Session 6 - Pressure Probes

THE PROBLEM OF STATIC PRESSURE MEASUREMENT IN TURBOMACHINERY ANNULI USING TRAVERSABLE INSTRUMENTATION

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SUMMARY

Traverse probes are used in component rig and engine testing at Rolls-Royce plc to measure a range of aerodynamic quantities. Of these quantities, static pressure is the least accurately indicated towards the wall of introduction.

This paper was prepared as the basis for a presentation on this subject given to the Xth Symposium on "Aerodynamic Measuring Techniques for Transonic and Supersonic Flow in Cascades and Turbomachines", at the VKI, Brussels, in September 1990. Three particularly problematic areas in the measurement of static pressure using specifically the wedge type traverse probe are explained, the discussion drawing on the findings of several researches in addition to 'in-house' Rolls-Royce experience. In view of the importance of an accurate knowledge of the static pressure field in determining turbomachine performance and efficiency levels, an experimental and theoretical study has been planned. With the ultimate goal of understanding the root causes of the static pressure measurement problem, details of this study are presented, a study which it is hoped will lead to an elimination of this fundamental problem, either through revised calibration procedures, or through new probe designs.

LIST OF SYMBOLS

B	:	Static pressure coefficient (Reference 5)
Cs	:	Static pressure coefficient (Reference 2)
Ct	:	Total pressure coefficient
Cyaw	:	Yaw angle coefficient
Ps	:	Gas static pressure
Pt	:	Gas total pressure
P1	:	Wedge probe measured total pressure
S2	:	) Wedge probe measured static pressures - See Figure 1
S3	:	)
X	:	Probe immersion, (distance from wall of introduction)

1.0 INTRODUCTION

Intrusive measurements of aerodynamic quantities within gas turbine engines and component rigs are made using a wide variety of fixed and traversable instrumentation, (Reference 1). The wedge type traverse probe, a typical design of which is shown in Figure 1, is often used by virtue of its small size and hence minimal flow disturbance to map out areas of the flow field at various planes within turbomachines. Given a suitable aerodynamic calibration, such a probe can be made to accurately indicate the absolute gas flow angle and the gas total pressure in a nominally steady flow, but the measurement of gas static pressure is far less satisfactory. A number of investigators have reported this fact (References 2, 3, 4), and have noted several specific problems, including:-

a) differences between aerodynamic calibrations of the same probe, performed in a variety of facilities, (Reference 4)

b) large variations in a probe's static pressure coefficient, Cs, within a region near to the wall through which the probe is introduced, (but well outside any fluid boundary layers)

c) a lack of knowledge concerning the behaviour of a wedge probe in an unsteady flow regime, (Reference 5).

Errors in static pressure measurement result in inaccurate flow velocity determination, and hence jeopardise any attempt to derive turbomachine temperatures or efficiencies. This paper has thus been prepared as the basis for a presentation to the Xth Symposium on "Aerodynamic Measuring Techniques for Transonic and Supersonic Flow in Cascades and Turbomachines", at the von Karman Institute for Fluid Dynamics, Brussels, (17 and 18 September 1990) and has the specific aims :

a) of summarising the information available to the author which relates to the fundamental and far from fully understood problem of static pressure measurement with wedge probes

b) of airing the situation before an audience of measurement techniques specialists and to encourage comment from any who may have experienced similar phenomena, and

c) of describing a programme of experimental and theoretical work which is currently being initiated to investigate the situation in a rigorous fashion.

2.0 PROBE CALIBRATION FACILITY DEPENDANCE

Wedge type pneumatic traverse probes are calibrated at the Rolls-Royce (Derby) site to determine non-dimensional coefficients of static and total pressure and yaw angle, Cs, Ct and Cyaw respectively. These coefficients are defined in a way which renders them suitable for use in probe data analysis routines and the definition of Cs is different from the static pressure coefficient, B, used by Fransson (Reference 4) and others, as shown below :

$$Cs = \frac{(Pt - Ps)}{(Ps)} \left(\frac{Sm}{P1 - Sm} \right) \quad \text{- Eqn. 1.}$$

where : $Sm = \frac{S2 + S3}{2}$

$$B = \frac{Ps - Sm}{Pt - Ps} \quad \text{- Eqn.2.}$$

Two facilities are regularly used for calibrating wedge probes at Rolls-Royce. The open-jet tunnel (Figure 2), designated '5 rig', is ideal for dynamic recovery factor calibrations of probes fitted with a thermocouple temperature sensor, and for pitch calibrations when required, but the closed tunnel (Figure 3), 9 rig, is more appropriate for Cs, Ct and Cyaw calibrations. However it has been noted on numerous occasions that static pressure calibrations for a given probe differ between the two facilities, those obtained from the closed tunnel being more credible. This is consistent with the findings of Reference 4, which discusses the calibration of a four hole pneumatic wedge probe at eleven European calibration channels, and which concludes that probe indicated static pressure was consistently higher on the open-jet tunnels. It has been suggested that the presence of the probe in the unbounded air stream causes the jet to break-up, which in turn marginally increases the local static pressure field, but this theory has not been substantiated.

3.0 WALL PROXIMITY EFFECTS

Several independent sources (Reference 2, 3 and 4) have observed that, when traversing a wedge type pneumatic probe radially across a closed duct, the probe's static pressure coefficient varies by a large degree within a region near to the wall through which the traverse probe is introduced. Depending on the particular geometry of the probe sensing head and support, this region may extend upto fifty millimetres from the wall, and is thus well outside any fluid boundary layers.

This so called 'wall-proximity' effect is illustrated in Figure 4a) which plots Cs against distance from the wall of introduction, X, for four different wedge probes. The Rolls-Royce (RR) probes, of which Figure 1 is typical, were calibrated in 9 rig at 0.5 Mach number, whilst the NACA sixty degree probe of Figure 5 was characterised in an eight inch diameter, circular, closed duct at Mach 0.45. The same information is presented in the form B vs. X in Figure 4b). It is of interest to note that, whilst the forty and sixty degree probes clearly suffer from wall-proximity effects, the two lesser angle probes are afflicted to a far lesser extent. However, putting this into context, if a forty degree wedge probe were used in a turbomachine annulus at twelve millimetres immersion, the Mach number derived from probe indicated pressures to which free stream Cs and Ct values had been applied would be in error by 0.05, or 10% given that the true flow conditions were Mach 0.5 and 1 bar total pressure, this as a result of the wall-proximity effect. It is of interest to note that static-pressure measurements made in small scale, high speed, core-compressor tests are likely to be compromised across the entire annulus.

Several explanations for this behaviour have been offered, including cross flow along the probe stem which then interferes with the flow structure at the sensing head, and vortex shedding at the probe tip, (Reference 3). The hole through which the probe is inserted may, at certain probe immersions, generate local disturbances which would again alter the static pressure field around the wedge.

The possible influence of probe cross-flow has been investigated at Rolls-Royce using the equipment shown in Figure 6 in conjunction with 9 rig. This enabled controlled flow rates either into or out of the duct to be established, along the probe stem itself. Figure 7 shows the results of this test on a forty degree (large angle) included angle wedge probe of the Figure 1 design, and indicates that the controlled leakage flow does not significantly lessen the extent of Cs variation. This contrasts sharply however with results from a similar experiment conducted on the twenty three degree wedge probe shown in Figure 8, which was inserted into the tunnel through a 12.5 mm diameter traverse hole. Under all conditions the wall proximity effect had largely disappeared, implying that flow disturbance at the probe/ wall of introduction interface is perhaps a more important mechanism than cross flow along the probe stem in contributing to the wall-proximity effect.

The design of the narrow stem region which supports the wedge head itself has also been shown experimentally to influence the extent of the wall proximity problem. A series of calibration exercises have been performed for the Ministry of Defence on a Royal Aerospace Establishment twenty three degree included angle wedge probe design (see Figure 9a)) by the Cranfield Institute of Technology. The results, gathered on an eight inch diameter closed section suction tunnel and presented in Figure 10), show the effects of wall-proximity upto 70 mm away from the wall of probe introduction. However by increasing the narrow stem length and altering the angle of transition from the narrow to the 6.25 mm diameter stem (see Figure 9b), a reduction in wall proximity effect to below 30 mm was demonstrated, (see Figure 10).

What is apparent overall is that no thorough and systematic investigation of the problem has ever been undertaken, and that the contributing mechanisms are not understood.

4.0 MEASUREMENTS IN UNSTEADY FLOW

Experimental investigation (Reference 5) has shown that, for a small sphere immersed in a pulsatile flow, the influence of the flow unsteadiness on measured static pressure becomes insignificant at the position on the sphere where the pressure corresponds to the static pressure of the free steam flow. Since the wedge face static tappings of a wedge probe indicate close to free steam static pressure, the spherical probe work has in many cases (for example, Reference 2) been taken as justification for neglecting unsteady effects on wedge probes. However the validity of this assumption has not been proved experimentally or analytically.

5.0 PROPOSED INVESTIGATION

In view of the seriousness of the static pressure measurement problem, its potential impact on turbomachinary testing and the unexplained mechanisms behind it, a three phase investigation has been planned, and is currently being initiated. The aims of each phase are outlined below :-

PHASE I : By adopting a parallel experimental and theoretical approach, to determine the fundamental mechanisms responsible for the calibration facility dependance and wall-proximity effects experienced with wedge probes.

PHASE II : Drawing on experience gained from Phase I, to devise a technique which returns a reliable static pressure measurement, and to validate this technique.

PHASE III : To investigate the behaviour of a wedge probe in an unsteady flow field by again employing experimental and theoretical methods.

Funding is currently being sought for Phase I of this study, which is to be conducted at the Cranfield Institute of Technology, UK. Details of the experimental and theoretical content have now largely been agreed, and are set out below.

5.1 EXPERIMENTAL STUDIES

The two aims of the experimentation are :

a) to obtain Cs characteristics for several geometries of wedge probe in a representative range of flow environments, and

b) to achieve qualitative information regarding the flow past wedge probes.

In order to achieve the first of these objectives, it is planned to incorporate into an existing CIT suction tunnel an annular working section designed to have a uniform static pressure field at the measurement plane. Laser Dopler anemometry will be used to determine the working section velocity profile which will in turn be combined with total pressure probe measurements to derive the static pressure field and thus check its uniformity. Several geometries of wedge probe will then be calibrated in this facility over a range of Mach numbers between 0.1 and 0.9, and at various incidences to the flow. It is also planned to take advantage of the large scale compressor rig (LSCR) at Cranfield, which has an inlet flare designed to the guidelines included in Reference 6, and thus a well established and characterised uniform static pressure field at compressor entry. A limited number of low velocity cross-calibrations will be performed on this facility to maximise confidence in the experimental results.

The second aim of the experimental study will be realised via low speed (up to Mach 0.2) flow visualisation tests on scaled-up model wedge probes in a clear sided, square section windtunnel. Using smoke as the visualised medium, the results of studies on a variety of probe geometries will be recorded photographically.

5.2 THEORETICAL STUDIES

It is believed that a theoretical approach to the static pressure measurement problem has potentially a very valuable role in establishing the root causes. Specifically, the aims of the study are threefold:

a) to demonstrate the ability of a Computational Fluid Dynamics (CFD) method to predict the behaviour of one representative geometry of wedge probe, including the modelling of the wall proximity effects,

b) to use this model in determining how best to overcome the wall proximity problem, and

c) by varying the boundary conditions, to help understand the differences between open and closed jet calibrations of the same probe.

A three-dimensional finite volume pressure correction method with compressible flow capability was considered necessary as a computational code for achieving the above aims. Three options were considered :

1 <u>'PHOENICS' Code supported by 'CHAM'</u>

This is a commercially available code, and as such is well supported, with powerful post-processing capability. However an agreement with 'CHAM' is required for commercial use, and there is no accessibility to the core code in the event of problems in obtaining a converged solution.

2 <u>'LAPWORTH and ELDER'</u>

Developed at CIT, and discussed in Reference 7, this code can be used freely and modified as required, although the post-processing facilities are more limited. However the body-fitted coordinate meshing technique on which it relies is less-well suited to the three dimensional geometry of a wedge probe.

3. <u>'MOORE ELLIPTICAL FLOW PROGRAMME, MEFP'</u>

Developed in-house at Rolls-Royce, this code uses a more appropriate meshing system, and has yielded successful results when employed in other Rolls-Royce/CIT collaborative projects, (Reference 8). It has therefore been chosen as the most suitable code available for this project.

Validation of the theoretical predictions will rely on experimental results of the work outlined in Section 5.1, and on previous experience with wedge probes. The flow visualisation study will provide a qualitative check on the theoretically predicted flow structure in the wedge probe vacinity, whilst the experimentally derived Cs characteristic for the probe in question will form a quantitative comparison.

6.0 CONCLUSION

It is hoped that Phase I of the study will start in early 1991, with a planned completion date of mid 1992. The conclusions from this work will inevitably impact on the remainder of the programme, but the current plan is to continue through Phases II and III to arrive at the ultimate goal of a traversable instrument which can be relied upon to return accurate static pressure measurements in a turbomachinary environment.

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FIGURE 1: ROLLS-ROYCE 30° PNEUMATIC WEDGE PROBE

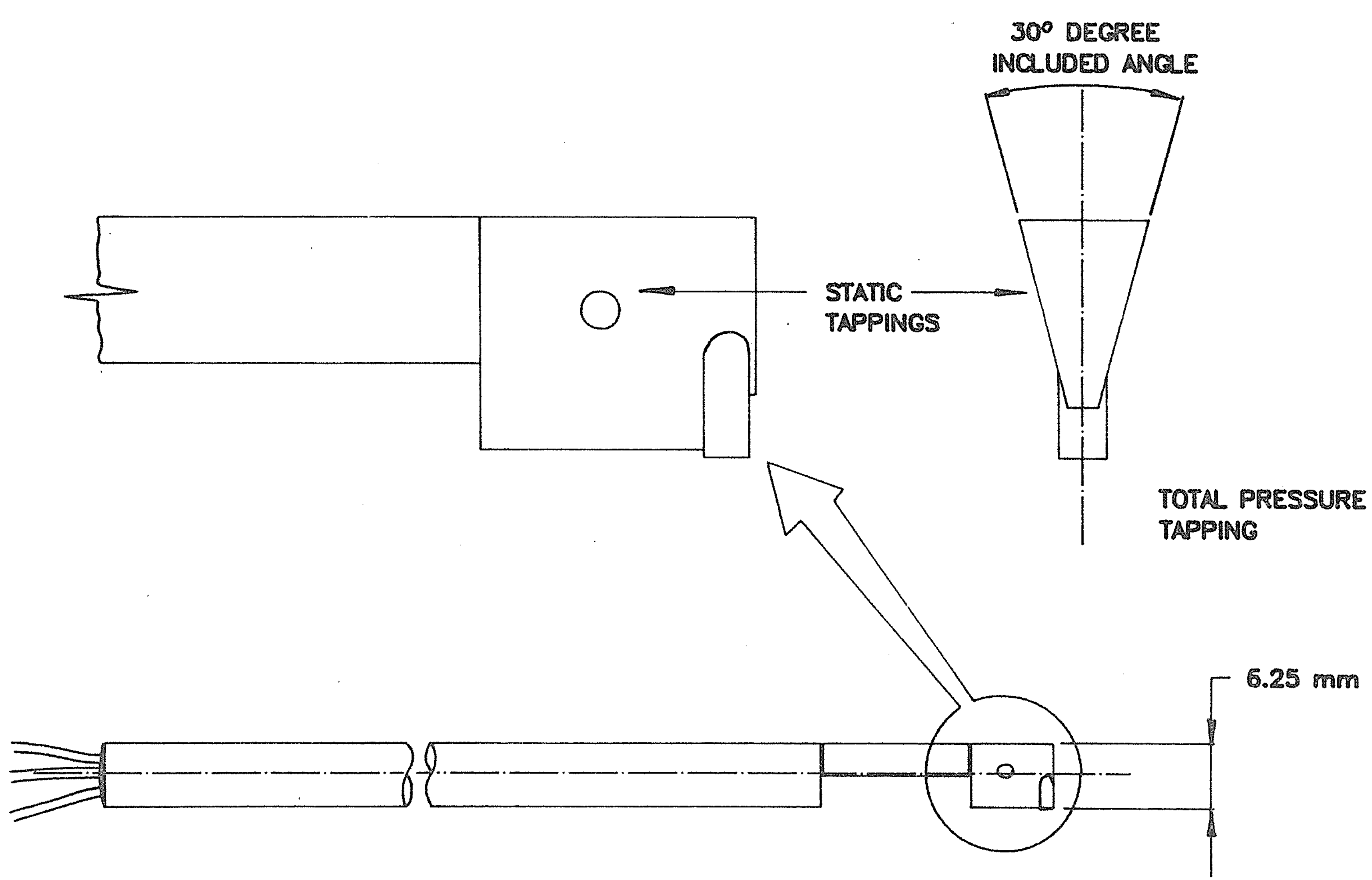


FIGURE 2: No. 5 RIG OPEN JET CALIBRATION FACILITY

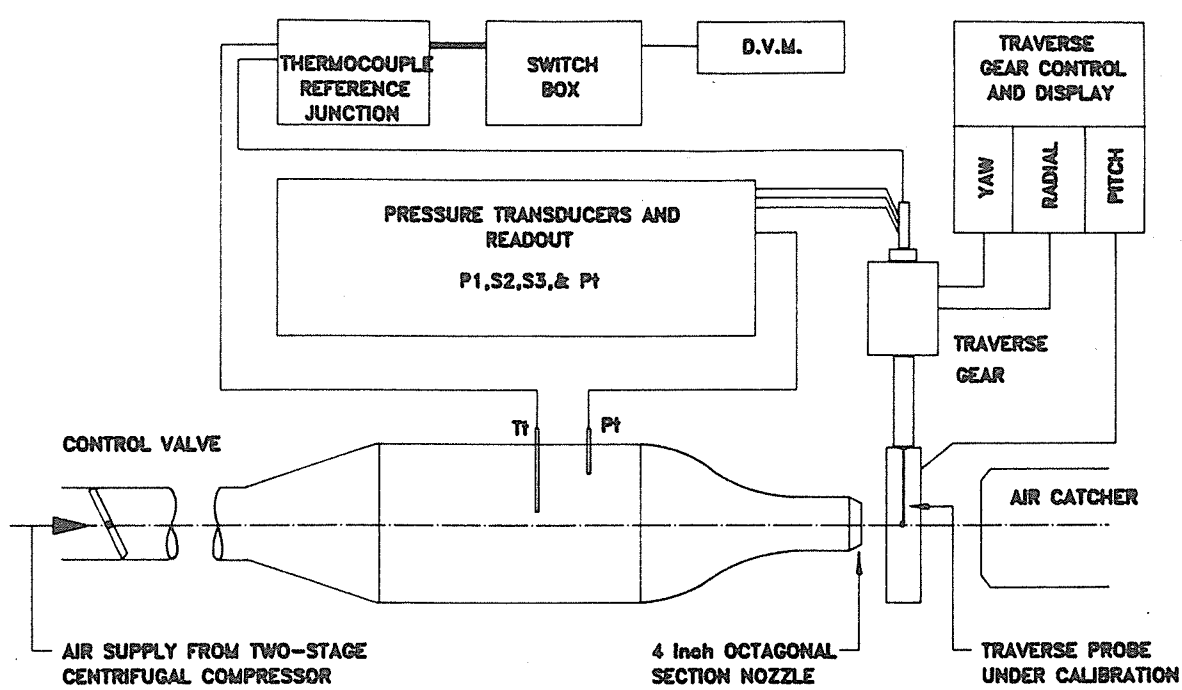


FIGURE 3: No.9 CLOSED SECTION CALIBRATION WIND TUNNEL

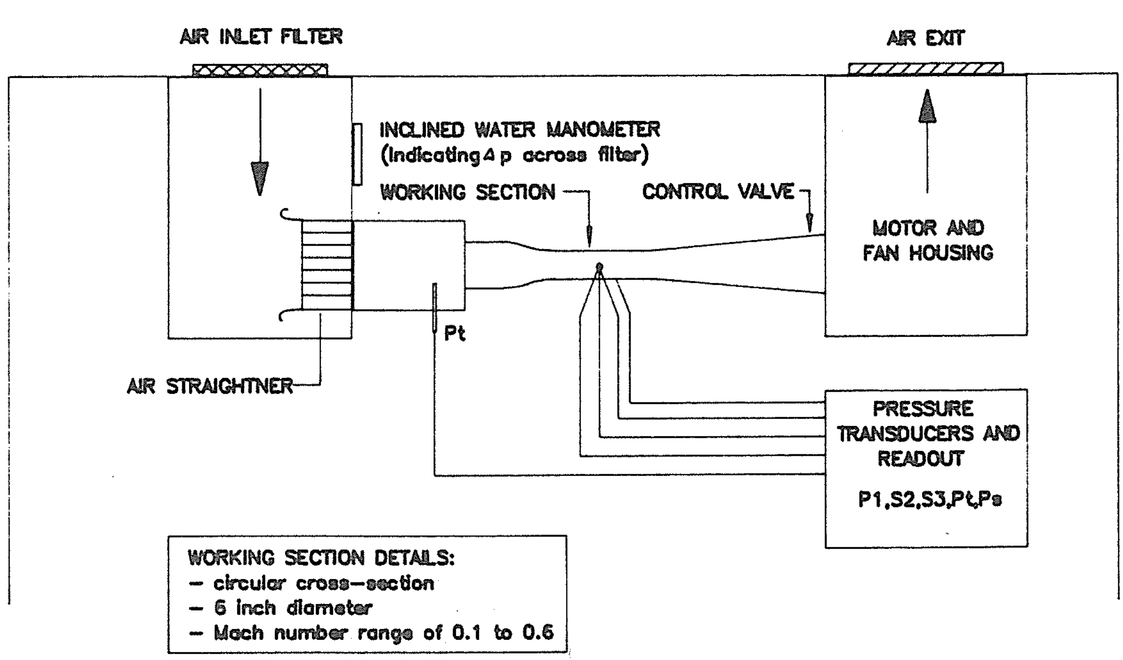


FIGURE 4a): WALL PROXIMITY EFFECTS WITH WEDGE PROBES

Variation in Coefficient of Static Pressure across Closed Duct

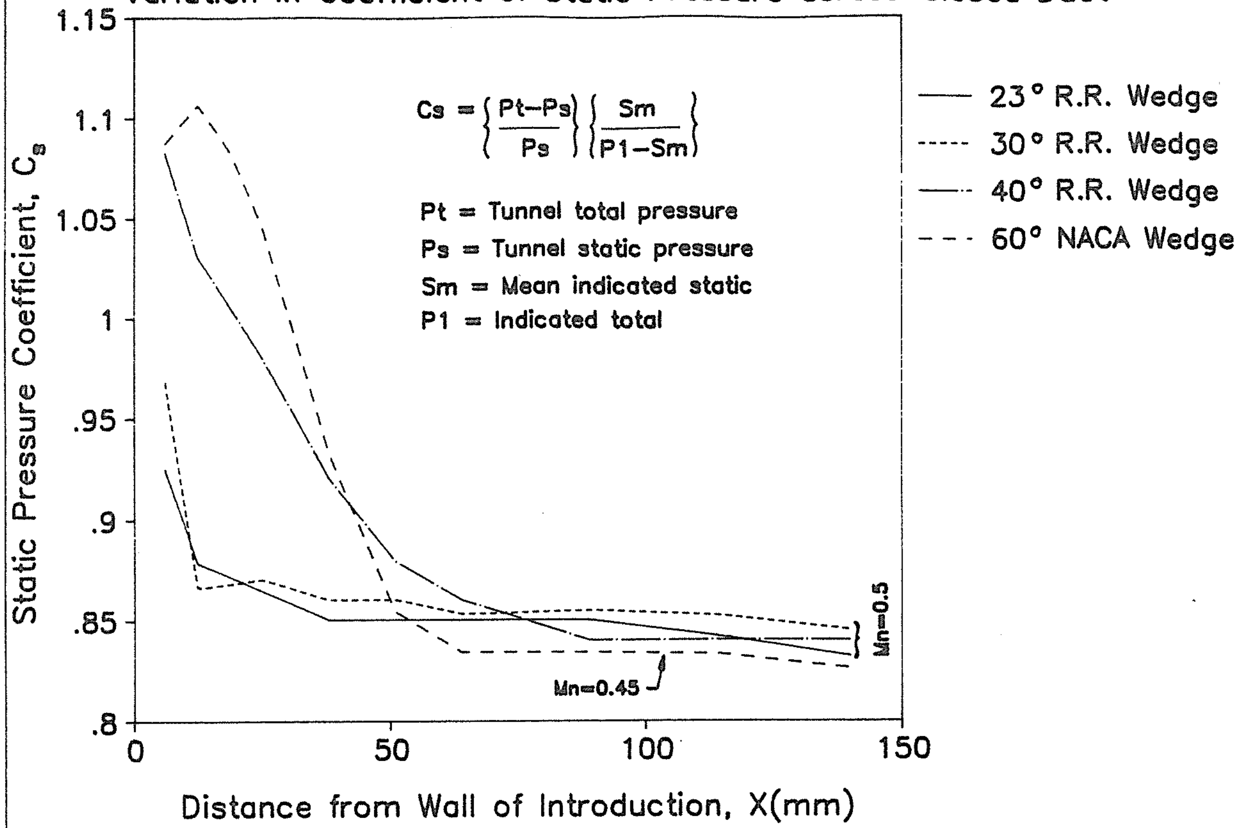


FIGURE 4b): WALL PROXIMITY EFFECTS ON WEDGE PROBES

Variation in Coefficient of Static Pressure across Closed Duct

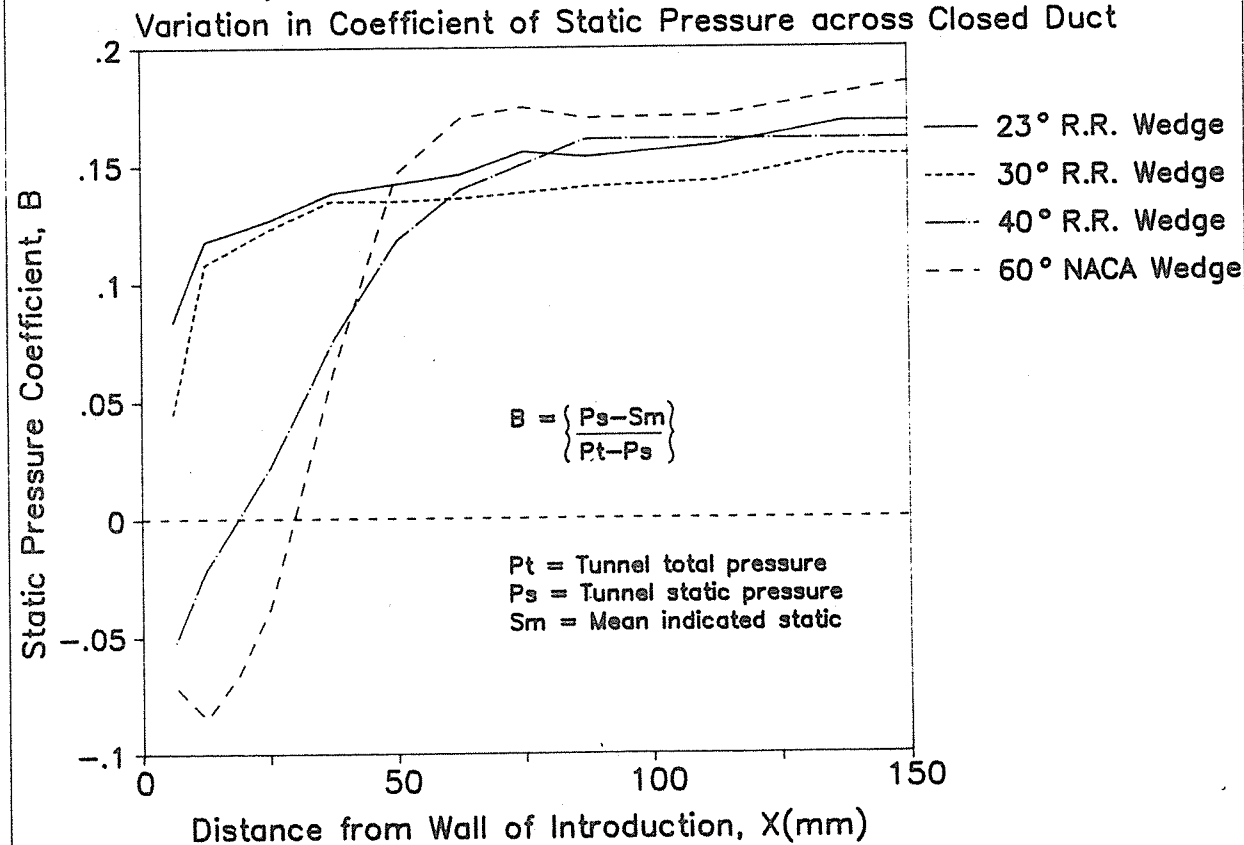


FIGURE 5: 'N.A.C.A.' DESIGN OF WEDGE PROBE

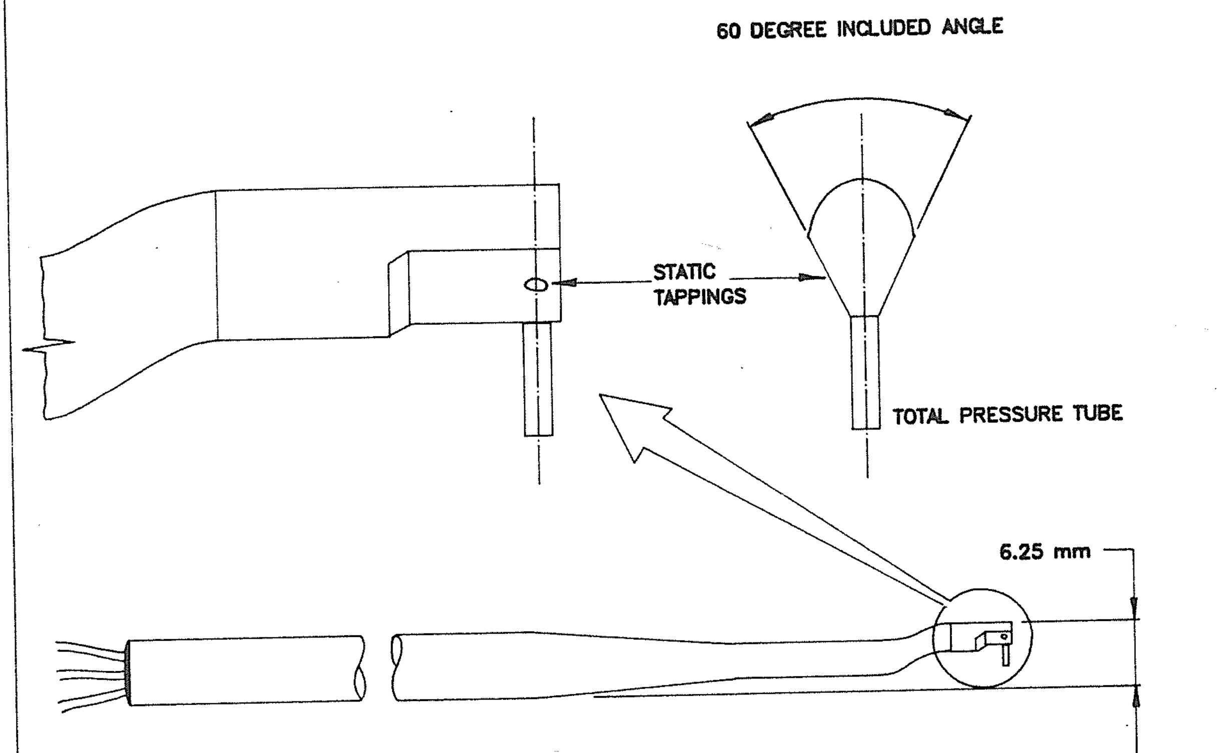


FIGURE 6: EQUIPMENT USED FOR CONTROLED LEAKAGE TESTS

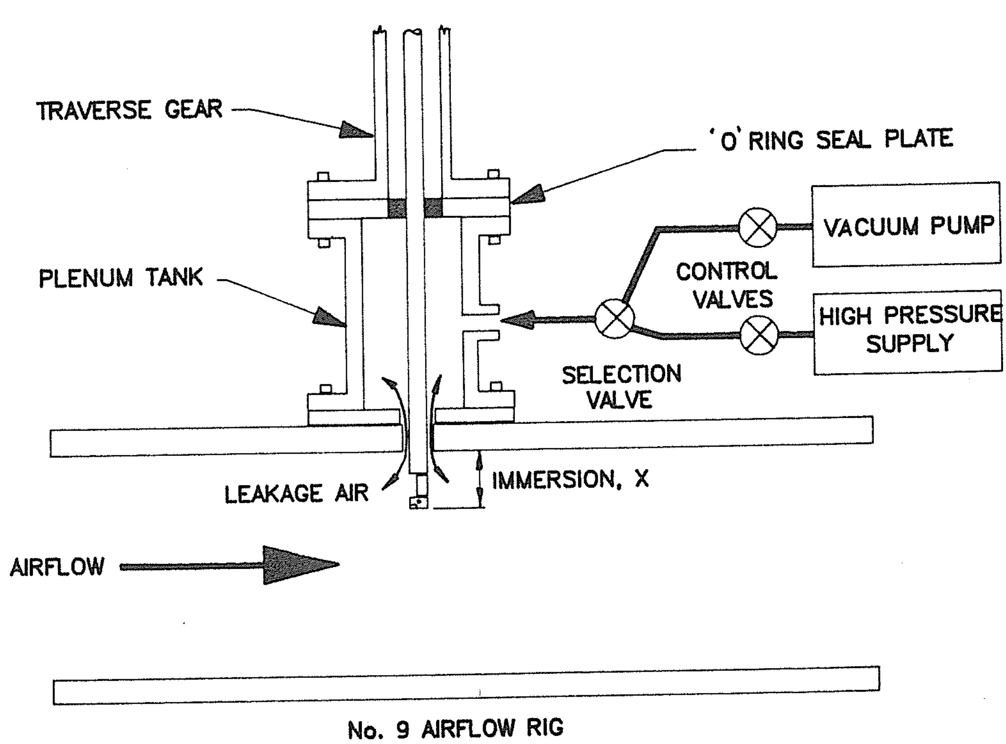


FIGURE 7: EFFECT OF LEAKAGE ALONG PROBE STEM

40 degree Wedge Probe in Mn = 0.5 Flow

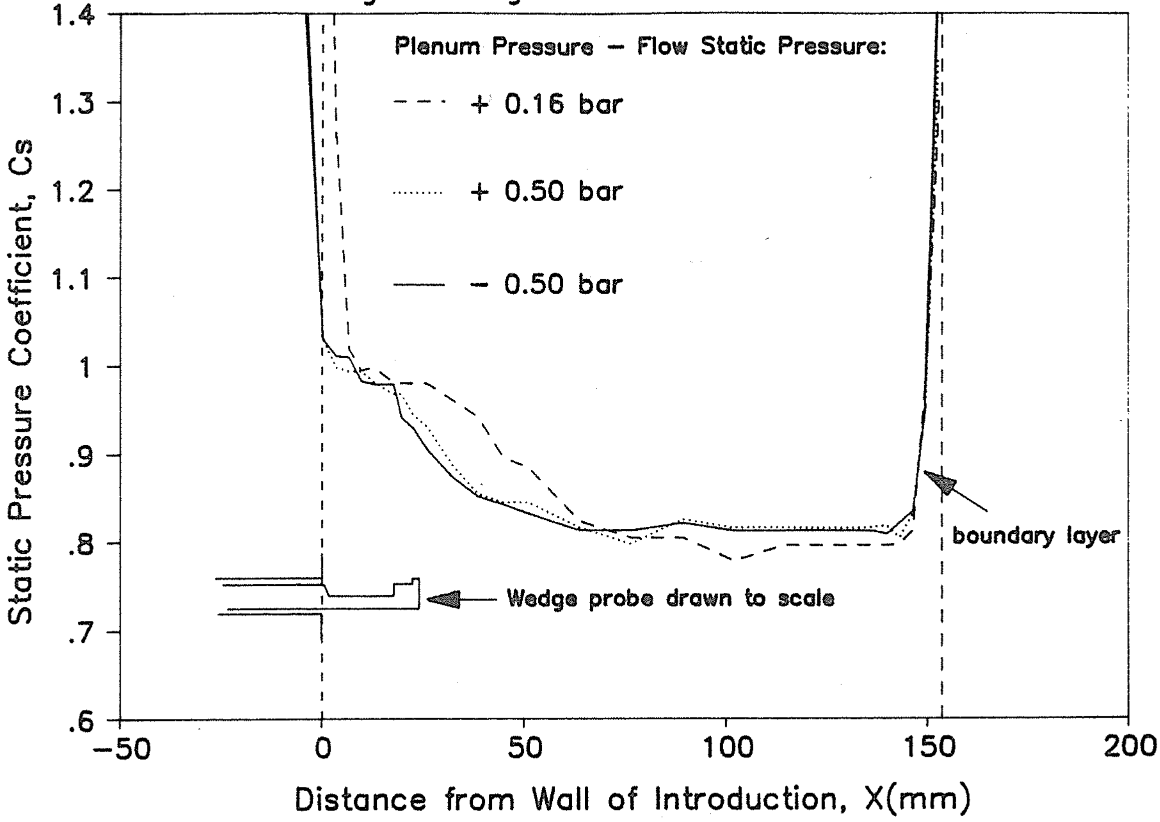
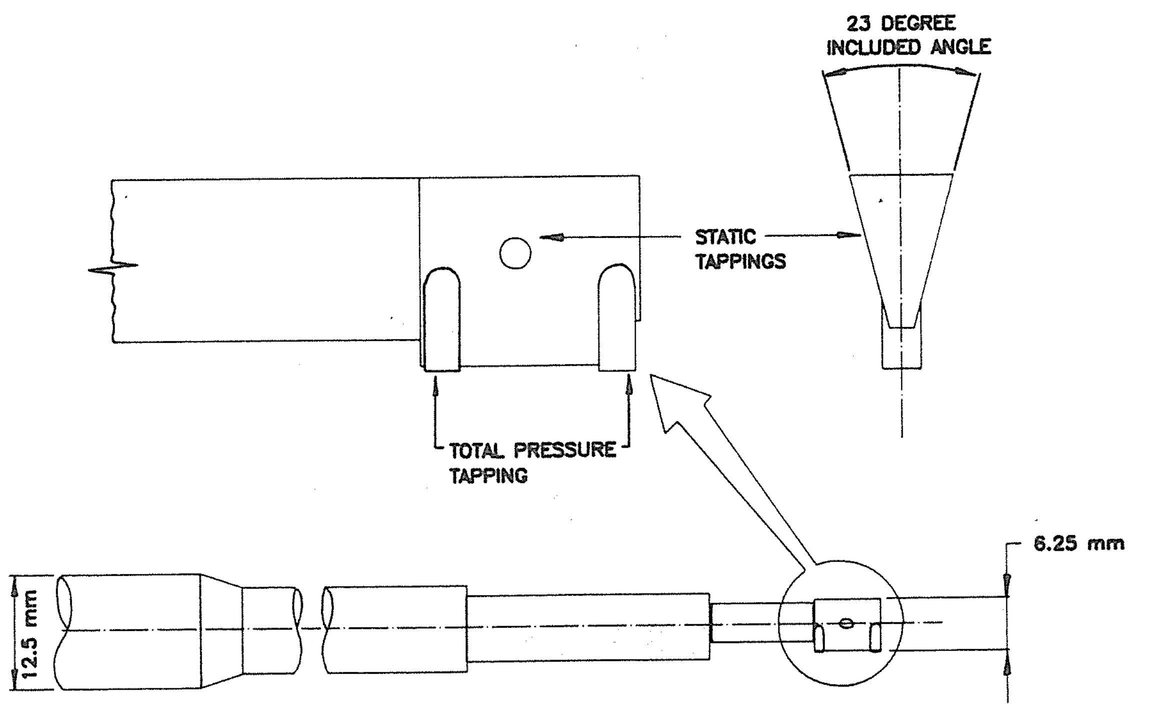


FIGURE 8: ROLLS-ROYCE 23° PNEUMATIC WEDGE PROBE
12.5 mm STEM DIAMETER



ROYAL AEROSPACE DESIGNS OF TWENTY THREE DEGREE INCLUDED ANGLE WEDGE PROBE

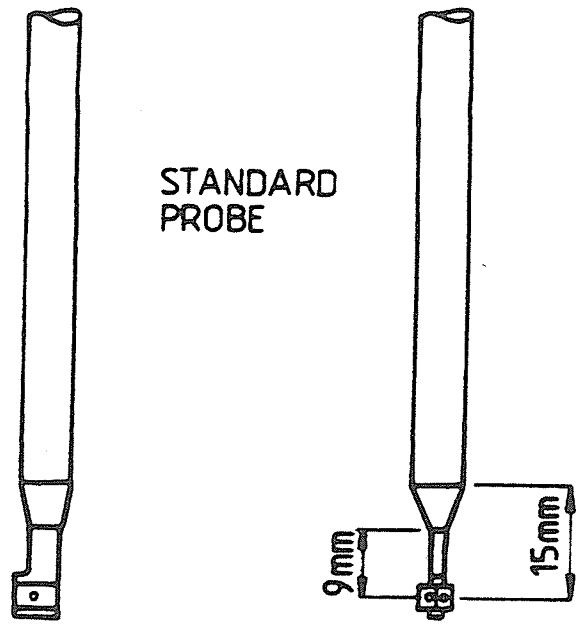


FIGURE 9a)

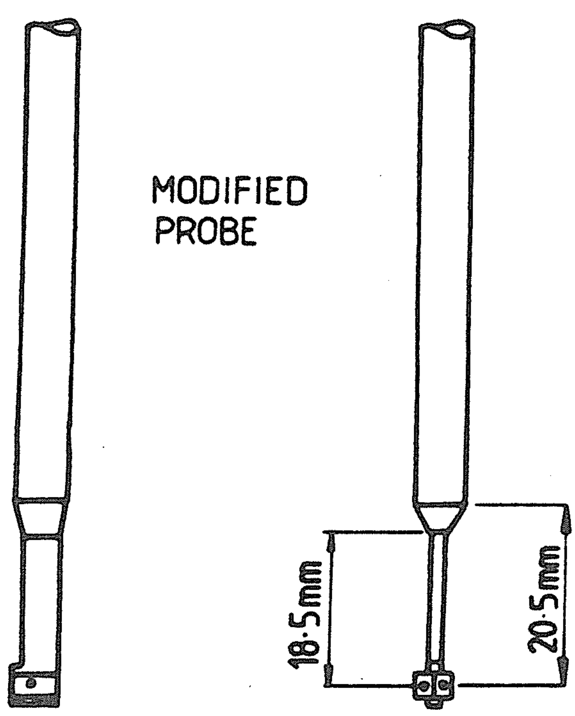


FIGURE 9b)

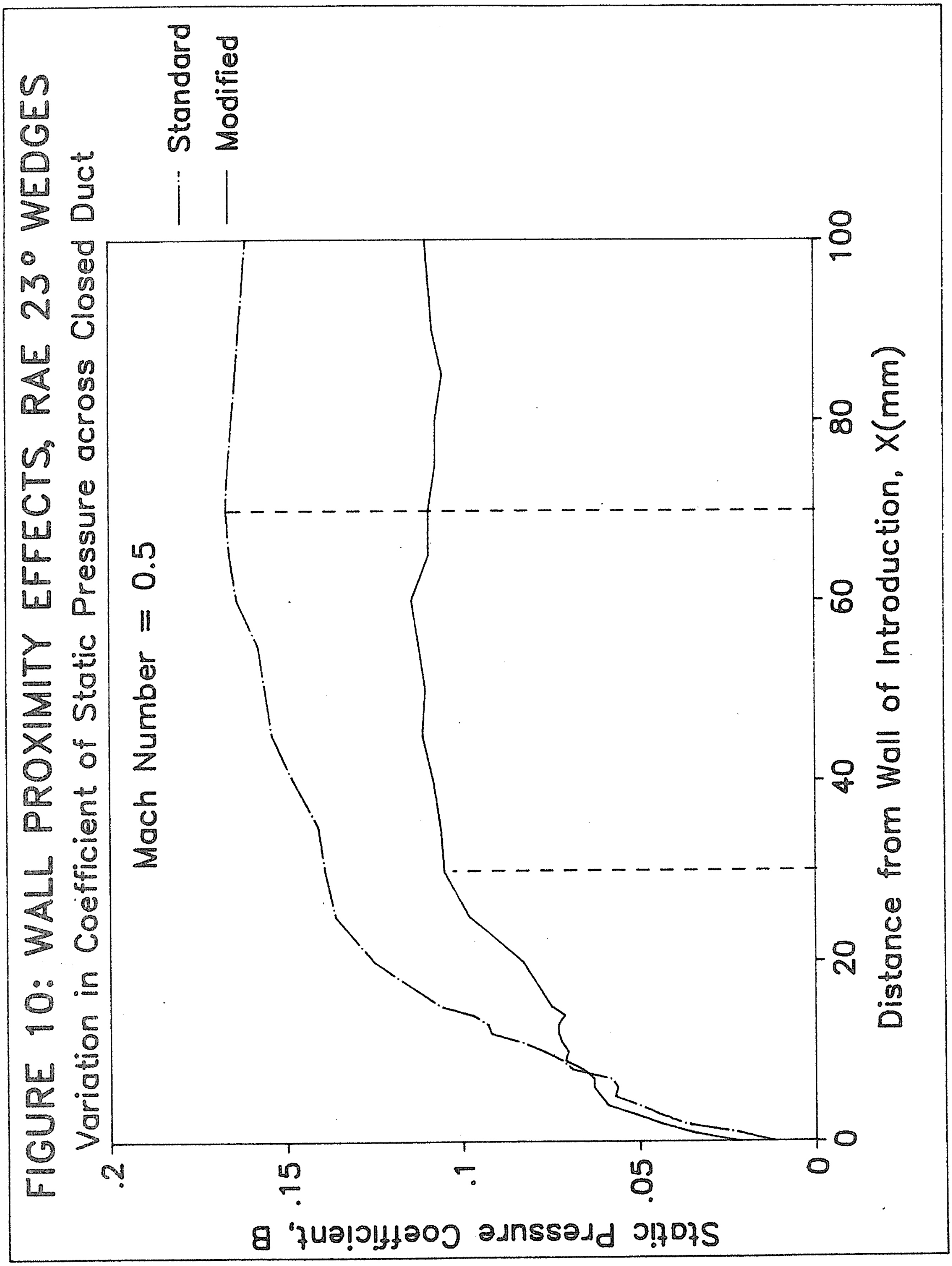


FIGURE 10: WALL PROXIMITY EFFECTS, RAE 23° WEDGES