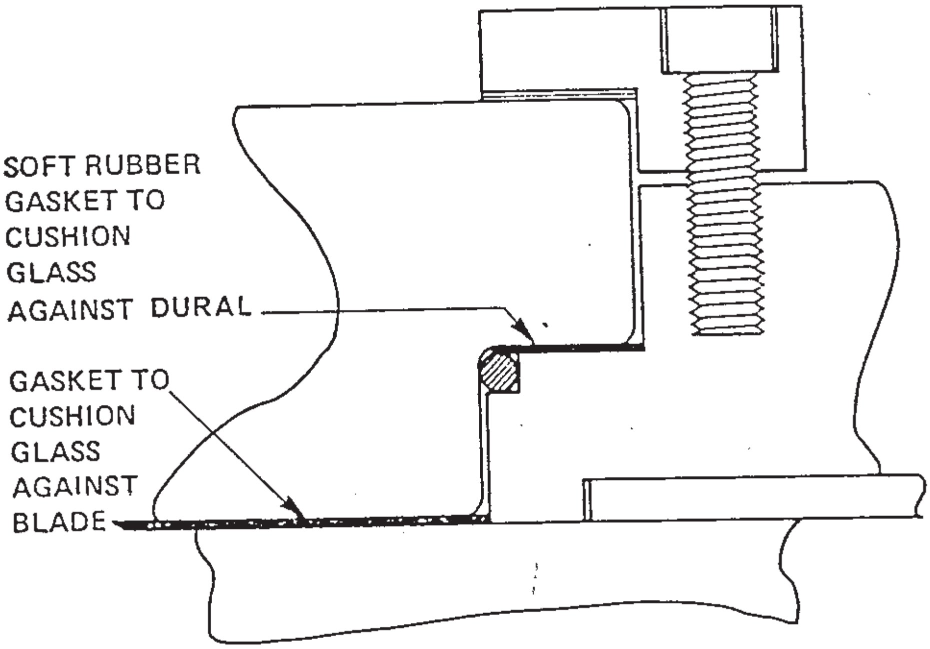


FIG. 1 TEST SECTION

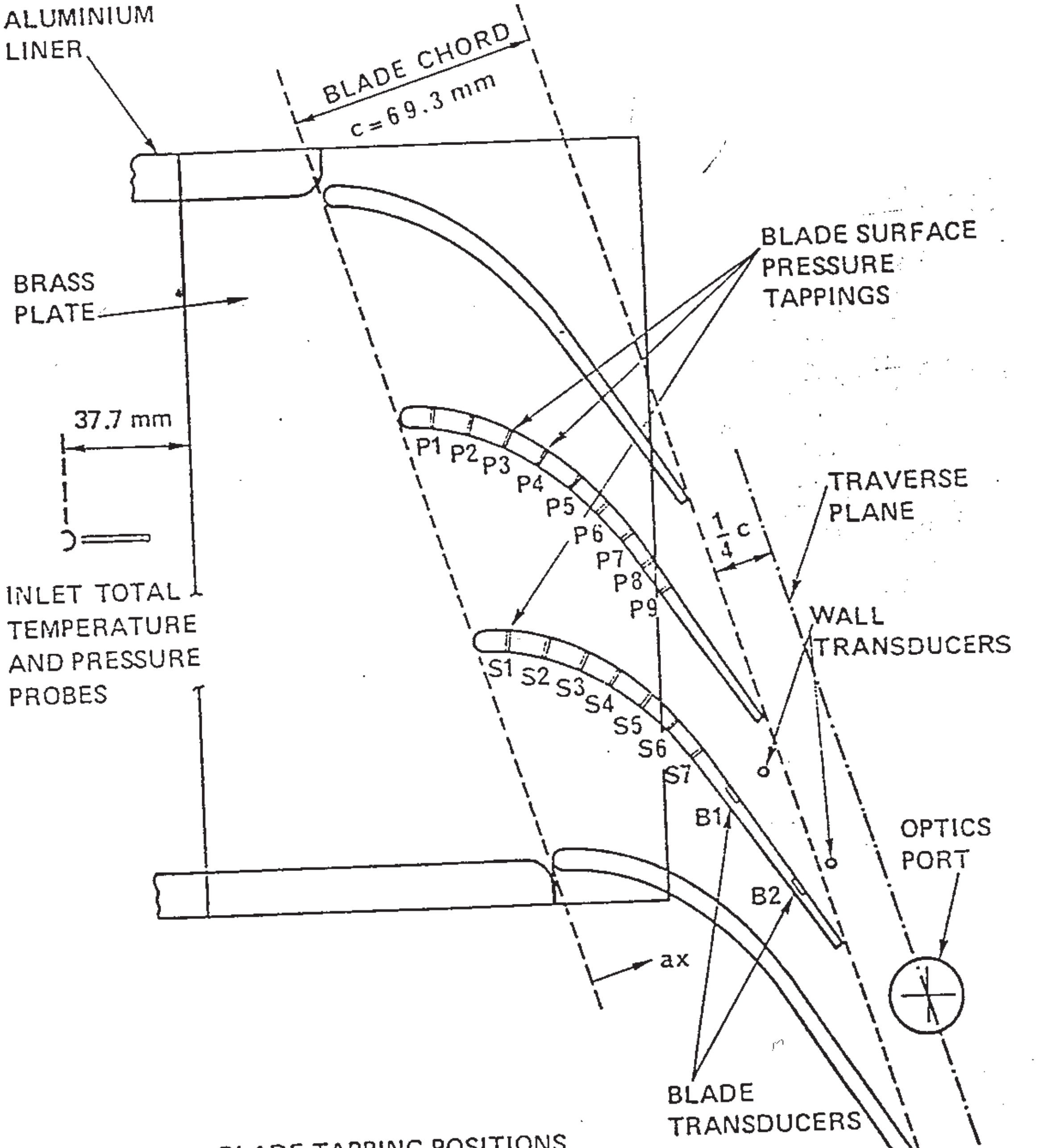


a) PERSPEX WINDOW



b) SCHLIEREN WINDOW

FIG. 2 WINDOW CLAMPING ARRANGEMENTS



BLADE TAPPING POSITIONS

PRESSURE SURFACE		SUCTION SURFACE	
TAPPING	ax/c	TAPPING	ax/c
P1	0.1271	S1	0.1472
P2	0.2464	S2	0.2873
P3	0.3509	S3	0.4083
P4	0.4472	S4	0.5162
P5	0.5355	S5	0.6058
P6	0.6174	S6	0.6922
P7	0.6735	S7	0.7534
P8	0.7131	B1	0.8009
P9	0.7559	B2	0.9076

FIG. 3 PROBE AND TAPPING POSITIONS

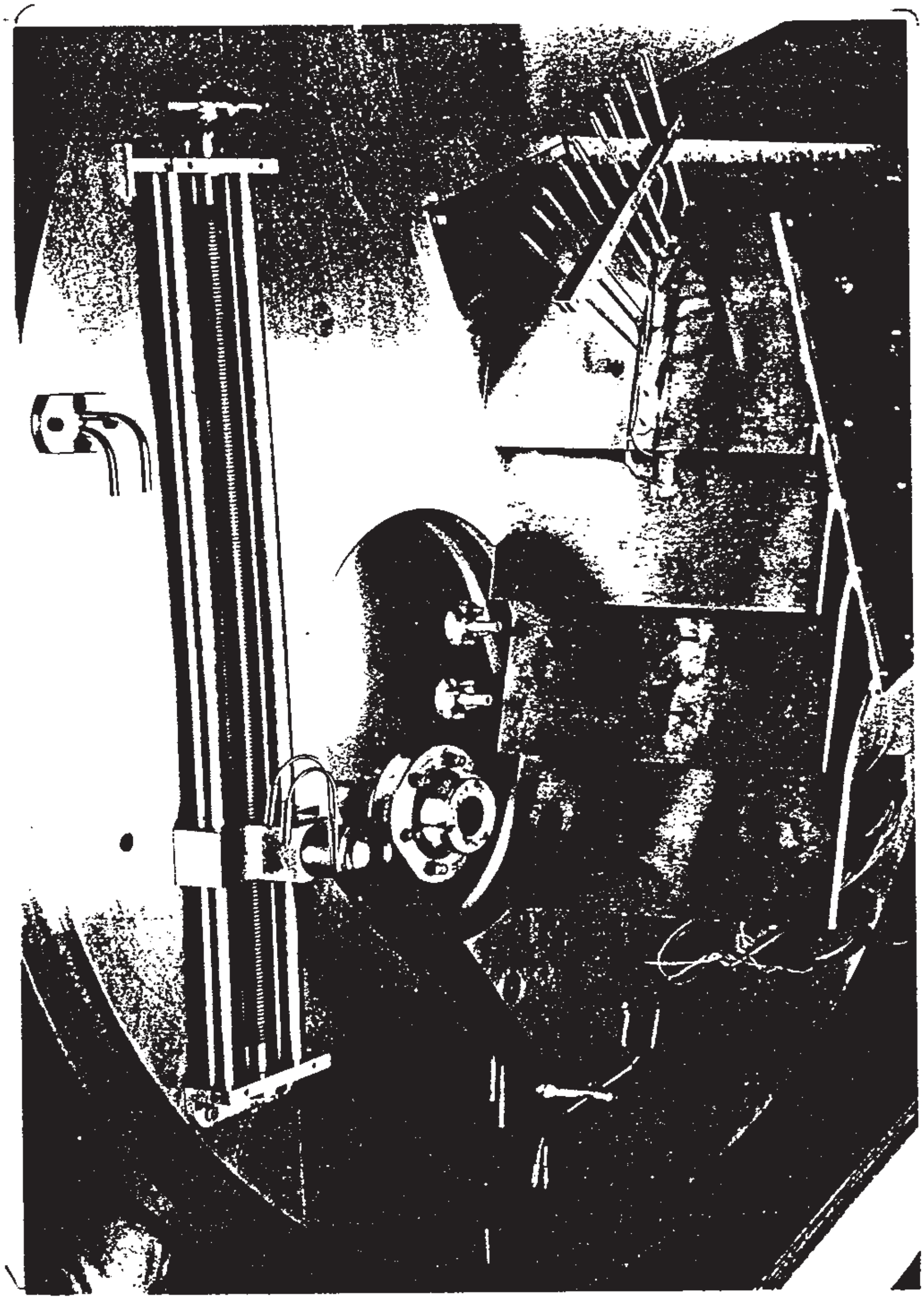


FIG. 4 VIEW OF BLADE AND WINDOW INSTRUMENTATION AND OF THE TRAVERSE MECHANISM

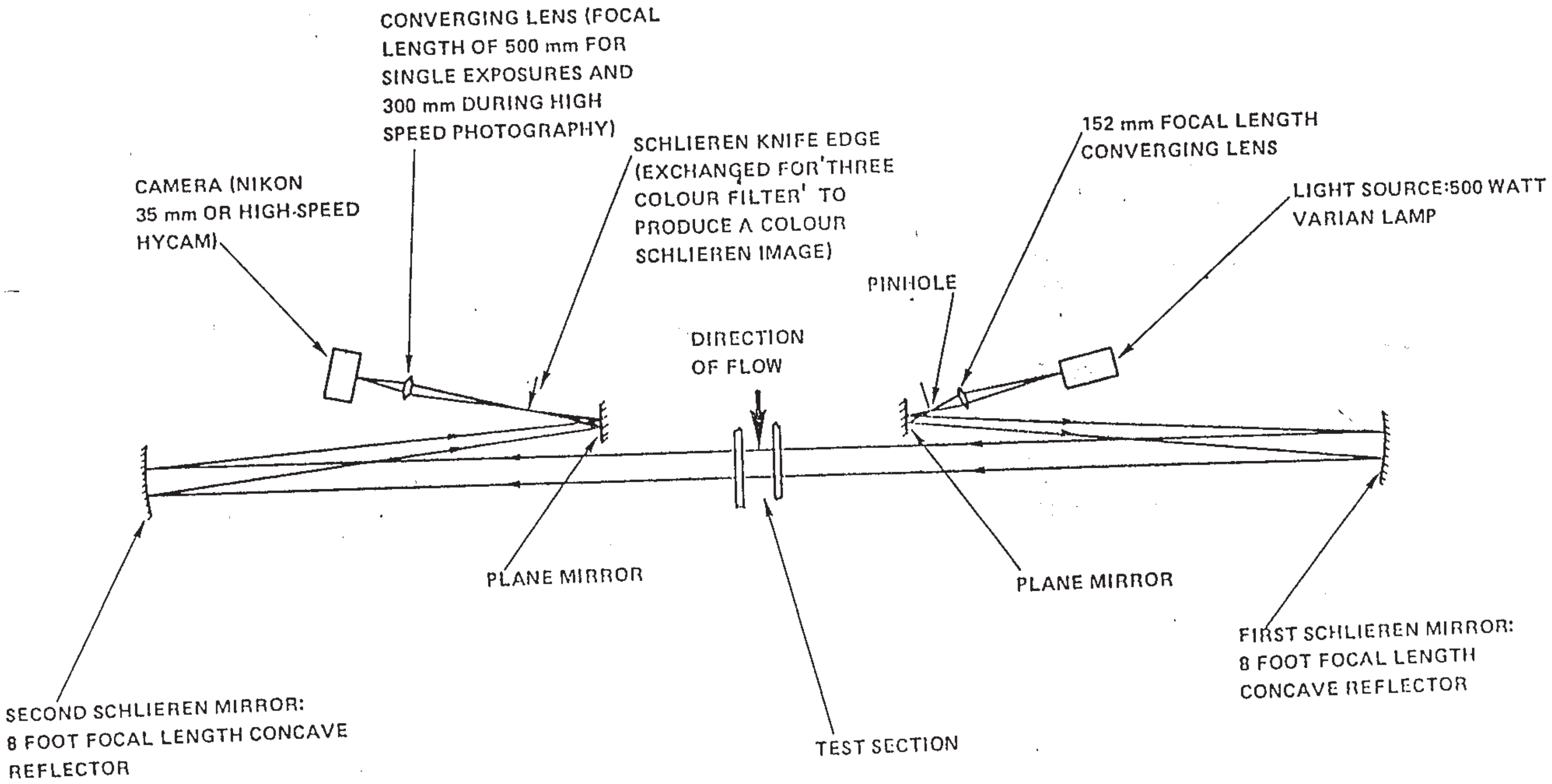


FIG. 5 SCHLIEREN SYSTEM

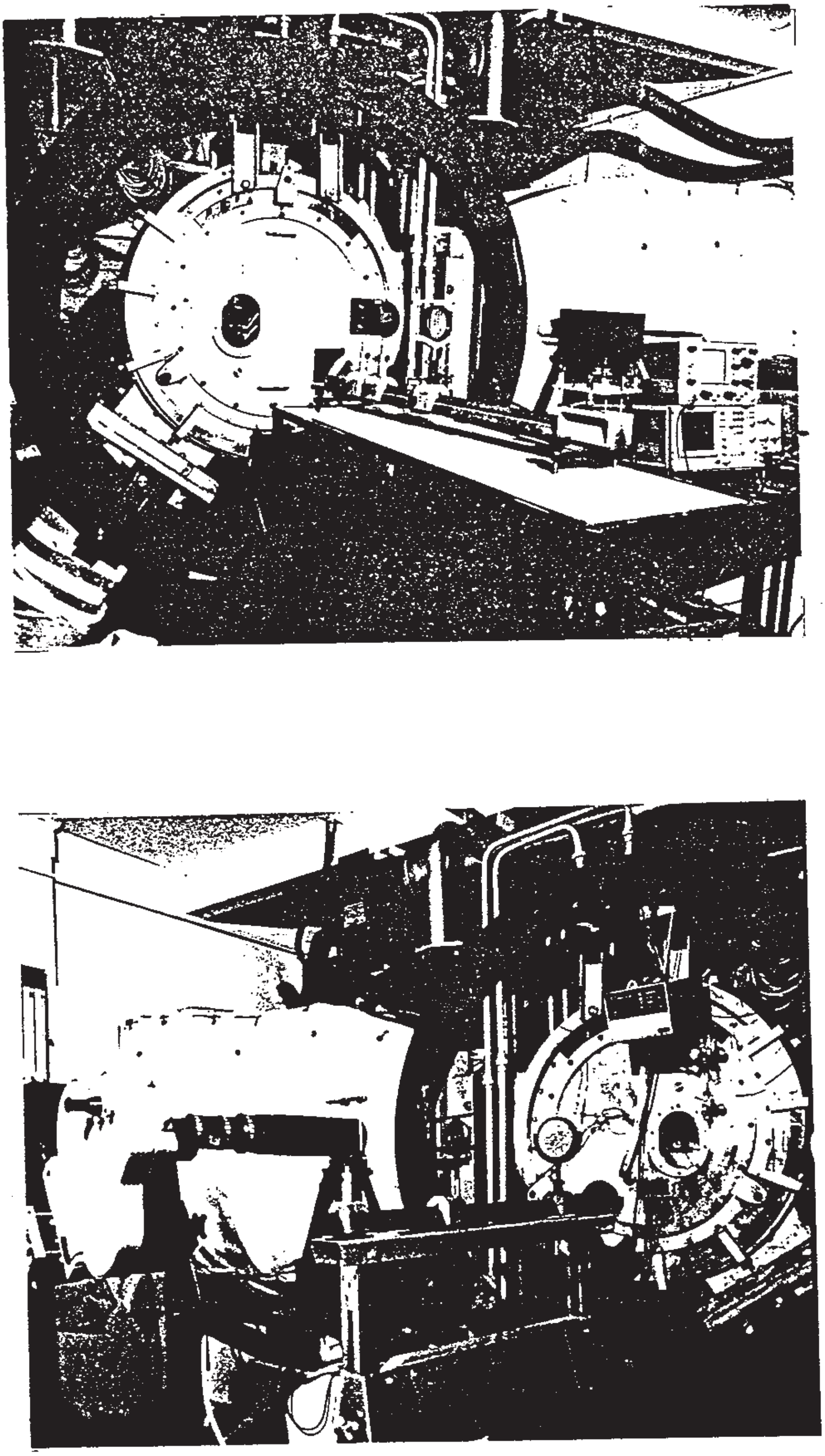


FIG. 6 SCHLIEREN ARRANGEMENT WITH HIGH SPEED CAMERA IN PLACE AS VIEWED FROM BOTH SIDES OF THE TEST SECTION

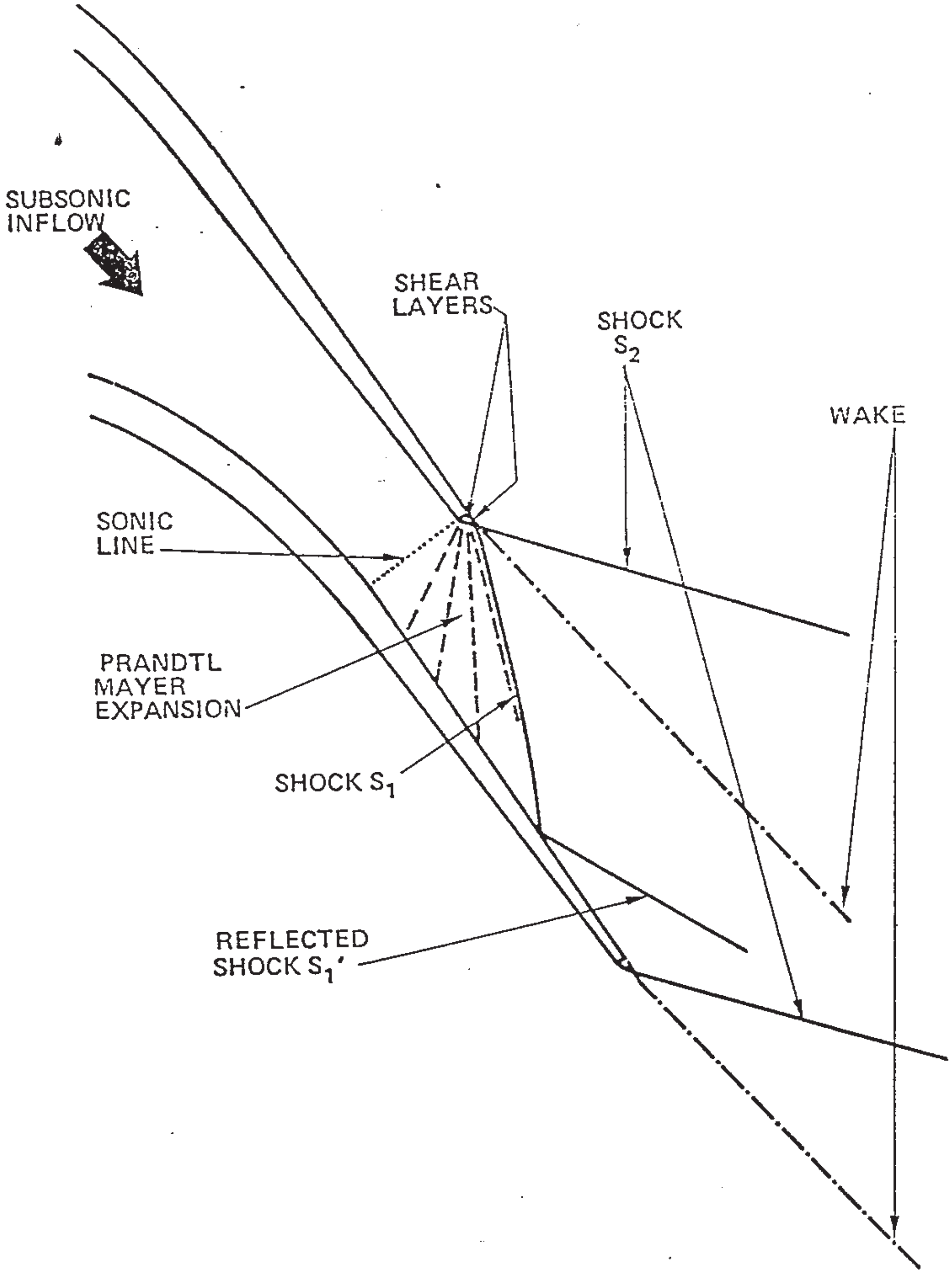


FIG. 7 TRANSONIC CASCADE FLOW STRUCTURE

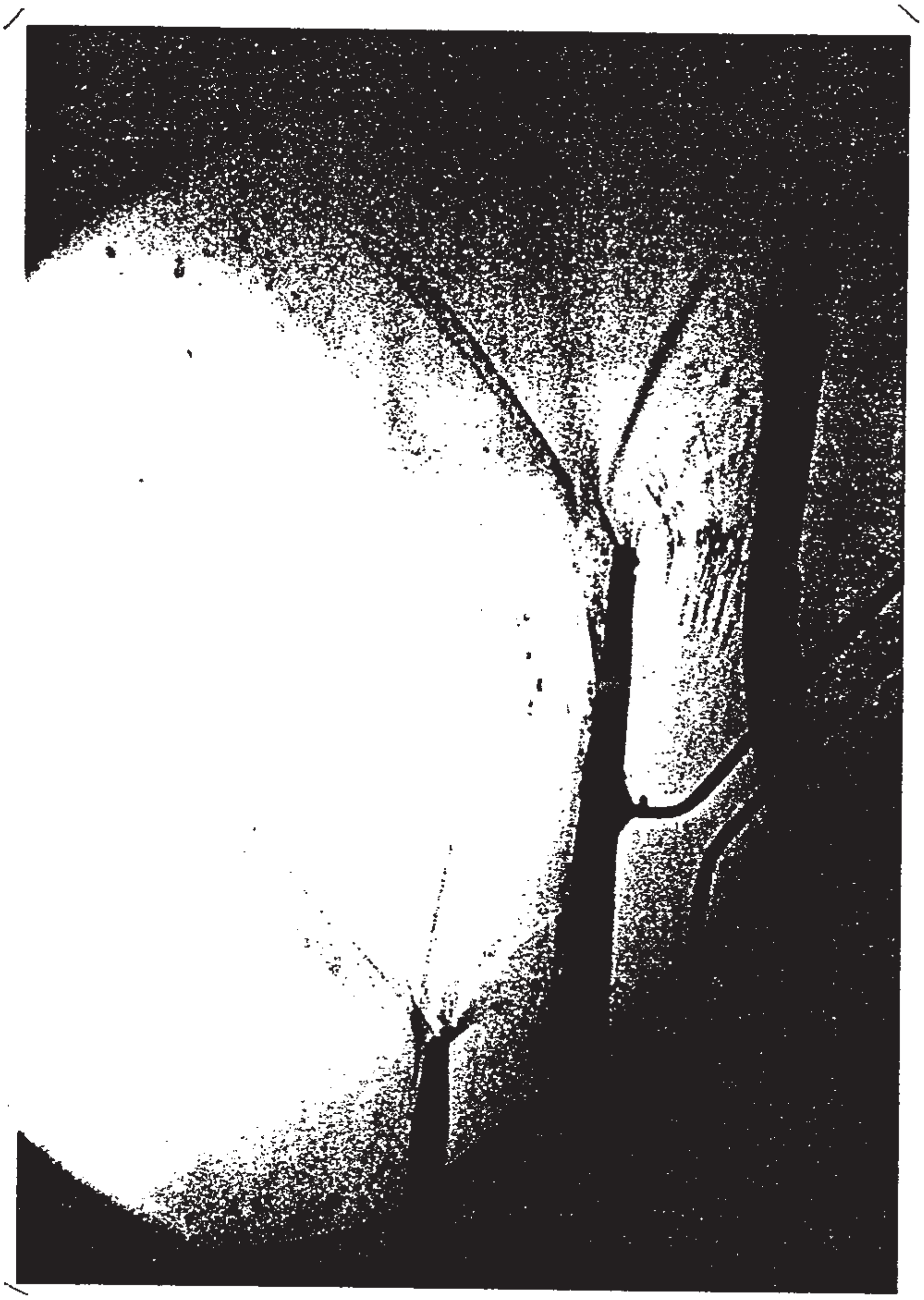


FIG. 8 HIGH INLET SUPERHEAT, $M_2 \simeq 1.49$

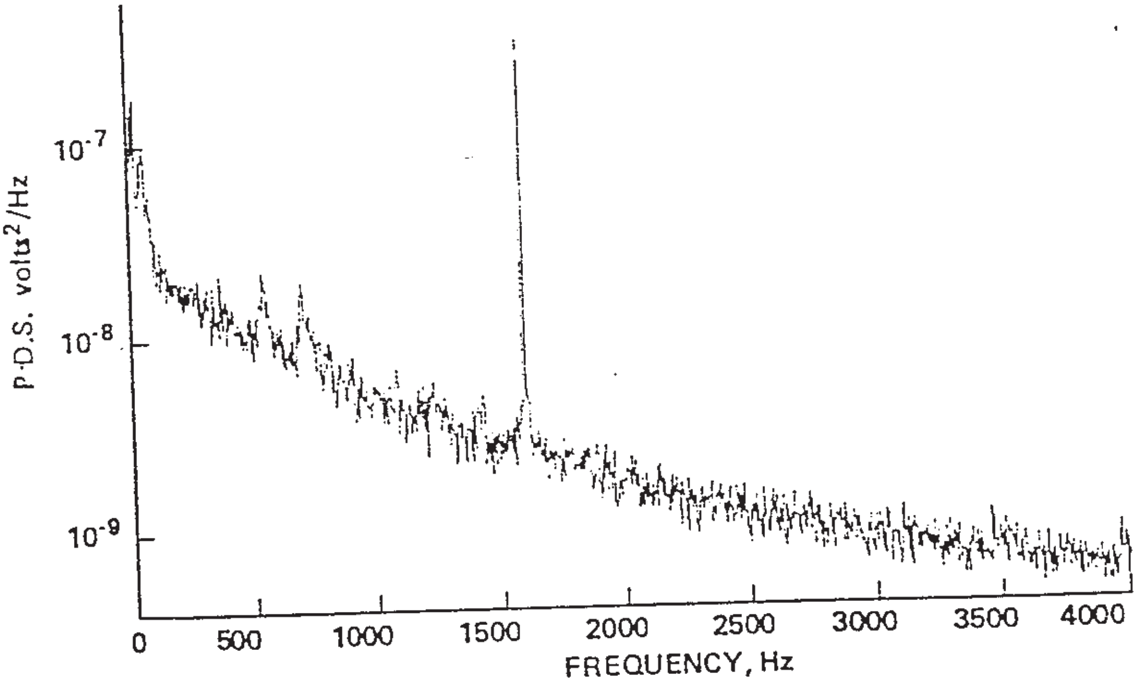


FIG. 9 LOW BACK PRESSURE OSCILLATION DETECTED AT WALL

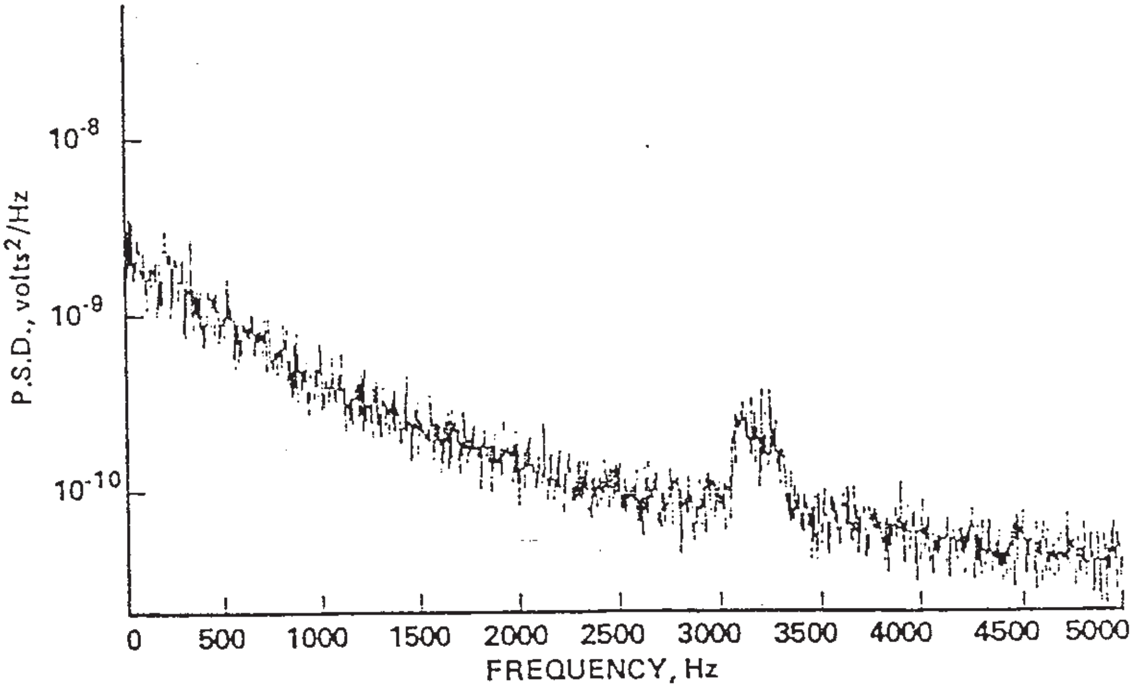
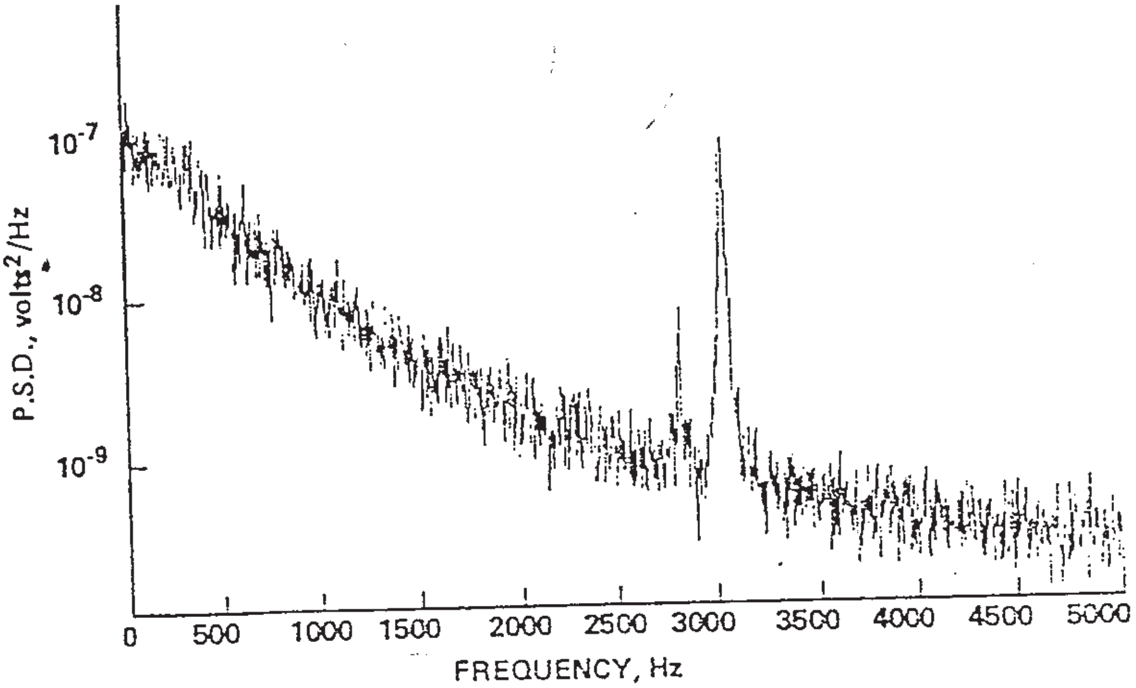


FIG. 10 INITIAL THROAT OSCILLATION DETECTED AT BLADE

(a) AT BLADE



(b) AT WALL

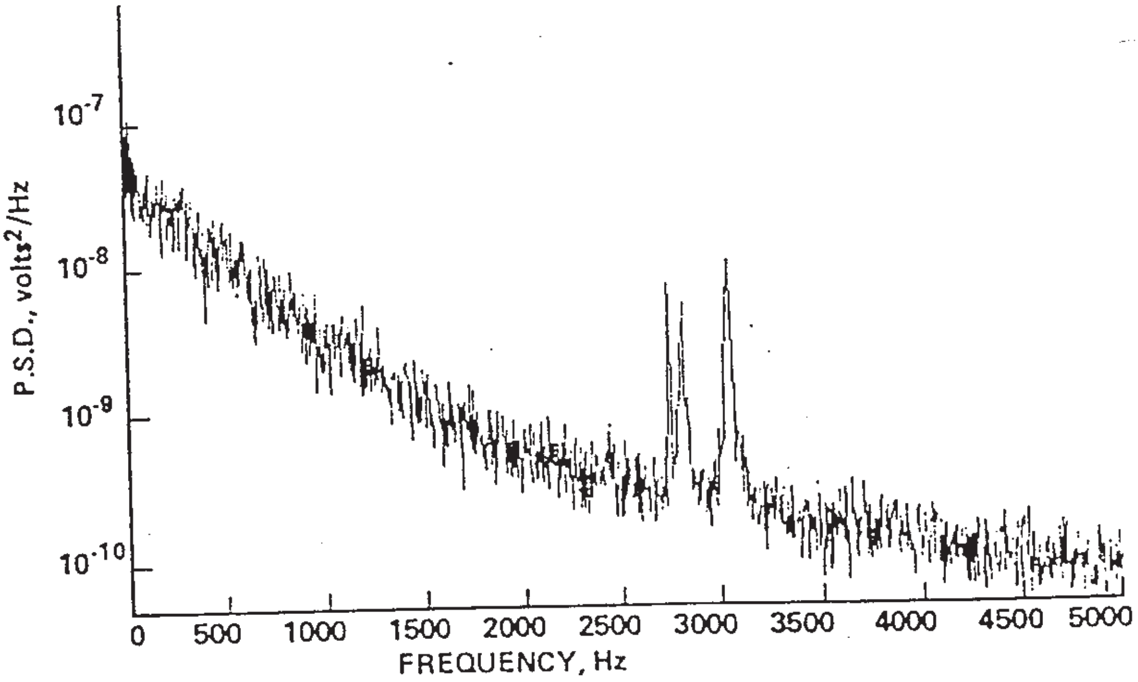


FIG. 11 THROAT OSCILLATIONS

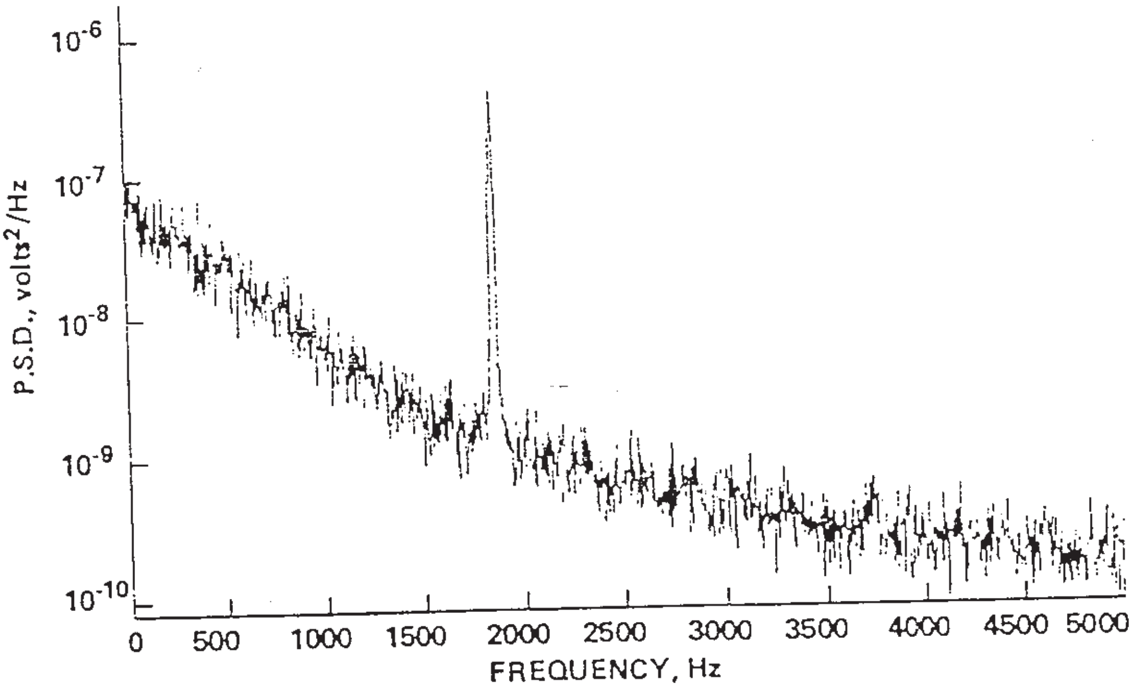


FIG. 12 FINAL OSCILLATION MODE DETECTED AT BLADE

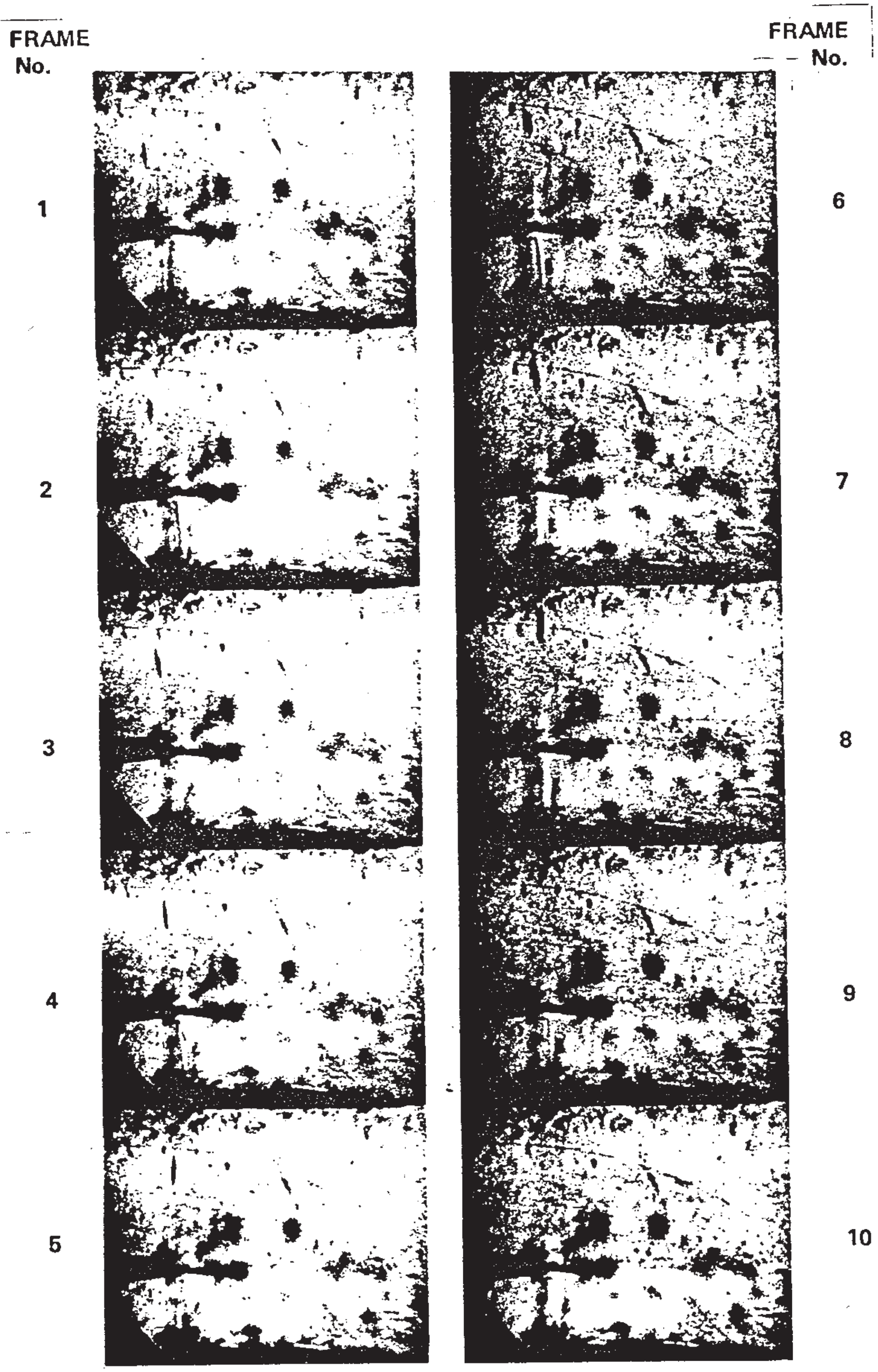


FIG. 13 HIGH SPEED FILM OF FLUCTUATING THROAT SHOCK FOR HIGH INLET SUPERHEAT AND $M_2 \simeq 0.81$