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More Tests with a Variable Ramp Intake having a Design Mach Number of 2.2

By

M. C. Neale and P. S. Lamb

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More tests with a variable ramp intake having a design Mach number of 2.2

- by -

M. C. Neale and P. S. Lamb

SUMMARY

Results are reported of tests on a two-dimensional combined external/internal compression intake having a design Mach number of 2.2.

The particular parameters investigated in the tests now reported are:-

(a) sidewall bleed,

(b) a 3 to 1 range of free stream Reynolds number,

(c) the length of subsonic diffuser,

(d) sidewalls cut back to the line of the second ramp shock.

The maximum pressure recovery obtained at the design Mach number was 90.9 per cent with 6.4 per cent bleed. A better performance was a pressure recovery of 90 per cent with only 3.4 per cent bleed. These figures were obtained at a Reynolds number, based on free stream conditions and intake capture height of 3.25×10^6.

It seems possible that these pressure recoveries may be close to the maximum attainable at Mach 2.2 in a mixed compression intake of acceptable mechanical complexity, and employing a simple four shock system.

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* Replaces N.G.T.E. M.370 - A.R.C. 25772

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1.0 Introduction

Some further tests are reported on the two-dimensional variable ramp intake described in Reference 1. The intake has a design Mach number of 2.2, and features combined external/internal compression in conjunction with boundary layer bleed from the ramp surface at the throat. The present paper describes tests with

(a) different forms of sidewall bleed slot,

(b) a 3/1 range of free stream Reynolds number,

(c) different lengths of subsonic diffuser,

(d) sidewalls cut back to the line of the second ramp shock.

2.0 Description of the model

A detailed description of the model is given in Reference 1. Figure 1 shows a general arrangement. The intake capture height and span were respectively $2\frac{1}{2}$ and $3\frac{1}{2}$ in., thus giving a capture plane aspect ratio of 1.4. The geometry could be varied by retracting the cowl backwards along the line AB in Figure 1, and also by lowering the ramp and one wall of the subsonic diffuser. The subsonic diffuser wall and the ramp could be positioned independently of each other - the ramp by pivoting about the point X in Figure 1 and the wall of the subsonic diffuser by pivoting about the position Y. Thus it was possible to obtain different throat bleed openings (in the sense of varying the extent of the ram scoop effect) for fixed positions of either the diffuser or the ramp. The bleed from the ramp surface was not throttled. It discharged into a plenum whence it was removed through two ducts acting as measuring lengths and containing pitot tubes and static tappings. In practice the ramp bleed mass flow was varied by moving the position of the diffuser tip whilst the ramp position remained fixed.

Sidewall windows in the plane of the throat permitted Schlieren observation of the throat flow. Sidewall bleed at the throat was accommodated by using special sidewalls fitted with throat windows wach containing the bleed slot. The bleed from each sidewall discharged initially into a plenum sandwiched between the inner sidewall window containing the bleed slot and an outer window. This detail for a typical bleed slot is shown in Figure 2. The arrangement had the advantage that, notwithstanding the complication of sidewall bleed, some Schlieren observation was possible.

Downstream from the plenum on each side of the model the sidewall bleed was led into a duct acting as a measuring length and containing a pitot tube and static tapping. A throttle at each duct exit controlled the bleed mass flow. The complete sidewall bleed assemblies were readily detachable from the intake which could, in consequence be run with and without sidewall bleed with equal facility.

The necessity for continuing the sidewall bleed slots throughout the full throat height, and the considerable experimental convenience of retaining a range of movement for the subsonic diffuser tip, rendered impossible the complete separation at the throat of the ramp and sidewall bleeds. Figure 2 shows how sidewall bleed could pass into the ramp bleed duct and vice versa. Thus although separate measurements were made in the ramp and sidewall bleed ducts, the only figure that is quoted in this paper is the total bleed, comprising the sum of the quantities measured in the different ducts. Where necessary, the ramp bleed could be estimated from earlier tests without sidewall bleed but featuring the same ramp bleed geometry[2].

The leading edges of the sideplates lay in the plane of the first ramp shock and had a chamfer angle of $27\frac{1}{2}^\circ$ measured perpendicular to the swept edge. A chamfer angle of this magnitude was necessitated by the requirement for making the model sufficiently robust to withstand the pressure loadings entailed in testing at high Reynolds numbers. It followed that the shocks generated by the sidewalls were detached, but earlier estimates[1] indicate that the effect on capture mass flow is small and unlikely to seriously affect the performance of the model.

As some interest had been shown in full scale intake installations featuring sidewalls that were cut back in order to reduce their wetted area, one test was made in which the sidewalls were cut back to the angle of the second external oblique shock. The sidewalls then followed the contour ADE in Figure 1. It was appreciated that because a steep chamfer angle was retained on the swept edge, the effect of the cut back on capture mass flow might be obscured by shock detachment effects. Nevertheless it was felt that the effect on pressure recovery should be representative.

Downstream of the subsonic diffuser exit the model differed from that described in Reference 1. For the present tests a flap valve as shown in Figure 1 was substituted for the original butterfly, and the valve was positioned further downstream. The new arrangement was thought to reduce the risk of interference with the diffuser exit distributions.

"Desynn" indicators were used to show the position of the movable components, except for the sidewall bleed throttles. The sidewall bleeds were controlled and equalised by observation of the manometers indicating the duct pressures.

The two subsonic diffusers used in the present tests are shown in Figure 3. Figures 4 and 5, reproduced from Reference 1, show respectively the method of mounting the intake in the test cell and two photographs of the assembled model.

2.1 Bleed geometries

The ramp bleed geometry is shown in Figure 6. This form of slot was chosen as the result of earlier tests[2] with different bleed designs. The sidewall bleed geometries are shown in Figure 7. Utilising the sidewall windows to accommodate bleed slots necessitated some compromises in the forms of the bleeds adopted. It was not possible, for example, to fair the downstream edges of all the slots. Nevertheless, as will be described in Section 4.1, the range of slots sufficed to demonstrate a definite advantage to the aerodynamic performance of the intake.

2.2 The shock pattern

The "design" shock pattern features two external oblique shocks each of 7° strength and focussed on the cowl tip, followed by a 10° internal oblique shock falling on the lip at the entrance to the subsonic diffuser. For a free stream Mach number of 2.2 this shock pattern theoretically gives a terminal supersonic Mach number of 1.38. Reference 2 describes how, by varying the second ramp angle and the position of the cowl tip, the terminal supersonic Mach number can be varied. A range of theoretical shock recoveries was thus possible. Rearwards movements of the cowl tip from the plane of the leading wedge shock necessarily entailed some spillage; in the tests the maximum calculated spillage was 6 per cent of the intake capture flow. If desired in a future intake the shock patterns produced in this manner could be readily reproduced without spillage over the cowl by suitably modifying the dimensions of the ramp.

The theoretical shock recovery obtained with a given ramp geometry can be varied by pitching the intake relative to the free stream. With a total ramp deflection of about 14° the theoretical shock recovery at first rises when the intake is pitched in such a way as to increase the flow deflection at the ramp tip. The decrease in the total pressure loss through the normal shock outweighs the simultaneous increase in the oblique shock losses; the effective cowl angle, and hence the drag, is also increased so that the overall optimum performance may still be at zero incidence. Beyond angles of pitch of about 2° the theoretical pressure recovery falls because the increased losses through the oblique shock system now outweigh the improvement in the normal shock recovery.

3.0 Test procedure and presentation of results

Prior to running the tunnel the "Desynn" indicators were calibrated to show the positions of the ramp and subsonic diffusers, and hence the bleed opening. The position of the diffuser tip was defined by its distance measured from the internal surface of the cowl, and that of the ramp by the size of slip gauge which fitted the bleed opening as in Figure 6.

For starting the intake the throttle at the exit from the subsonic diffuser was opened wide. The ramp and diffuser tip were set at predetermined positions whilst the cowl was adjusted so that the internal oblique shock from the cowl tip, when viewed through Schlieren apparatus, impinged on the lip at the entrance to the subsonic diffuser.

Testing was normally carried out with a nozzle inlet total pressure of 40 in.Hg abs, which gave a Reynolds number, based on free stream conditions and intake capture height, of approximately 1×10^6. In addition, some tests were made with an inlet total pressure of $4\frac{1}{2}$ atm abs, which gave a test Reynolds number, defined as previously, of 3.25×10^6. Prior to the high pressure tests the tunnel was "started" at approximately 40 in.Hg abs in order to reduce the transient pressures on the model.

3.1 A note on the presentation of the diffuser exit distributions

Allowable distortions at the subsonic diffuser exit are sometimes defined in terms of a parameter such as V_{max}/V_{mean}, i.e., the maximum flow velocity divided by the mean velocity. The interpretation of changes in the values of such parameters becomes complicated however when the mean duct Mach number is simultaneously changing. This is the situation that arises in the work now described. Changes in bleed flow, for example, which are found to influence the distribution, also affect the diffuser exit Mach number, because of the accompanying changes in the pressure recovery and in the mass flow entering the subsonic diffuser. Hence although values of maximum flow velocity divided by mean velocity are quoted, the plots showing the variation of total pressure across the diffuser exit plane are considered to be more useful.

V_{max}/V_{mean} has been calculated from the rake total pressures and the measured wall static pressures in the plane of the rake, assuming a constant static pressure throughout the diffuser exit plane. A further distribution parameter that has been derived from the rake total pressure readings is $\dfrac{P_{tot,max} - P_{tot,mean}}{P_{tot,mean}}$.

4.0 Results and discussion

4.1 The influence of sidewall bleed design on pressure recovery

Results are shown in Figure 8 for the various forms of sidewall bleed. Some of the sidewall bleed configurations apparently reduce the pressure recovery for a given total bleed flow by about 1 per cent compared with no sidewall bleed. However the bleed configuration "G" in Figure 7 increases the pressure recovery by roughly 1 per cent for a given total bleed. The same sidewall bleed arrangement but with the slot width halved, (geometry "F" in Figure 7), shows in one instance an improvement of about $\frac{1}{2}$ per cent on pressure recovery, but the other points obtained with this slot show negligible effect.

The reductions in pressure recovery incurred by the introduction of the sidewall bleed configurations "C" and "D" probably reflect, to some extent at least, the design compromises entailed in fitting the slots into the model. These were mentioned in Section 2.1. It seems reasonable to expect for example that had it been possible to provide an appropriate chamfer on the downstream edge of geometry "D" a better result might have been obtained. It is also probable that the results obtained with sidewall bleed geometries must be related to the particular supersonic diffuser used in the tests. For example, Goldsmith[3] concluded that sidewall bleed was most beneficial in the area covered by the configuration "D". This conclusion probably resulted in part from the increased strength of the internal oblique shock in the intakes he tested leading to an increased amount of sidewall secondary flow. It was shown in Reference 1 that this flow is deflected along the line of the internal oblique shock towards the area covered by the bleed configuration "D", and that in the present model much of the secondary flow apparently passes into the ramp bleed slot. Without the latter feature it is probable that a greater benefit could be obtained from sidewall bleed than noted here. However this would compensate a probably lower performance without sidewall bleed, so that the maximum pressure recovery would be very similar to that obtained in the present tests.

In view of its favourable effect in the present tests the sidewall bleed geometry "G" was adopted in all subsequent tests with sidewall bleed.

4.2 The effect of Reynolds number on pressure recovery

Figure 9 shows the results of tests with a constant opening to the ramp bleed slot such as to give an estimated ramp bleed of rather less than 3 per cent. (Reference 2 suggests that higher pressure recoveries might have been obtained with larger ramp bleeds, but the rate of exchange between pressure recovery and bleed for the higher ramp bleed flows is such as to make the resultant pressure recoveries of doubtful practical value.) The ramp was set at its optimum deflection of 7°, as found in previous experiments[4]. In the test at the high Reynolds number the tip of the subsonic diffuser at the bleed slot was raised 0.02 in. compared with its position during the lower Reynolds number tests, in order to compensate for the observed downward deflection of this component under the increased pressure loadings. The deflection might otherwise have significantly altered the bleed slot geometry. The effect of the compensating movement on pressure recovery - through very slightly modifying the initial rate of subsonic diffusion - should be very slight.

At the higher test Reynolds number the maximum pressure recovery is seen to be 90.9 per cent, the accompanying bleed being 6.4 per cent of the capture flow. The rate of exchange of pressure recovery with sidewall bleed is very low. With only 3.4 per cent total bleed the pressure recovery remains as high as 90 per cent. Thus sidewall bleeds in excess of about 1 per cent of the capture flow appear to yield little profit.

For a given total bleed Figure 9 indicates that the increase in Reynolds number from 1×10^{6} to 3.25×10^{6} increases the pressure recovery by about 0.5 per cent. The absence of any form of boundary layer control on the cowl is probably largely responsible for the improvement in pressure recovery with Reynolds number being maintained at the higher bleed flows. The improvement is somewhat less than in Reference 2 where an increase of $1\frac{1}{2}$ per cent was obtained over the same range of Reynolds number. However the intake described in Reference 2 featured ramp bleed only. It might have been expected that the introduction in the present tests of sidewall bleed would reduce the Reynolds number effect. Moreover the terminal supersonic Mach number (based on the cowl static pressure at mid span) in the present tests was, at 1.22, somewhat lower than in the earlier work, in which it was 1.28. The corresponding reduction in the static pressure rise at the normal shock might also reduce the change in the viscous losses over the Reynolds number range.

4.3 The effect of Reynolds number on diffuser exit distributions

Figures 10 and 11 show the effect of Reynolds number on the distribution of total pressure at the exit from the subsonic diffuser, each Figure being for a particular throat bleed. Figure 10 also defines the method employed for drawing the distribution curves. At both bleed flows the Reynolds number effect is very similar. In the spanwise direction the total pressure near the duct walls is increased, but is substantially unchanged near the duct centre. In the vertical plane (the ramp surface here being considered "above" the cowl) the increase of test Reynolds number appears to somewhat alter the distribution. In particular, as

Figure 12 makes clear, the total pressures measured adjacent to that wall of the subsonic diffuser formed by a continuation of the cowl surface are considerably increased by the increase of Reynolds number. On the other hand the total pressures adjacent to the subsonic diffuser wall formed by a continuation of the ramp are substantially unchanged. The values of the distribution parameters, as quoted near the foot of each figure, do not appear to follow any definite trend with Reynolds number.

4.4 The effect of sidewall bleed on diffuser exit distributions

Comparison of the Figures 10 and 11, just discussed, with Figures 18 and 19, which were obtained without sidewall bleed, shows a change in the shape of the vertical distribution curves, but again the values of the distribution parameters do not seem to follow a definite trend. (The change in shape may be primarily ascribed to the effect of sidewall bleed rather than to the subsonic diffuser length for, as will be noted in Section 4.5, the distributions obtained with the two subsonic diffusers were very similar.) Figure 13, which uses data extracted from Figures 10 and 11, shows that an increase in the sidewall bleed, so as to increase the total bleed from 3.3 per cent to 6.4 per cent, produced only a small effect on the profile shape.

In general V_{max}/V_{mean} lies between 1.4 and 1.3. In some applications much lower figures, in the region of 1.1, have been suggested as being the maximum allowable distortions in the circumferential direction at a compressor entry face. However figures closer to those shown in Figures 10 and 11 have been suggested for the radial direction. In the present tests the rectangular cross-section at the subsonic diffuser exit makes differentiation between the radial and circumferential directions uncertain. Nevertheless, as in the case of the all external compression intake[5], there seems a strong case for considering methods of improving the distributions. The problem is discussed in Section 4.9.

4.5 The effect of a change in the length of the subsonic diffuser

Figure 14 compares the pressure recoveries obtained in tests with the two subsonic diffusers shown in Figure 3. The ramp bleed geometry was fixed in order to maintain a constant ramp bleed estimated at about 2½ per cent of the capture flow, and the sidewall bleed was varied.

The figure shows that there is little difference between the pressure recoveries given by the two diffusers. Such a result agrees with earlier work without sidewall bleed[1,2] which showed that differences between the two diffusers were eliminated if a "clean" normal shock was stabilised at the entrance to the subsonic diffuser. The distributions measured with the two diffusers were also very similar.

4.6 Intake performance with cut back sideplates

Figure 15 shows that cutting back the sideplates increased the pressure recovery by about 1 per cent - presumably by reducing the sidewall wetted area. A smaller improvement would probably be obtained at Reynolds numbers nearer the full scale value. The change in distribution at the subsonic diffuser exit was also small (see also Section 4.8).

It might be thought surprising that the improvement in pressure recovery effected by the reduction in sidewall area equalled that produced by the sidewall bleed. However, as mentioned earlier, the ramp bleed design probably reduced the effect of the bleeds from the sidewalls. Bearing in mind that the original level of recovery of the intake - with the sidewall secondary flow passing into the subsonic diffuser - was 83 per cent, the results are not inconsistent with the view that the need for careful treatment of the sidewall boundary layers is most important in the region of the throat.

It was found that with 3½ per cent bleed the introduction of the cut back sidewalls apparently reduced the subsonic diffuser mass flow (calculated from the measured total pressure and the flap position) by 0.5 per cent. With 4.1 per cent bleed however the same change of sidewalls apparently increased the mass flow to the subsonic diffuser by 0.5 per cent. For the reasons mentioned in Section 2.0 great importance should not be attached to these figures.

4.7 Tests at pitch

Figure 16 shows the critical pressure recoveries from tests in which the intake was pitched relative to the free stream, in the sense giving an increase in the total flow deflection at the ramp. During the tests the second ramp angle relative to the model was kept constant, while the cowl was adjusted to maintain the internal oblique shock focussed on the bleed lip as described in Section 3.0. In the figure the changes of pressure recovery caused by changes of bleed within the ranges of firstly 3½ to 4½ per cent, and secondly 4 to 6 per cent, have been ignored as being too small to influence the general trends that are shown. Both experimental curves exhibit the maximum of the theoretical curve, which occurs at non-zero pitch for the reasons discussed in Section 2.2.

4.8 The prospects for further improvement in the pressure recovery

With the present intake model the maximum theoretical shock recovery that can be obtained by varying the second ramp angle is 95.6 per cent. The best experimental performance, measured with shock strengths fairly closely corresponding to the theoretical optimum, is a recovery of 90.9 per cent with 6.4 per cent bleed, or 90 per cent with 3.3 per cent bleed. In round terms, therefore, both the shock loss and the extra to shock loss have been reduced to between 4 and 5 per cent, for a bleed of about 5 per cent.

The present level of performance has largely been accomplished by developing the model to give as close as possible correspondence between the experimental and theoretical shock patterns. As the differences between the two patterns have been reduced, so the extra to shock losses have gradully decreased to their present value. Very close agreement between the experimental and theoretical patterns has now been achieved. The possibility of serious losses in the subsonic diffuser seems rather remote in view of the pressure recovery being independent of the length of the subsonic diffuser for the two lengths tested. Any improvement that might result from dividing the profiling in the subsonic diffuser equally between the two opposite walls, instead of concentrating it all on one wall as in the present model, would tend to be offset by the additional curvature at the throat necessary to keep the cowl line of the intake within a given external envelope. Three of the four walls at the throat now feature boundary layer bleed. The introduction of cowl bleed might further reduce the extra to shock losses, although the local Mach number (based on the static pressure at mid span) is, at 1.22, sufficiently low to render serious trouble at the normal shock interaction rather unlikely. Moreover the introduction of bleed on a full scale installation on such a difficult structural member as the cowl would almost certainly pose considerable problems. Extrapolation of the measured Reynolds number effect to the full scale value of about 5×10^6 (corresponding with $M = 2.2$ cruise at 60,000 ft) does not suggest any significant reduction in the extra to shock loss. On the whole, therefore, it becomes difficult to see methods for reducing the extra to shock loss below the present level of 4 to 5 per cent. This figure compares reasonably with the corresponding value in external compression intakes[5] of about 3 per cent, and Reference 5 suggests no obvious method of reducing the latter figure. The much smaller supersonic wetted areas and the more favourable sidewall secondary flow pattern would tend to result in smaller extra to shock losses in the external compression intake than in the mixed compression design. On the other hand the improvement would tend to be offset by any losses associated with the increased throat turning necessary in the intake with all external compression.

The preceding arguments seem to lead to the conclusion that the most likely method of increasing the pressure recovery lies in increasing the theoretical shock recovery. Calculations indicate that by substituting some degree of isentropic compression upstream of the normal shock for the existing system of three discrete shocks the theoretical shock recovery can be increased by approximately 2 per cent. Thus, if this increase can be reflected in the performance of the intake, the pressure recovery might be raised to about 93 per cent. It perhaps should be emphasised that in a practical installation, such as that proposed for a supersonic transport aircraft, the amount of isentropic supersonic compression that can be introduced is limited. The ramp must commence at an appreciable angle to the free stream direction. Smaller angles than about 7° would lead to excessive lengths of ramp, with the associated boundary layer penalties, quite apart from introducing an undesirable bend into any main plane boundary layer diverter. Similarly, in order to maintain a low cowl drag, an appreciable shock is necessary at the cowl tip, even when an additional shock is included between the cowl tip and the throat.

4.9 On the improvement of the diffuser exit distributions

The maximum total pressures measured at the exit from the subsonic diffuser correspond fairly closely with the theoretical shock recovery of the intake. Thus the calculated values of the distribution parameter based on total pressures, i.e., $\dfrac{P_{tot,max} - P_{tot,mean}}{P_{tot,mean}}$, correspond with the extra to shock losses. It would be wrong however to deduce that the necessary improvement in distribution is therefore dependent on a considerable reduction of the extra to shock losses - fortunately so, for as discussed in the preceding Section, methods of achieving a reduction are not obvious. From one point of view the problem of improving the distribution might be regarded as one of reducing the peak total pressures to values nearer the mean, preferably of course by the transference of energy to those regions of the flow nearer the duct walls. The theoretical penalties entailed solely in eliminating the peak total pressures, assuming no mixing losses and no transference of energy, can be illustrated by considering the distribution shown in Figure 10 for the lower Reynolds number. The highest individual pitot tube reading at the subsonic diffuser exit was 94.7 per cent, and the area mean total pressure recovery was 89.7 per cent. The corresponding calculated value of V_{max}/V_{mean} is 1.33. If now those measured total pressures exceeding 90 per cent are all reduced to 90 per cent (a loss of nearly 5 per cent on pressure recovery in the region of highest total pressure) the area mean pressure recovery is reduced by 1.1 per cent to 88.6 per cent, and V_{max}/V_{mean} is reduced to 1.15. If instead of 90 per cent a figure of 89 per cent is assumed, then the area mean total pressure recovery reduces by a further 0.5 per cent to 88.1 per cent, and the corresponding value of V_{max}/V_{mean} becomes 1.09. Such arguments should be used with caution as engine malfunctioning may depend mainly on the regions of low total pressure, and these have not necessarily been affected in the preceding process. Moreover the V_{max}/V_{mean} criterion cannot be expected to be independent of the form of the maldistribution. In general there is need for more investigation. The experimental work should include determining the effect both of yaw, and of the transition from the rectangular cross-section of the capture plane to the circular cross-section of the engine.

4.10 A note on control

It has long been appreciated that the intake featuring internal compression poses a problem of control different from that associated with the purely external compression design. This arises because, on moving forward from the critical position, the normal shock in the mixed compression intake moves into a convergent duct where it is inherently unstable. Hence the shock jumps forward to some position forward of the cowl, and the capture mass flow and pressure recovery fall sharply. In the general case the variable geometry then has to be re-cycled in order to "re-start" the intake. However, as was mentioned in Reference 1, the intake described here is self-starting, i.e., after shock expulsion the supersonic flow can be re-established inside the intake just by opening the throttle, the variable ramp being left in its design position. The usual one-dimensional criterion for the performance of second throats[6] suggests, assuming inviscid flow and a normal shock in the plane of the cowl tip perpendicular to the ramp, that the internal contraction produced by a 7°, 7°, 10° shock pattern is almost 5 per cent too large for the intake to be self-starting. The self-starting property of the model intake tested here may be influenced by a number of factors, among which the following can be listed.

(a) The effect of the removal of the bleed upstream of the internal oblique shock, i.e., before the completion of the internal contraction.

(b) In practice, because of boundary layer growth, the internal oblique shock falls in its "design" position when the ramp deflection angle is between 1 and 2° less than that indicated by inviscid theory. In the present tests the actual internal contraction (measured to the tip of the subsonic diffuser) then corresponds very closely with the theoretical limiting internal contraction for self starting.

(c) The criterion for "starting" assumes a normal shock at the commencement of the converging section. It has been observed however[7] that immediately prior to the "starting" of an intake the "normal" shock forms as a strong oblique shock near the intake surfaces, and gradually turns into a normal shock nearer the centre of the entrained stream tube. Hence the loss of total pressure in the shock may be less than in a purely normal shock.

The extent to which the self-starting property of the intake influences the control problem is at present uncertain. Clearly it is advantageous if the variable geometry does not have to be re-cycled after shock expulsion. The question still remains however, whether shock expulsion is permissible at all. The question is obscured in the present case by the behaviour of the intake when the exit throttle is closed very slightly beyond the position for critical operation. The internal oblique shock and the normal shock then commence to "flit" to and fro between their critical position and some position upstream of the throat. It is not at present certain if this phenomenon truly derives solely from the intake, or whether it results from small fluctuations that have been measured in the test cell flow[8]. However it is hoped to resolve the question in a forthcoming test programme.

In the meantime it is worth considering the most frequently advocated solution to the problem of controlling the position of a normal shock in an intake featuring internal compression, namely, arranging for the intake to be slightly supercritical during normal operation. The extent of the reduction of the pressure recovery from the critical value is so arranged that during a typical flow pulsation from the engine the normal shock does not move forwards beyond the throat and into the unstable region. Figure 17 shows Schlieren photographs of the throat flow of an intake featuring ramp bleed only. These photographs were taken during the tests of the intake with cut back sideplates (Section 4.6). The normal shock is shown both in the critical position and also in a supercritical position such that the pressure recovery is reduced from the critical value by 1.5 per cent. (A reduction of 2 per cent has been frequently suggested as a control margin.) The axial displacement of the normal shock corresponding to the 1.5 per cent change in pressure recovery is very small, being roughly equal to 30 per cent of the throat height. The corresponding distributions at the exit from the subsonic diffuser (which was the shorter of the two shown in Figure 3) are shown in Figure 18. The deterioration of the profile following a reduction of the critical pressure recovery by $1\frac{1}{2}$ per cent is only slight. Figure 19 shows some diffuser exit distributions obtained in another test, also made without sidewall bleed and with the shorter of the two subsonic diffusers but with the normal sideplates. Here the normal shock was moved back in stages into the subsonic diffuser until the supercritical pressure recovery was roughly 6 per cent below the critical value. In Figure 19 the deterioration in profile with a pressure recovery only 1.6 per cent below the critical value is more marked than in the previous figure. This may result from the change of sideplates. Another possibility, and perhaps a more likely one, is that the change results from the terminal supersonic Mach number for the tests reported in Figure 18 being rather lower than for those reported in Figure 19. (The Mach numbers based on the static pressure at mid span in the plane of the throat, and on the free stream total pressure minus the oblique shock loss, were respectively 1.30 and 1.40.) It has been observed that as the terminal supersonic Mach number is reduced from 1.40 to approximately 1.25 so the throat flow pattern with the intake critical becomes noticeably more steady. Whereas with the low terminal supersonic Mach number the normal shock can be positioned with reasonable precision, with the higher terminal supersonic Mach number the normal shock tends to dart to and fro in the general region of the entrance to the subsonic diffuser. The amplitude of the oscillation is roughly half a subsonic diffuser entry height and, in order to prevent the normal shock "flitting" to some position forward of the cowl tip, the upstream limit of the oscillation must be arranged not to pass upstream of the subsonic diffuser tip. Thus whilst during critical operation at the low supersonic Mach number the normal shock is positioned on the subsonic diffuser tip, at the higher supersonic Mach number the mean position of the normal shock will be some distance downstream from the subsonic diffuser entrance. Hence with a given degree of supercritical operation the normal shock may be expected to be further downstream when the terminal supersonic Mach number is high than when it is low.

A further factor relevant to this discussion is that notwithstanding the critical pressure recovery being 3 per cent higher in Figure 18 than in Figure 19, the value of $\frac{P_{tot,max} - P_{tot,mean}}{P_{tot,mean}}$ is also appreciably higher. On this criterion the total pressure distribution during critical operation is not so good in Figure 18, and so perhaps a smaller deterioration of distribution with the critical pressure recovery reduced by $1\frac{1}{2}$ per cent might be expected. It thus becomes difficult to reach firm conclusions.

In both Figure 18 and Figure 19 as the pressure recovery is reduced the total pressure at the diffuser exit falls most markedly in a region adjacent to the profiled surface of the subsonic diffuser. Presumably a separation occurs on this wall during supercritical operation when the normal shock moves into the subsonic diffuser. The associated losses are probably aggravated by the reduction in the ramp bleed that occurs as the normal shock moves downstream from the critical position. In both figures the bleed opening was fixed, but the ramp bleed decreased from 4 per cent to 3.3 per cent whilst the supercritical pressure recovery was reduced to $1\frac{1}{2}$ per cent below its critical value. Pressures feeding upstream through the subsonic portions of the boundary layers are presumably responsible for these changes in the bleed. The possible variation of bleed would have to be carefully considered in the design of an intake control system based on supercritical operation.

5.0 Summary of results

(1) A two-dimensional intake with combined external/internal compression has been developed to give a maximum pressure recovery of 90.9 per cent at a free stream Mach number of 2.2 and with a total of 6.4 per cent bleed from the ramp and sidewall surfaces. The free stream Reynolds number was 3.25×10^6. With only 3.4 per cent bleed, and at the same Reynolds number and Mach number, a pressure recovery of 90 per cent was measured. It seems possible that these pressure recoveries may be close to the maximum attainable at Mach 2.2 in a mixed compression intake of acceptable mechanical complexity, and employing a simple four shock system. The pressure recovery may perhaps be raised by

about 2 per cent through the adoption of partly isentropic systems of compression.

(2) For a given total throat bleed, the introduction of sidewall bleed in addition to ramp bleed raised the pressure recovery about 1 per cent above the figure obtained with ramp bleed only. This result was the best of a number obtained with different forms of sidewall bleed slot.

(3) Under the particular test conditions an increase of test Reynolds number from approximately 1×10^6 to 3.25×10^6 raised the pressure recovery by 0.5 per cent.

(4) The introduction of sidewall bleed and an increase in the test Reynolds number altered the total pressure distribution at the subsonic diffuser exit. The corresponding changes in the flow distribution parameters that were considered do not permit firm conclusions to be drawn. Nevertheless it is thought that methods of improving the distributions should be actively considered.

(5) The performance of the intake did not vary with the two lengths of subsonic diffuser that were tested.

(6) Cutting back the intake sideplates, so that their leading edges lay in the plane of the second oblique shock instead of the first, raised the pressure recovery by about 1 per cent.

(7) With the intake running supercritically, a reduction of pressure recovery of about 2 per cent from the critical value produced some deterioration in distribution. It is suggested that in intakes having a high recovery - in effect, that is, having a low terminal supersonic Mach number - the deterioration may be less severe than in lower performance designs. However, the experimental evidence on this point is not conclusive. A marked deterioration ensued from reducing the supercritical pressure recovery by a further 4 per cent.

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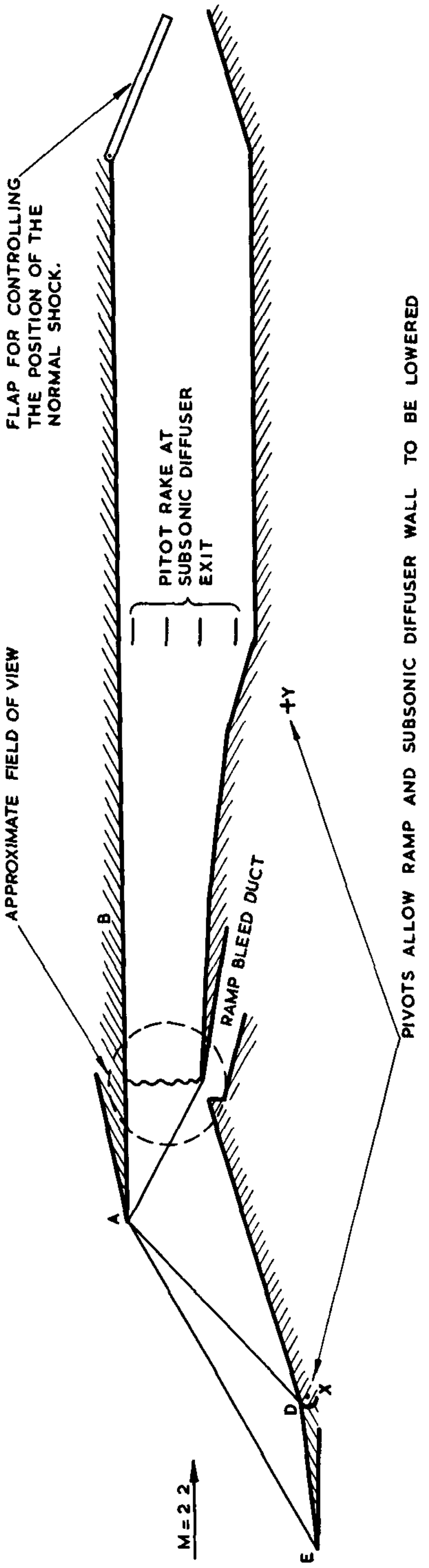
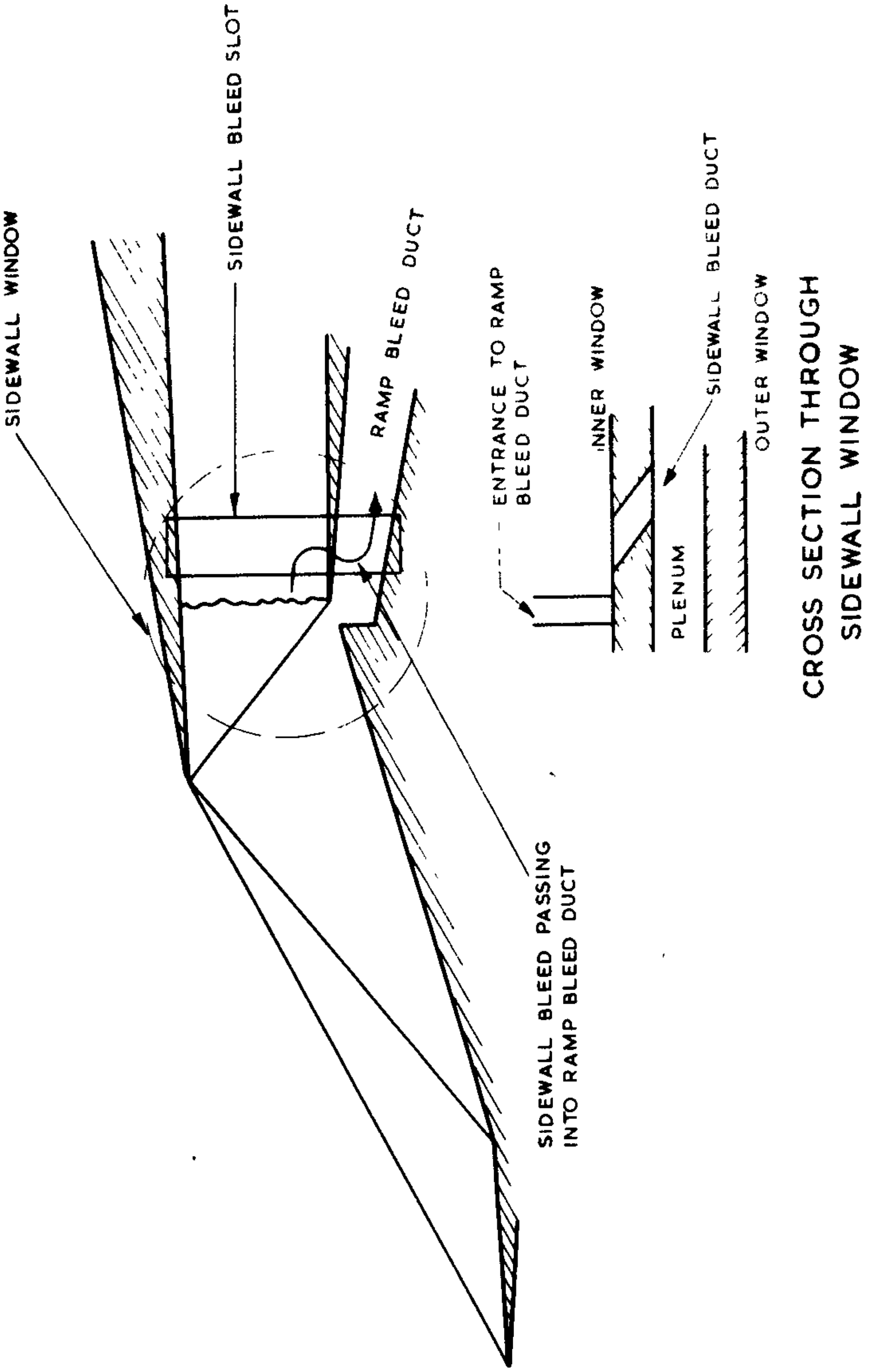
No.	Author(s)	Title, etc.
1	M. C. Neale P. S. Lamb	Tests with a variable ramp intake having combined external/internal compression and a design Mach number of 2.2. N.G.T.E. Memorandum No. M.358, August, 1962 A.R.C. C.P. No. 805
2	M. C. Neale P. S. Lamb	Further tests with a variable ramp intake having combined external/internal compression and a design Mach number of 2.2. A.R.C. C.P. No. 826, February, 1963
3	E. L. Goldsmith	Unpublished M.O.A. Report
4	M. C. Neale P. S. Lamb	Unpublished M.O.A. work
5	M. C. Neale P. S. Lamb	Tests with a two-dimensional intake having all external compression and a design Mach number of 2.0. A.R.C. C.P. No. 937, September, 1963
6	L. Howarth et al (Editor) Part XI by D. W. Holder, D. C. Macphail and J. S. Thompson	Modern Developments in Fluid Mechanics. High Speed Flow, Volume II. XI Experimental Methods. Section 1 Wind tunnels and moving bodies. Art. 7. Oxford, Clarendon Press, 1953
7	R. Hawkins	Private communication, September, 1962
8	R. D. Swift	Unpublished M.O.A. work

FIG.1



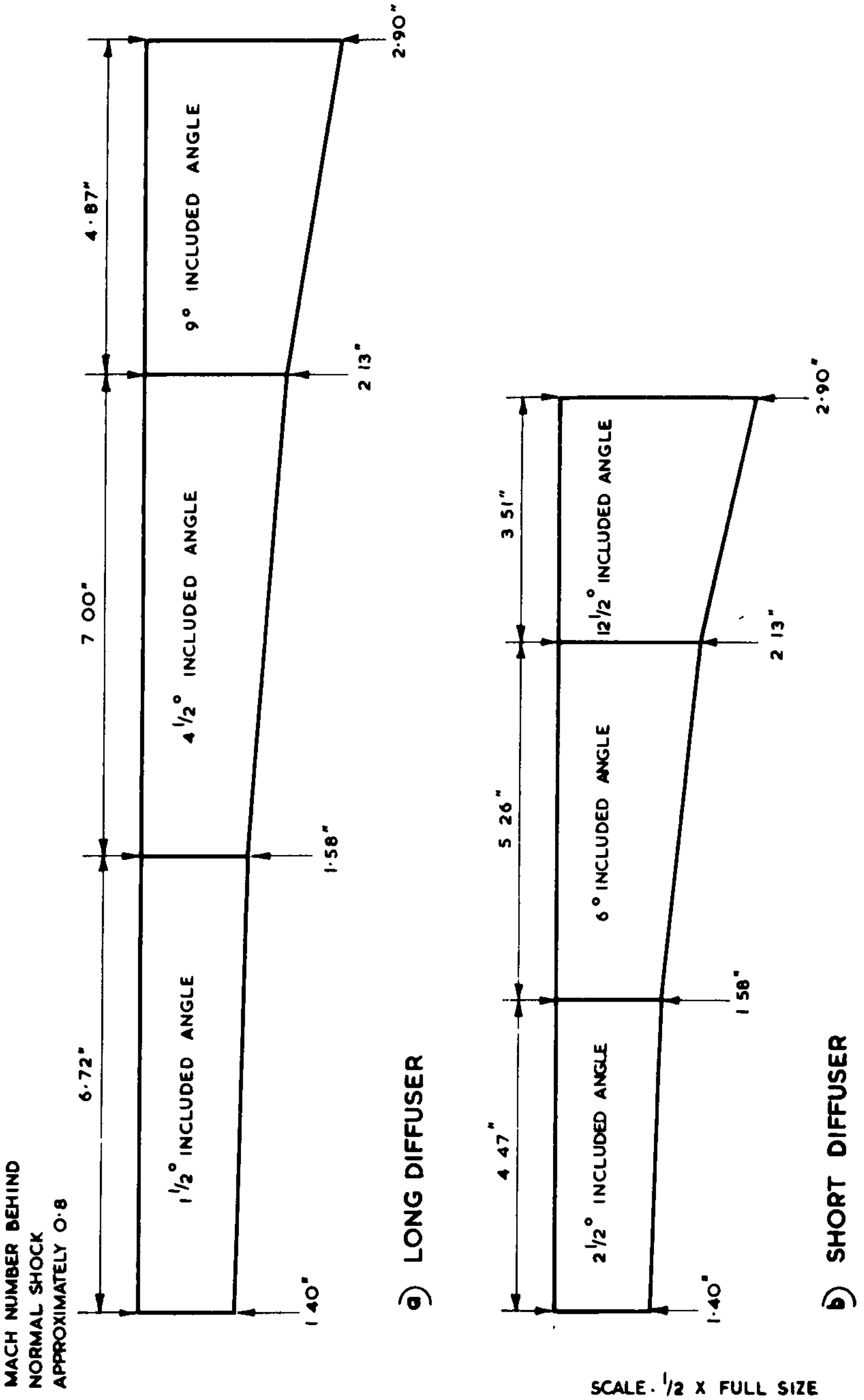
BASIC ARRANGEMENT OF MODEL

FIG 2



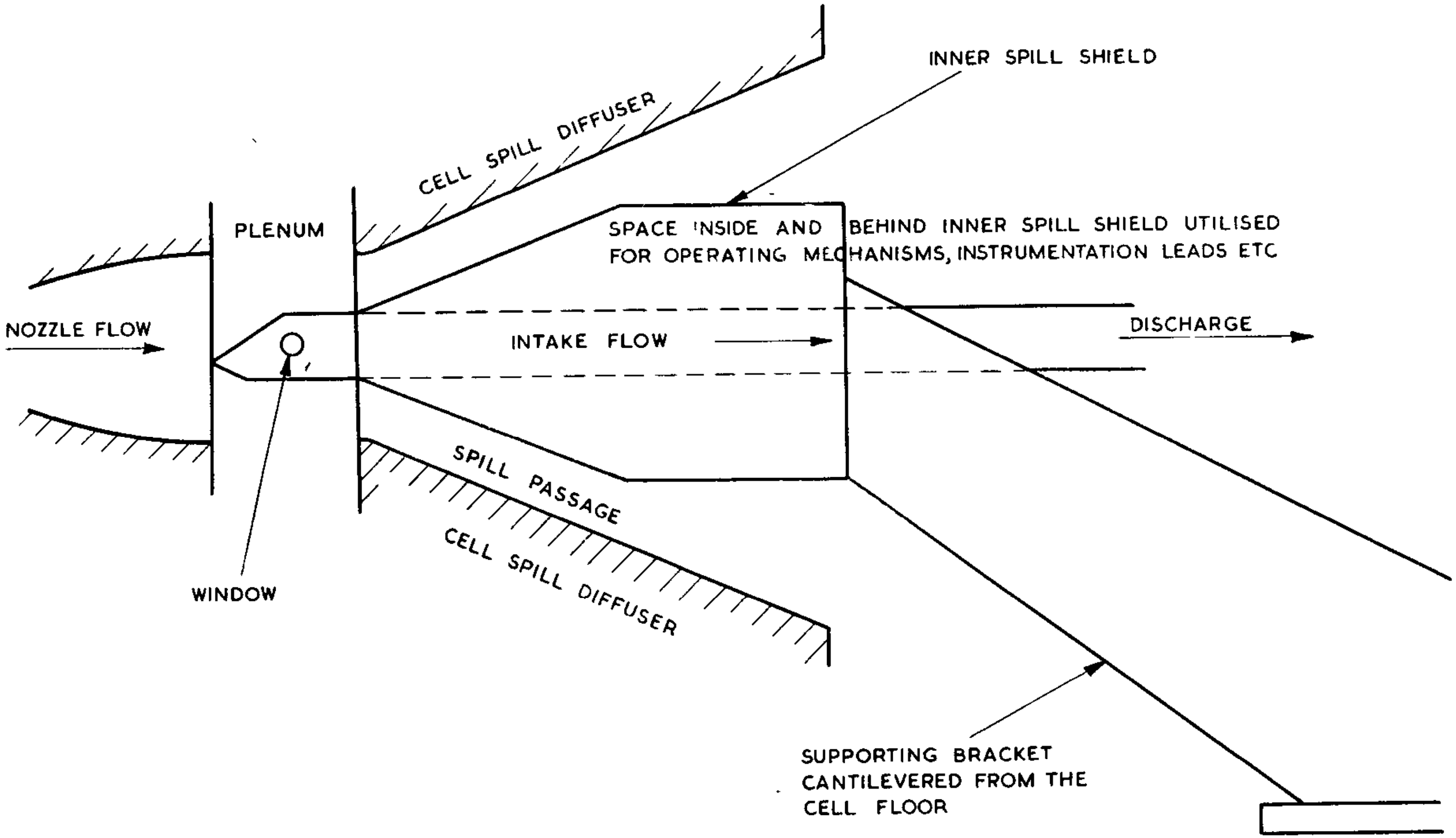
SIDEWALL BLEED ARRANGEMENT

FIG. 3.



SCALE · 1/2 X FULL SIZE

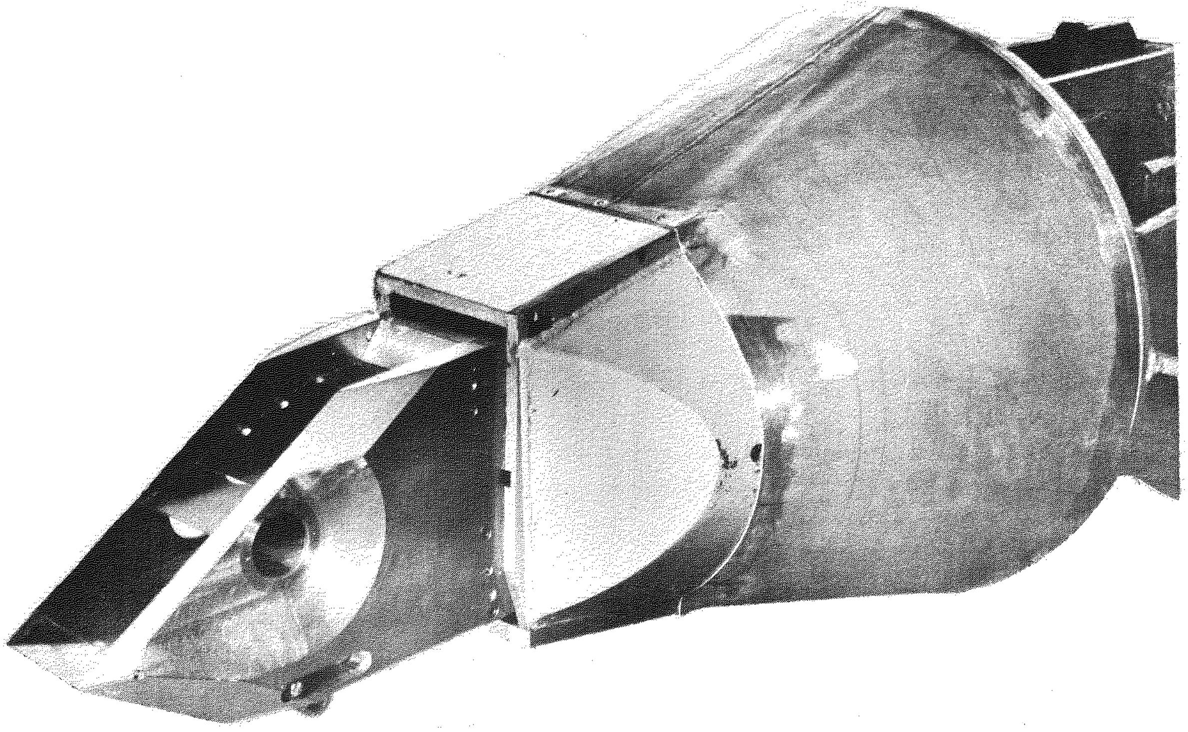
THE TWO SUBSONIC DIFFUSERS TESTED



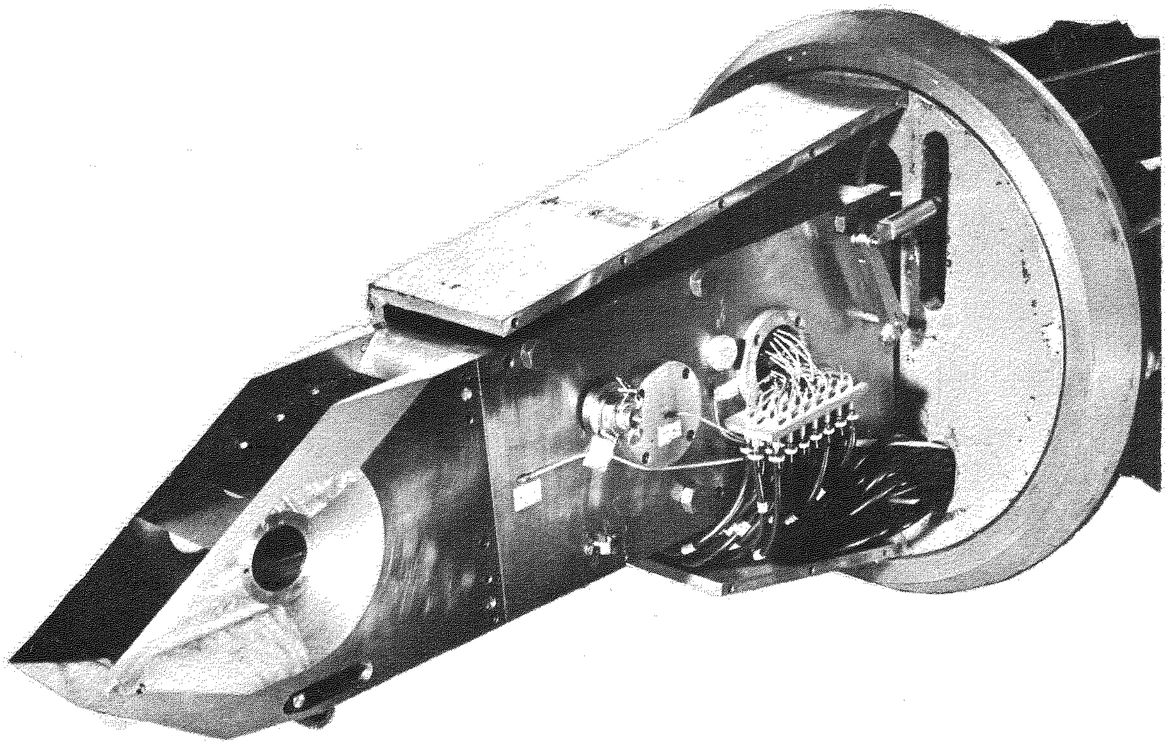
THE MODEL MOUNTED IN CELL 1

FIG. 4

FIG. 5

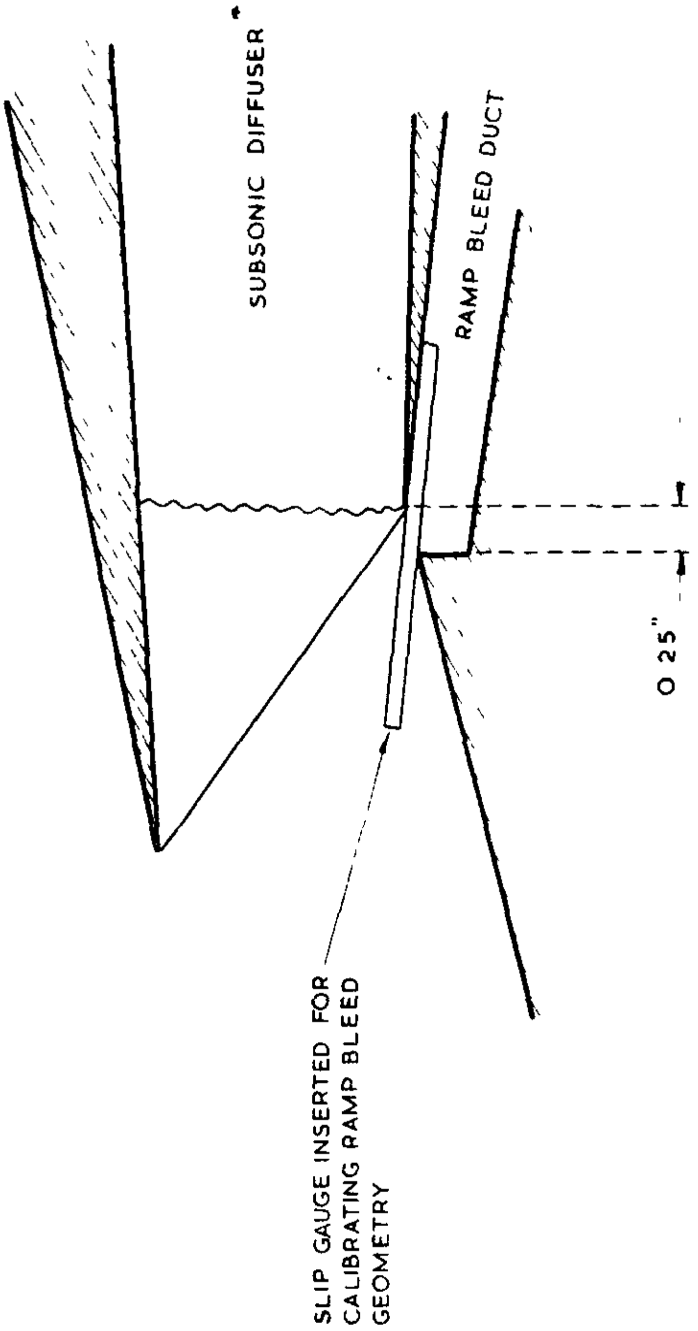


(a) THE MODEL ASSEMBLED AND READY FOR TESTING



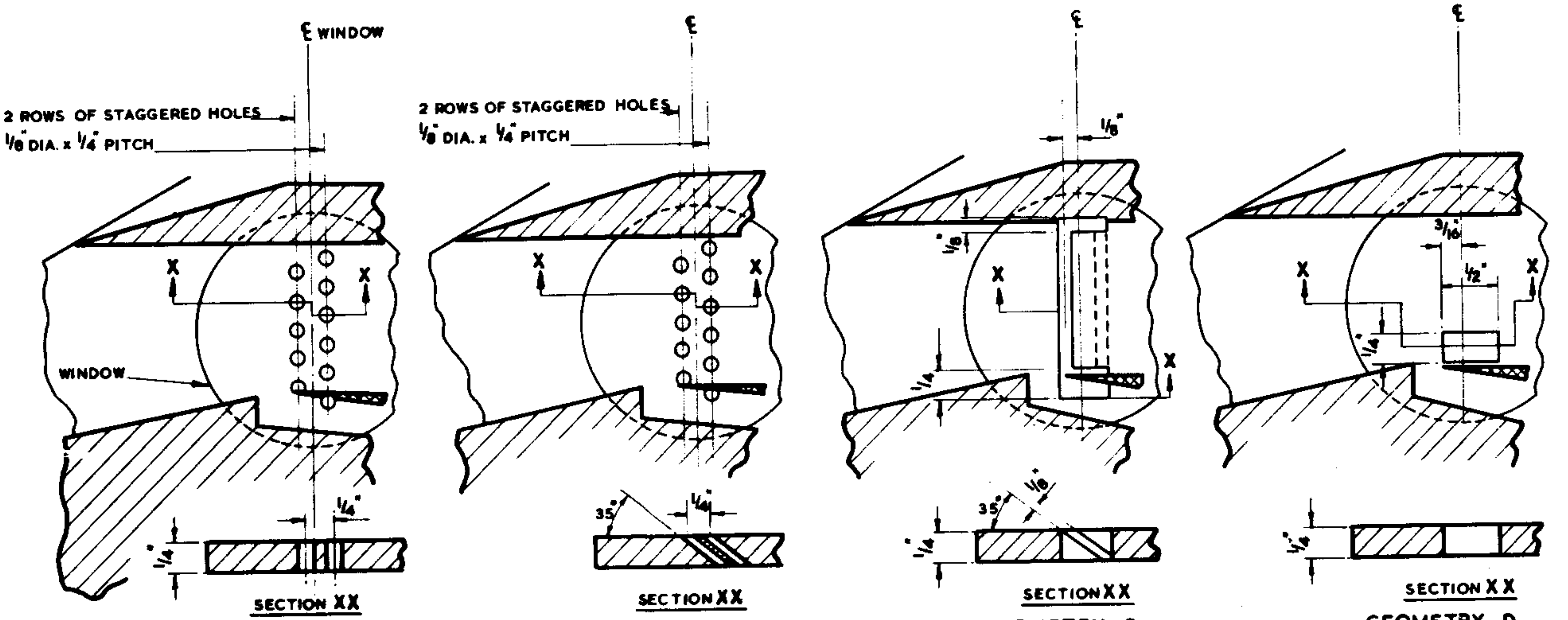
(b) THE MODEL WITH THE INNER SPILL SHIELD REMOVED

FIG. 6



RAMP BLEED GEOMETRY

FIG.7

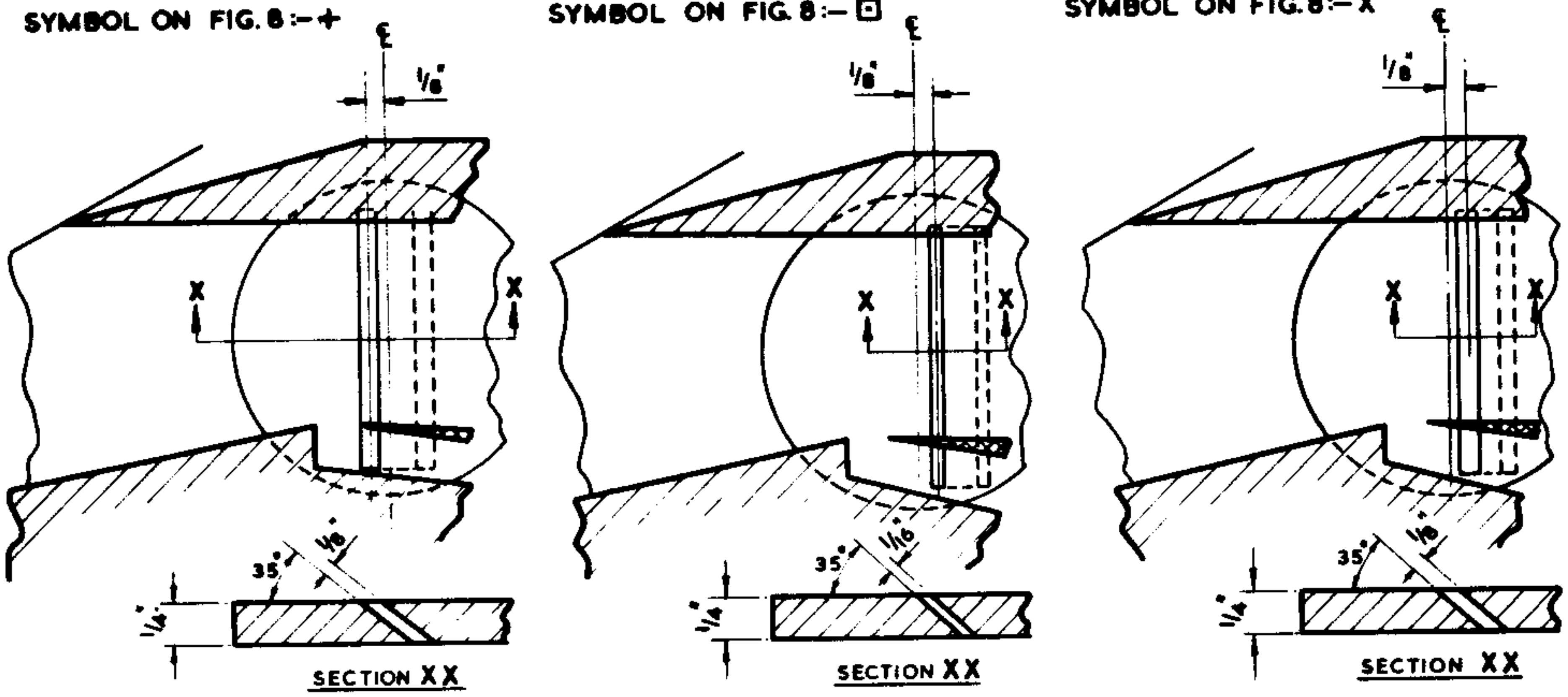


GEOMETRY A.
SYMBOL ON FIG. 8:- +

GEOMETRY B.
SYMBOL ON FIG. 8:- ⊡

GEOMETRY C.
SYMBOL ON FIG. 8:- X

GEOMETRY D.
SYMBOL ON FIG. 8:- ⊙



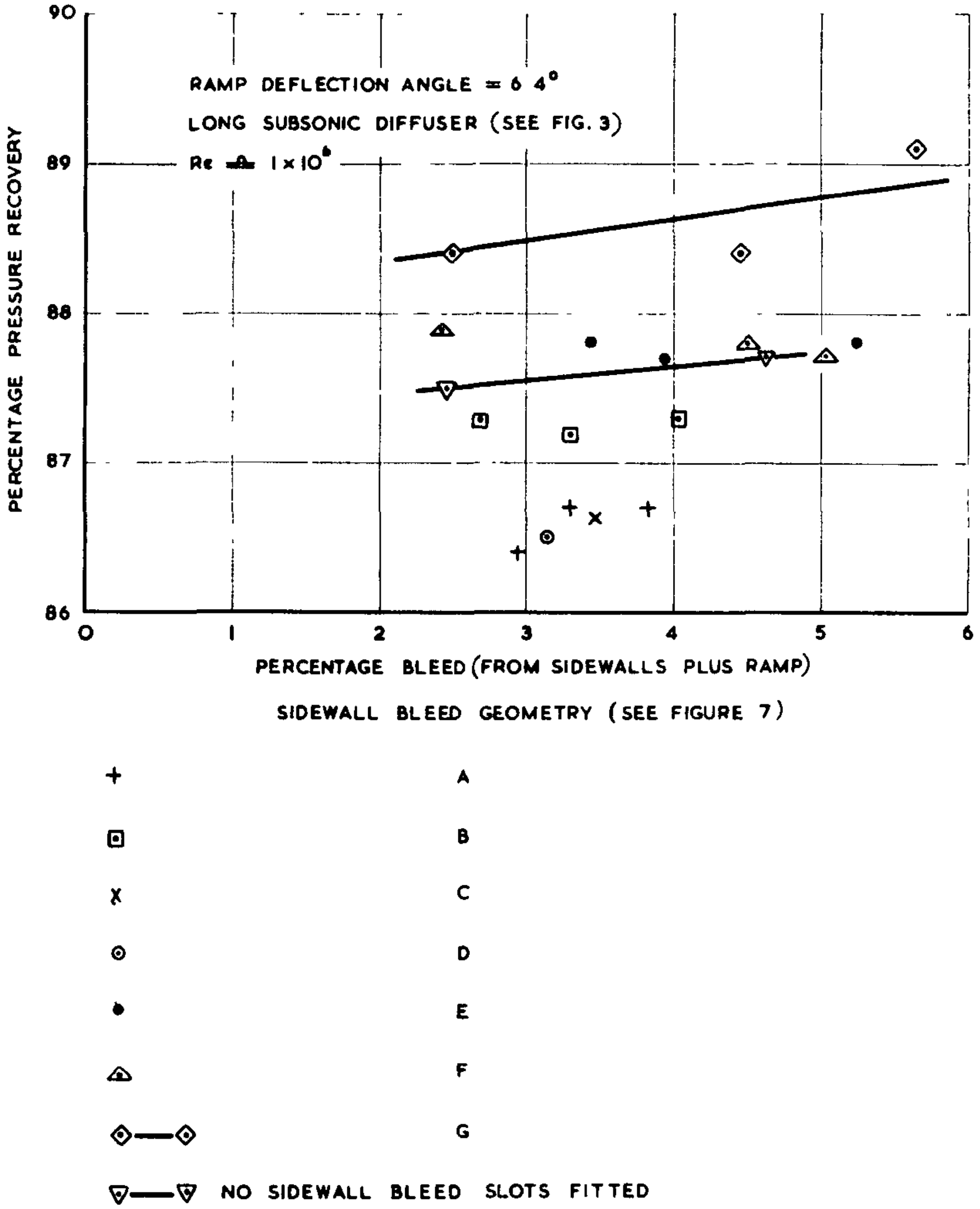
GEOMETRY E.
SYMBOL ON FIG. 8:- •

GEOMETRY F.
SYMBOL ON FIG. 8:- △

GEOMETRY G.
SYMBOL ON FIG. 8:- ◇

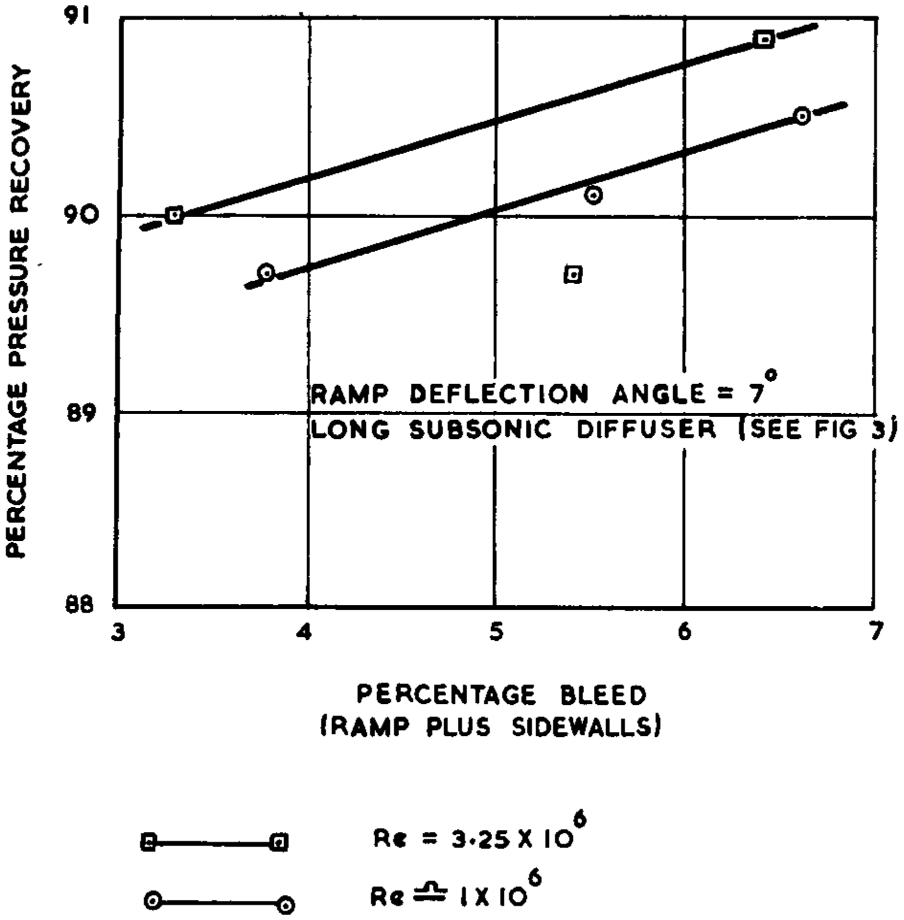
SIDEWALL BLEED GEOMETRIES.

FIG. 8



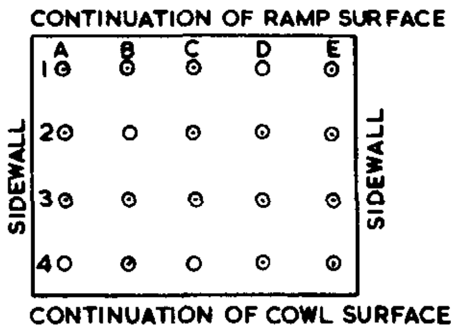
INTAKE PRESSURE RECOVERY WITH DIFFERENT FORMS OF SIDEWALL BLEED SLOT

FIG 9



EFFECT OF REYNOLDS NUMBER

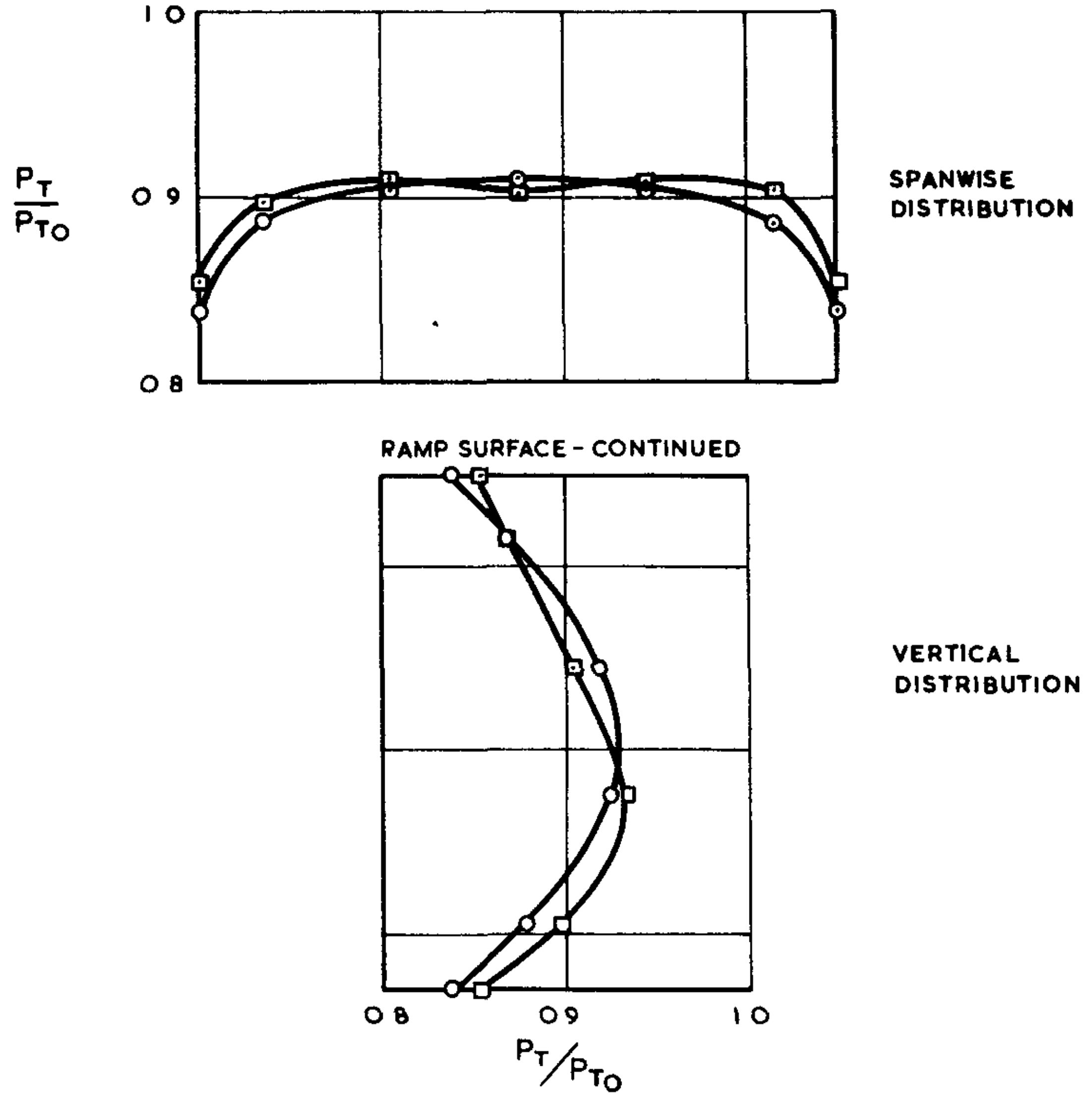
FIG. 10.



DIFFUSER EXIT PLANE

NOTE – IN THE FOLLOWING DISTRIBUTION CURVES 'SPANWISE' DISTRIBUTIONS ARE THE MEAN VALUES OF THE COLUMNS A, B, C, D, E

'VERTICAL' DISTRIBUTIONS ARE THE MEAN VALUES OF THE ROWS 1, 2, 3, 4



R_e	PRESSURE RECOVERY	BLEED*	MEAN DIFFUSER EXIT MACH NUMBER	$\frac{P_{TOT_{MAX}} - P_{TOT_{MEAN}}}{P_{TOT_{MEAN}}}$	$\frac{V_{MAX}}{V_{MEAN}}$
○——○ ≏ 1×10^6	89·7%	3·8%	0·32	5·6%	1·33
□ □ $3\cdot25\times10^6$	90%	3·3%	0·28	4·8%	1·36

* RAMP PLUS SIDEWALLS

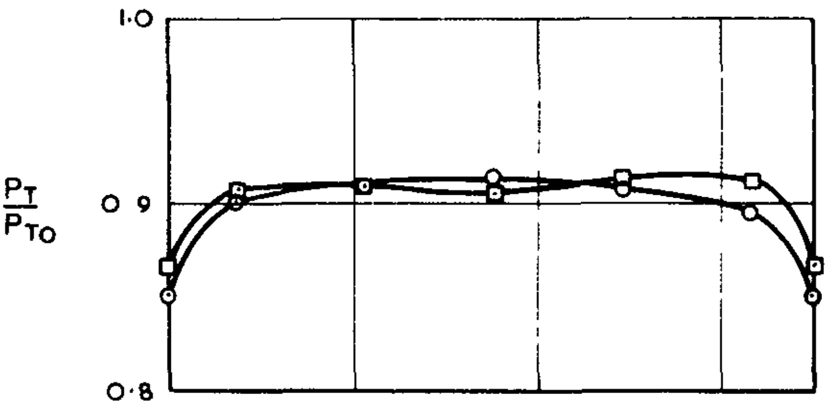
LONG SUBSONIC DIFFUSER

SIDEWALL BLEED GEOMETRY 'G' (SEE FIG.7)

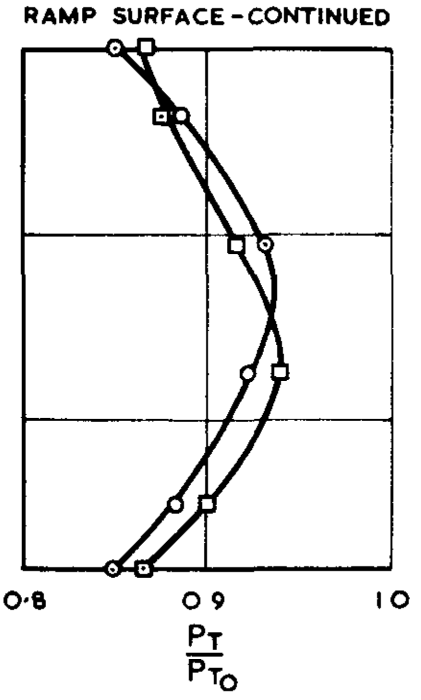
EFFECT OF REYNOLDS NUMBER ON DIFFUSER EXIT DISTRIBUTIONS

(3½ PER CENT BLEED)

FIG. 11.



SPANWISE DISTRIBUTION



VERTICAL DISTRIBUTION

	Re	PRESSURE RECOVERY	BLEED*	MEAN DIFFUSER EXIT MACH NUMBER	$\frac{P_{TOT\,MAX}\ \ P_{TOT\,MEAN}}{P_{TOT\,MEAN}}$	$\frac{V_{MAX}}{V_{MEAN}}$
○—○	≙ 1×10^6	90·5%	6·7%	0·30	4·1%	1·28
□—□	$3{\cdot}25 \times 10^6$	90·9%	6·4%	0·26	4·1%	1·37

* RAMP PLUS SIDEWALLS

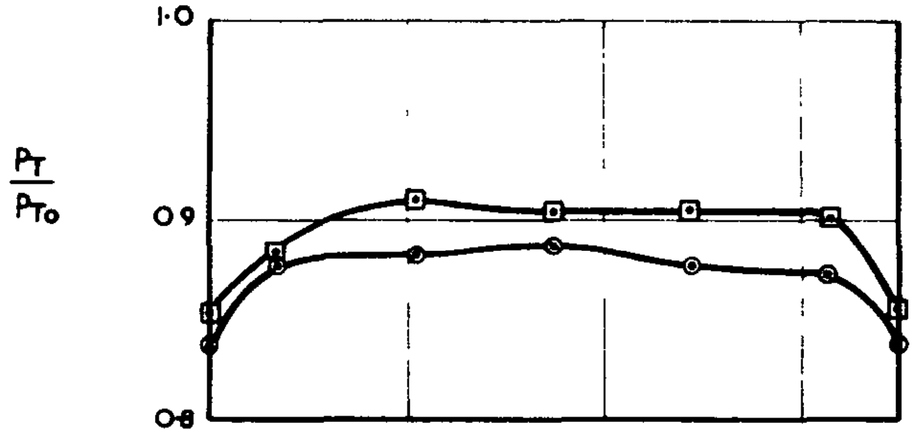
LONG SUBSONIC DIFFUSER

SIDEWALL BLEED GEOMETRY "G" (SEE FIG 7)

EFFECT OF REYNOLDS NUMBER ON DIFFUSER EXIT DISTRIBUTIONS

(6 1/2 PER CENT BLEED)

FIG.12



SPANWISE TOTAL PRESSURE DISTRIBUTION IN ROW 4 OF PITOT RAKE (SEE FIG.10)

	Re	PRESSURE RECOVERY	* BLEED
⊙——⊙	≃ 1×10^6	89·7%	3 8%
⊡——⊡	3 25×10^6	90%	3·3%

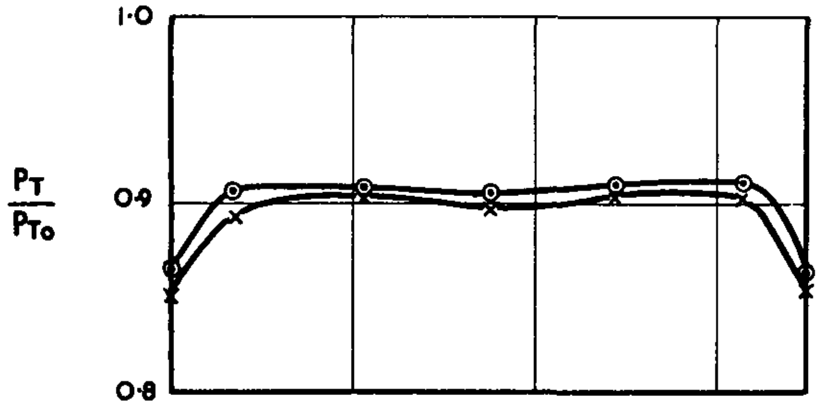
* RAMP PLUS SIDEWALLS

LONG SUBSONIC DIFFUSER

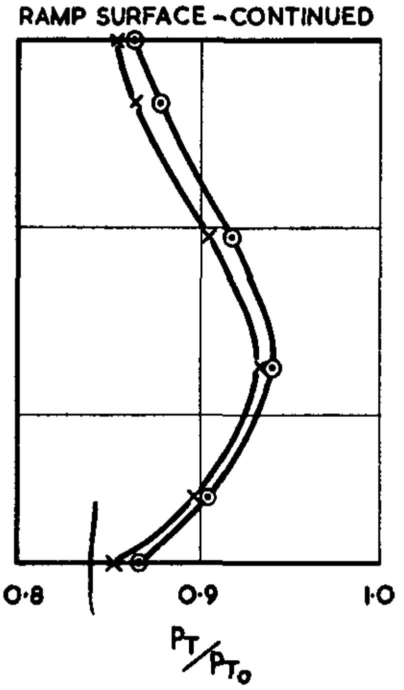
SIDEWALL BLEED GEOMETRY 'G' (SEE FIG 7)

EFFECT OF REYNOLDS NUMBER ON
DIFFUSER EXIT DISTRIBUTIONS
ADJACENT TO COWL SURFACE

FIG.13



SPANWISE TOTAL PRESSURE DISTRIBUTION



VERTICAL DISTRIBUTIONS

	PRESSURE RECOVERY	BLEED	MEAN DIFFUSER EXIT MACH NO	$\frac{P_{TOT\,MAX} - P_{TOT\,MEAN}}{P_{TOT\,MEAN}}$	$\frac{V_{MAX}}{V_{MEAN}}$
⊙——⊙	90·9%	6·4%	0·26	4·1%	1 37
x——x	90%	3·3%	0·28	4·8%	1·36

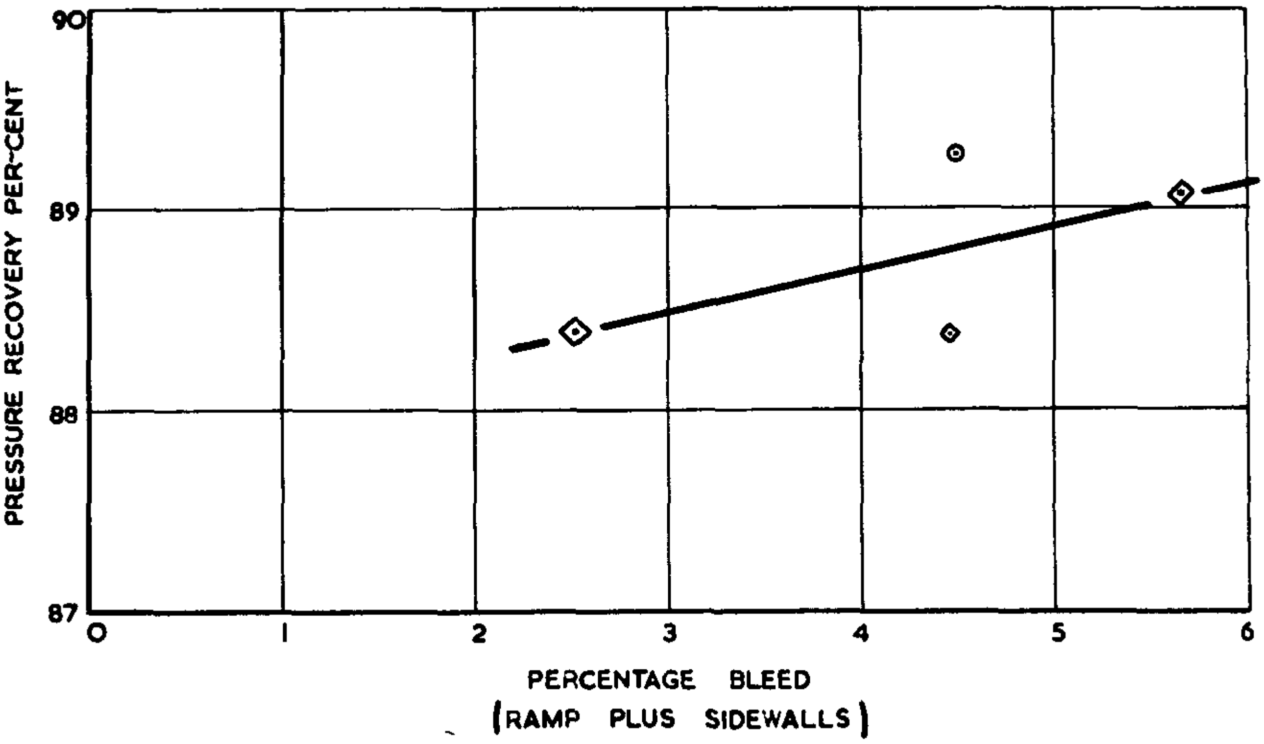
R_e $3{\cdot}25 \times 10^6$

SIDEWALL BLEED GEOMETRY "G" (SEE FIG 7)

LONG SUBSONIC DIFFUSER

EFFECT OF AN INCREASE IN SIDEWALL BLEED ON DIFFUSER EXIT DISTRIBUTIONS

FIG 14



◇ LONG SUBSONIC DIFFUSER

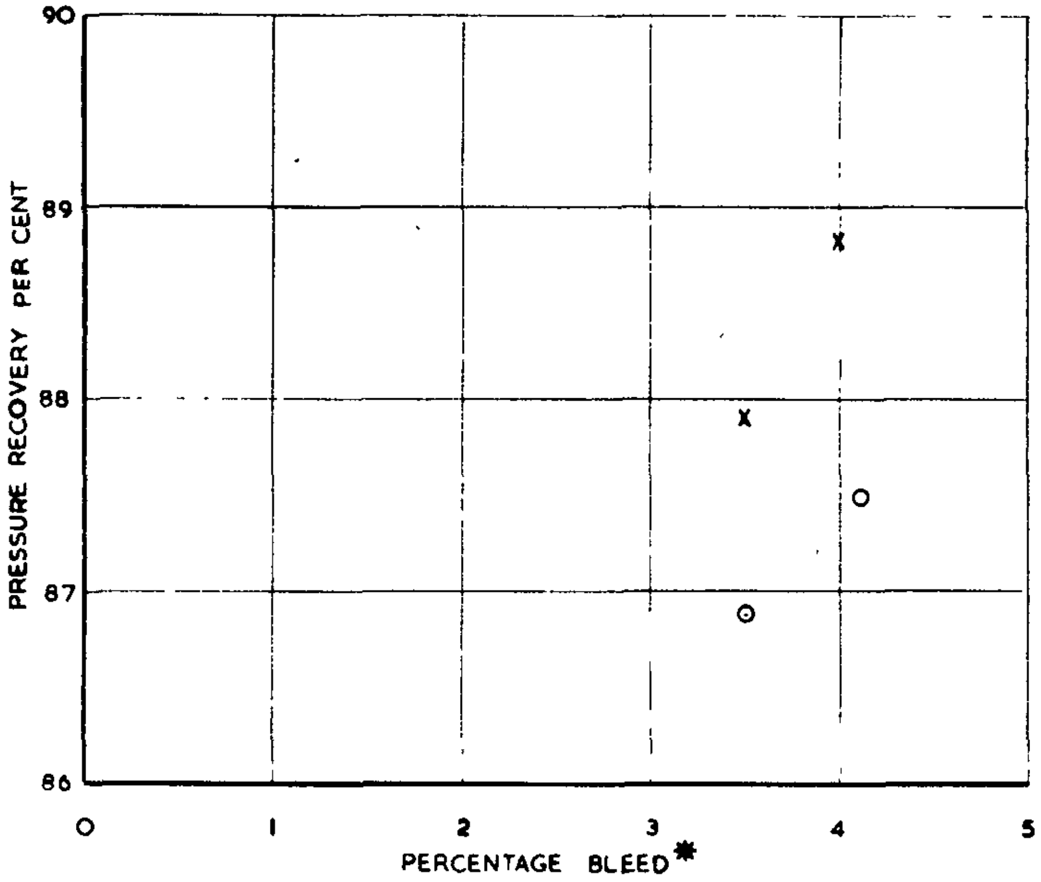
⊙ SHORT SUBSONIC DIFFUSER

$Re = 1 \times 10^6$

SIDEWALL BLEED GEOMETRY 'G' (SEE FIGURE 7)

RAMP DEFLECTION ANGLE = 6·4°

EFFECT OF SUBSONIC DIFFUSER LENGTH ON PRESSURE RECOVERY

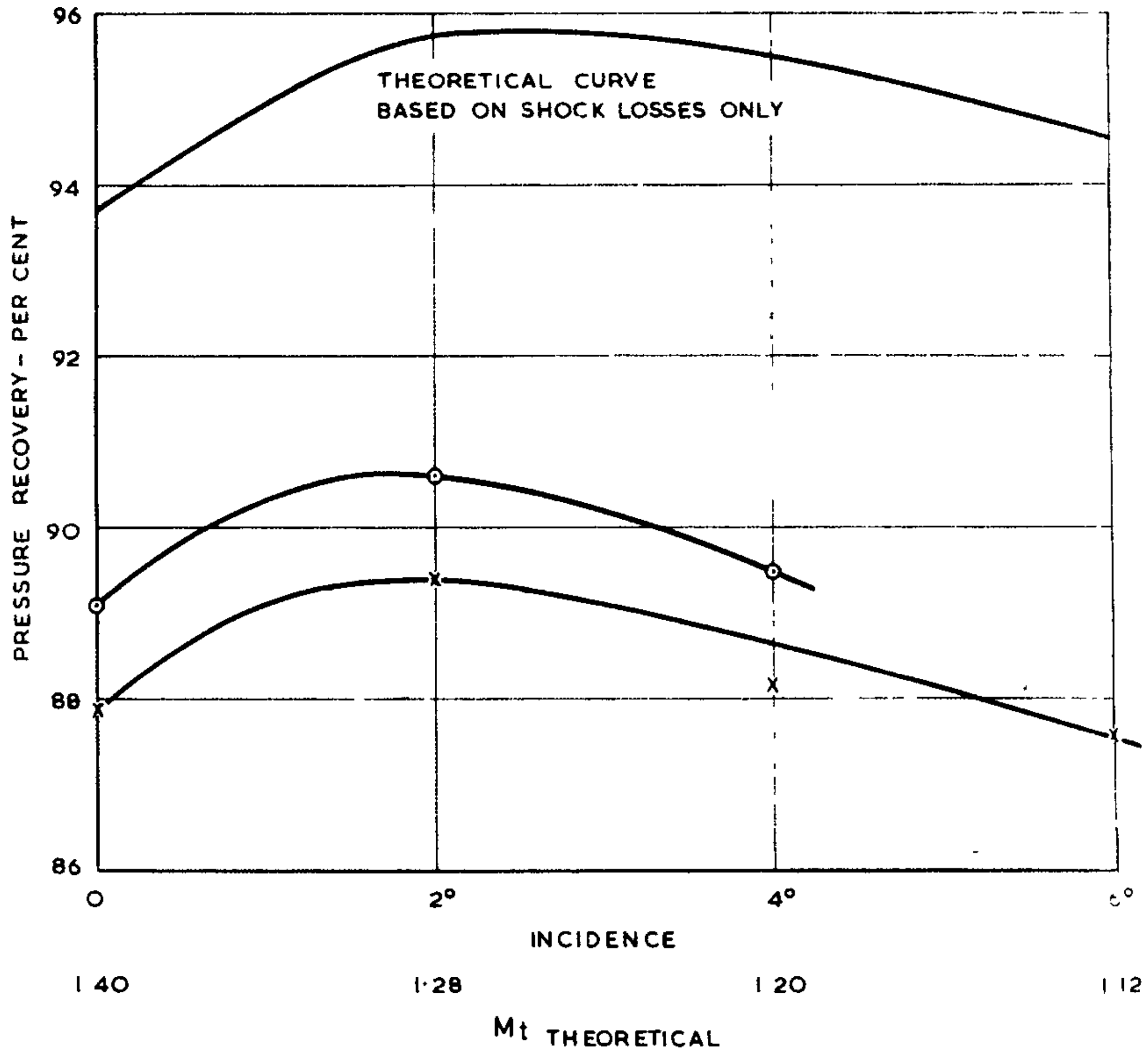


RAMP ANGLE : 6 4°
Re 1×10^6 SHORT SUBSONIC DIFFUSER
⊙ —— ORIGINAL SIDEPLATES
X —— CUT BACK SIDEPLATES

* BASED ON CAPTURE MASS FLOW WITH ORIGINAL SIDEWALLS
RAMP BLEED ONLY NO SIDEWALL BLEED

EFFECT OF CUT BACK SIDEPLATES

FIG 16.

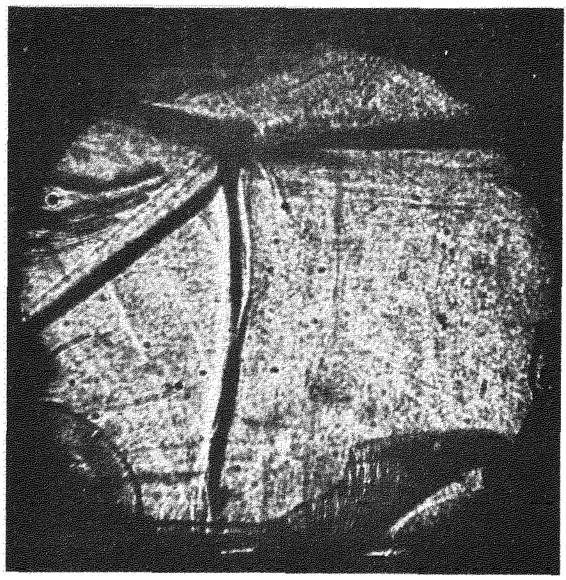


RAMP DEFLECTION ANGLE = 6·8°
REYNOLDS No $\simeq 1 \times 10^6$

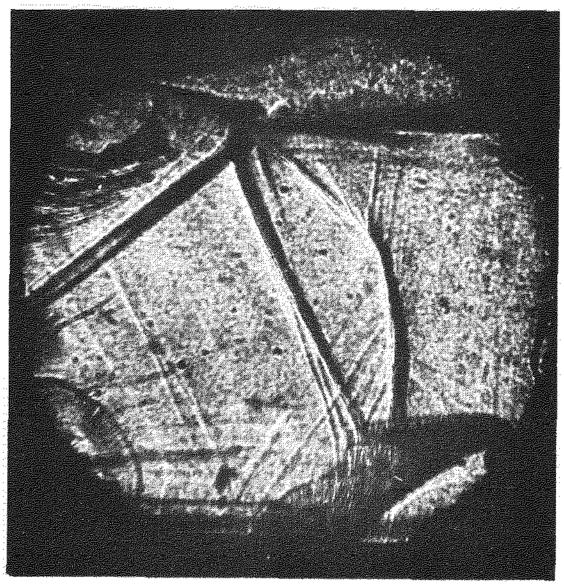
⊙ { TOTAL BLEED (RAMP PLUS SIDEWALLS) – 4 TO 6 PER CENT
1/8 IN. SIDEWALL SLOTS LONG SUBSONIC DIFFUSER

X { CUT BACK SIDE PLATES TO PROFILE "A,D,E" IN FIG 1
SHORT SUBSONIC DIFFUSER RAMP BLEED — 3½ TO 4½ PER CENT
(NO SIDEWALL BLEED)

EFFECT OF DIFFERENT RATIOS OF EXTERNAL TO INTERNAL COMPRESSION



(a) INTAKE CRITICAL



(b) INTAKE SUPERCRITICAL. PRESSURE RECOVERY REDUCED FROM THE CRITICAL VALUE BY 1½ %

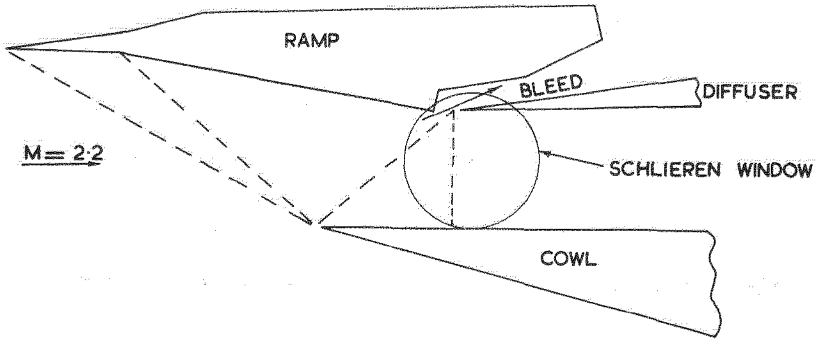
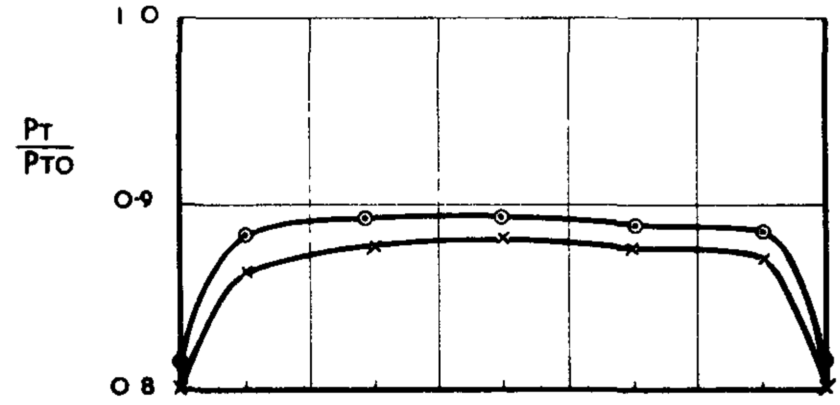
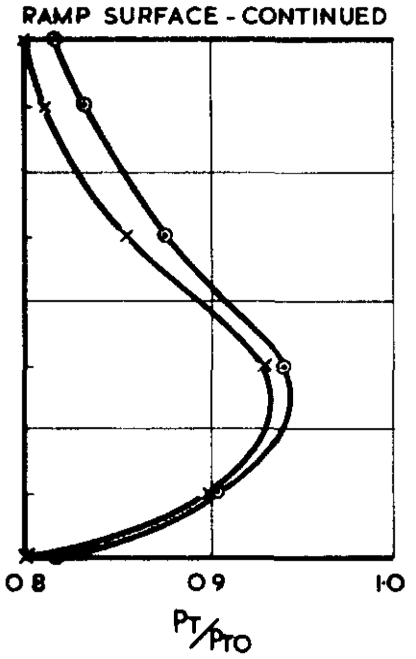


FIG.18



SPANWISE TOTAL PRESSURE DISTRIBUTION



VERTICAL DISTRIBUTION

MEAN DIFFUSER EXIT MACH NUMBER			η	BLEED*	$\frac{V\,MAX}{V\,MEAN}$	$\frac{P_{TOT\,MAX} - P_{TOT\,MEAN}}{P_{TOT\,MEAN}}$
0·346	⊙——⊙	INTAKE CRITICAL	88·8	4·0	1·36	7·1 %
0·355	×——×	INTAKE SUPERCRITICAL	87·3	3·4	1·34	7·9 %

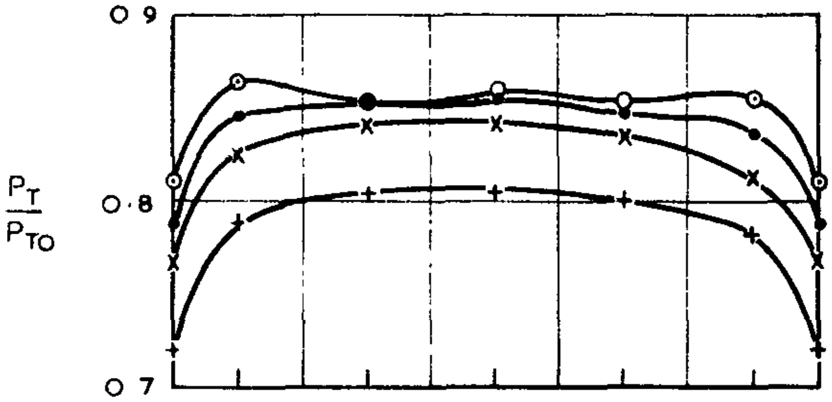
$Re \simeq 1 \times 10^6$ · SHORT SUBSONIC DIFFUSER

*BLEED FROM RAMP SURFACE ONLY

CUT BACK SIDEPLATES (TO THE LINE ADE IN FIGURE 1)

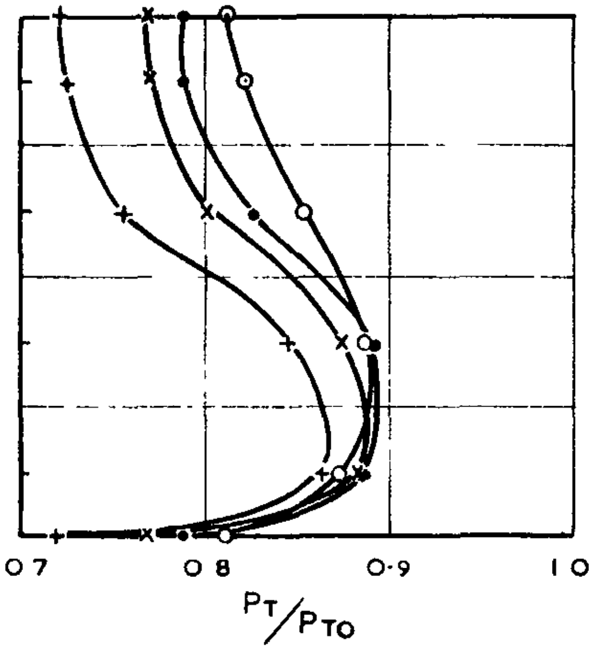
EFFECT OF RUNNING SUPERCRITICALLY ON DIFFUSER EXIT DISTRIBUTIONS

FIG. 19.



SPANWISE TOTAL PRESSURE DISTRIBUTION

RAMP SURFACE - CONTINUED



VERTICAL DISTRIBUTION

MEAN DIFFUSER EXIT MACH NUMBER		η	BLEED*	$\frac{V_{MAX}}{V_{MEAN}}$	$\frac{P_{TOT_{MAX}} - P_{TOT_{MEAN}}}{P_{TOT_{MEAN}}}$
0·38	+ —— +	79·6%	1·32%	1·43	11·68
0·34	x —— x	83·1%	2·1%	1·46	9·75
0·31	• —— •	84·2%	3·3%	1·38	7·1
0·29	o —— o	85·8%	4%	1·31	4·7 CRITICAL

$Re \simeq 1 \times 10^6$ THROUGHOUT SHORT SUBSONIC DIFFUSER

* BLEED FROM THE RAMP SURFACE ONLY

EFFECT OF RUNNING SUPERCRITICALLY ON DIFFUSER EXIT DISTRIBUTIONS

D 86729/1/129528 K4 5/67 CL

A.R.C. C.P. No. 938 533.697.2 620.1

November 1963

Neale, M. C. and Lamb, P. S.

MORE TESTS WITH A VARIABLE RAMP INTAKE
HAVING A DESIGN MACH NUMBER OF 2.2

Results are reported of tests on a two-dimensional combined external/internal compression intake having a design Mach number of 2.2.

The particular parameters investigated in the tests now reported are -

(a) sidewall bleed,
(b) a 3 to 1 range of free stream Reynolds number,
(c) the length of subsonic diffuser,
(d) sidewalls cut back to the line of the second ramp shock.

P.T.O

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P.T.O

DETACHABLE ABSTRACT CARDS

The maximum pressure recovery obtained at the design Mach number was 90.9 per cent with 6.4 per cent bleed. A better performance was a pressure recovery of 90 per cent with only 3.4 per cent bleed. These figures were obtained at a Reynolds number, based on free stream conditions and intake capture height, of 3.25×10^6.

It seems possible that these pressure recoveries may be close to the maximum attainable at Mach 2.2 in a mixed compression intake of acceptable mechanical complexity, and employing a simple four shock system.

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