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Some Tests with Trapped Vortices in Supersonic Flow

By

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Some tests with trapped vortices in supersonic flow

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B. S. Stratford and M. C. Neale

SUMMARY

An arrangement known briefly as a vortex bearing, or trapped vortex, is described. This was devised initially with the object of improving supersonic air intakes featuring internal compression and focussing of the compression waves at the throat. Tests were made with simple rigs to check various aspects of the performance of such vortex bearings. It was concluded that employment of the device in certain installations might prove beneficial.

Replaces N.G.T.E. Note No. NT.449 - A.R.C.22 254

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1.0 Introduction

The work described in this paper was prompted by the discussion of the proposal for a supersonic internal compression air intake featuring focussing of the compression waves on the throat lips, as shown in Figure 1. Whilst a number of advantages were hoped for from such an intake, it was appreciated that as is the usual experience, the design was not without its shortcomings. The one germane to the present paper is the sensitivity of the intake performance as a whole to the exact reproduction of the compression wave network. It was a search for a possible means of ameliorating this disadvantage that led to the device which has subsequently become known as the vortex bearing.

2.0 Theory of operation

It will assist the reader in assessing the usefulness of the vortex bearing if some account is given of the purposes which it was hoped it would serve.

Mention has been made of the intake shown in Figure 1, and, for the present purpose, attention need be directed to only one feature of the intake. This is the location of the boundary layer bleed slots immediately adjacent to the throat, making it possible to avoid passing the supersonic boundary layer through the compression fans. However, if through inaccuracies of focussing there is a region of sharp pressure rise in front of the bleed slot entrance, the probability is that the boundary layer will separate with consequent deterioration of intake performance.

The vortex bearing, which is shown incorporated in the shock focussing intake in Figure 2, was suggested as a possible means of overcoming these disadvantages. It features the removal of the solid boundary in the region of the throat and its replacement by a free streamline. In this way, it was suggested, those compression waves not accurately focussing on the throat lips are reflected from the free streamline as expansions, with consequent easing of the pressure gradient at the entrance to the boundary layer bleed slots. Additionally a circular or near circular cut out section would allow the formation inside it of a forced vortex so that little loss might be expected at the free streamline interface between the vortex and the free stream.

Later proposed applications of vortex bearings made use of other properties. It was thought that the vortex bearing might confer an improvement in the uniformity of the velocity distribution in the boundary layer, consequent upon the removal of the zero slip condition at the free stream boundary. As a consequence there would be a reduction in the boundary layer displacement thickness and an increase in the area mean total pressure, so that a thick boundary layer might subsequently pass more easily through the pressure rise associated with a normal shock. If a vortex bearing were used for this purpose it would simultaneously provide a by-pass of the supersonic stream. For example, if the normal shock were situated near the downstream lip of the bearing a change of pressure in the subsonic flow downstream of the shock would reach the flow in the bearing and would then be transmitted to the supersonic flow adjacent to it, a shock wave or expansion wave being generated at the upstream lip.

Such a mechanism might be used for influencing the Mach number approaching the normal shock, or, by diverting some of the approach flow, for providing stable sub-critical operation in an intake. Ordinarily, of course, it would be impossible for the supersonic flow upstream of the shock to be influenced from downstream, except for the limited effects transmitted by the boundary layer.

In addition to the above effects the possibility existed that the replacement of the fixed free stream boundary by one rotating in the same direction as the main flow might reduce boundary layer losses.

In the light of these considerations it was thought worth while to carry out some experiments on simple rigs in order to check both on the losses which such vortex bearings might entail if incorporated in proposed intake designs, and also on the likelihood of their facilitating the passage of the boundary layer through a normal shock. The experiments would also show whether the flow is basically stable, as has been assumed in the preceding discussion.

In appearance the vortex bearing is similar to the "trapped vortex". This is a device which has been tested[1,2,3,*] as a means for preventing breakdown in the flow in steep angled diffusers and in the trailing edge region of aerofoils at high lift coefficients. Now the cause of the breakdown in the flow in such regions is the steep pressure rise resulting from the rapid diffusion of the main stream. The pressure rise prevents the passage of the low momentum air in the boundary layer which consequently tends to build up at a point of pressure rise until it displaces the main stream from the surface, thus producing "separation" and breakdown of the flow. Hence, from one point of view, a trapped vortex, which consists essentially of low momentum air, might be expected to be the cause of a breakdown of the flow rather than a cure, the almost "dead" air in the vortex being unable to sustain a pressure gradient. In the present concept of a vortex bearing, however, the air in the bearing is used essentially as a region of constant pressure, so that a priori it could be expected to fulfil its role rather more successfully than the previous trapped vortex.

3.0 The first series of experiments

The object of the first part of the experimental programme was to investigate the probable effect of the vortex bearing on the boundary layer and main stream air passing adjacent to the free streamline interface with the vortex. For the intake shown in Figure 2, where the bearing is a relatively small part of the intake, it was only necessary to show that the bearing provided a stable flow not suffering excessive losses.

The first rig was obtained by embodying a simple modification in a rig previously used for work on supersonic turbine blading and described in detail in Reference 4. The following brief description is taken from this Reference, as is the photograph of the rig reproduced here as Figure 3. "A low turbulence and a uniform velocity distribution at the inlet to the

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*See also:- Migay, Teplo Energetica, 10, 1962.

nozzle of the tunnel was obtained by passing the air through a gauze, honeycomb, settling length and contraction, the latter having an area ratio of 15/1 to the throat. The Mach number was 1·9 at inlet to the cascade, which consisted of one blade and two passages. The blade was of aluminium with a span of 3·11 in. and a chord of 4 in. and, to enable observation of the flow through the working section, the end walls were of $\frac{1}{2}$ in. thick perspex. The remainder of the tunnel was constructed of wood."

The rig was modified from its original form for the present work by the removal of the solid boundary along the length A.B.C. in Figure 4, and the incorporation in turn of various shapes of cut out. In the first place a near circular cut out was used, in order to facilitate the formation of a vortex. Subsequently, it was envisaged that in some instances where a vortex bearing might advantageously be used space would not permit a cut out of circular form. Right angled and triangular cut outs were therefore fitted as shown in Figures 5 and 6, with the object of determining the losses which such arrangements entailed.

The total pressure before the nozzle, i.e., $P_{tot,\ inlet,}$ was measured by means of a retractable $1\frac{1}{2}$ mm diameter pitot tube placed upstream of the contraction section to the nozzle.

At the outlet from the cascade, 0·3 in. downstream from the trailing edge of the single blade, traverses were made for the pitot and static pressures using the probes shown in Figure 7, the pitot pressure being corrected to total pressure in the standard manner.

3.1 Comparison between conditions in the rig and those in an intake

In the first instance the free stream Mach numbers, 1·9 in the rig, and 2·07 in one particular intake having an entry Mach number of 3·0, are of the same order. In both cases too, compression waves are arranged to impinge on the free stream boundary between the vortex and the main fluid flow. On the other hand the free stream in the rig is turned through an angle of 140°, and the solid boundary is removed over a length corresponding with this angle, whereas the vortex bearing as suggested for the intake shown in Figure 2 has the solid boundary removed over a length of the surface corresponding to a change in the flow angle of 20° only. Thus it can be argued that any effect of the vortex bearing on losses should be more marked in the rig than in the intake proper. Also, as mentioned at the beginning of Section 3.1, the bearing would be only a relatively small part of an intake, whereas it represents almost the whole of the present test region.

3.2 Experimental procedure

In the previous experimental programme four blade designs had been tested. Reference 4 reports tests on the first blade design, which was found to suffer from focussing of the compression waves and severe interaction between the resulting shocks and the boundary layer. The same reference reports the tests on the fourth design. In the present programme the first test was made using the first blade design and, as in the previous work, this led to compression wave focussing and to the formation of strong shocks. It was then decided that more truly representative conditions would be obtained using the fourth design, which was therefore used in all subsequent tests.

The Mach number from the nozzle was checked during the tests by measuring the angle of the shock wave emanating from the leading edge of the blade, and found to be within the range reported in Reference 4. Finally in order to ensure as valid a comparison as possible between the present work and that referred to above, attention was given to the effect of contraction as discussed in the earlier papers. In these, contraction is defined as the proportional reduction in passage area between entry and mid-chord, and it was argued, with the support of experimental evidence, that a net gain should result from contraction, although care has to be taken to avoid choking troubles. In the main this view rests on the fact that since the flow is supersonic, the initial contraction diffuses the inlet flow to give a reduced mean Mach number at mid-chord and a subsequent acceleration before the exit. The boundary layers at entry are thin and so the diffusion should cause little difficulty, whereas at exit the boundary layers are thicker and contain secondary flow, so that the acceleration would be expected to be beneficial.

In the present work the removal of the solid boundary on the convex side of the inner passage in the mid-chord region of the blade precludes the adjustment of the geometry of the model to obtain some predetermined amount of contraction, whilst it was not possible from examination of Schlieren photographs of the airflow to determine precisely the boundary between the free stream and vortex flows at the mid-chord point. However, tests showed that there was a rise in static pressure through the cascade, whilst in addition the removal of the solid boundary on the convex surface of the passage would increase the tendency towards the formation of secondary flow. It was therefore felt that on the whole the results obtained from the earlier work with zero contraction would provide the fairest yardstick against which to assess the performance of the rig as modified by the cut out. It should be noted that in the previous tests at zero contraction the losses included those from a narrow bubble of reverse flow.

For the present tests interest was centred on the behaviour of the inner passage as it was the flow here that was directly affected by the vortex bearing. Consequently, no special care was taken to ensure the outer passage being the same as in the previous tests, and in fact in order to facilitate the progress of the investigation both blade designs were tested in the tunnel for the first cascade.

Traverses were made at 50 per cent and at 20 per cent span, the latter providing a check on the uniformity of the velocity distribution across the span.

3.3 Tests performed and results

(i) Build using the first blade design

Schlieren photographs of the flow pattern obtained with this build are shown in Figure 8. Imperfections in the surface of the perspex sidewalls

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also show up in these photographs, and in those in Figure 10, but the flow pattern is readily distinguished. A vortex sheet will be observed running from the upstream lip of the bearing, indicating the boundary between the entry flow and that recirculating in the vortex. The focussing of the compression waves emanating from the concave surface of the blade, and their termination in a normal shock, is most noticeable, as is the near normal shock which extends beyond the focal point to the vortex sheet. Downstream of the normal shock there would seem to be a mixture of subsonic and supersonic flow. A second vortex sheet is visible, running from the focal point and forming the boundary between the relatively high energy air which has passed through the compression fan prior to the normal shock and that which has undergone the less efficient compression through a single shock.

The shock pattern of Figure 8 would not be expected to produce a high performance flow and examination of the pressure traverses plotted in Figure 9 shows that in fact this is the case. At 20 per cent span the pressure coefficient, here defined as the ratio of the area mean total pressure at the passage outlet to the total pressure at inlet, is 0·682, compared with the corresponding figure of 0·724 obtained in the previous tests without the cut out, whilst at 50 per cent span the figures are respectively 0·614 and 0·715. Thus the introduction of the cut out reduces the pressure coefficient by approximately 6 per cent at 20 per cent span, and 15 per cent at mid-span. The fall-off in the value of the pressure coefficient towards mid-span was to be expected from the earlier work with this apparatus, when it was surmised that it resulted from the low energy air contained in the secondary flow on the side walls being swept towards the centre of the passage. Compared with the earlier work the present results show a greater proportional loss towards the centre, perhaps resulting from the secondary flow on the end walls continuing into the cut out region before accumulating at mid-span.

The principal changes in the shock pattern are the formation, in the present flow, of the normal shock subsequent to the compression fan, and the near normal shock emanating from the focal point. In the previous flow the family of expansion waves from the convex solid surface of the passage reduced the rate of pressure rise and prevented these shocks. Estimates suggest that the near normal shock contributes a significant proportion of the additional loss.

The normal shock could probably have been prevented by increasing the width of the passage at exit, thereby reducing the static pressure both at exit and in the cut-out, and producing an expansion fan in the main flow at entry. Such a scheme was not tested but attention diverted instead to the fourth design blade.

(ii) <u>Build using the "fourth" blade design</u>

Schlieren photographs of the flow pattern obtained with this configuration are shown in Figure 10. The vortex sheet at the boundary between the circulating air in the cut out section and the main stream at entry to the inner passage is most marked, as is the absence of the very strong shock which was a major source of loss in the previous build. Also faintly visible are the family of expansion waves formed by the reflection at the free stream boundary of the compression waves running from the concave surface of the blade. It will be recalled that it was such a series of expansions which were originally suggested as easing the pressure rise upstream of the bleed slots in the intake, and thus decreasing the likelihood of boundary layer separation.

The pitot and static traverses shown in Figure 11 confirm that the pressure coefficient is improved, the figures being 0·709 and 0·675 at 20 per cent and 50 per cent span respectively. However, they still represent a loss when compared with the same build prior to the incorporation of the cut out, for which the corresponding figures were 0·751 and 0·740. In particular the greater loss towards mid-span will again be noted, tending to strengthen the view that it results from increased secondary flow on the side walls.

(iii) Build using the "fourth" blade design with secondary flow spoilers

The results of the previous build led to the decision to fix spoilers, or secondary flow fences, in the form of narrow shims of metal projecting into the airflow around the periphery of the cut out section, i.e., along the dotted line A.B.C. in Figure 4, with the object of deflecting and breaking up the secondary flow on the side walls. The amount of projection was fixed, somewhat arbitrarily, at $\frac{3}{16}$ in., this giving a spoiler of reasonable size whilst at the same time not being so large, compared with the cascade span of 3·11 in., as to compromise the object of the test in determining the effect of the cut out. Unfortunately, it was not possible to take satisfactory Schlieren photographs of the flow with this arrangement, as the milling of the slots in the perspex for the spoilers caused considerable photo-elastic effects. However, it was still possible to observe the flow pattern visually, and this was seen, as would be expected, to be similar to that obtained with the previous build.

It is the pressure distributions plotted in Figure 12 that reveal the significant effect of the spoilers. These are shown to increase the pressure coefficient from 0·675 and 0·709 at 50 per cent and 20 per cent span respectively, to 0·708 and 0·717. Thus not only is the pressure recovery as a whole improved, but also the "dip" in recovery towards mid-span is reduced by a factor approximately 4, so lending weight to the view that the increased loss previously noted was due to increased secondary flow on the side walls. The fitting of the shims has in fact brought the measured pressure coefficients to within 4 per cent of the values obtained without the cut out. The remaining difference may be a real one although it is probably within the limits of the accuracy of the measurement. A note on accuracy is contained in Reference 4, in which, in particular, attention was drawn to the importance of the static and pitot pressures in the downstream traverses being measured at the same points. In the present series of tests it is even more important that the measurement positions should be the same for the pitot and static pressures as the static pressure is rather lower, and undergoes more variation across the passage. At its maximum, the variation of static pressure is of the order of 2 per cent of the inlet total pressure per turn of the traverse feed screw, so that if the pessimistic assumption is made that the location of the static reading was incorrect by half a turn (i.e., 2 per cent of the passage width) then the static pressure reading is in error by about 1 per cent of the inlet total pressure. The Rayleigh relationship is such that this could lead to an error of the order of $2\frac{1}{2}$ to 3 per cent in the calculated value of the total pressure at outlet from the cascade.

(iv) Builds with 'V' shape and rectangular cut outs

The secondary flow spoilers were retained in the builds with the 'V' shape and rectangular cut outs shown in Figures 5 and 6. The pressure traverses plotted in Figures 13 and 14 show the pressure coefficients to have been reduced from the figures reported with the previous build to 0•625 and 0•671 with the 'V' shape cut out, and 0•677 and 0•689 with the rectangular cut out, these sets of figures corresponding in each case with traverses taken at 50 per cent and 20 per cent span respectively. The shock systems were generally similar to those obtained with the previous builds, except that the shock formation appeared more severe, contributing to the additional losses reported above.

(v) By-pass of a supersonic stream

When the back pressure at the exit from the rig was increased sufficiently to displace the normal shock upstream as far as the downstream lip of the vortex bearing, changes of back pressure were found to be transmitted, via the bearing, to the stream at entry to the bearing, despite the main flow around the bearing being supersonic. The ability of a bearing to provide a by-pass to supersonic flow as suggested in Section 2.0 is therefore confirmed.

3.4 Discussion

The preceding tests have shown that the flow with a vortex bearing is quite stable and that there appear to be no exceptionally large losses. It could, therefore, be suitable for the original application envisaged for it, an application in which the bearing occupies only a small region of the intake. Alternatively it would be suitable where only required to operate at off-design conditions. The ability to by-pass supersonic flow, thus being able to control from the subsonic diffuser the flow upstream of the normal shock, is also confirmed.

The tests show, however, that, while the losses are not exceptionally large, they are still larger than for a plain wall and, in fact, larger than for a wall with a narrow bubble of reverse flow. There appears also to be no improvement in the boundary layer profile. Thus the more optimistic advantages suggested in Section 2.0 have not materialized.

The explanation for the failure to improve the pressure coefficient probably lies in the mixing losses between the main stream and the vortex flow, with these rather more than offsetting any advantages gained from the removal of the zero slip condition at a solid boundary. It is suggested that the boundary, being no longer solid, ceases to act as a dampening influence on the local turbulence intensity, and thus mixing takes place as in a free jet, or as in a wake, despite the forward rotation of the vortex.

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The skin friction on the vortex walls would dissipate the energy thus transmitted to the vortex. It could also be argued in the present experiments that the local normal shock at the downstream lip has caused a deterioration of profile.

However, as previously stated, the net effect on the losses is not such as to rule out on this count the application of the vortex bearing to an intake, particularly when for the reasons stated in Section 3.1 it is borne in mind that in the application originally envisaged a reduced effect would be expected.

4.0 The second series of experiments

The second part of the experimental investigation was aimed at determining directly the extent to which the vortex bearing might prove useful in assisting a boundary layer through the pressure rise associated with a normal shock. To this end the apparatus shown photographically in Figures 15 and 16, and diagrammatically in Figures 17 and 18, was built. The principal details of its construction are clear from the figures. Basically it consists of an axisymmetric convergent-divergent nozzle, fed with dry air at approximately atmospheric pressure, and discharging at a Mach number of between 1·5 and 1·7 into a perspex chamber of circular cross-section. This chamber is surrounded by an annulus shaped so as to facilitate the formation inside it of a vortex; downstream the air enters a subsonic diffuser. The construction of the annulus was such that the length of the interface between the annular space and the main passage could readily be varied, while maintaining accurate alignment between the upstream and downstream walls of the main flow. Further variation in the rig geometry was permitted by the inclusion of different lengths of pipe between the nozzle exit and the annular cut out, so that in this way the thickness of the boundary layer approaching the bearing could be varied. Finally a throttle downstream of the rig provided a means of varying the position of the normal shock.

Instrumentation is shown in Figures 17 and 18; in addition the total pressure was measured upstream of the entrance to the nozzle.

4.1 Tests performed

Tests were carried out firstly with a 6 in. length of pipe between the nozzle exit and the perspex section, and secondly with the nozzle leading directly into the section. The following configurations of the annulus were tested:-

	Annulus opening to main flow 'x' (see Figure 17)
6 in. pipe between nozzle exit and perspex section	0·5 in. 0·25 in.
Nozzle discharging directly into perspex section	0·8 in. 0·5 in. 0·25 in.

Runs/

Runs were made at a number of different throttle openings, which were successively adjusted with the object of achieving the stable location of the normal shock immediately abreast of the annular cut out.

4.2 Results and discussion

The results are presented in Figures 19 to 23 in the form of static pressure plots along the length of the rig, these pressures being referred to the total pressure at inlet in the conventional manner. In this way the position of the normal shock in the rig is clearly shown. A quick glance through the figures just mentioned will suffice to show that in no instance was the vortex bearing successful in making possible the sharp rise in static pressure corresponding with a "clean" normal shock, with the boundary layer passing without difficulty to the region of higher pressure. In all cases the pressure recovery through the shock is relatively slow, and it will be noted that static pressures corresponding to fully subsonic flow are not obtained until some distance downstream of the perspex section. This slow recovery of static pressure, indicative of interaction between the normal shock and the boundary layer, is probably due to the presence of the "shock train", characteristic of normal shocks in ducts in the presence of boundary layers (see Reference 5 for example).

A closer look at the results obtained with the 6 in. pipe included in the rig shows that the recovery of static pressure across the vortex bearing was greater with the smaller of the two annulus openings.

Comparison of the two sets of results, with and without the 6 in. pipe included between the nozzle and the test section, shows that the recovery of static pressure across the vortex bearing is more rapid without the 6 in. pipe present. Removing the 6 in. pipe from the rig of course reduces the thickness of the boundary layer approaching the vortex bearing, and so a "cleaner" normal shock would be expected. Evidently however the nature of the flow in the bearing is not such as to improve the boundary layer profile to such an extent that the flow may pass cleanly through the normal shock. As in the experiments described in Section 3.0 the explanation probably lies in the mixing losses between the mainstream and the vortex flow.

Examination by shadowgraph of the flow in the bearing showed that, with the back pressure suitably adjusted, weak oblique shocks were formed at the upstream lip, together with a normal shock in the core of the flow positioned within the length of the bearing. The flow was not very stable at this condition, in that very slight movement of the throttle displaced the shock system from the region of the bearing.

5.0 Conclusions

Experiments have been made with a "vortex bearing" in order to assess its effect on the performance of a supersonic air intake. The experiments were kept as simple as possible, and their scope was not extended to include an investigation of the nature of the flow in the bearing.

The flow associated with a vortex bearing has proved stable. The interface between the mainstream and the vortex was effective in reflecting compression waves as expansion waves, thereby maintaining a constant static pressure at the boundary of the main stream. The losses at the bearing were not excessively great, so that application to an intake could be acceptable if the bearing represented only a small part of the flow or if it functioned only at off design. The bearing appeared successful in providing a by-pass to the supersonic stream such that the flow upstream of the shock could be influenced from the subsonic diffuser.

The more optimistic advantages suggested for the bearing did not materialize. The losses at the interface appeared to exceed those for an ordinary turbulent boundary layer at a solid wall and to exceed slightly those for a narrow bubble of separation. There appears to be no significant improvement in the shape of the velocity profile of the boundary layer, with the result that shock boundary layer interaction was virtually unaffected. The greater losses in a bearing are attributed to the more intense mixing which could result from the removal of the dampening influence of the solid wall on the turbulence.

A circular shape for the bearing cut out gives less loss than rectangular or 'V' shaped cut outs.

ACKNOWLEDGEMENT

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The more optimistic advantages suggested for the bearing did not materialize. The losses at the interface appeared to exceed those for an ordinary turbulent boundary layer at a solid wall and to exceed slightly those for a narrow bubble of separation. There appears to be no significant improvement in the shape of the velocity profile of the boundary layer, with the result that shock boundary layer interaction was virtually unaffected. The greater losses in a bearing are attributed to the more intense mixing which could result from the removal of the dampening influence of the solid wall on the turbulence.

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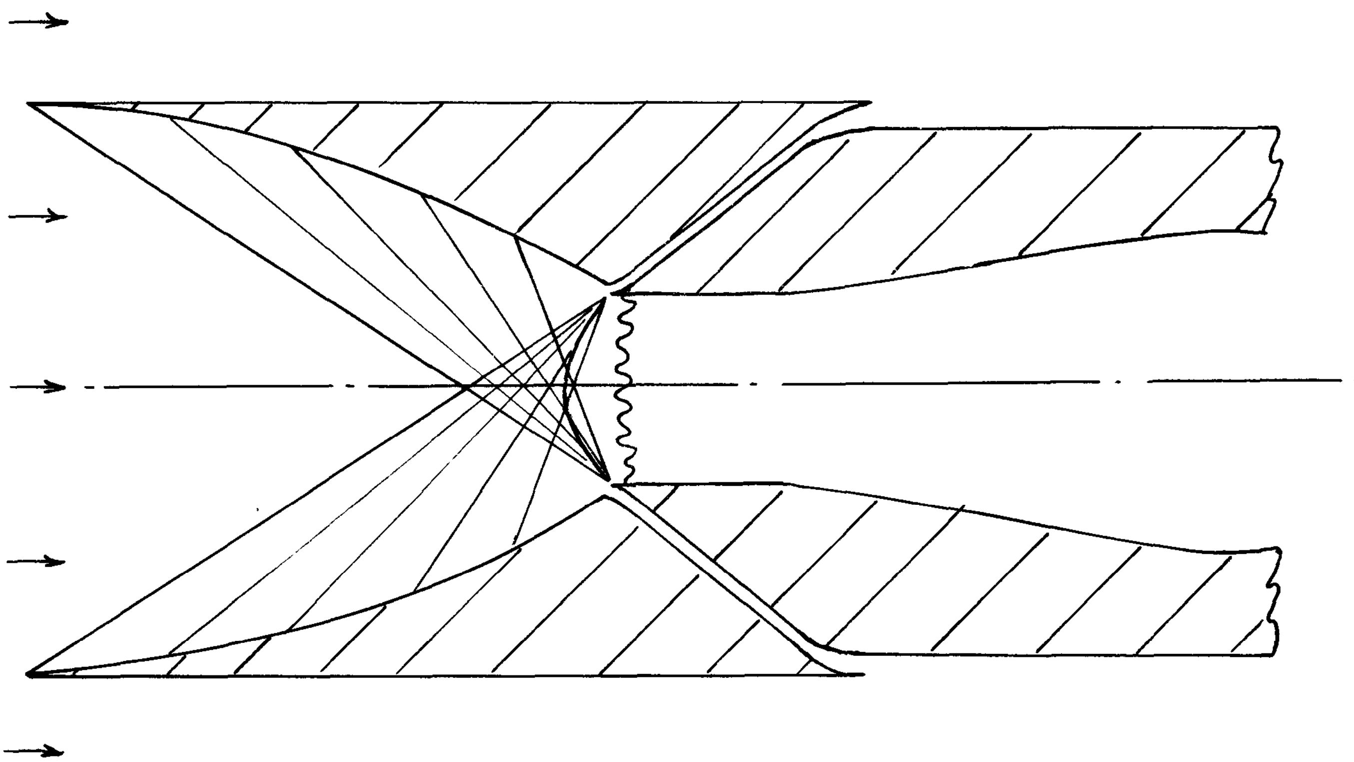
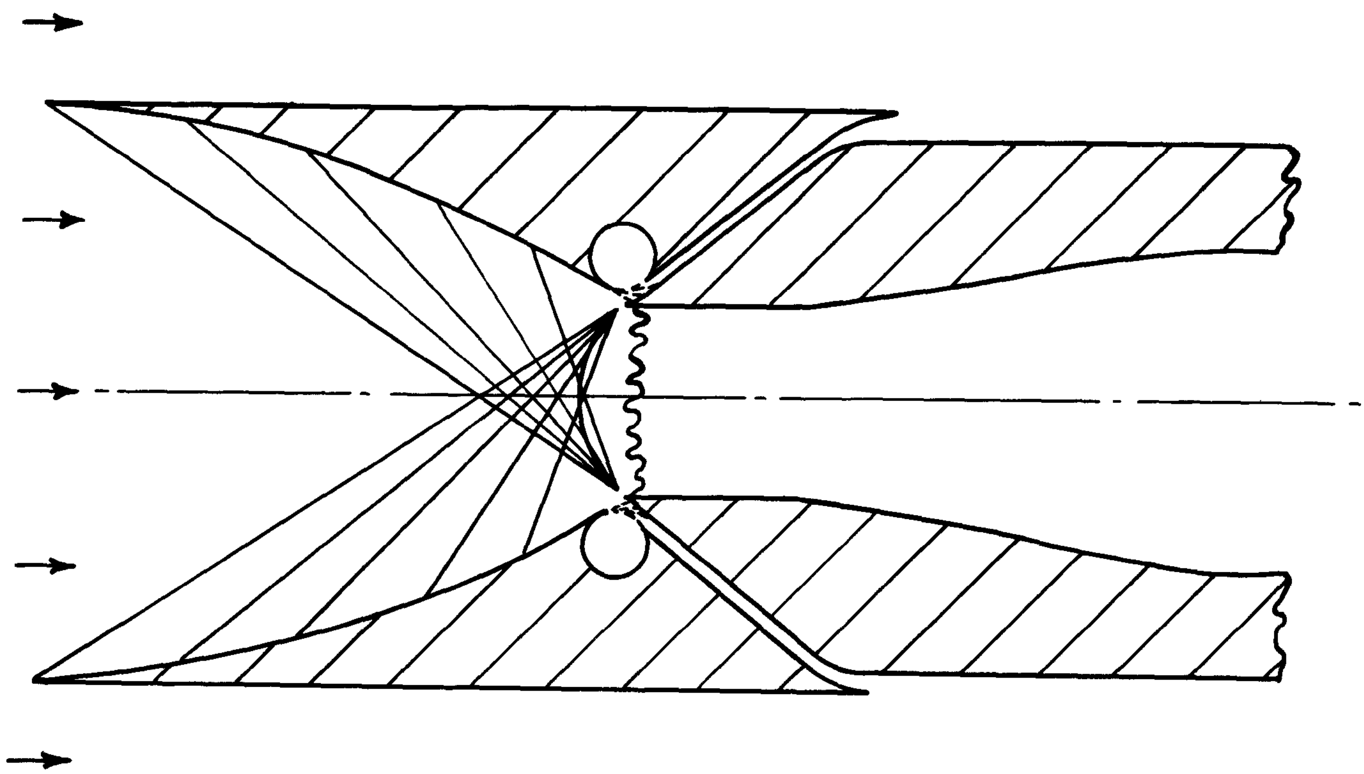
FIG. 1.



NOTE: NOT TO SCALE

A SHOCK - ON - LIP INTERNAL COMPRESSION INTAKE

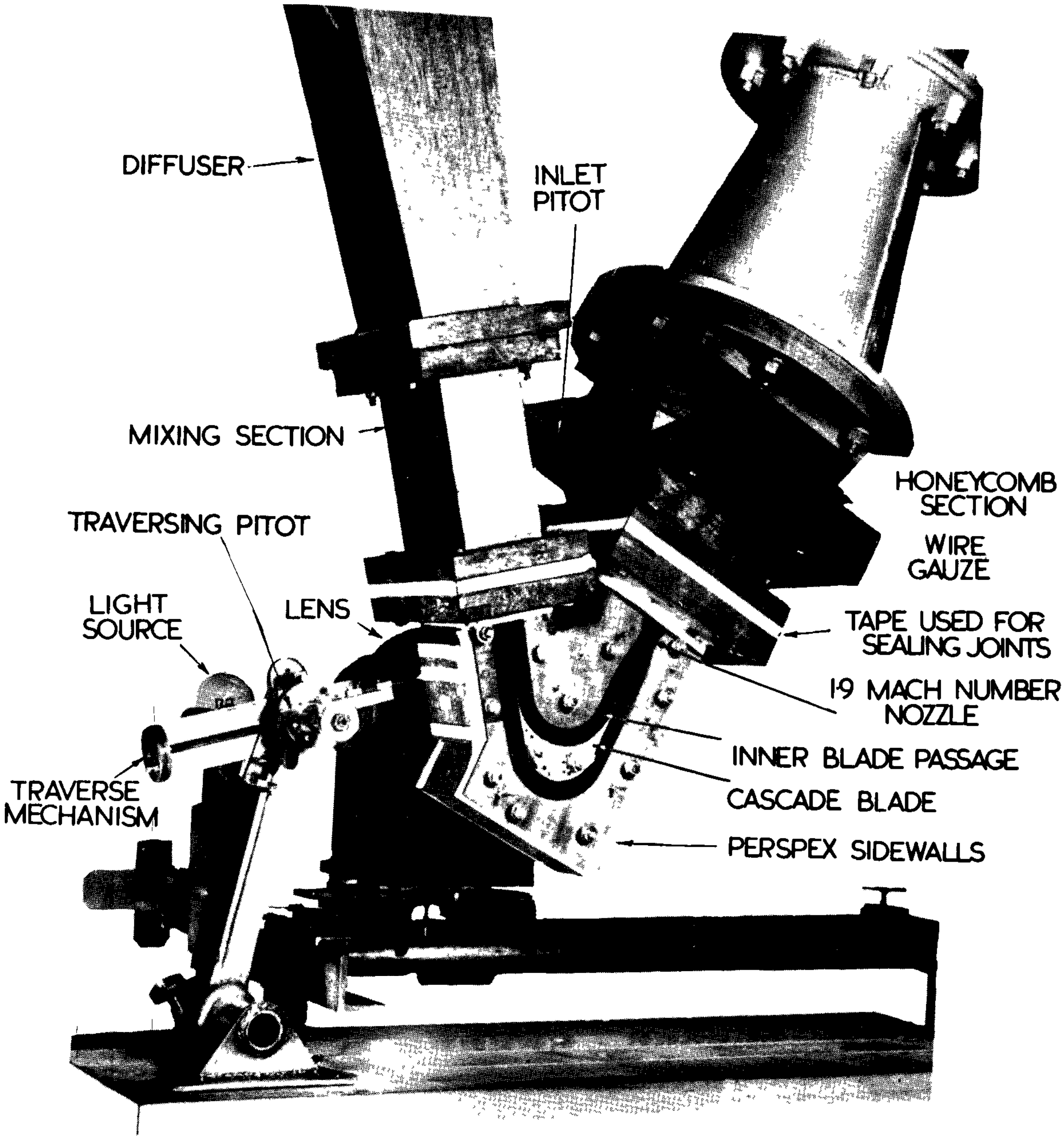
FIG. 2



NOTE: NOT TO SCALE.

A SHOCK FOCUSSING INTAKE FITTED WITH VORTEX BEARINGS.

(A) PHOTOGRAPH OF THE APPARATUS USED FOR THE FIRST SERIES OF EXPERIMENTS



(B) SCHEMATIC DIAGRAM OF SCHLIEREN SYSTEM

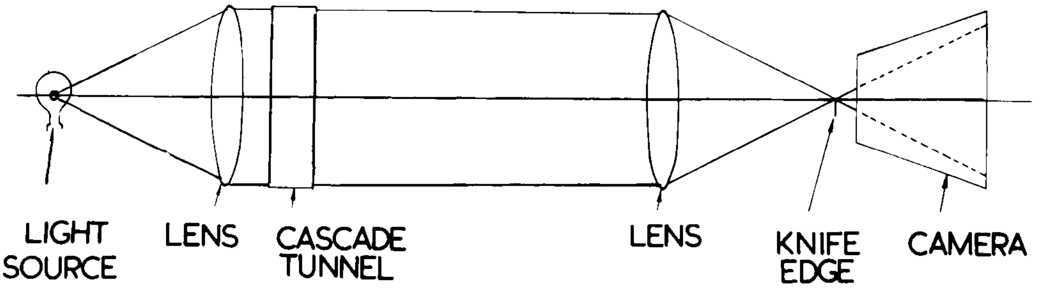
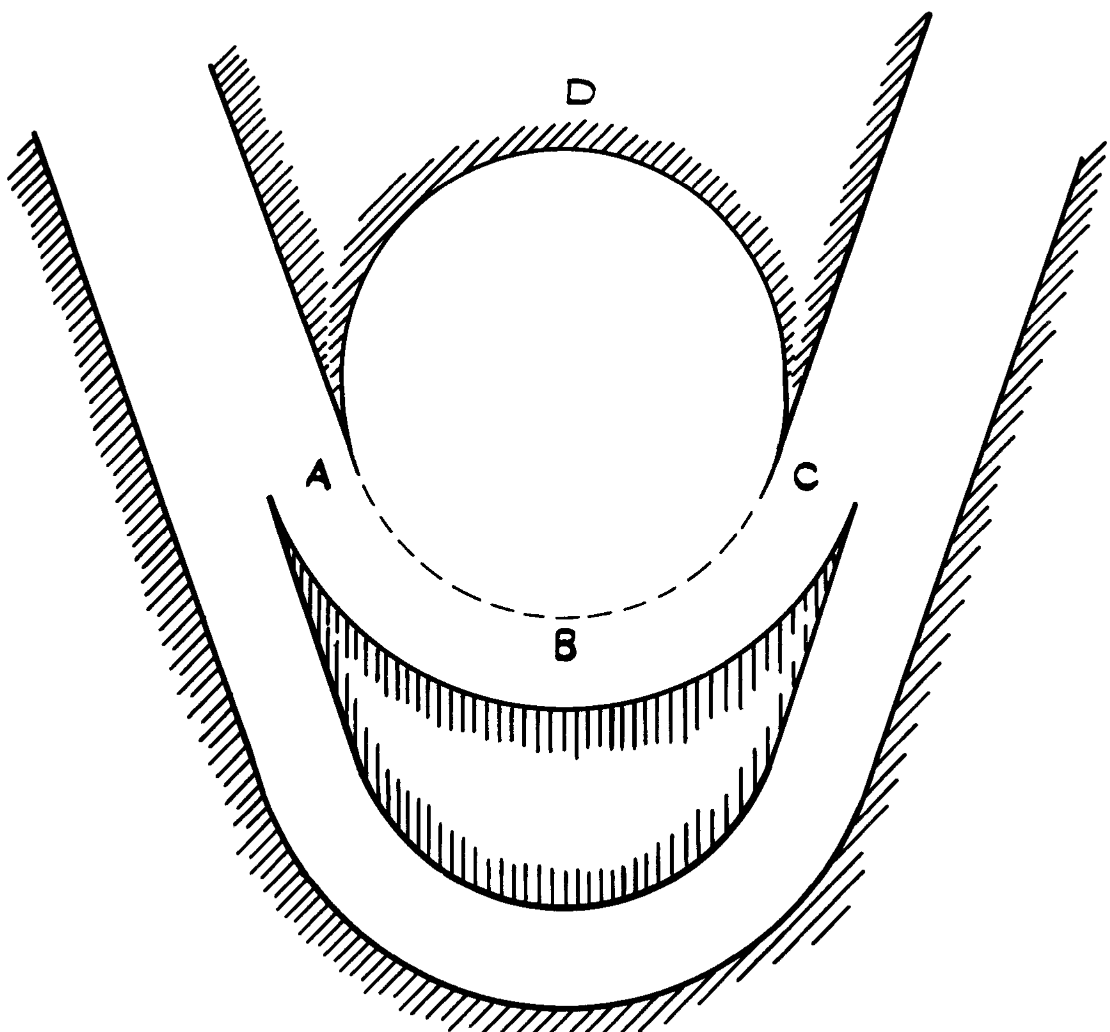
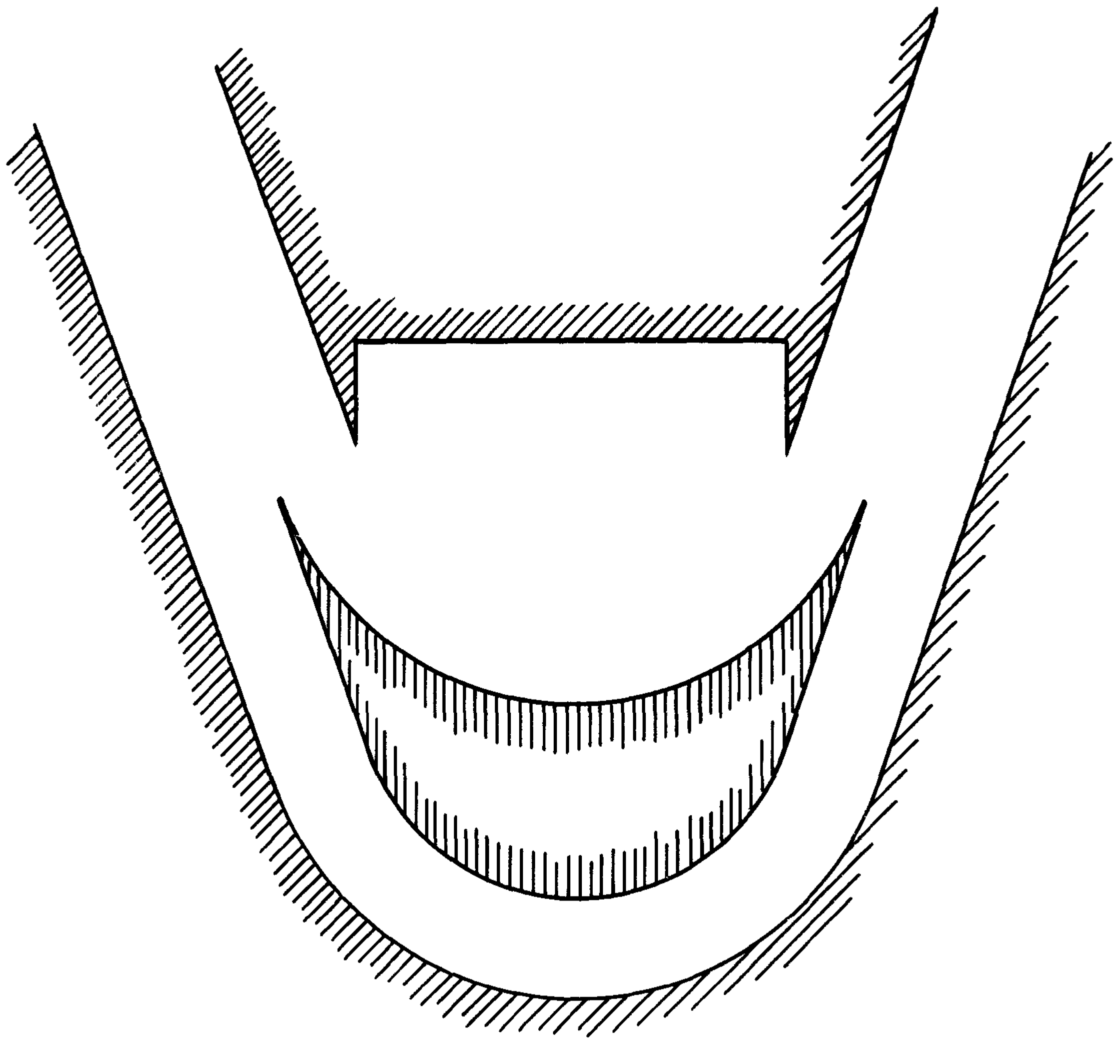


FIG. 4



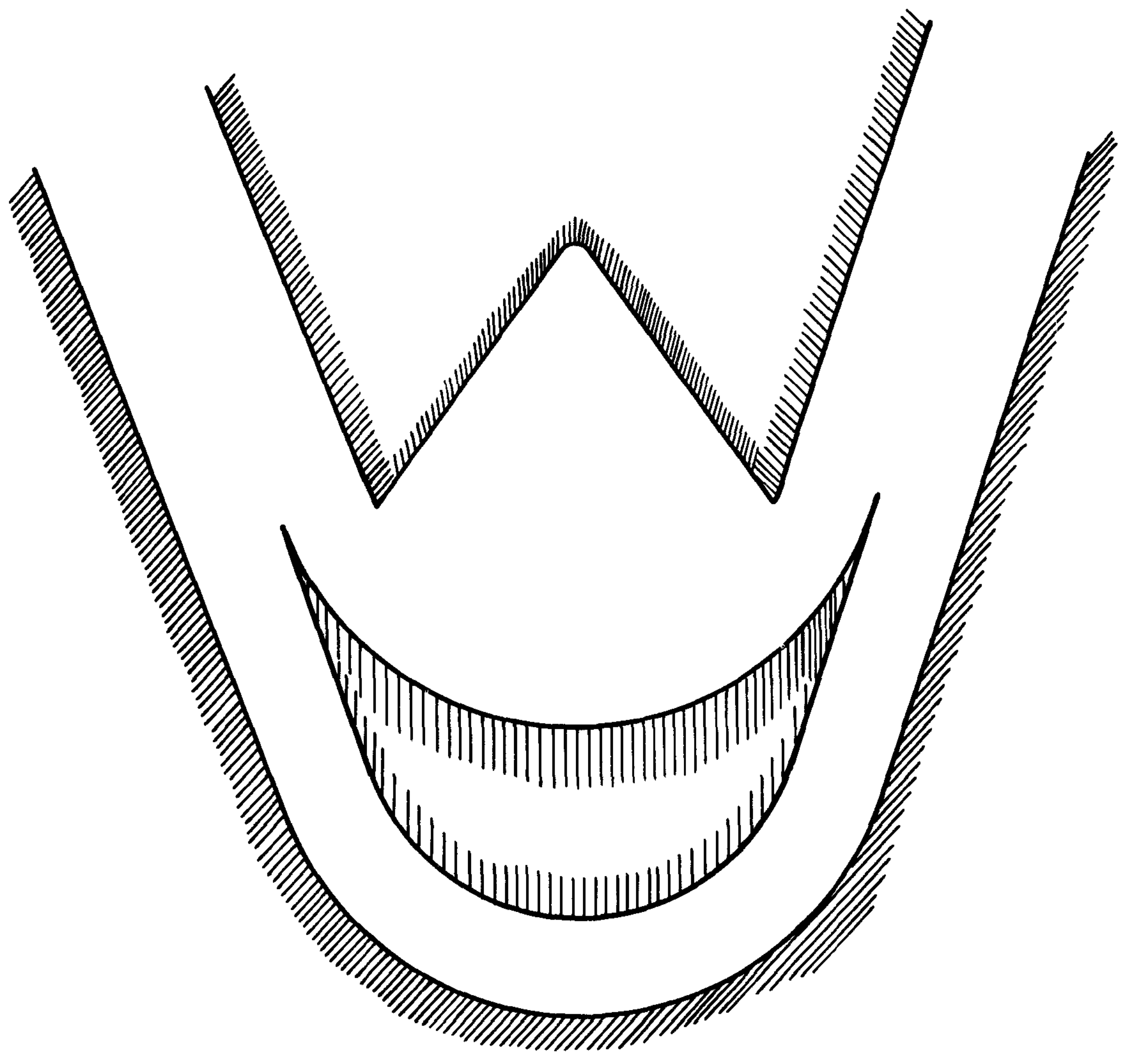
DEMONSTRATING THE REMOVAL OF THE SOLID BOUNDARY ALONG A.B.C. AND THE SUBSTITUTING OF A CUT OUT OF CIRCULAR FORM A.D.C.

FIG. 5



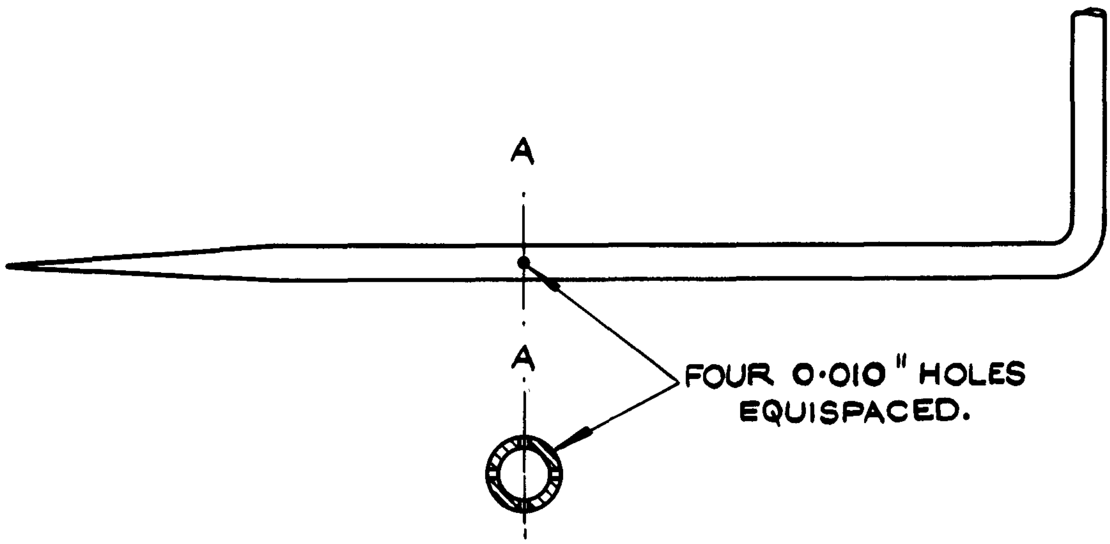
BUILD WITH RECTANGULAR CUT OUT.

FIG. 6



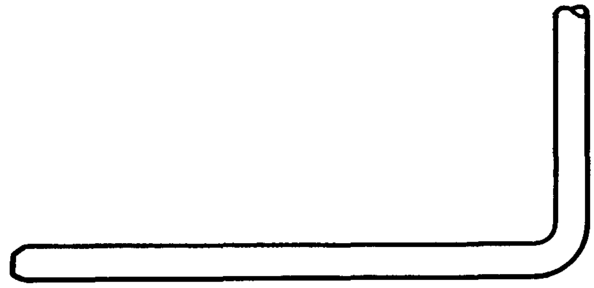
BUILD WITH V SHAPE CUT OUT.

FIG. 7



SECTION THROUGH AA (6 X FULL SIZE.)

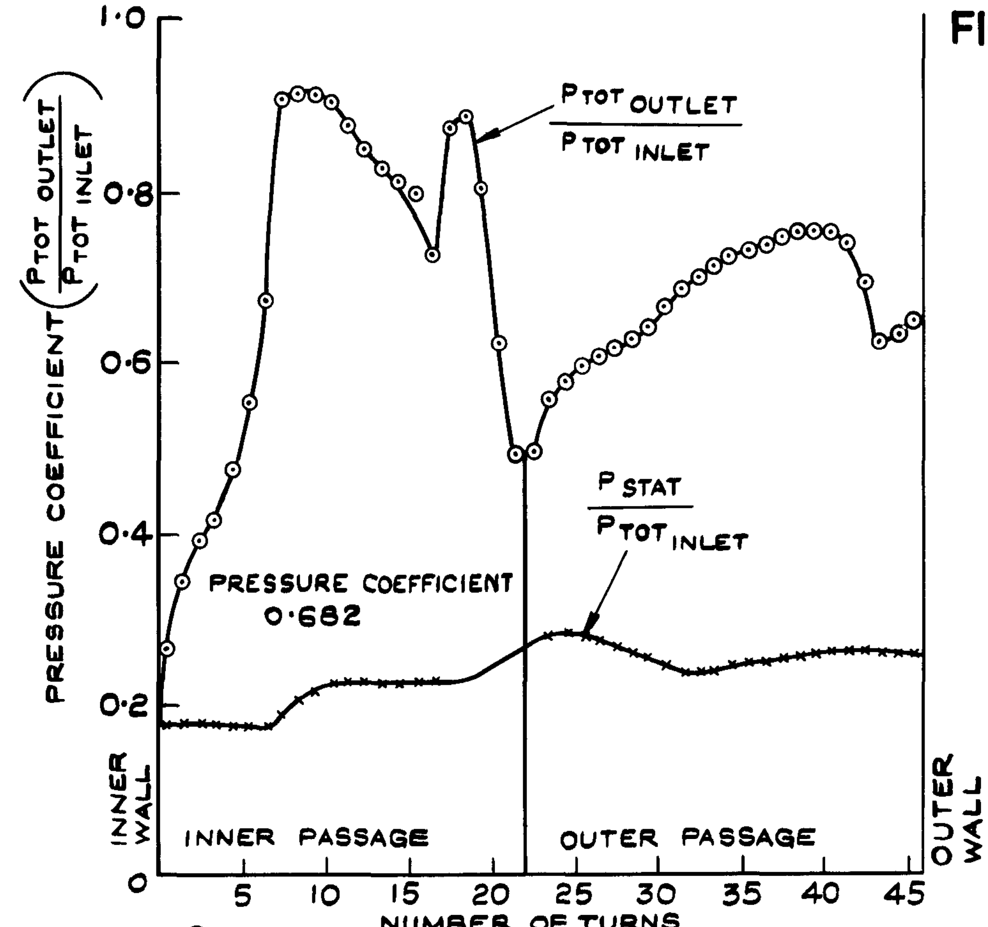
(a) FOUR HOLE TYPE STATIC PROBE
(3 x FULL SIZE.)



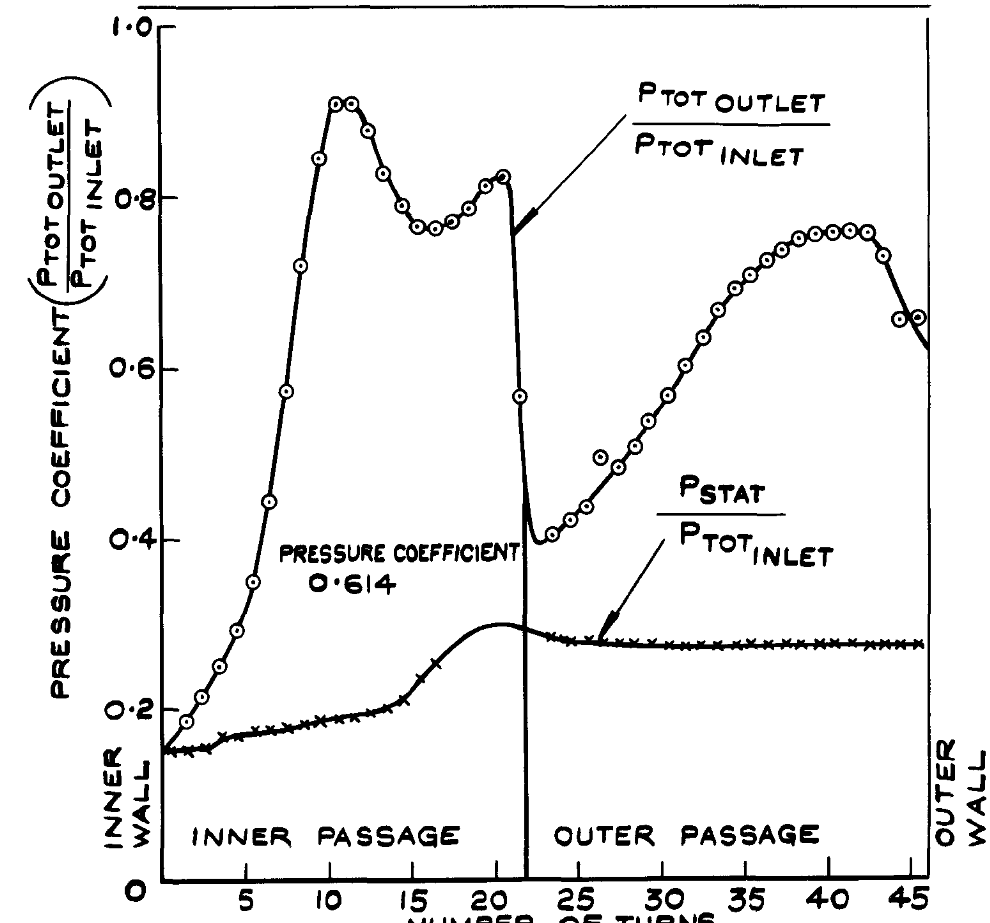
(b) $1\frac{1}{2}$ m.m PITOT TUBE
(3 x FULL SIZE)

PRESSURE MEASUREMENT PROBES.

FIG. 9

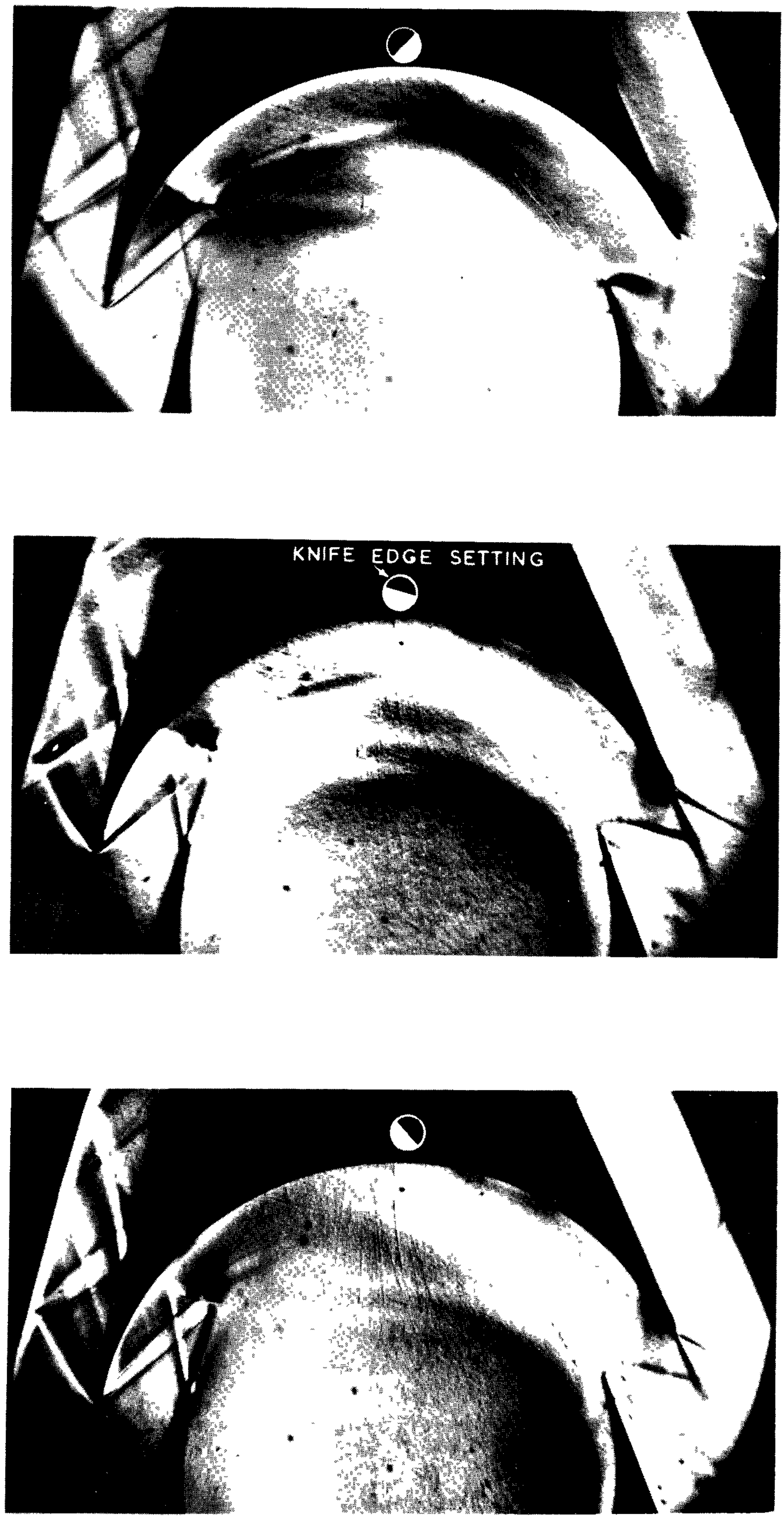


(a) 20% SPAN PRESSURE TRAVERSES WITH THE FIRST BLADE DESIGN.



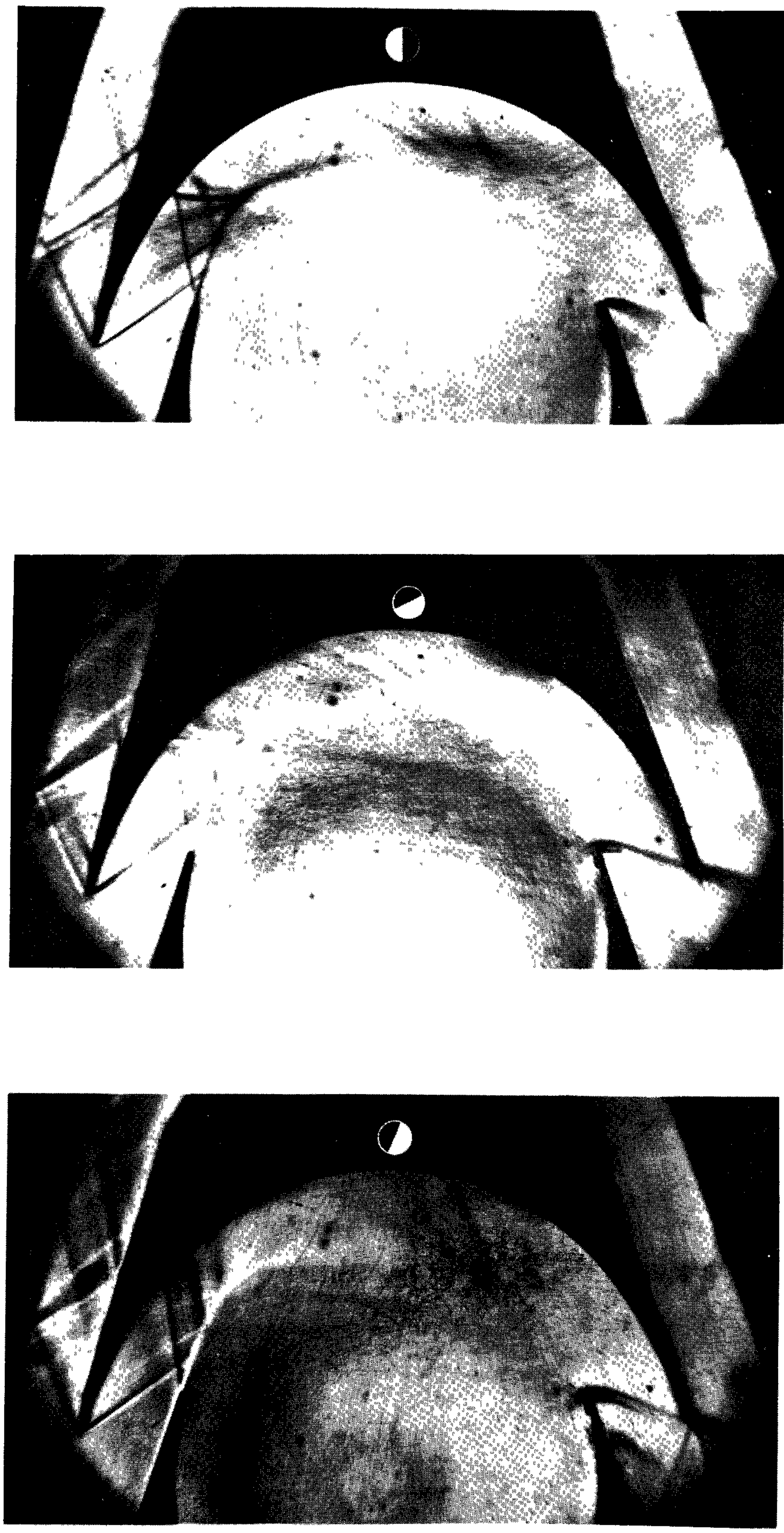
(b) 50% SPAN PRESSURE TRAVERSES WITH THE FIRST BLADE DESIGN.

FIG. 8.



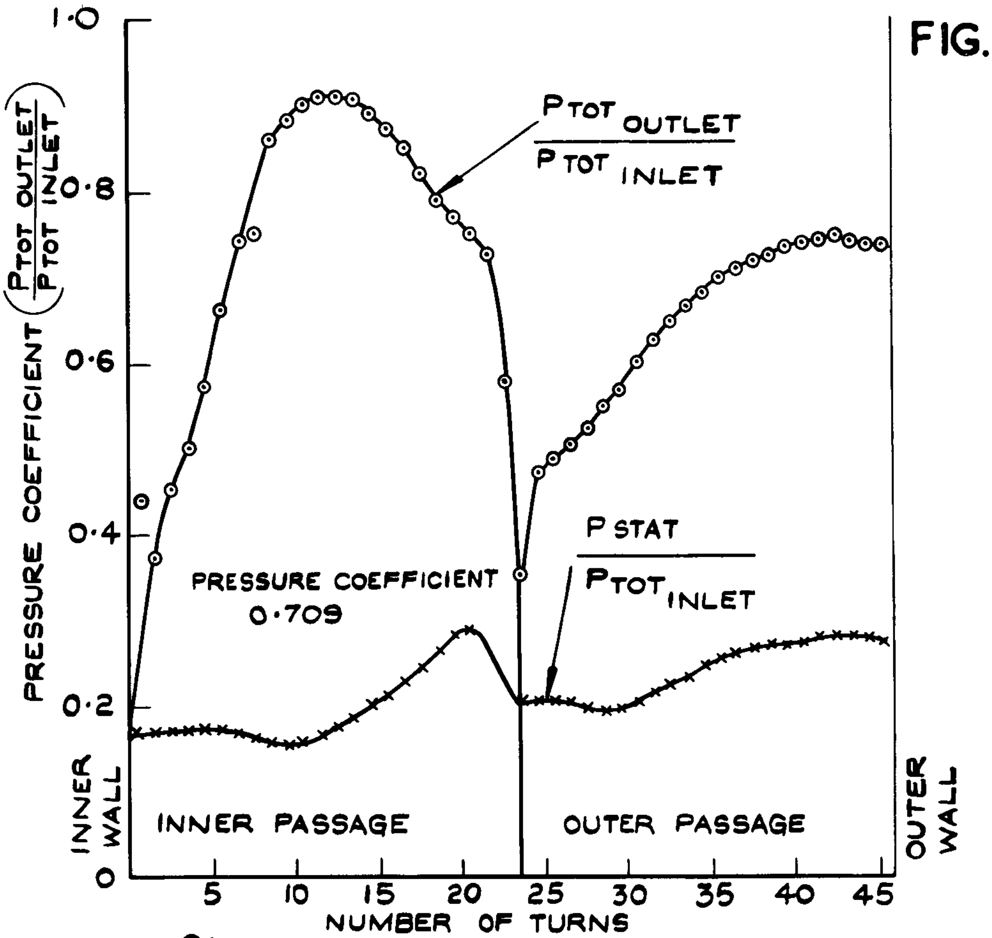
FLOW WITH THE FIRST BLADE DESIGN

FIG. 10.

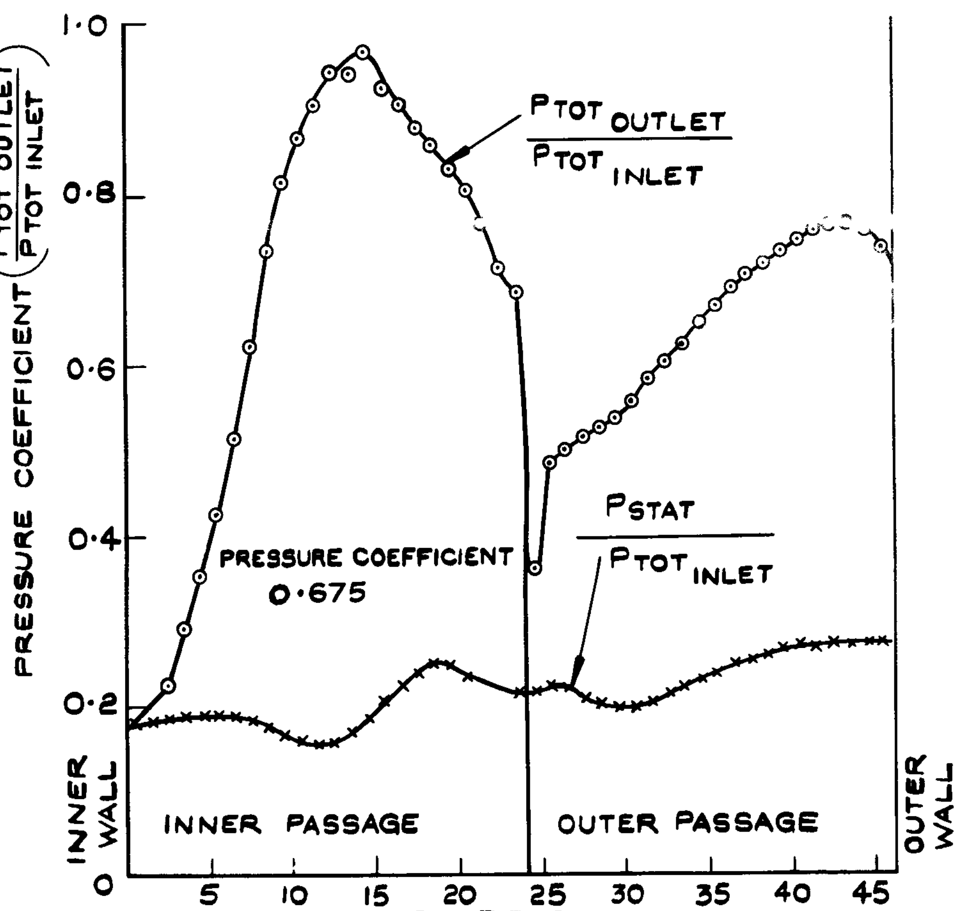


FLOW WITH THE FOURTH BLADE DESIGN

FIG.11

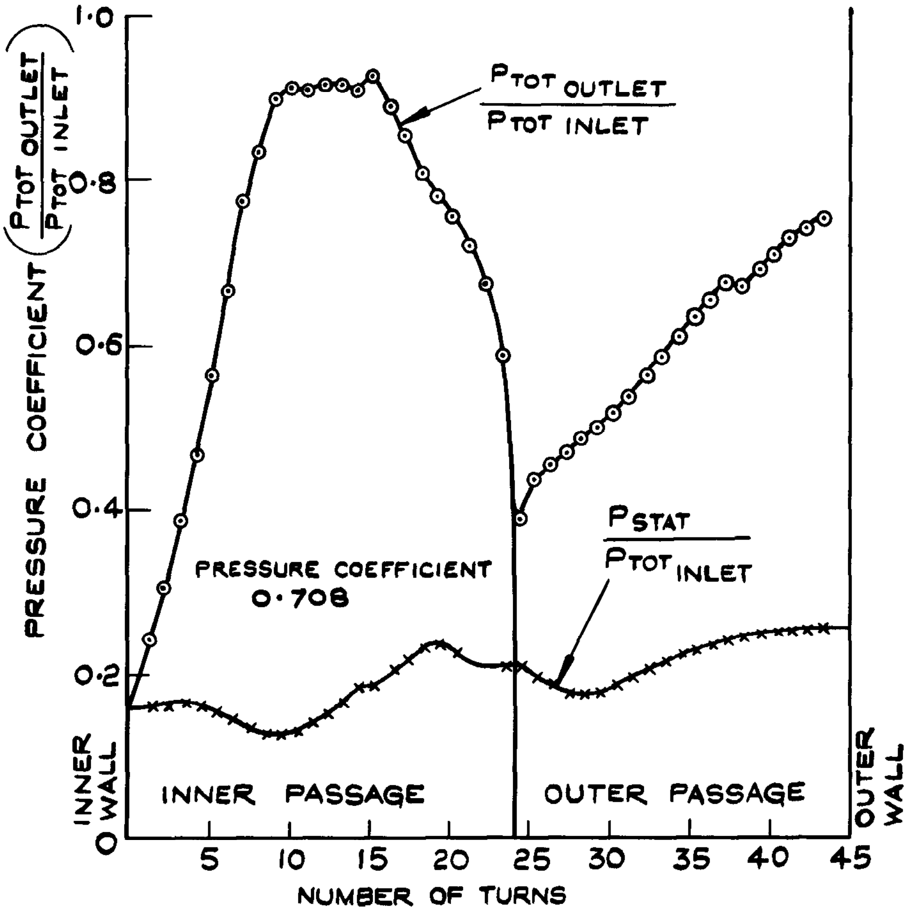


(a) 20% SPAN PRESSURE TRAVERSES WITH THE FOURTH BLADE DESIGN.

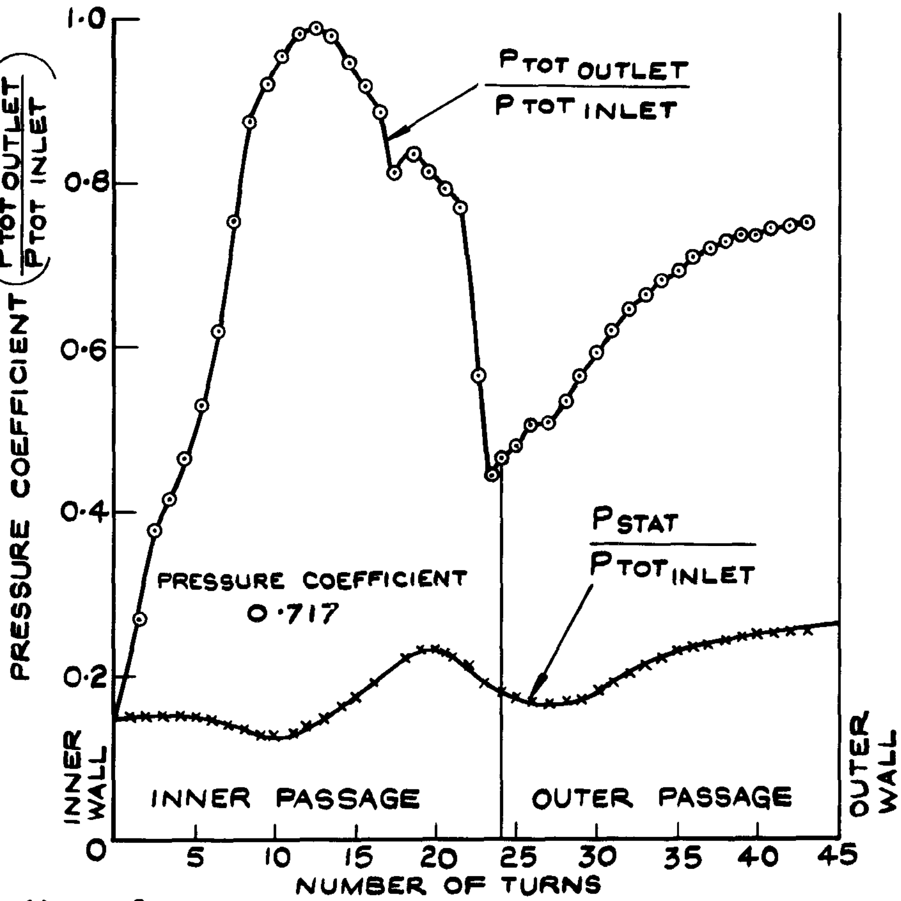


(b) 50% SPAN PRESSURE TRAVERSES WITH THE FOURTH BLADE DESIGN.

FIG.12

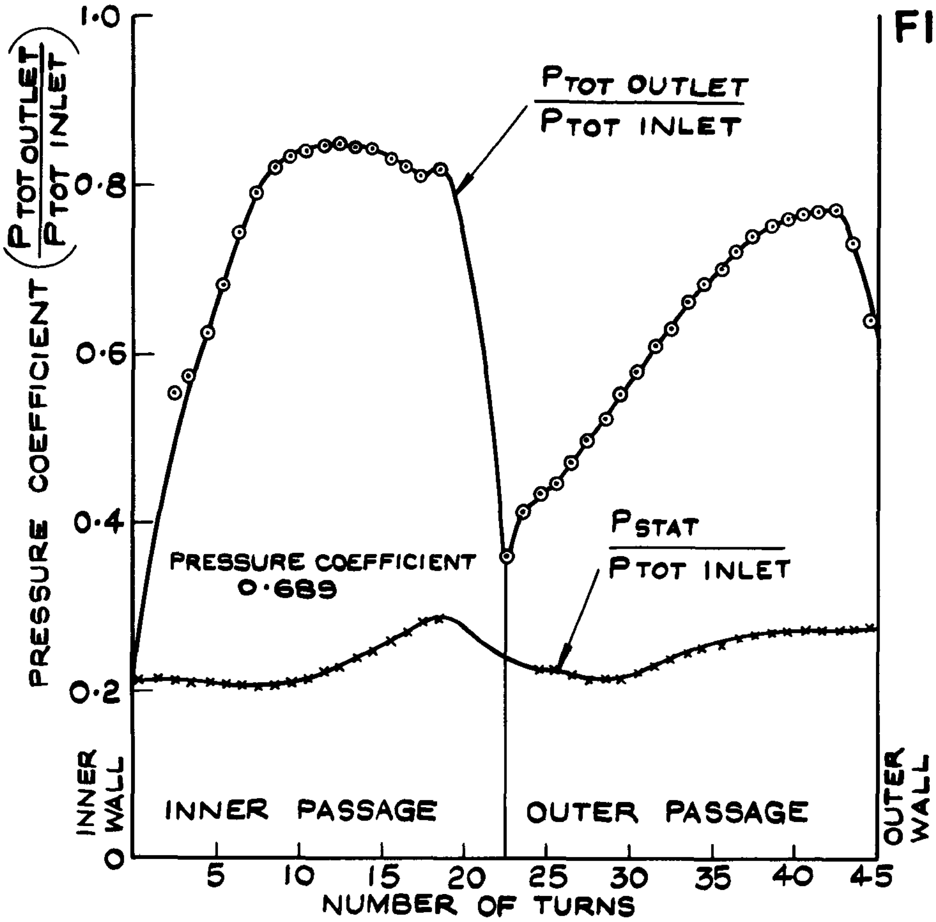


(a) 50% SPAN PRESSURE TRAVERSES WITH THE FOURTH BLADE DESIGN AND SECONDARY FLOW SPOILERS.

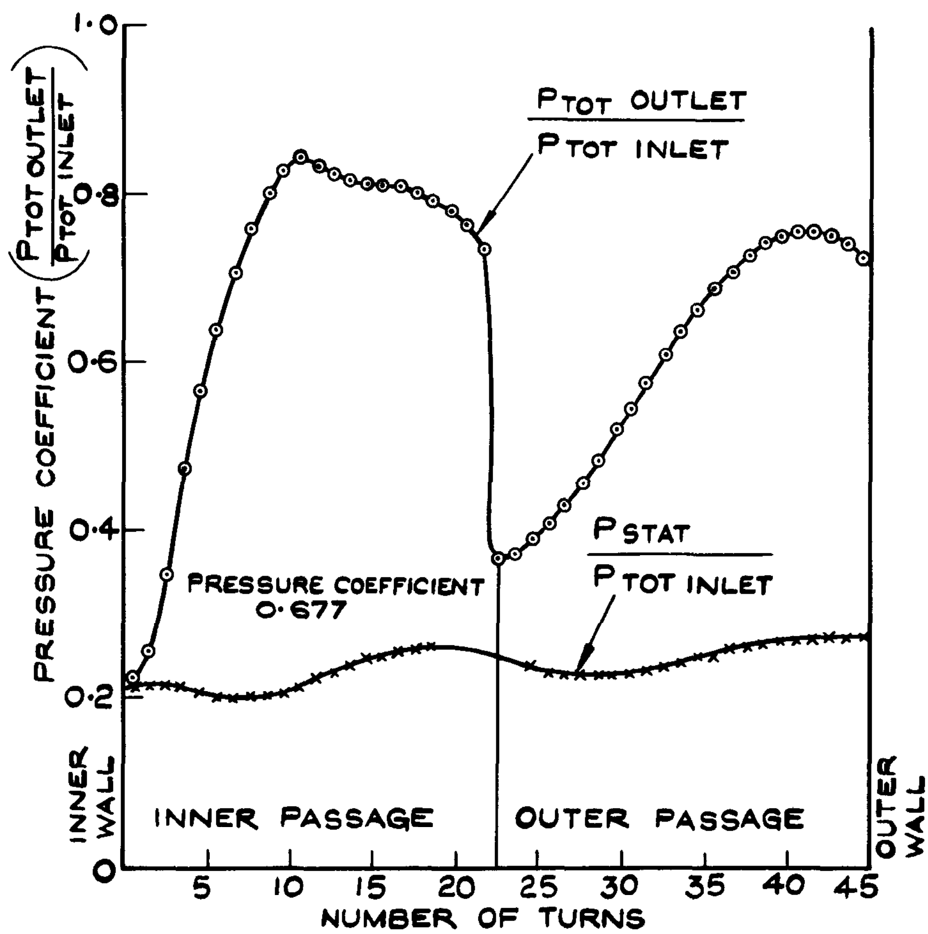


(b) 20% SPAN PRESSURE TRAVERSES WITH THE FOURTH BLADE DESIGN AND SECONDARY FLOW SPOILERS.

FIG. 13

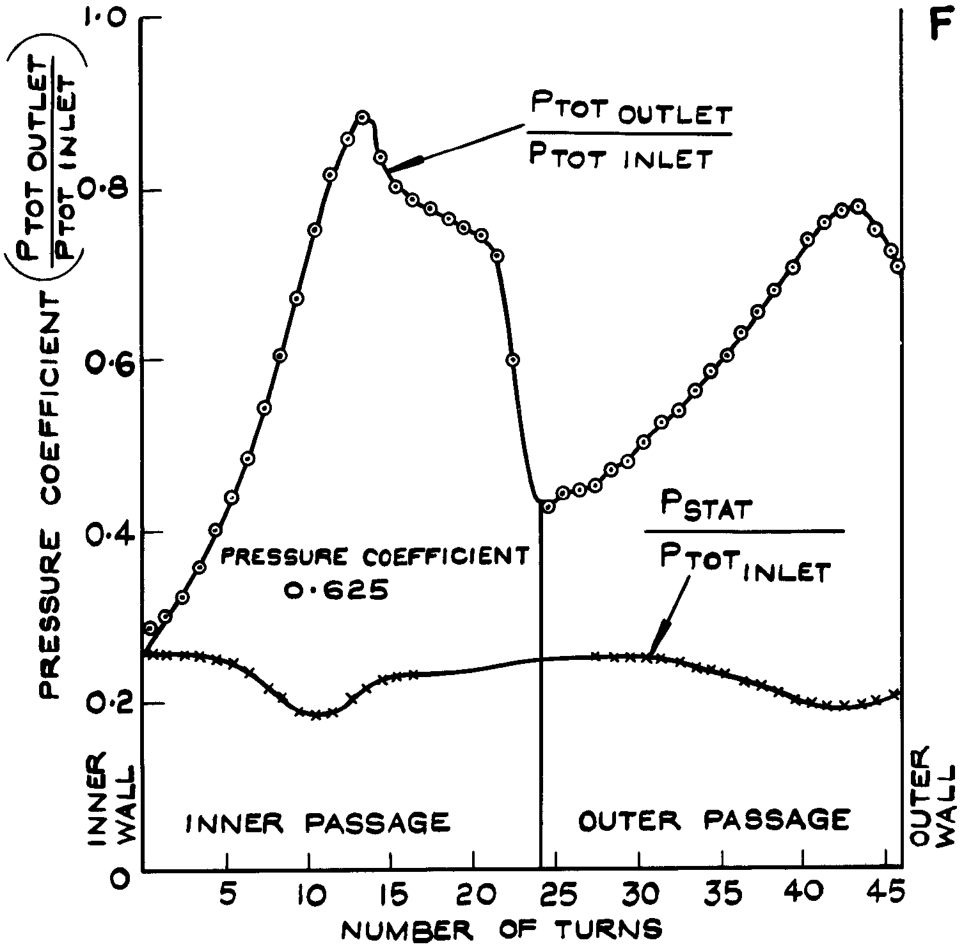


(a) 20% SPAN PRESSURE TRAVERSES WITH THE RECTANGULAR CUT OUT.

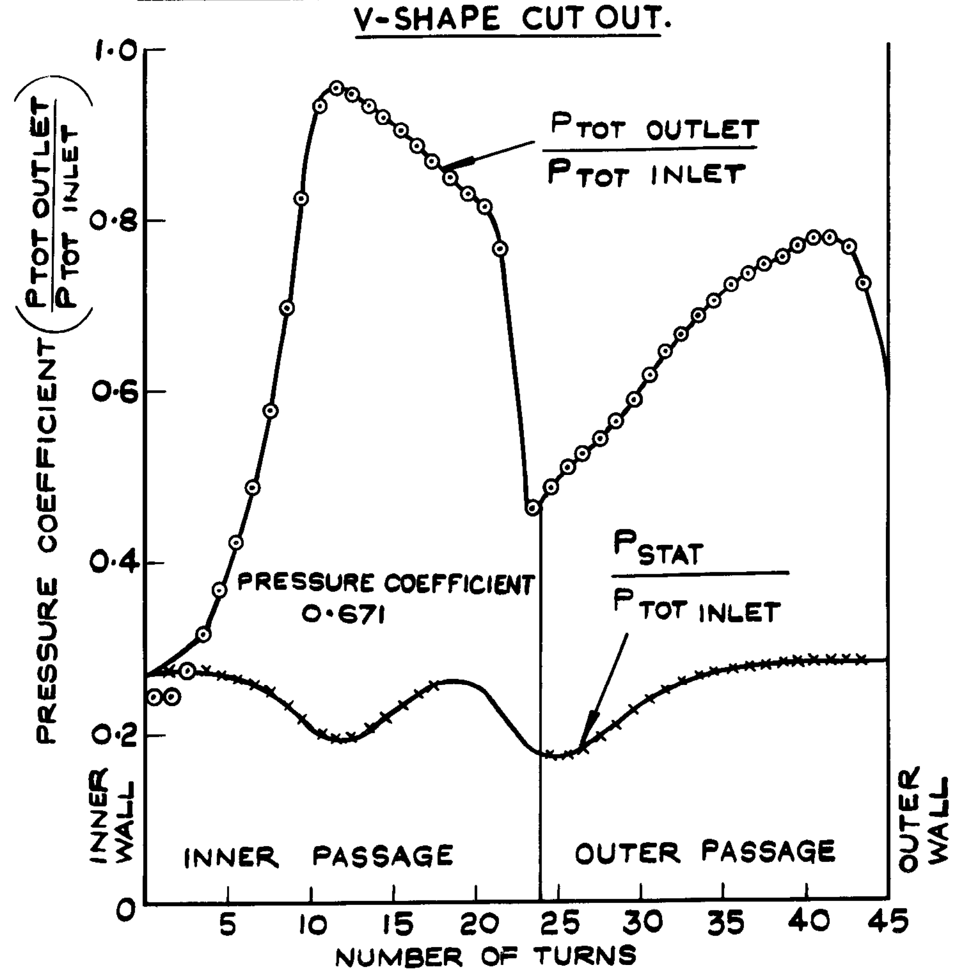


(b) 50% SPAN PRESSURE TRAVERSES WITH THE RECTANGULAR CUT OUT.

FIG.14

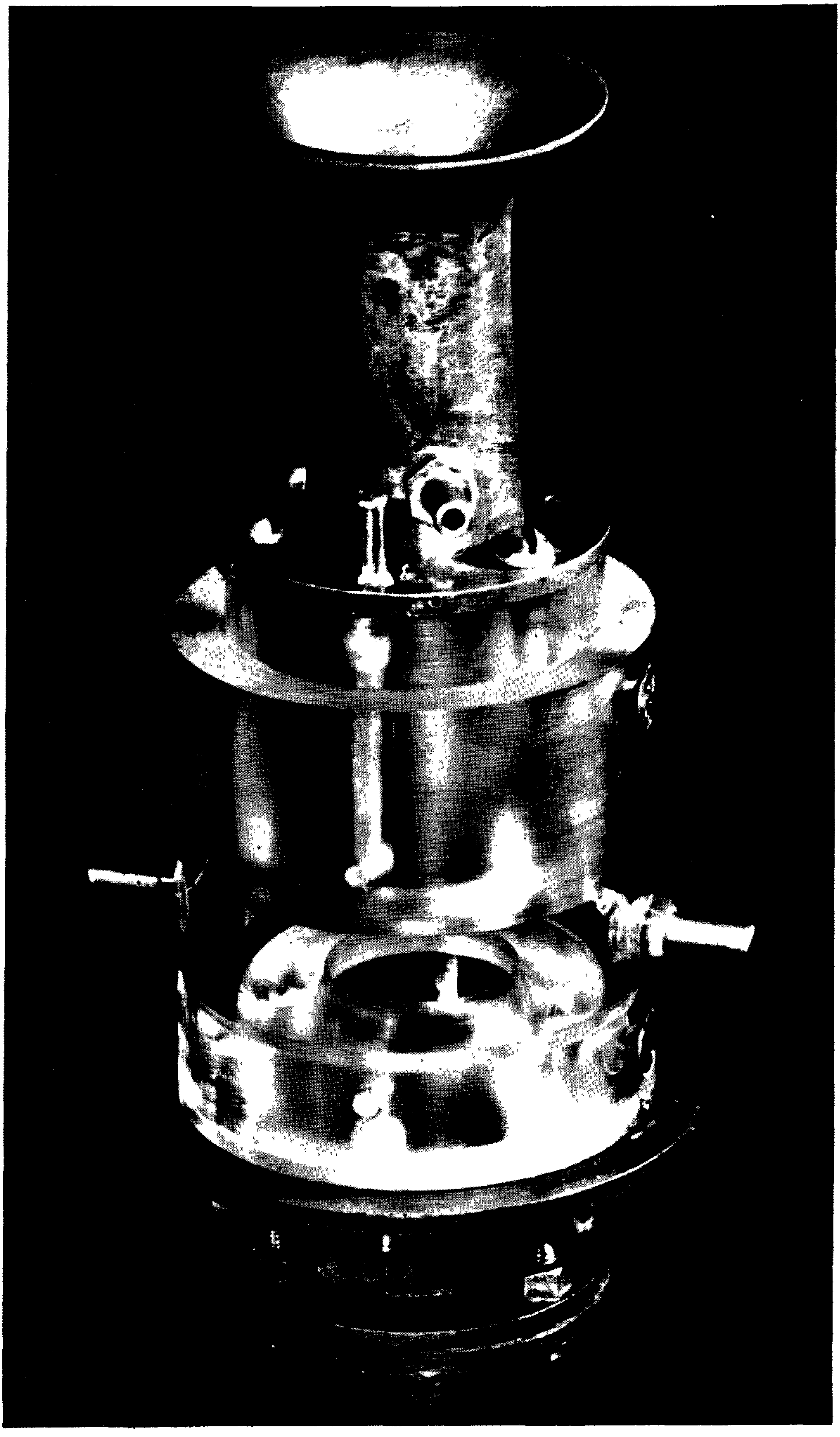


(a) 50% SPAN PRESSURE TRAVERSES WITH A V-SHAPE CUT OUT.



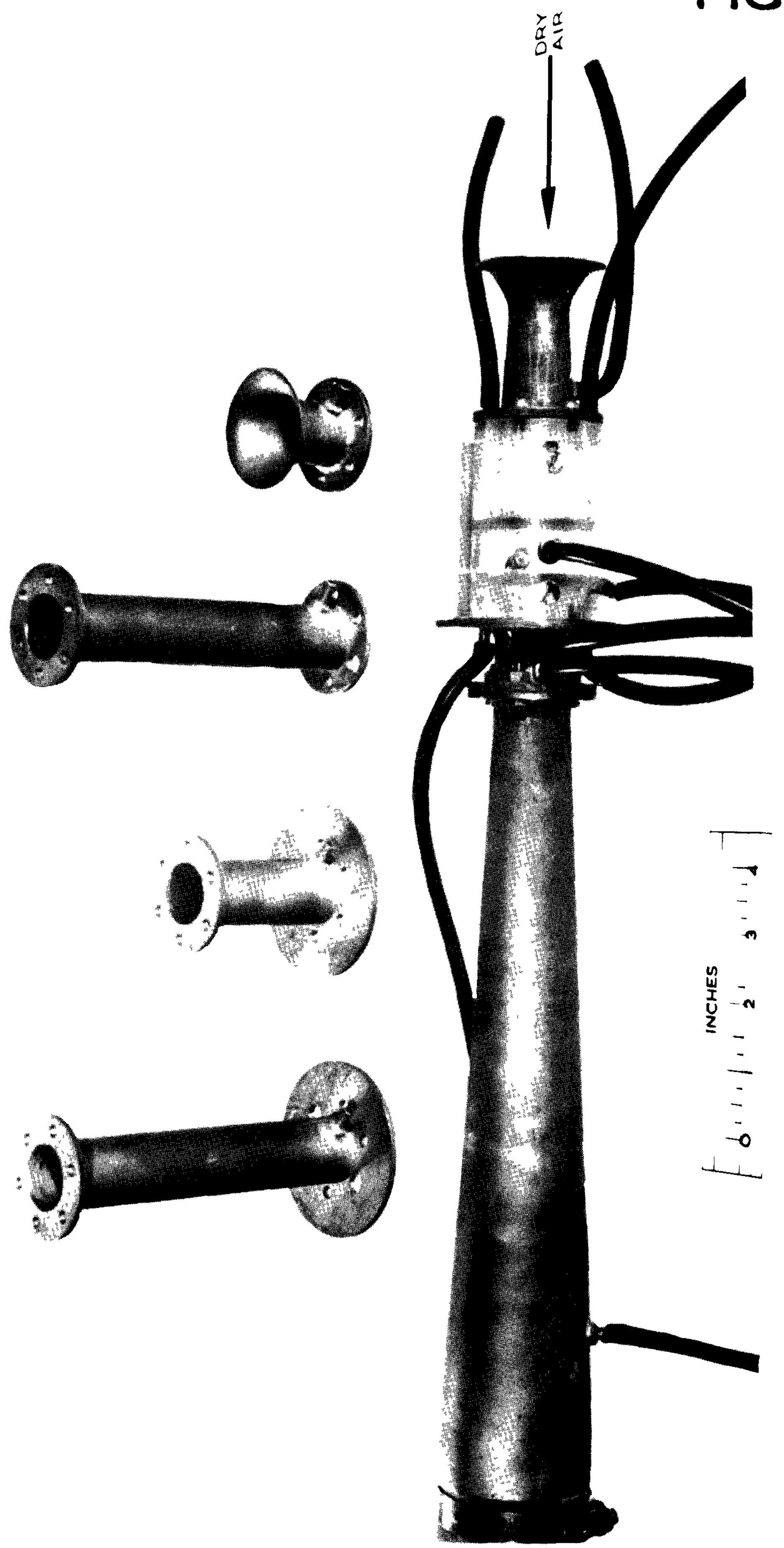
(b) 20% SPAN PRESSURE TRAVERSES WITH A V-SHAPE CUT OUT.

FIG. 15.



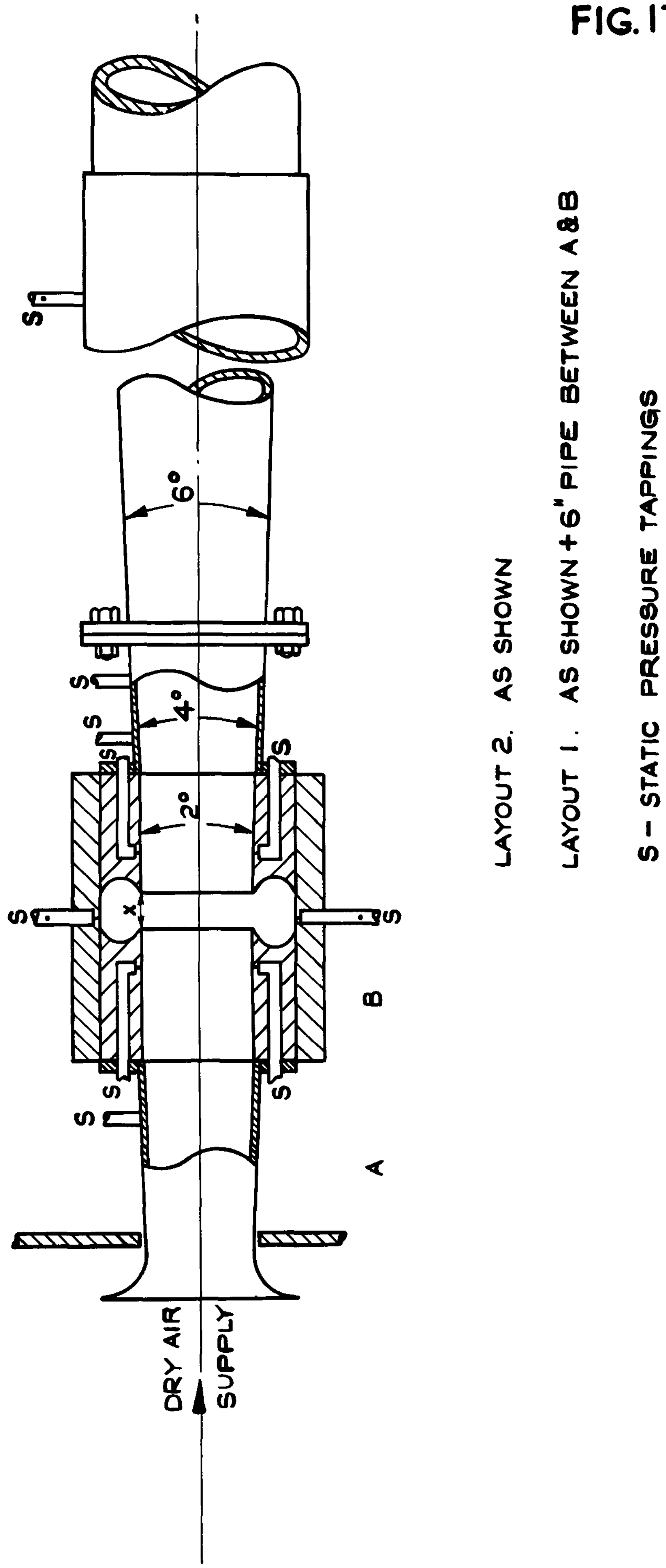
PHOTOGRAPH OF THE VORTEX BEARING RIG

FIG. 16.



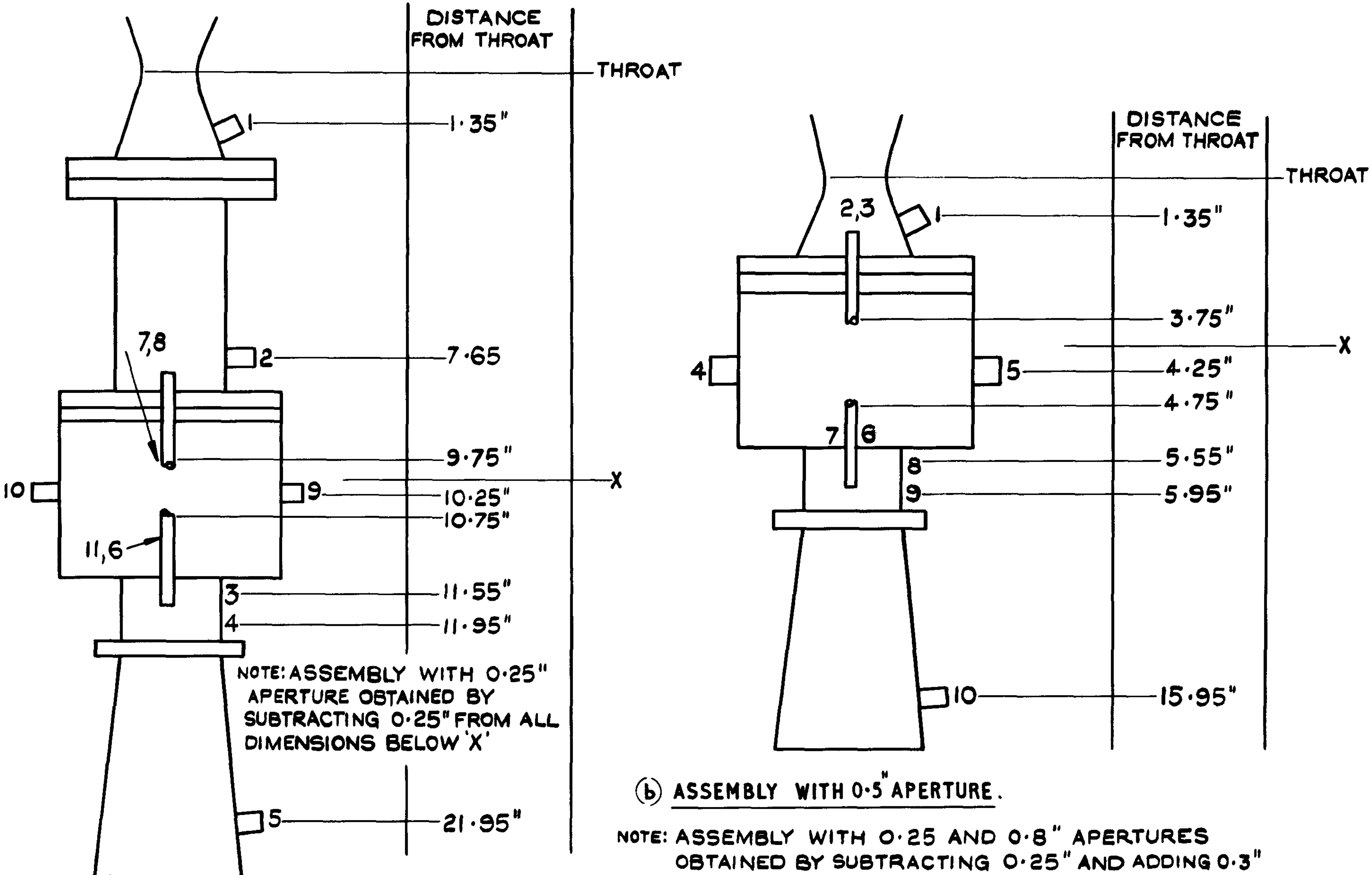
ANOTHER VIEW OF THE VORTEX BEARING RIG

FIG. 17



2nd. VORTEX BEARING TEST RIG.

2nd. VORTEX BEARING TEST RIG.



(a) ASSEMBLY WITH 0·5" APERTURE AND 6" PIPE.

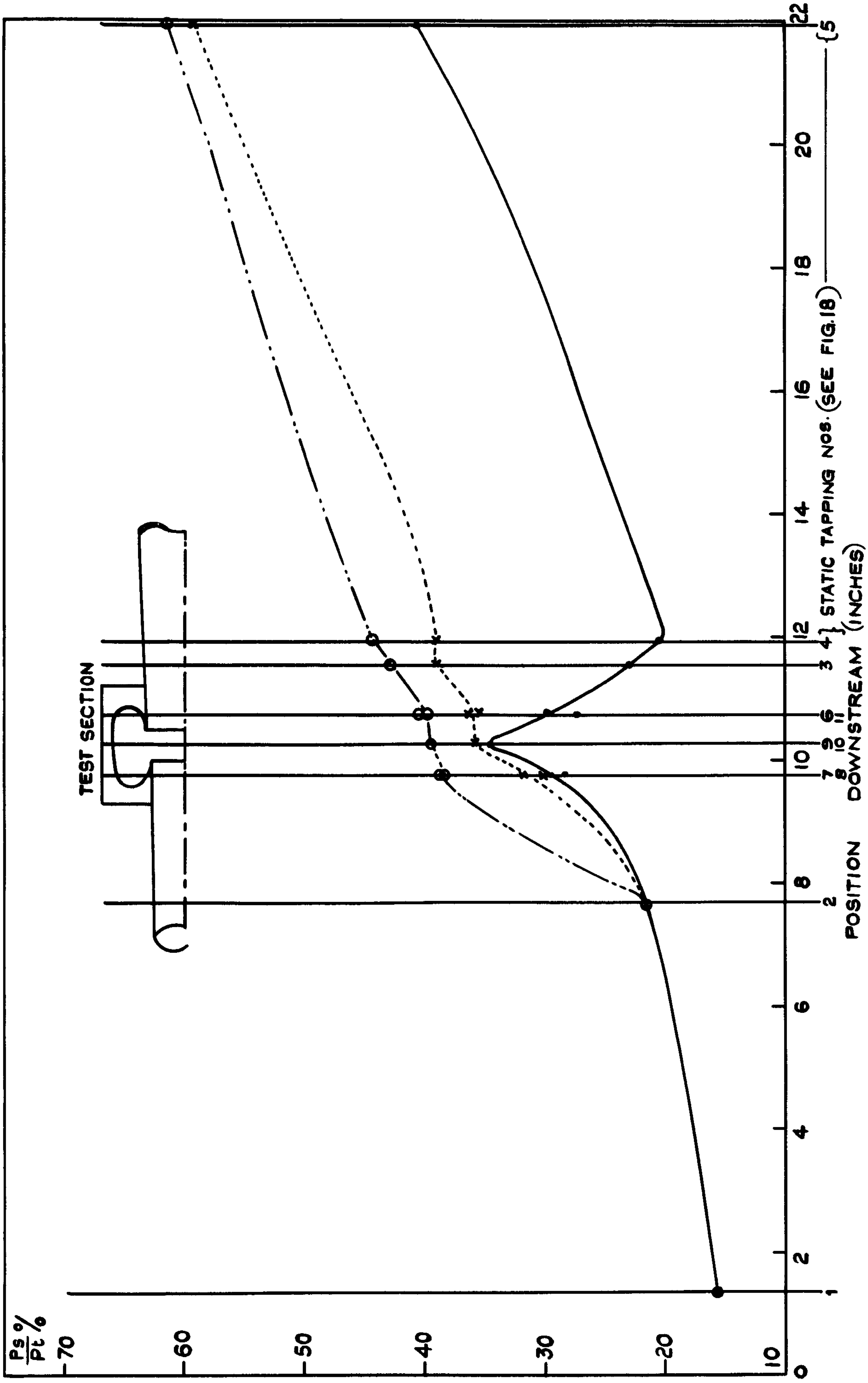
NOTE: ASSEMBLY WITH 0·25" APERTURE OBTAINED BY SUBTRACTING 0·25" FROM ALL DIMENSIONS BELOW 'X'

(b) ASSEMBLY WITH 0·5" APERTURE.

NOTE: ASSEMBLY WITH 0·25 AND 0·8" APERTURES OBTAINED BY SUBTRACTING 0·25" AND ADDING 0·3" RESPECTIVELY FROM ALL DIMENSIONS BELOW 'X'.

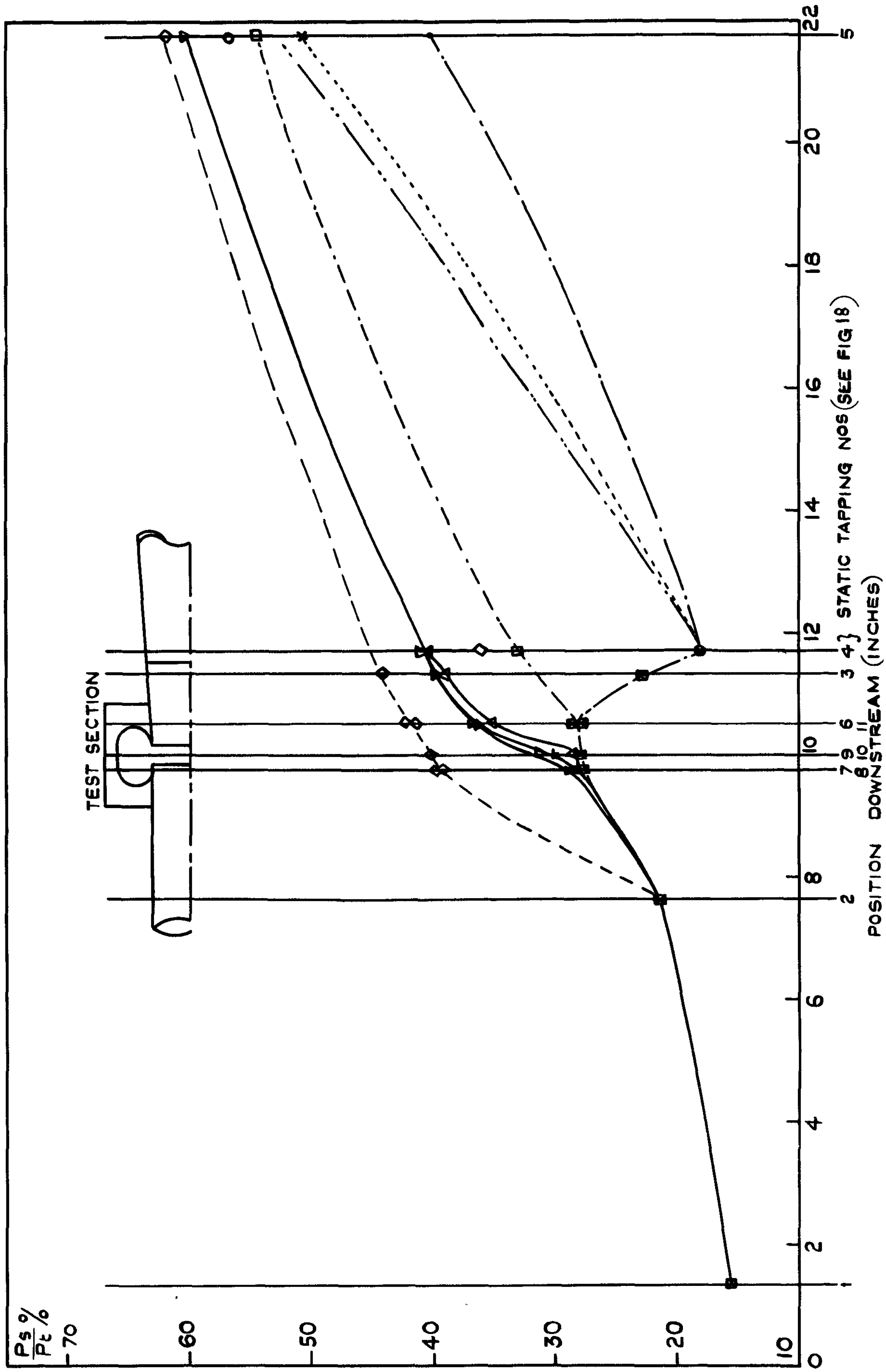
FIG. 18

FIG. 19

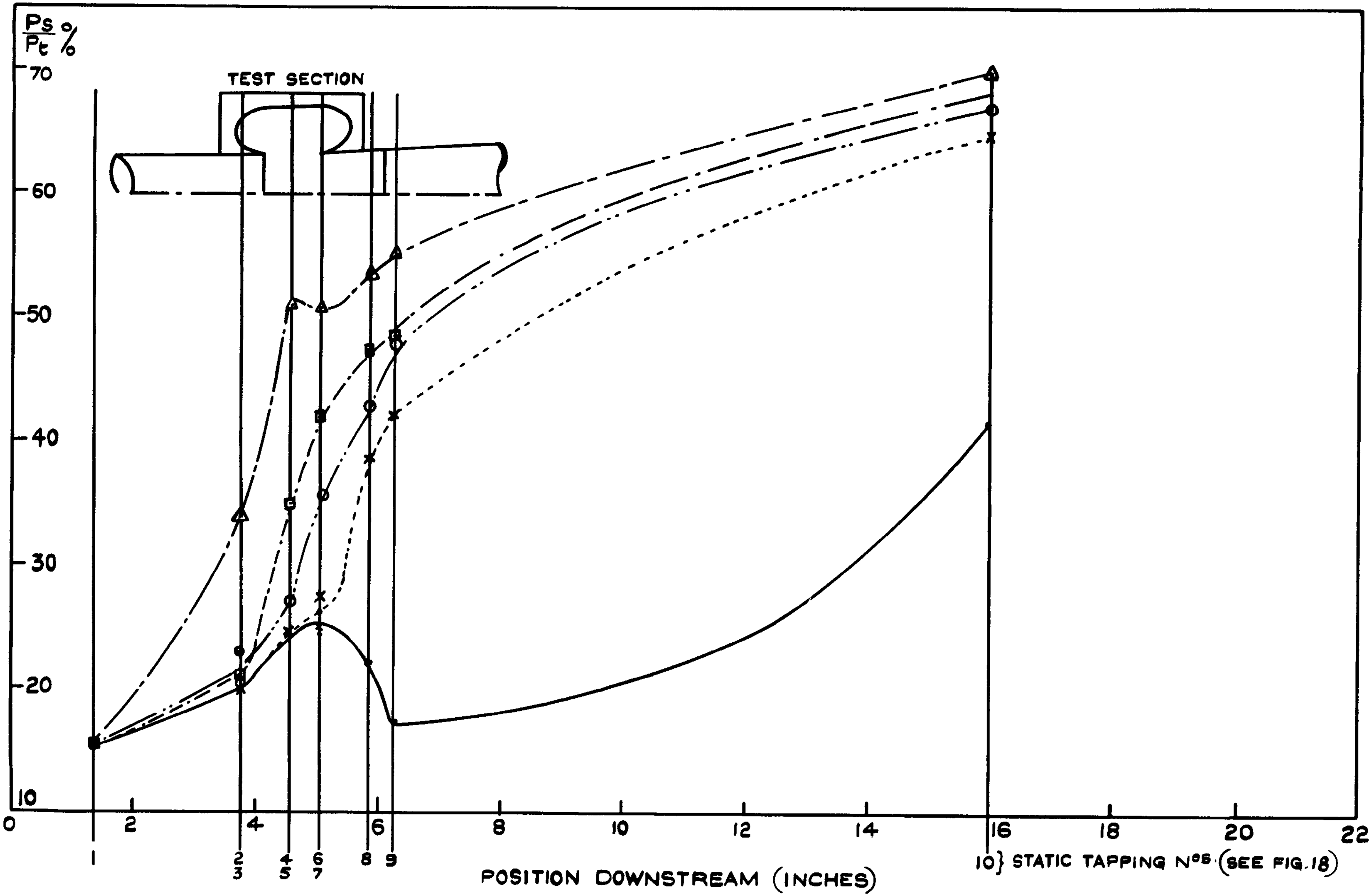


STATIC PRESSURE PLOT: 6" PIPE BETWEEN NOZZLE EXIT AND PERSPEX SECTION: ANNULUS OPENING 0·5"

FIG. 20



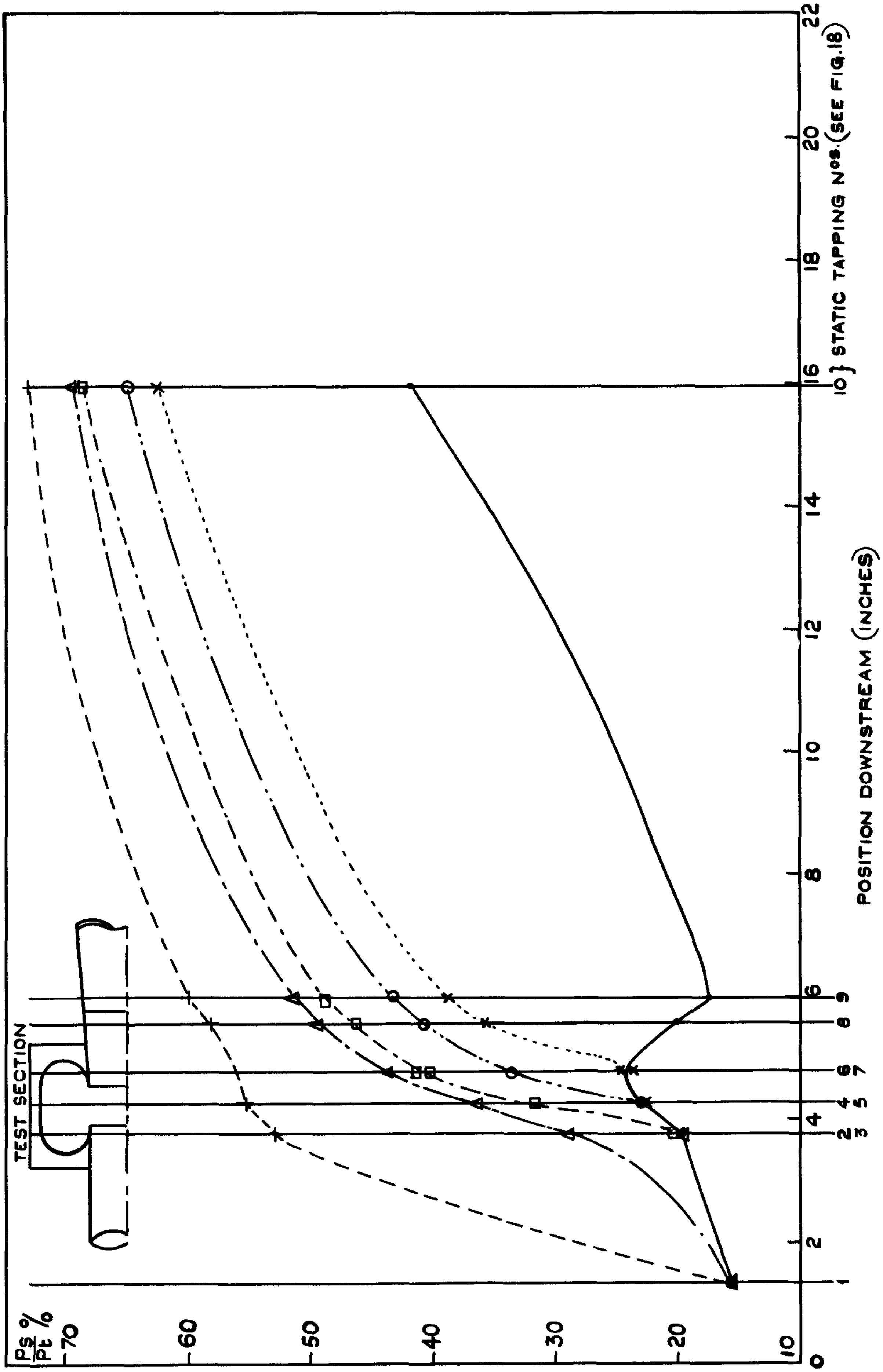
STATIC PRESSURE PLOT: 6" PIPE BETWEEN NOZZLE EXIT AND PERSPEX SECTION: ANNULUS OPENING 0·25"



STATIC PRESSURE PLOT: ANNULUS OPENING 0·8"

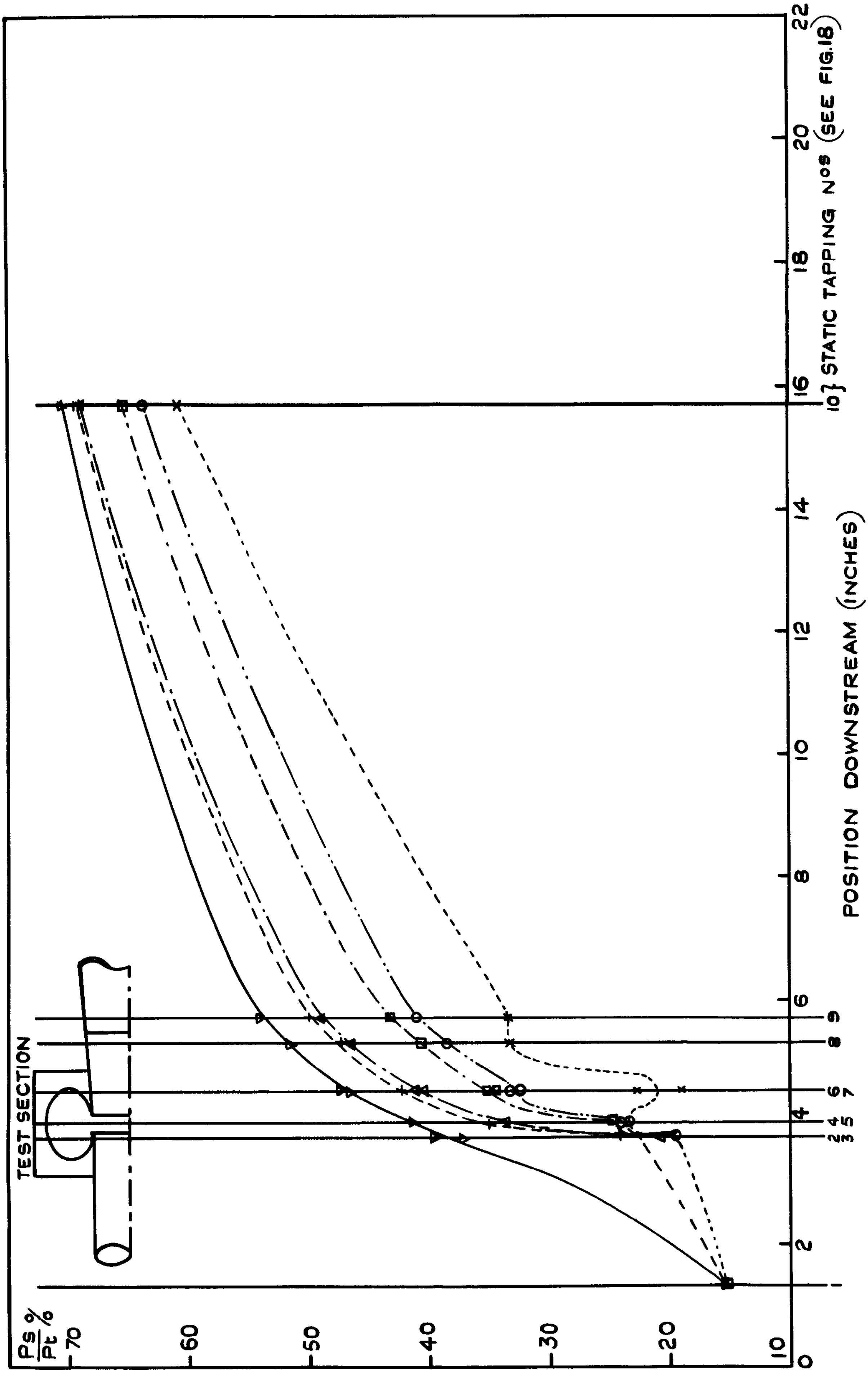
FIG. 21

FIG. 22



STATIC PRESSURE PLOT: ANNULUS OPENING 0·5"

FIG. 23



STATIC PRESSURE PLOT: ANNULUS OPENING 0·25"

A.R.C. C.P. No. 716
September, 1960
B. S. Stratford and M. C. Neale.

SOME TESTS WITH TRAPPED VORTICES
IN SUPERSONIC FLOW

An arrangement known briefly as a vortex bearing, or trapped vortex, is described. This was devised initially with the object of improving supersonic air intakes featuring internal compression and focussing of the compression waves at the throat. Tests were made with simple rigs to check various aspects of the performance of such vortex bearings. It was concluded that employment of the device in certain installations might prove beneficial.

C.P. No. 716

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