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Tests with a Two-dimensional Intake having All-external Compression and a Design Mach Number of 2.0

By

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SUMMARY

Results are reported of tests on a two-dimensional external compression intake having a design Mach number of 2.0. A pressure recovery of 93 per cent was measured with 3.3 per cent bleed from the ramp surface at the throat. The introduction of a small contraction in the throat improved the stable sub-critical margin of the intake. The test Reynolds number based on free stream conditions and intake capture height was approximately 1 × 10^6.

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* Replaces N.G.T.E. M.368 - A.R.C. 25544

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1.0 Introduction

At N.G.T.E. the performance of a mixed compression intake at its design Mach number of 2.2 has been developed to what is thought to be very close to the maximum attainable with a simple four shock design[1]. The tests now described initiated a complementary investigation of the problems associated with external compression intakes. The first tests were made at a free stream Mach number of 2.0. At this Mach number the theoretical considerations outlined in the Appendix show the external compression intake in a rather more favourable light than at M = 2.2. It was also known that tests at O.N.E.R.A.[2] with external compression intakes at M = 2.0 had yielded pressure recoveries as high as 93 per cent. High pressure recoveries had also been measured at the N.A.S.A.[3]. Tests at M = 2.2 are described in Reference 4, and provide a more direct comparison with the earlier N.G.T.E. work on the mixed compression design.

2.0 Description of the model

The rig and most of the model was that used in Reference 5 and designed initially for testing combined external/internal compression intakes. The substitution of suitably designed components allowed the model to be adapted so that external compression and mixed compression intakes could be tested with equal facility.

2.1 Aerodynamic and mechanical design

Some of the factors influencing the design of external compression intakes are considered in the Appendix. The aerodynamic design of the first intake tested in the present work is shown in Figure 1. The ramp consists of an initial wedge inclined at 8° to the free stream direction, followed by a further 8° turn and finally three angles each of 1°. The total ramp turning is thus 19°, so arranged that at M = 2.0, and without allowing for boundary layer growth, the shocks focus on the cowl tip. The internal surface at the cowl tip is inclined initially at 14° to the free stream, so that the flow deflection of the internal flow at the tip is 5°. The procedure adopted in the design of the cowl was to continue the internal surface along a straight line to the point at which a perpendicular from the surface intersected the foot of the strong solution shock emanating from the cowl tip. Subsequently a radius of 4.2 throat heights returns the internal cowl surface to the free stream direction. This particular radius was chosen as representing a fair average of the many different radii employed in the numerous investigations, both in this country and the United States, of axisymmetric intakes with external compression. At the time of the design there was a view prevalent that extra-to-shock losses increased both with the flow deflection at the cowl tip and the downstream rate of turn. With this philosophy the cowl angle and curvature represented a compromise between external drag and internal performance.

The original design intention was to position the terminal shock at the upstream edge of the bleed slot, as opposed to the downstream edge employed in tests with a mixed compression design[1]. The forward movement of the shock relative to the bleed was thought desirable in view of previous experience elsewhere[3], and also from considering the likely sidewall secondary flow patterns (see the Appendix). Viscous effects, through reducing the Mach number upstream of the cowl shock, and also through increasing the effective flow deflection at the cowl tip, bring the foot of the strong solution cowl shock downstream of the design position based on inviscid theory. With the object of allowing for this displacement the final ramp deflection of 19° relative to the free stream continues until approximately 0.1 capture heights downstream of the theoretical terminal shock (assuming inviscid flow) at which point the ramp terminates in the upstream edge of the ramp bleed slot. Downstream from this point the geometric construction is continued by an arc, concentric with the cowl radius, into a subsonic diffuser having an initial divergence of $1\frac{1}{2}^{\circ}$ and shown in detail in Figure 2. This diffuser is about 50 per cent longer than the subsonic diffuser currently mooted for the supersonic transport application. Further tests will be made with shorter diffusers. The bleed slot extends over an axial distance of about 0.4 throat heights, and thus covers the greater part of the turn on the continuation of the ramp surface. The downstream lip of the bleed slot has a sharp edge and an included angle of 5°. After passing into a plenum chamber the bleed enters two ducts serving as measuring lengths and containing pitot tubes and static tappings. A throttle at the exit from the measuring ducts controls the bleed mass flow.

The intake sidewalls commence on the line joining the ramp and cowl tips with a chamfer angle of 16° in the free stream direction, which means that the shocks generated by the sidowalls are detached from their leading edges. However chamfer angles of this magnitude are dictated by the simultaneous requirements of mechanical robustness - sufficient to allow ultimate testing at full scale Reynolds numbers - and large sidewall windows to permit observation of the throat flow. As Reference 4 points out, the effect of the shock detachment on the performance of the intake appears to be very small.

The intake capture height was $2\frac{1}{2}$ in. and the span $3\frac{1}{2}$ in. giving an aspect ratio based on the capture plane dimensions of 1.4. The latter figure corresponds fairly closely with the aspect ratios currently proposed for supersonic transport installations.

Mechanical drives provided originally for earlier combined external/internal compression intakes permitted the following movements:-

(a) an axial translation of the cowl

(b) a rotation of that portion of the ramp downstream of the pivot position P in Figure 1

(c) a rotation of that wall of the subsonic diffuser forming a continuation of the ramp surface. Here the pivot was sufficiently far downstream for the angular movement of the diffuser wall to be disregarded. The movement, which was essentially one of translation, was used in the present tests to provide changes both in the geometry of the bleed slot and in the cross-sectional area at the entrance to the subsonic diffuser.

Of these three movements the first two were not employed in the tests now reported. The third was used to obtain the different diffuser positions shown in Figures 1 and 3. In addition a flap downstream of the subsonic diffuser exit was used to position the terminal shock at the intake throat. The throttle in the bleed ducts has already been mentioned.

Following tests with the intake shown in Figure 1 some tests were made with the design shown in Figure 3, in which the bleed slot was moved slightly forward. The only other change from the earlier design is in the profile of the surface commencing at the downstream edge of the bleed slot. Whereas the intention of the design shown in Figure 1 was to provide a constant area during the throat turning, in Figure 3 the subsonic diffuser tip provides a contraction prior to the commencement of subsonic diffusion. Such a contraction had, in Reference 6 for example, been found to influence appreciably the extra-to-shock losses. Difficulties arise however in introducing throat contractions into intakes designed for high pressure recoveries. The necessity for diffusing supersonically down to a Mach number of about 1.38 prior to the terminal shock means that there is very little difference between the throat area and the area that could cause choking. Thus there is little scope for the introduction of contractions. In the present tests the facility for moving the diffuser tip allowed the maximum allowable contraction to be determined experimentally. Ideally perhaps, the geometry incorporating the maximum contraction would be obtained by increasing as far as possible the rate of turn on the cowl, and thus reducing the cowl drag.

2.2 Instrumentation

In addition to the bleed duct instrumentation the principal item was a rake of 20 total head tubes distributed on an equal area basis in the exit plane of the subsonic diffuser. Also provided were a number of static tappings distributed between the ramp surface, the bleed plenum, the subsonic diffuser sidewalls, and the subsonic diffuser exit plane.

The throat flow was observed by Schlieren apparatus. A pressure transducer was positioned in the intake sidewall at the exit plane of the subsonic diffuser.

3.0 Test procedure

Testing was 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. Tests were made with a number of different bleed flows, and with the various diffuser tip positions shown in Figures 1 and 3. With each intake configuration readings were taken at a number of positions of the terminal shock ranging from supercritical operation, through the critical condition, to buzz.

4.0 Results and discussion

4.1 Tests with the geometry of Figure 1

Figure 4 shows some results obtained with the intake geometry of Figure 1. A maximum pressure recovery of 93.1 per cent was measured with 4.2 per cent bleed at a diffuser position intermediate between A and C. With diffuser position A a pressure recovery of 93 per cent was measured with only 3.3 per cent bleed. For a given bleed, within the experimental range of bleed flow, Figure 4 shows that the diffuser position B gives a pressure recovery about 2 per cent lower than that obtained with diffuser positions A and C. The fall of pressure recovery accompanying the introduction of a slight ram scoop effect into the bleed recalls the early tests of the mixed compression intake at N.G.T.E.[5]. These showed that the knife edge at the ram scoop slot caused a considerable disturbance in the throat flow pattern. The losses associated with the disturbance were considerably reduced following the adoption of a more nearly flush type of slot. A comparison of Figures 5(a) and 5(b) shows that in the present tests too the slight ram scoop effect produced by the diffuser in position B leads to a small disturbance at the foot of the terminal shock.

It will be noted that with the diffuser in position A the terminal shock is perfectly straight, and corresponds with a strong solution across the full throat height. The measured shock angle relative to the ramp in Figure 5(a) is 75°, compared with 82° given by the design shock pattern assuming inviscid flow. The boundary layer effects mentioned in Section 2.1 and probably the three-dimensional effects suggested below presumably account for the difference. As a result the foot of the terminal shock is positioned adjacent to the upstream edge of the bleed slot as intended in the initial design.

In Figure 5(a) the difference between the recovery of the design shock pattern, calculated assuming inviscid flow, and the measured pressure recovery is only 2.4 per cent of the free stream total pressure. The measured pressure recoveries of 93.1 per cent plotted in Figure 4 further reduce the difference to 2.2 per cent. It is difficult to be precise however about the exact level of the extra-to-shock losses. A static pressure measurement on the ramp suggests that after the 19° of ramp turning the Mach number is reduced to 1.29, compared with the design figure (assuming inviscid flow) of 1.36. The measured Mach number, taken in conjunction with the 5° cowl deflection, gives an overall theoretical shock recovery of about 96.8 per cent, and individual tubes on the pitot rake at the subsonic diffuser exit read this level of pressure. On this basis the minimum extra-to-shock losses are 3.7 per cent of the free stream total pressure. However, the measured Mach number represents an additional 1.9° of turning above the design figure. Thus the effective cowl deflection might be taken as 5° plus 1.9° plus some boundary layer growth on the cowl. This would give a detached shock at the cowl tip, and the Schlieren photographs show some curvature of the external cowl shock. However careful observation to check this point during the tests showed that the shock was definitely attached. So far as the authors can tell at present, the only method of reconciling the measured ramp Mach number with the attached cowl shock and the maximum pitot rake readings lies in the assumption of three-dimensional effects within the intake. It is suggested that the sidewall boundary layer growth causes spanwise mainstream flow deflections. The regions of influence of the resultant pressure fields spreads towards mid span as the flow approaches the intake throat. Thus whilst the local Mach numbers are reduced, the effective turning at the cowl tip is unchanged and so detachment does not occur. Moreover, because the local Mach numbers are reduced relative to the design values, the loss of total pressure through the cowl shock is also reduced. In the present tests the reduction of total pressure loss would amount locally to $1\frac{1}{2}$ per cent. The sensitivity of the terminal shock angle to small variations in the flow angle and local Mach number, both of which it has been pointed out are not known accurately, render the value of deductions based on the shock angle rather doubtful.

Difficulties arise in assessing the proportion of the flow at the throat likely to be influenced by spanwise pressure gradients. Here the obvious need is for throat traverses. In the meantime, because the exact level of the theoretical shock recovery is uncertain, and the difference between it and the measured pressure recovery is small, it is impossible to state the extra-to-shock losses with precision. However they are unlikely to differ appreciably from 3 per cent.

The preceding discussion raises the question of the value of the extra-to-shock losses as a parameter of intake performance. The authors feel that where the losses are, for example, about 10 per cent of the free stream total pressure, the parameter may serve as a yardstick of the state of development of the intake. The losses are so great that any lack of precision in stating the theoretical shock recovery is probably of no consequence. However, in more sophisticated intakes the magnitude of the uncertainties surrounding the precise level of the theoretical shock recovery may be very similar to the magnitude of the losses themselves. In such circumstances the extra-to-shock loss parameter needs interpreting with care.

A reduction of the extra-to-shock losses (whatever their precise value) might be achieved by introducing sidewall bleed, and also by raising the test Reynolds number. However, consideration of the tests with the combined external/internal compression intake does not encourage the view that the combined effect of these two parameters would raise the pressure recovery by more than about 1 per cent. Moreover, the engineering complication of sidewall bleed is such that it is preferably avoided. At the present time therefore the authors cannot see the possibility of reducing the extra-to-shock losses in the external compression intake operating at $M = 2.0$ to less than between 2 and 3 per cent of the free stream total pressure. There is scope for further work in attempting to retain this level of extra-to-shock loss whilst increasing the rate of turnover on the cowl.

Within the range of bleed flow from 1 to approximately 3 per cent Figure 4 shows that the rate of exchange of pressure recovery with bleed is quite high, an increase of $1\frac{1}{2}$ per cent in the bleed for example raises the pressure recovery by approximately 2 per cent. Even with only 1 per cent bleed, Figure 6(a) shows that the terminal shock remains perfectly "clean". This photograph was taken with the diffuser lowered to position C. Higher diffuser positions with only 1 per cent bleed caused the terminal shock to move forward from the cowl tip.

The conditions governing the formation of the strong solution shock at the cowl tip are of considerable interest. They are discussed in Reference 4, which describes some tests with external compression intakes at $M = 2.2$. The cowl tips of the $M = 2.2$ intakes produced shocks which initially, that is adjacent to the cowl surface, corresponded with the strong solution. Further towards the ramp however the shock gradually weakened to a solution leading to supersonic flow downstream of the shock. A weak normal shock in the patch of supersonic flow downstream of the cowl shock completed the transition to subsonic conditions. In Figures 5 and 6(a) the terminal shock corresponds with the strong solution across the full throat height. Figure 6(b) shows the cowl shock with the intake running supercritically. The position and shape of the visible portion of the cowl shock suggests, as indicated on the Figure, that the weak solution shock is initially formed at the cowl tip, but the subsequent cowl turning produces the equivalent of shock detachment. During the transition to critical operation the weak throat shock at the extreme right of the picture moves to the left and merges with the terminal shock.

On all the Schlieren photographs presented here it can just be seen that the external oblique shocks are slightly forward from their focal position at the cowl tip. The discrepancy from design is attributed to boundary layer growth. It has been calculated that as a result a spill of roughly 4 per cent of the capture flow occurs over the cowl tip.

Figure 4 shows the stable sub-critical margins obtained with the intake geometries just discussed. The degree of sub-critical stability is expressed as the maximum percentage reduction of the mass flow from its critical value prior to the onset of buzz. It is most apparent that whilst the geometry with the slight ram scoop effect in the bleed is the worst from the point of view of pressure recovery it is the only one from Figure 1 that has any margin of sub-critical stability. The experimental evidence, and that of subsequent tests[4], does not permit an exact determination of the aerodynamic mechanisms relating the diffuser tip position to the sub-critical margin.

The results suggest the possibility of a slightly changed initial rate of subsonic diffusion affecting the stable sub-critical margin. An alternative explanation may be that the additional contraction of the flow to the subsonic diffuser caused by the ram scoop bleed may lead to sonic conditions across a part of the flow at some point downstream of the cowl shock, and effectively insulate the supersonic compression system from buzz inducing influences.

It was also observed that with the diffuser in the position giving the slight ram scoop effect the onset of "buzz" was very gradual, so that the precise determination of the stable sub-critical limit was difficult, and to some extent arbitrary. The initial oscillations had an amplitude of only 1½ per cent of the free stream total pressure at a frequency of 35 c/s. Because of uncertainties concerning the smoothness of the tunnel flow as discussed in Reference 1 these Figures are offered with some reservation. However it is thought that the all external compression intake is less likely to be influenced by small perturbations in the tunnel flow than the self-starting mixed compression design.

With the diffuser in lower positions than that just considered the onset of buzz was much more clearly defined. The initial amplitude of the oscillations was now about 4 per cent of the free stream total pressure, again at a frequency of about 35 c/s.

The photographs shown in Figure 7 were taken during stable sub-critical operation with the diffuser tip in position B. In Figure 7(a) the terminal shock has just moved forwards from the cowl tip; Figure 7(b) was taken just short of the stable sub-critical limit.

Comparison with Figure 5(b) shows that as the terminal shock moves forwards it changes in form from the strong oblique solution to a normal shock, perpendicular to the ramp surface. A factor here presumably is the elimination of flow deflection at the terminal shock as the shock moves forward from the cowl tip. During the forward movement the pressure recovery rises by almost 0.5 per cent. As theoretically the shock recovery falls somewhat (because of the changed form of terminal shock), the rise is attributed to either an accompanying small increase in the bleed, equal to about 0.5 per cent of the capture flow, or perhaps a cleaner initial flow under the cowl tip. It is interesting that even in sub-critical positions the terminal shock retains the slight kink near the foot that was noted earlier (Figure 5(b)) as being introduced in critical operation by the diffuser tip in position B.

4.2 Tests with the geometry of Figure 3

Results are shown in Figure 8. The curve of pressure recovery against bleed for diffuser position 1 suggests a recovery of 92.4 per cent with 3.3 per cent bleed, as opposed to the recovery of 93 per cent measured with the same bleed with the geometry shown in Figure 1. However, whereas the latter geometry gave no stable sub-critical margin with recoveries of approximately 93 per cent, with the diffuser in position 1 the geometry of Figure 3 gave stable sub-critical margins of between 3 and $1\frac{1}{2}$ per cent.

The pressure recovery versus bleed flow characteristics plotted in Figure 8 do not show such marked variations with diffuser position as those plotted in Figure 4, and the rate of exchange of pressure recovery with bleed is very much less. However the stability regions plotted in Figure 8 exhibit very similar trends to those considered earlier. The diffuser position 2 imposing the maximum throat contraction produces the largest stable sub-critical margin, the maximum Figure being $3\frac{1}{2}$ per cent. As the throat contraction is progressively reduced through diffuser positions 1 and 3 so the stable sub-critical margin is decreased. With the exception of the stable sub-critical margins plotted in Figure 8 for diffuser position 2, all the stable sub-critical margins plotted in both Figures 4 and 8 indicate that for a given diffuser position the sub-critical stability deteriorates as the bleed is increased. Such a result would be expected on the argument that throat contraction improves the stability. The effective contraction can be varied either by moving the diffuser position, the bleed remaining constant, or by changing the bleed, the diffuser position remaining fixed.

The amplitude and frequency of the oscillations measured at the onset of buzz were very similar to those measured with the geometry of Figure 1. In no case did the amplitude exceed about $3\frac{1}{2}$ per cent in pressure recovery, whilst the frequency was roughly 35 c/s.

The throat shock structures are again of considerable interest. Figure 9 shows two Schlieren photographs of the throat flow with the diffuser in position 3. The intake was running critically in both cases, in Figure 9(a) with 2 per cent bleed (the minimum possible without the cowl shock moving forward from the tip), and in Figure 9(b) with 2.8 per cent bleed. With the smaller bleed the cowl shock was of a form identical with that noted in the earlier tests and it was possible to position the foot of the shock in the opening to the bleed slot. However a short distance downstream of the cowl shock will be observed a faint normal shock, emanating from the opening to the bleed and disappearing altogether after traversing a little over one third of the throat height. As the flow behind the strong solution shock from the cowl is presumably subsonic, perhaps the turning at entry to the subsonic diffuser induces a local re-expansion and thus a patch of supersonic flow. It is possible that such a throat flow pattern may have existed in the tests discussed in the preceding Section, but with the faint normal shock located further downstream and thus out of the field of view. With an increased bleed Figure 9(b) shows that the form of cowl shock is changed. Near the cowl tip the shock corresponds with the theoretical strong solution. Further towards the ramp the shock gradually weakens, and runs towards the foot of a normal shock which is now rather stronger than in Figure 9(a), but unchanged in position. The flow pattern shown in Figure 9(b) is very similar to that described in Section 4.1 where reference is made to some tests with external compression intakes at M = 2.2. Reference 4 considered with the present work shows that the form of cowl shock is dependent on the internal cowl contour, the contour of the diffuser downstream of the bleed slot, and the quantity of bleed, all of which presumably influence the pressure downstream of the shock. The pressure recovery of the intake when operating with the more complex throat flow pattern shown in Figure 9(b) was 92.3 per cent. The bleed flow was 2.8 per cent. Comparison of these Figures with those obtained with the intake geometry of Figure 1 suggests that at least from the point of view of the pressure recovery so far measured for a given bleed there is little penalty entailed in departing from the uniform strong solution shock covering the full throat height. The influence, if any, of the terminal shock structure on the stable sub-critical margin is at present uncertain.

4.3 Total pressure distributions at the subsonic diffuser exit

Diffuser exit distributions are presented in Figure 10. For the reasons discussed in Reference 1 total pressure distributions have been preferred here as a method of indicating the degree of uniformity of the flow, although values of $\frac{P_{tot,max} - P_{tot,mean}}{P_{tot,mean}}$ and V_{max}/V_{mean} are also given on the Figures. V_{mean} was calculated on the basis of the mean diffuser exit Mach number, itself based on the mean pitot rake reading and the local static pressure. V_{max} was calculated from the maximum reading on the rake.

The distributions shown in Figure 10(a) were obtained with the intake geometry of Figure 1. The fact that movement of the diffuser tip from position A to position B causes the total pressure to fall most on the ramp side of the diffuser strengthens the view expressed earlier that the fall of pressure recovery accompanying the raising of the diffuser to position B is associated with disturbances at the diffuser tip. Nearer the opposite wall of the diffuser the effect is very small.

The distributions shown in Figure 10(b) were obtained with the intake geometry of Figure 3. As would be expected, the effect of increasing the bleed flow is reflected in a change in total pressure in a region on the ramp side of the diffuser. Comparison of Figures 10(a) and 10(b) shows that the differences between the intake geometries of Figures 1 and 3 do not produce any marked effect on the diffuser exit distribution.

The distributions shown in Figure 10(c) were also obtained with the intake geometry of Figure 3. The two sets of curves show the effect of increasing the bleed whilst simultaneously the cowl shock changed from the strong solution across the full throat height, as in Figure 9(a), to the curved form shown in Figure 9(b). The trend indicated by the curves is what would be expected from the change of bleed (as shown for example in Figure 10(b)). Hence, provisionally at least, it may be concluded that the strong solution shock across the full throat does not necessarily lead to more uniform diffuser exit distributions than more complex throat flows. It might be that the asymmetry of the subsonic diffuser in the present model (and in some full scale installations) could render unattractive the attainment of completely uniform conditions at the throat. The additional shock introduced by passing the flow through the weak solution and then a normal shock, instead of directly through the strong solution can theoretically raise the local total pressure by about 2 per cent.

There seems little to choose between the distributions shown in Figure 10 and those obtained earlier with a mixed compression intake. Admittedly the best mixed compression distributions presented in Reference 1 were obtained with the addition of sidewall bleed. On the other hand they were obtained at a free stream Mach number of 2.2 as opposed to the Mach number of 2.0 used in the present tests. It seems fair to conclude, as in Reference 1, that possible methods of improving the diffuser exit distributions should be actively examined.

5.0 A comparison with other work

A comparison of the present work with some reported elsewhere is made in Figure 11. With $21\frac{1}{2}^{\circ}$ of ramp turning as opposed to the 19° used in the present tests, and for a given bleed, the pressure recoveries reported by Vargo et al[3] exceed those reported in the present work by about 2 per cent. About a quarter of the discrepancy can be accounted for by the somewhat higher theoretical shock recovery in Reference 3 arising from the additional $2\frac{1}{2}^{\circ}$ of ramp turning. However it should be noted that although the cowl geometry is not given in Reference 3 the terminal supersonic Mach number would be so low (1.22 assuming inviscid flow) as to preclude all but 1° or 2° of flow deflection at the cowl tip. Thus the internal cowl angle relative to the free stream would be approximately 6° higher than the figure of 14° used in the present tests, so that the cowl drag would be appreciably higher. The remaining discrepancy between the pressure recoveries, of about $1\frac{1}{2}$ per cent, may derive from the very weak terminal shock effecting a reduction in the extra-to-shock losses. After allowance for boundary layer effects the terminal supersonic Mach number in Reference 3 was probably about 1.1, so that it seems reasonable to regard the ramp turning as being the maximum attainable at the test Mach number. Thus the geometry represents one extreme of the range of compromises possible between theoretical shock recovery and cowl angle. In summary, therefore, the effect of moving to the extreme compared with the present work, is that the pressure recovery with 4 per cent bleed was increased at the most by 2 per cent, from 93 per cent to 95 per cent, at the expense of increasing the internal cowl angle from 14° to a deduced figure of about 20°. It may also be noted that the initial discrepancy between the pressure recoveries can be considerably reduced if the values given in Reference 3 are plotted on a basis of changes in the mass flow ratio at the subsonic diffuser exit instead of changes in the bleed; there appear to be discrepancies between these two quantities.

At O.N.E.R.A.[2], Leynaert and Brasseur quote a maximum pressure recovery at $M = 2.0$ of 93.5 per cent with 2.5 per cent bleed. These figures compare with the pressure recovery of 93 per cent with 3.3 per cent bleed obtained with a similar ramp turning and internal cowl angle in the present tests. Reasons for the difference are not obvious. There are slight differences between the throat geometry employed in Reference 2 and that shown in Figures 1 and 3. In particular the rate of turn on the cowl in Reference 2 was slightly more rapid than in the present work. However it is not easy to see the possibility of improving the throat flow pattern shown, for example, in Figure 5(a). The capture plane aspect ratio of the model tested at O.N.E.R.A. was 2.0 and thus considerably exceeded the figure of 1.4 employed at N.G.T.E. The latter figure, as mentioned earlier, corresponds fairly closely with the aspect ratios currently proposed for supersonic transport installations. Uncertainty surrounds the effect of aspect ratio on intake performance. The present work suggests the presence of three-dimensional flows, but at the present time it is difficult to compare their effects in models of different aspect ratio.

6.0 Conclusions

A two-dimensional all external compression intake has given a pressure recovery of 93 per cent for 3.3 per cent bleed when tested at its design Mach number of 2.0 at zero incidence and at a Reynolds number of approximately 1×10^6.

The introduction of some contraction into the flow to the subsonic diffuser, immediately downstream of the bleed slot, appears to provide a margin of sub-critical stability. However, a contraction introducing a ram scoop effect at the bleed slot reduced the pressure recovery by approximately 2 per cent. More gradual contractions, while producing the favourable effect on the sub-critical stability, only reduced the pressure recovery by about $\frac{1}{2}$ per cent.

It is considered that possible methods of improving the distributions at the exit from the subsonic diffuser should be examined, while the adequacy of the buzz margins obtained experimentally also requires investigation. Much interest in future work will attach to determining the maximum possible rate of turn on the cowl. However, the performance of the intake at incidence requires investigation, and in addition tests are required with a subsonic diffuser of a length more representative of full scale installations.

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APPENDIX I

Some design considerations

The two-dimensional external compression intake conventionally comprises a ramp generating a system of oblique shocks which terminate in a normal shock formed at the cowl tip. The internal angle of the cowl relative to the free stream is then equal to the total turning on the ramp; in other words, the flow deflection at the cowl tip is zero. Such intakes become attractive above free stream Mach numbers of about 1.5, when the total pressure loss through the normal shock of a simple pitot intake becomes appreciable. At higher Mach numbers, between about 2.2 and 2.5, the design of the external compression intake becomes more difficult. In particular the cowl drag rises rapidly, because the cowl angle has to be increased to match the progressively larger amounts of ramp turning that are required to ensure a high theoretical shock recovery. Hence the use of some internal compression has been widely advocated for supersonic intakes operating at free stream Mach numbers of about 2.2 and above.

The introduction of internal compression can be deferred to a higher Mach number than might be indicated by the argument outlined above by the introduction of flow deflection at the cowl tip. Such intakes have been extensively tested, for example, at O.N.E.R.A.[2], where high levels of performance have been attained. As Figure 12 shows, the geometry as far downstream as the cowl tip can be unchanged from the configuration discussed initially. Downstream of the cowl tip however, the introduction of flow deflection reduces the cowl angle relative to the free stream, and hence the cowl drag. Because the transition to subsonic flow now occurs in the presence of flow deflection the terminal shock is oblique, rather than normal as in the conventional arrangement. The terminal shock drawn in Figure 12(b) is in fact the stronger of the two solutions that are theoretically possible when flow at a given Mach number is deflected. The strong solution leads to subsonic flow, whereas the weak solution leads to supersonic flow.

A further consequence of the introduction of flow deflection at the cowl tip is that the theoretical shock recovery based on the strong solution shock is slightly raised above the figure assuming transition to subsonic flow through a normal shock. The improvement in shock recovery increases with the amount of flow deflection. The latter is limited by shock detachment at the internal surface of the cowl, so that the maximum possible flow deflection whilst avoiding shock detachment increases with the Mach number upstream of the cowl shock. For practical intake designs operating at flight speeds of about $M = 2$ the Mach number upstream of the cowl shock is unlikely to significantly exceed 1.5. The detachment angle at the cowl is then approximately 12° so that a practical maximum deflection of 10° may be considered as an initial step. The total pressure loss across the strong solution shock is then 5.7 per cent compared with a loss of 7 per cent through a normal shock at the same Mach number. (Were it possible to increase the deflection angle to that at which detachment occurs the loss of total pressure would be half that given by a normal shock.) The difference between the efficiencies of the normal and strong solution oblique shocks decreases rapidly as the Mach number upstream of the shock decreases. Thus, for a practicable deflection at the cowl tip, the difference between the two figures is only 0.2 per cent at $M = 1.3$.

It is thought that M = 1.5 is a likely terminal supersonic Mach number for an external compression intake operating at a flight speed of M = 2.2, and that at M = 2.0 the terminal supersonic Mach number is likely to be in the region of 1.3.

As it is at Mach numbers of about 2.0 to 2.2 that, even with flow deflection at the cowl, the cowl angles of the external compression intake start to become considerable, e.g., 15° and more, it is of interest to compare the potential performances of the external and mixed compression intakes within this range of flight Mach number.

A comparison can be made on the basis of the theoretical shock recovery. However it is more profitable to include some assessment of the extra-to-shock losses, and here Figure 13 suggests that there are some important differences between the two types of intake. It will be seen that for a given amount of supersonic compression the supersonic wetted area is appreciably greater with the mixed compression intake than with the external compression design. Moreover, the sidewall secondary flow pattern on the mixed compression intake tends to deflect low energy air from the sidewalls into the subsonic diffuser, whereas with the external compression intake the shock pattern is such that the low energy air tends to be swept over the cowl tip. These factors have to be weighed against the additional throat turning necessary in the external compression intake. Intuitively however, it might be expected that the overall extra-to-shock losses in the external compression intake would be less than those occurring in the mixed compression design - at least at the present level of Mach number where the shoulder turning is small.

At M = 2.0, 19° of turning suffice to decelerate the flow to approximately M = 1.38. A 5° cowl deflection, giving an internal cowl angle of 14°, then leads to an overall shock recovery for the external compression intake, based on the strong solution cowl shock, of 95.3 per cent. A combined external/internal compression intake can readily be designed with a much lower cowl angle to give a higher theoretical shock recovery. However the nett pressure recovery will probably be about the same because of the higher extra-to-shock losses attributed in the previous paragraph to the mixed compression design.

At M = 2.2 the theoretical differences between the two types of intake are widened. In order to design for a terminal supersonic Mach number of about 1.38 (which is necessary for a theoretical shock recovery of 95 per cent) 25° of turning are necessary. Cowl angles on the external compression intake now become extremely high, and the avoidance of shock detachment a real problem. A better compromise between the internal performance and external drag would be achieved with a smaller amount of ramp turning. With only 20° of turning for example, a deflection of 5° at the cowl tip - which seems readily obtainable in practice - allows an internal cowl angle of 15°. The corresponding theoretical shock recovery would be about 92 per cent. The combined external/internal compression intake operating at the same free stream Mach number can be designed to give a theoretical shock recovery of up to 97 per cent, and with extra-to-shock losses of the level reported in Reference 1 measured pressure recoveries of 92 per cent could seem possible. Thus at M = 2.2 there is apparently the possibility that the mixed compression intake will give a higher pressure recovery than the external compression design, with of course the additional advantage of a lower cowl angle.

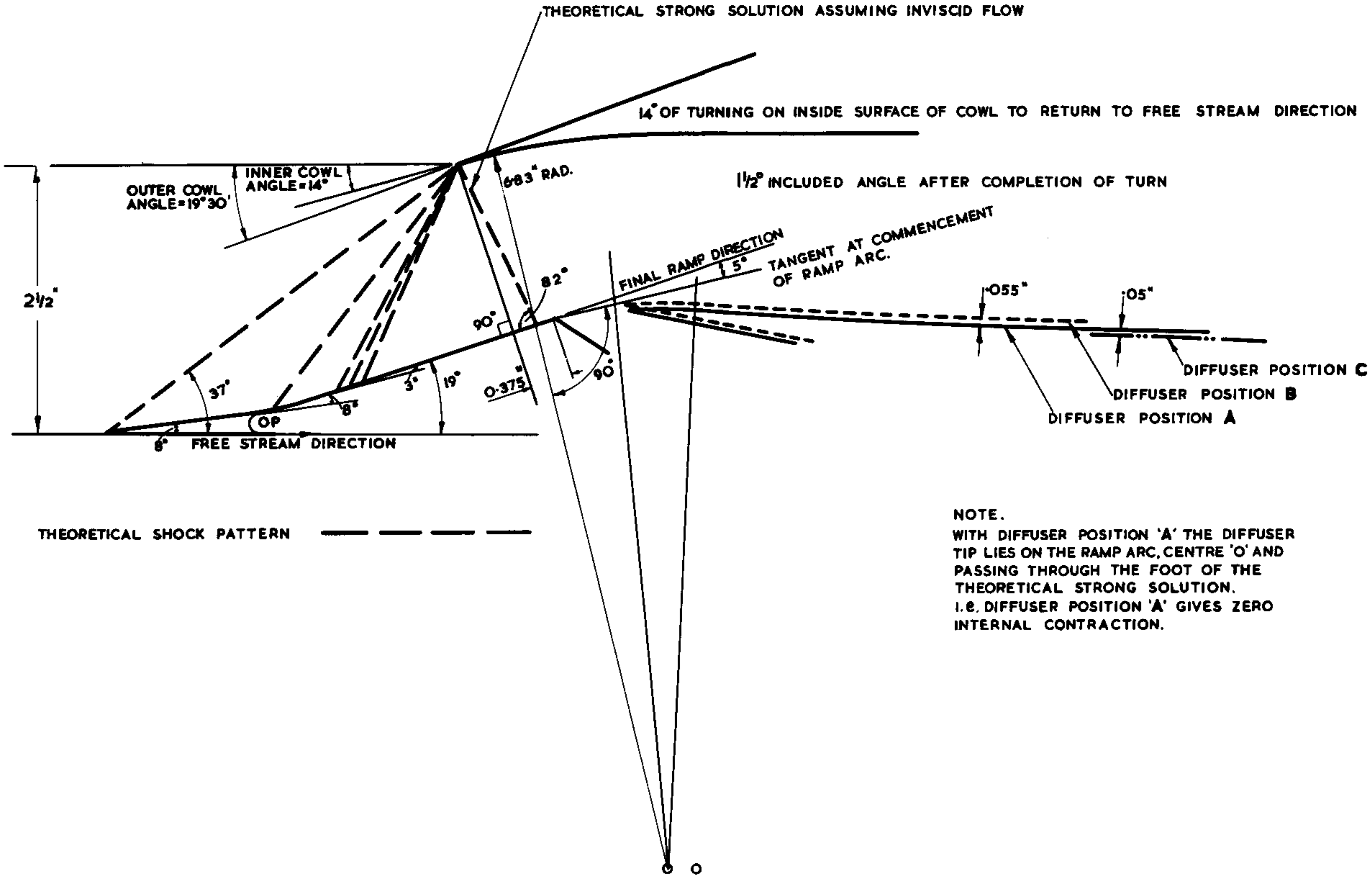
Further factors complicate the comparison. Although the external compression intake necessitates a high initial cowl angle, the flow underneath the cowl is subsonic and so it is possible to commence turning the cowl towards the free stream direction earlier than with the mixed compression intake. Moreover, there is very limited value in considering the cowl contours in isolation from the whole power plant installation when comparing the lip drags of the mixed compression and all external compression designs. The particular installation in mind for the intakes discussed here is the Anglo-French supersonic transport aircraft, on which the interference effects between the power plant nacelle and under surface of the wing cannot be ignored. In addition, on the installation currently proposed, some outward inclination of the cowl is necessary in order to accommodate the engine.

A quite different question is that of control. It is well known that intakes featuring internal compression pose a special difficulty here, and at the present time it seems that in normal operation the mixed compression intake operating at $M = 2.2$ might have to run supercritically in order to provide a margin against shock expulsion.

Less frequently emphasised perhaps, but discussed in Reference 4, is a corresponding control penalty associated with the external compression intake. It has been widely found that in order to provide some margin against buzz during critical operation it is necessary to position the shocks generated by the ramp upstream of the cowl tip. Air is thus spilled over the cowl upstream of the terminal shock. How much spill would be necessary on a practical installation is at present uncertain.

Possible differences of performance at incidence and off design Mach numbers must also be borne in mind when comparing the two types of intake, and in these particular fields there is at present a dearth of experimental data.

FIG. I.



NOTE.
WITH DIFFUSER POSITION 'A' THE DIFFUSER TIP LIES ON THE RAMP ARC, CENTRE 'O' AND PASSING THROUGH THE FOOT OF THE THEORETICAL STRONG SOLUTION.
I.E. DIFFUSER POSITION 'A' GIVES ZERO INTERNAL CONTRACTION.

AERODYNAMIC DESIGN OF INTAKE MODEL
M=2·O EXTERNAL COMPRESSION INTAKE
(SCALE - FULL SIZE)

THE SUBSONIC DIFFUSER

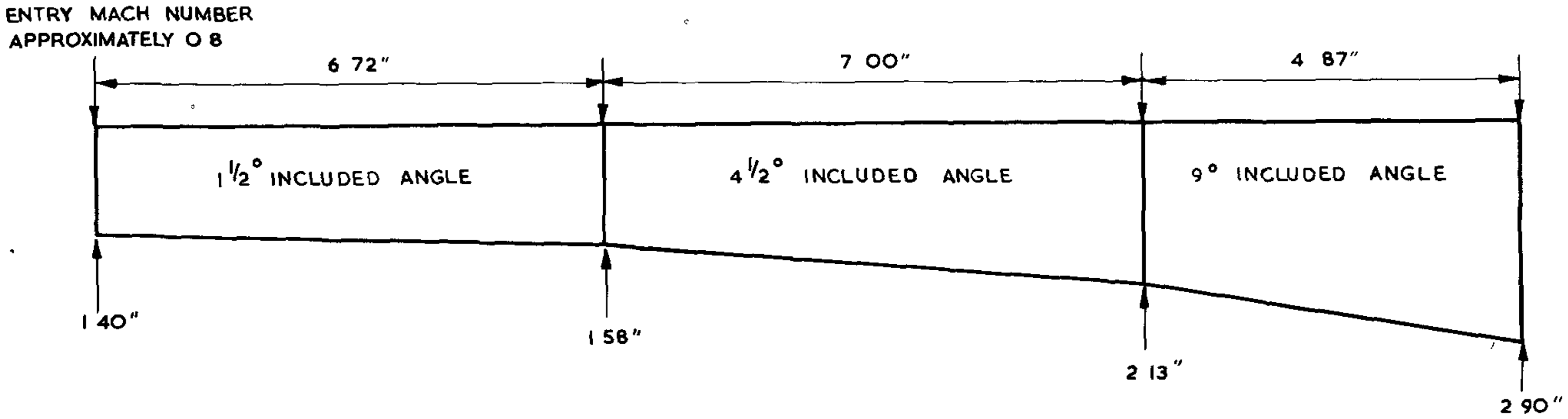
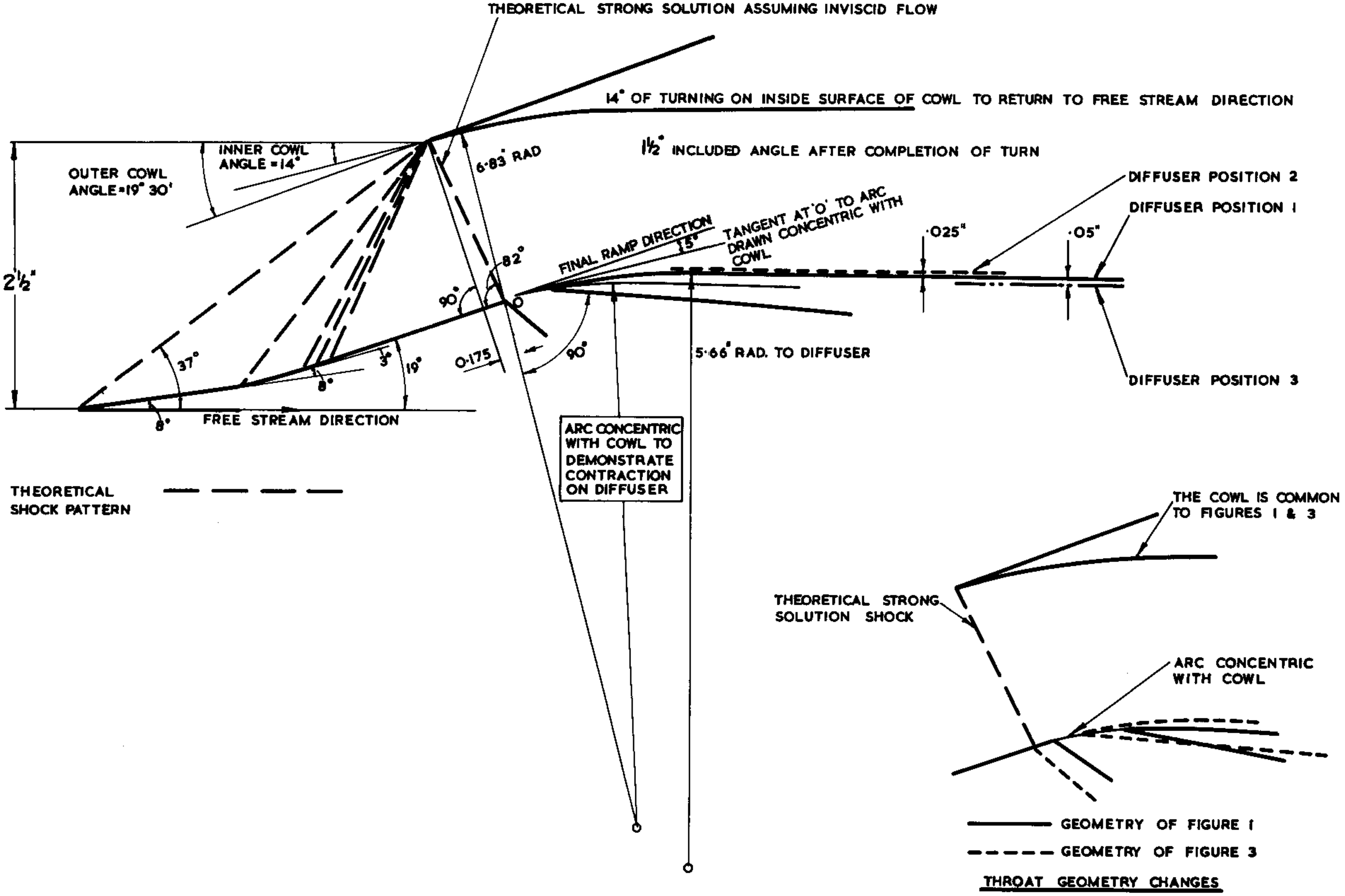


FIG. 2.

FIG. 3

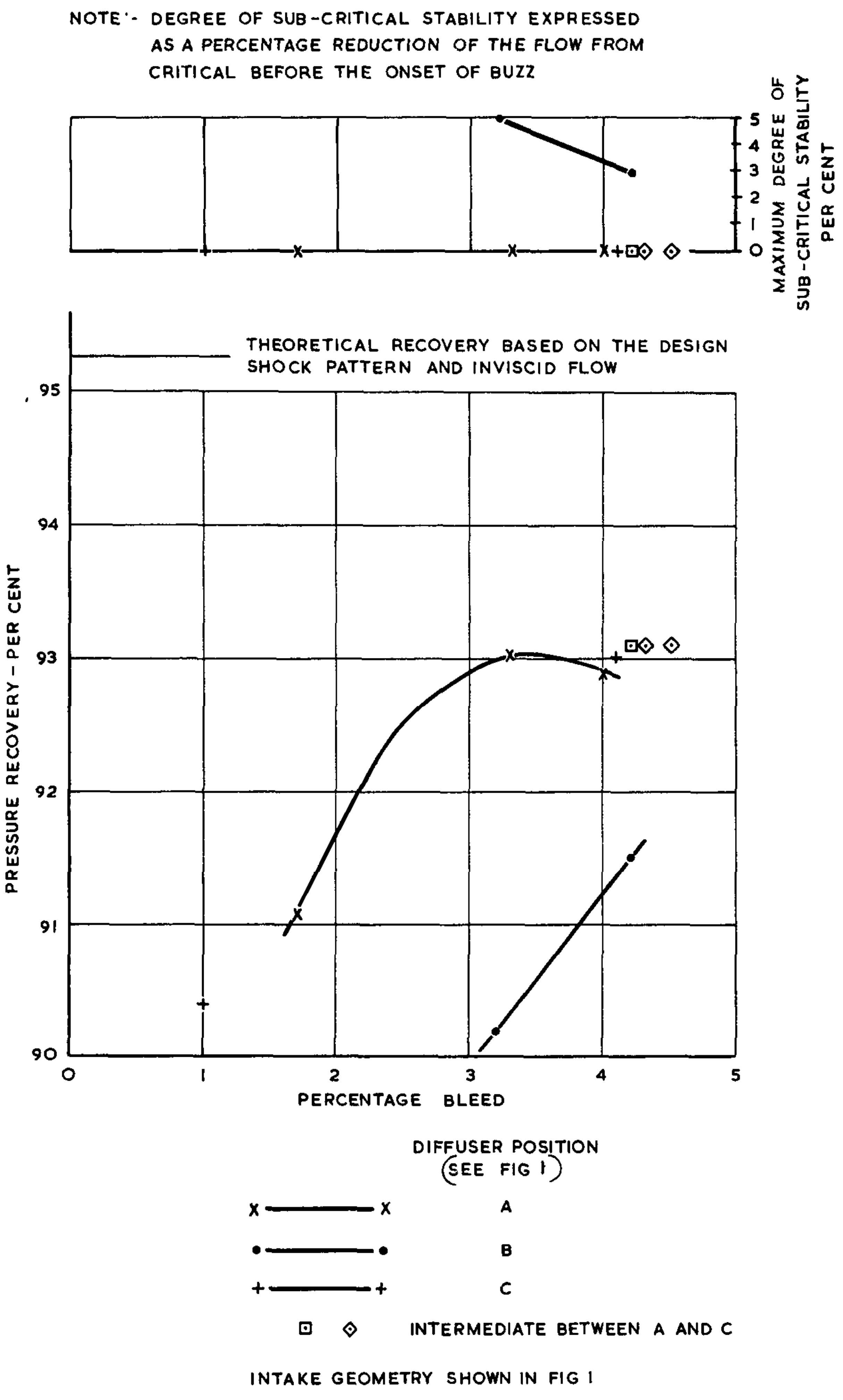


AERODYNAMIC DESIGN OF INTAKE MODEL WITH INCREASED INTERNAL CONTRACTION.

M=2·0 EXTERNAL COMPRESSION INTAKE

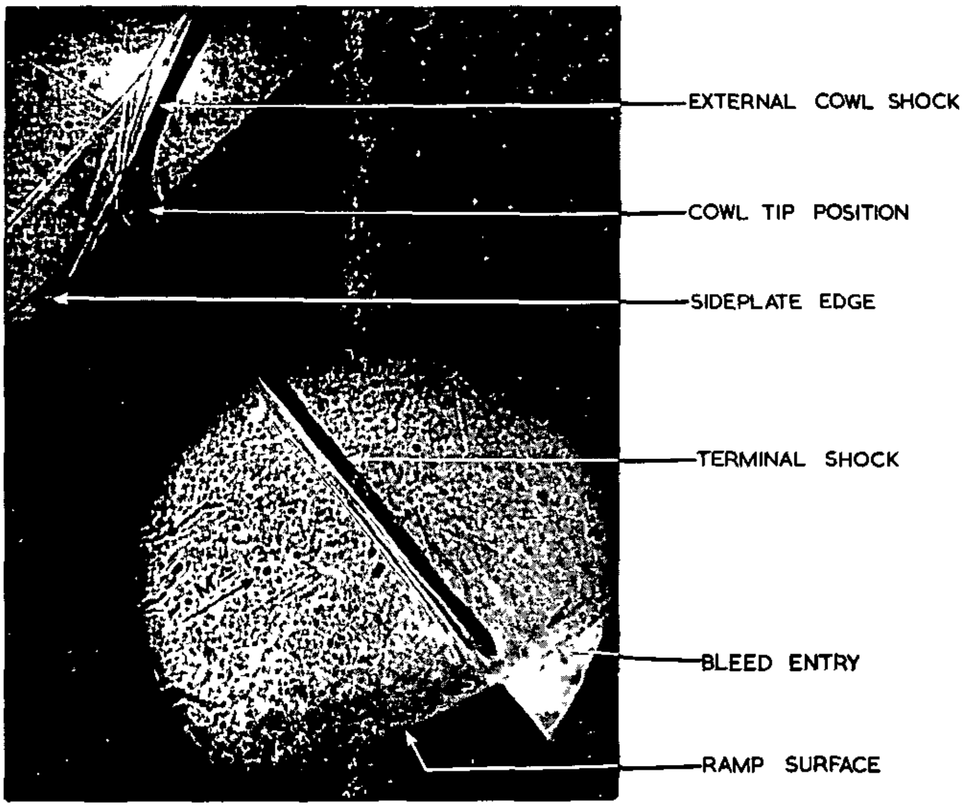
(SCALE - FULL SIZE)

FIG. 4.

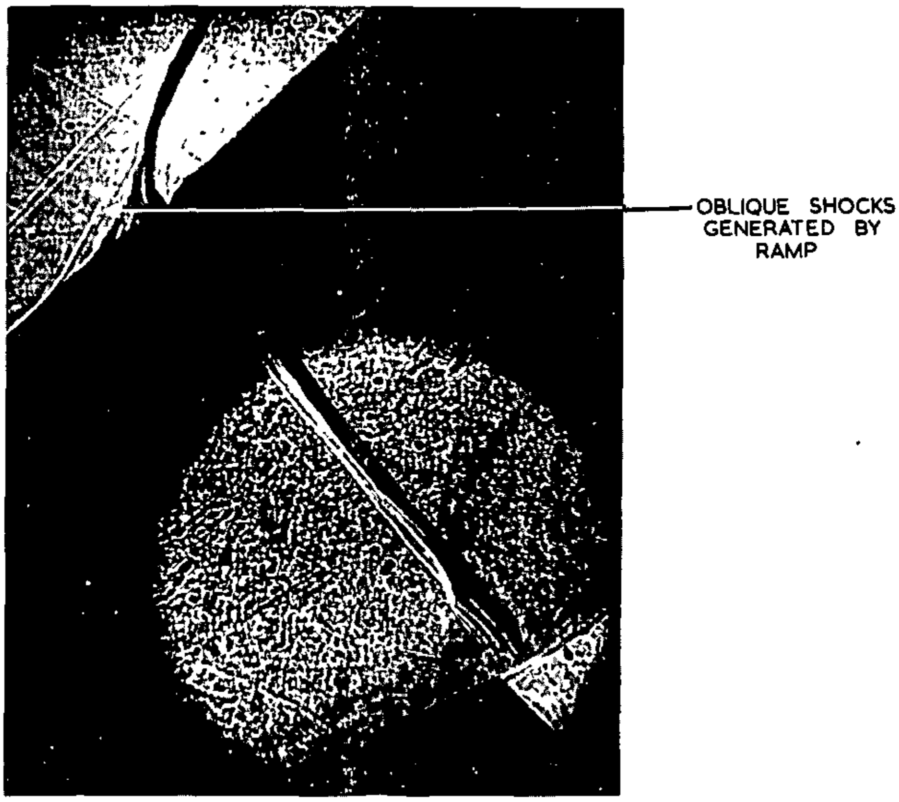


INTAKE PRESSURE RECOVERIES AND STABILITY REGIONS

FIG. 5



(a) DIFFUSER POSITION A η = 92 9 PERCENT BLEED = 4 PERCENT.

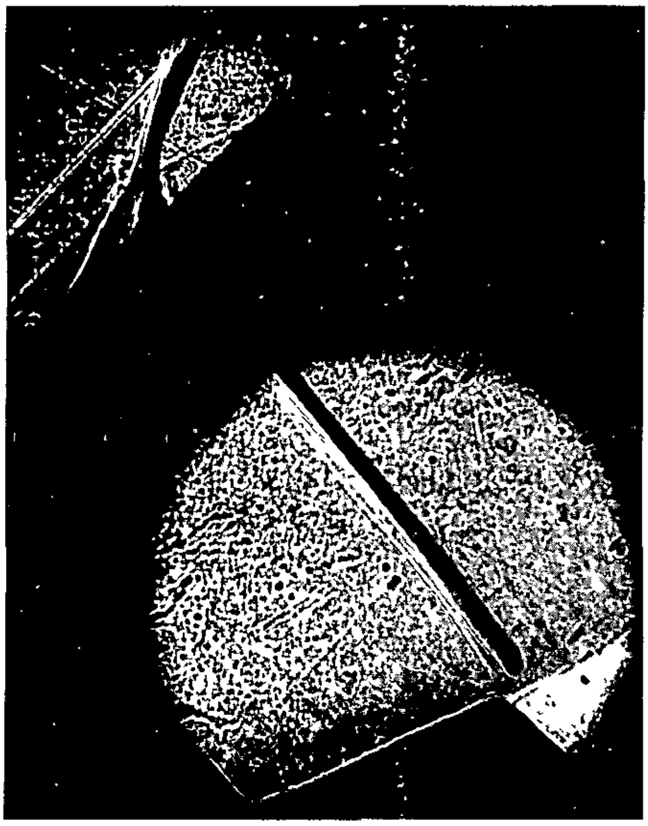


(b) DIFFUSER POSITION B η = 91 5 PERCENT BLEED 4 2 PERCENT

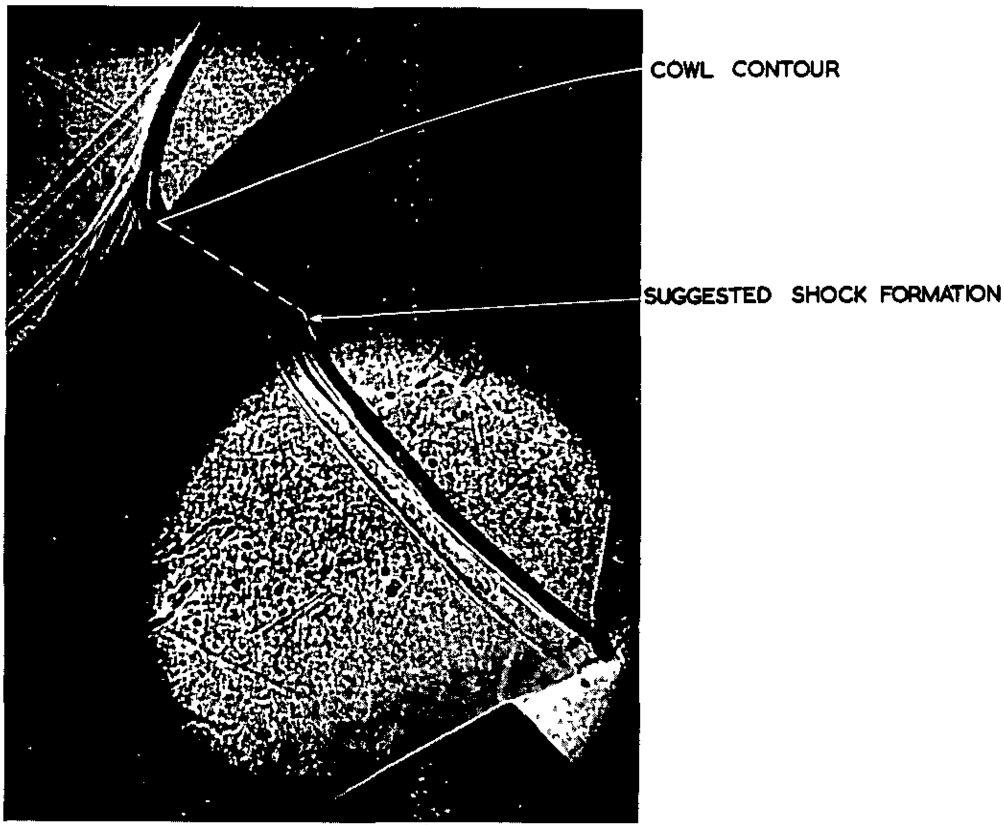
INTAKE CRITICAL GEOMETRY OF FIGURE 1

SCHLIEREN PHOTOGRAPHS OF THE THROAT FLOW PATTERN

FIG. 6



(a) DIFFUSER POSITION C INTAKE CRITICAL η=90·4 PERCENT. BLEED=1 PERCENT

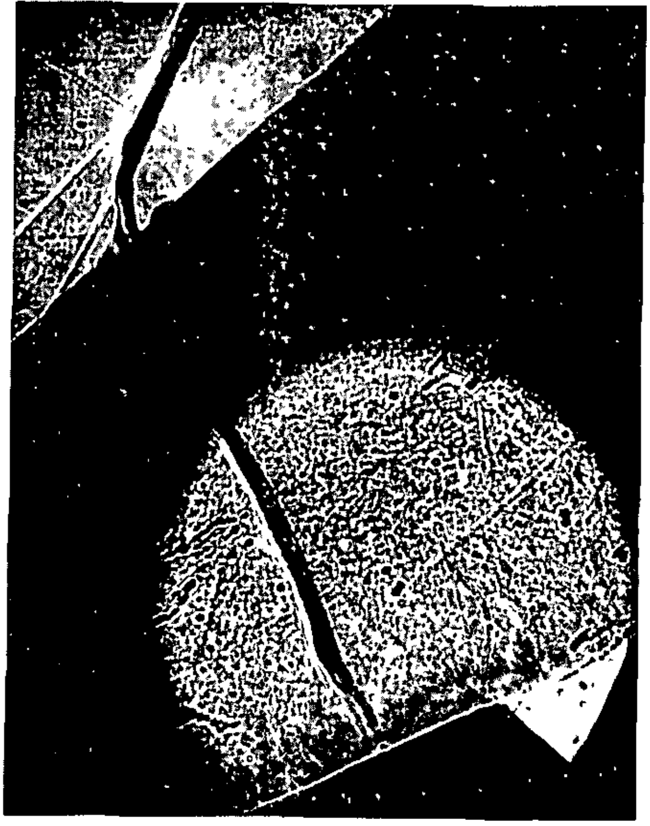


(b) DIFFUSER POSITION INTERMEDIATE BETWEEN A AND C INTAKE SUPERCRITICAL

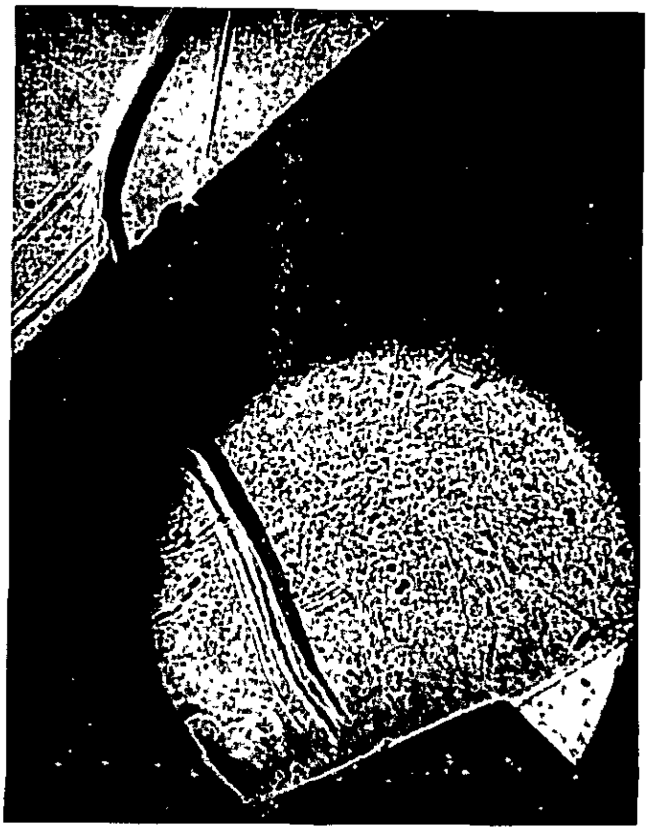
GEOMETRY OF FIGURE 1

SCHLIEREN PHOTOGRAPHS OF THE THROAT FLOW PATTERN.

FIG. 7



(a) CRITICAL MASS FLOW REDUCED BY 1 PERCENT.

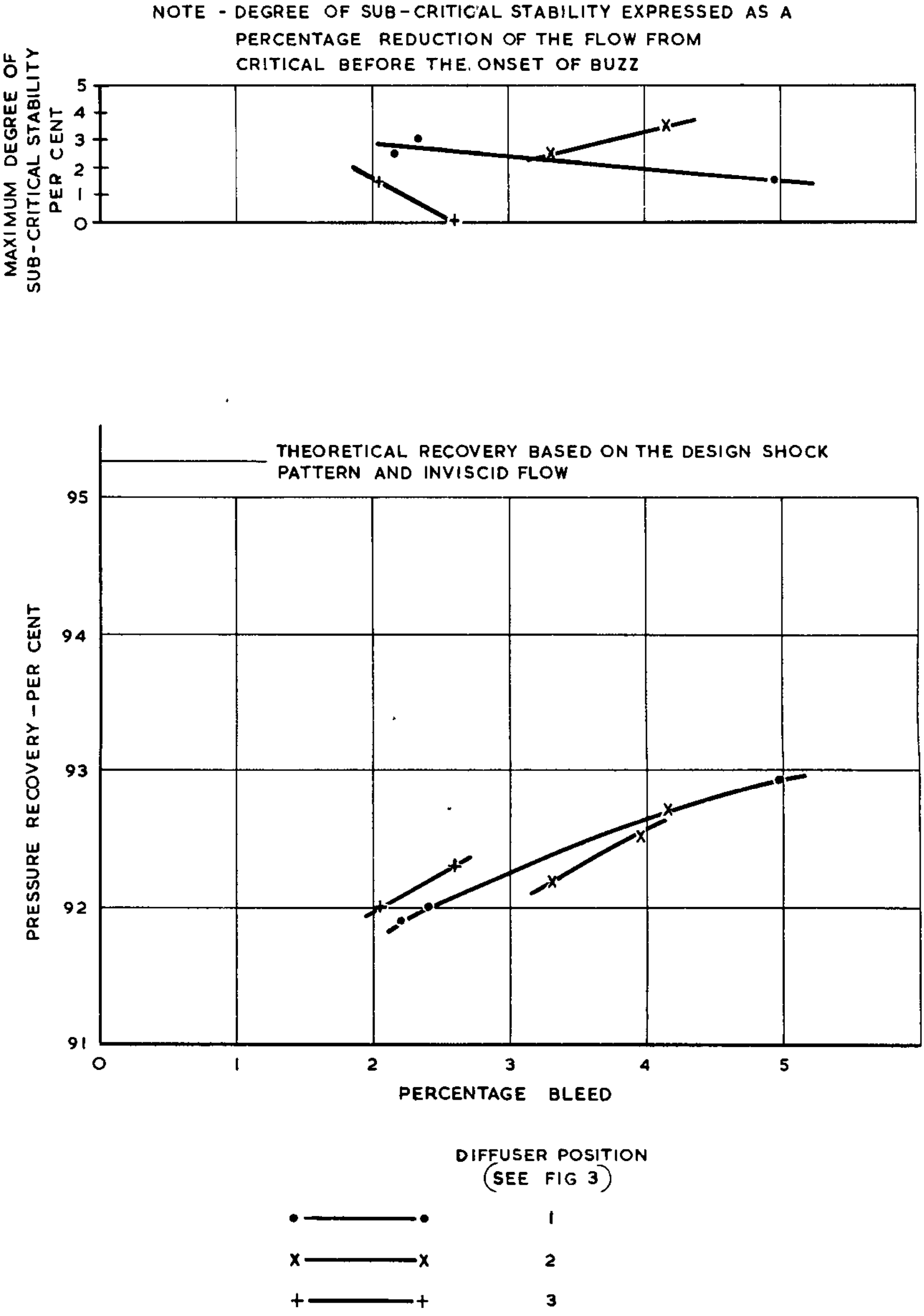


(b) CRITICAL MASS FLOW REDUCED BY 3.5 PERCENT

DIFFUSER POSITION B GEOMETRY OF FIGURE 1

SCHLIEREN PHOTOGRAPHS OF THE THROAT FLOW PATTERN DURING STABLE SUB-CRITICAL OPERATION

FIG. 8.



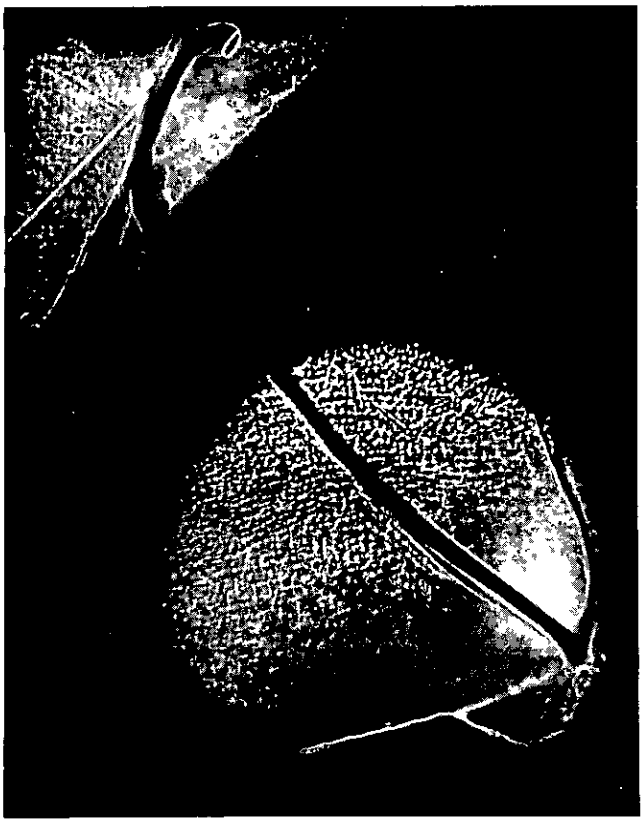
NOTE - DEGREE OF SUB-CRITICAL STABILITY EXPRESSED AS A PERCENTAGE REDUCTION OF THE FLOW FROM CRITICAL BEFORE THE ONSET OF BUZZ

INTAKE GEOMETRY SHOWN IN FIG 3

INTAKE PRESSURE RECOVERIES AND STABILITY REGIONS

FIG. 9

(a) η = 92 PERCENT BLEED = 2 PERCENT

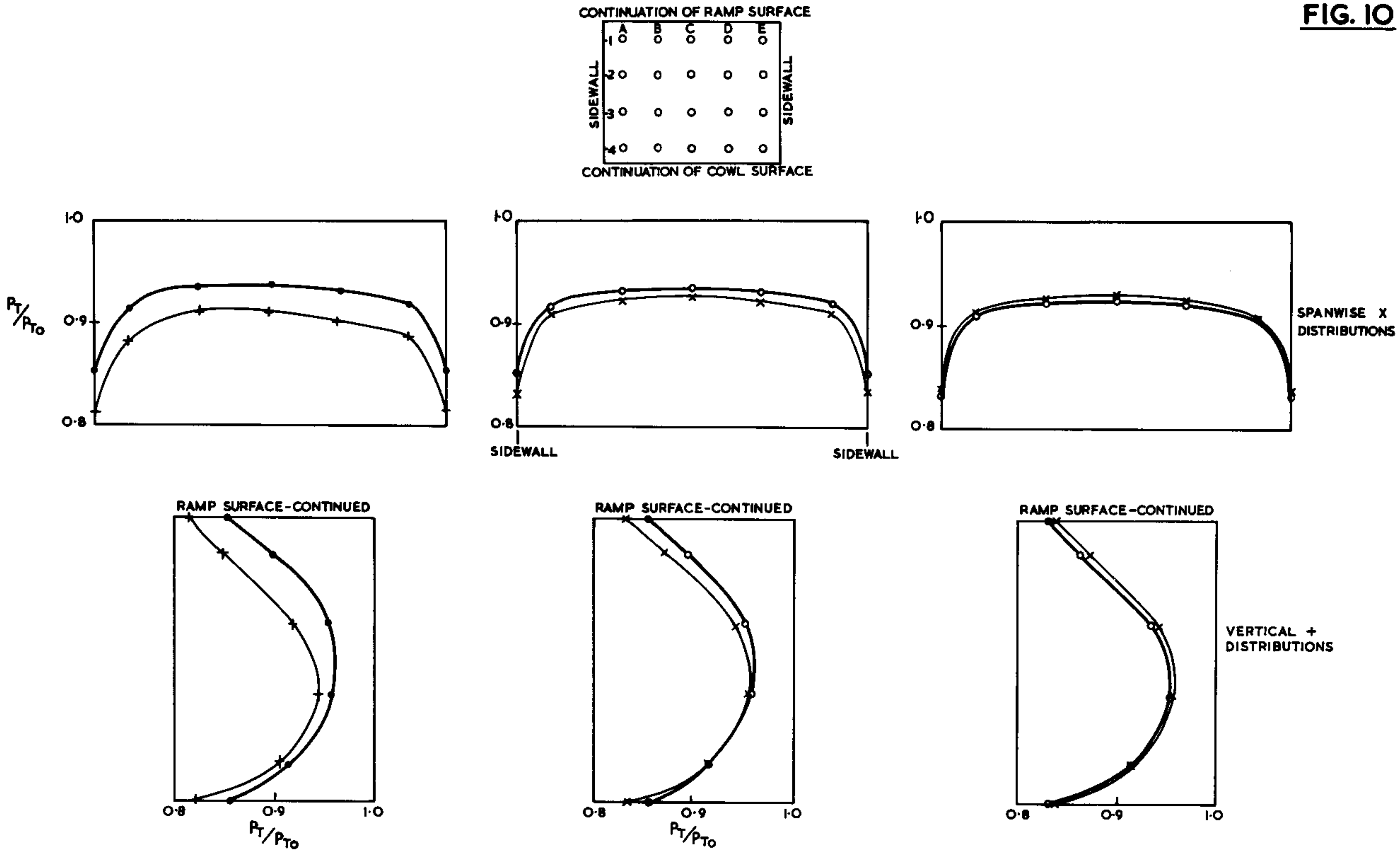


(b) η = 92·3 PERCENT BLEED = 2 8 PERCENT

INTAKE CRITICAL DIFFUSER POSITION 3 GEOMETRY OF FIGURE 3

SCHLIEREN PHOTOGRAPHS OF THE THROAT FLOW PATTERN

FIG. 10



	DIFF. POSN.	η%	BLEED %	VMAX/VMEAN	D*
●—●	A	93	3·3	1·21	3·9
+—+	B	90·2	3·2	1·20	6·3

(a) EFFECT OF DIFFUSER POSN.

(BLEED CONSTANT)
GEOMETRY OF FIG. 1.

	η%	BLEED %	VMAX/VMEAN	D*
o—o	92·9	4·96	1·19	4·1
x—x	92	2·4	1·24	5·1

(b) EFFECT OF BLEED

(DIFF. TIP POSITION CONSTANT)
GEOMETRY OF FIG. 3.

	COWL SHOCK	η%	BLEED %	VMAX/VMEAN	D*
o—o	STRAIGHT	92	2	1·24	5·1
x—x	CURVED	92·3	2·8	1·24	5

(c) EFFECT OF CHANGES OF COWL SHOCK AND BLEED

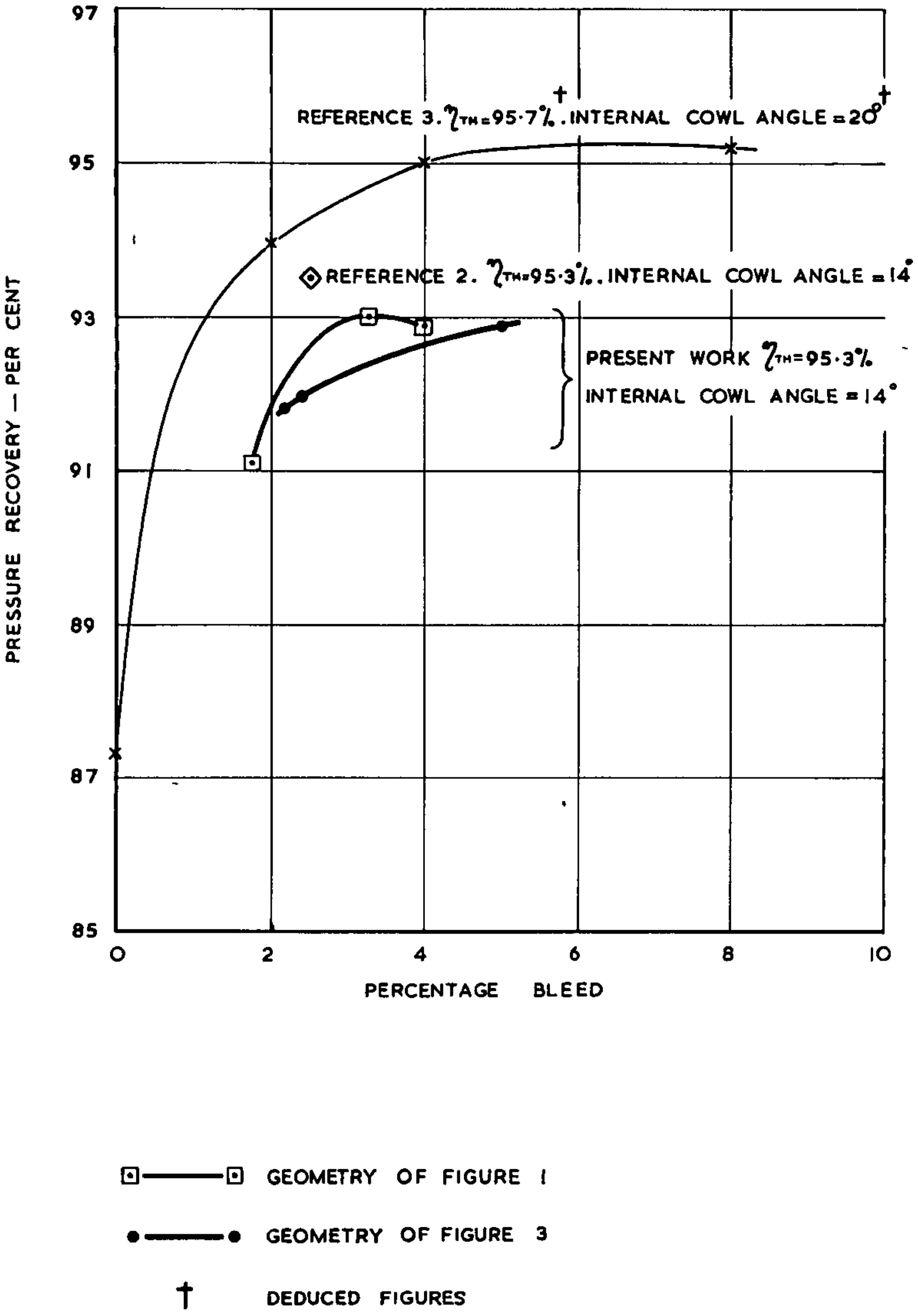
(DIFF. TIP POSITION 3.)
GEOMETRY OF FIG. 3.

X SPANWISE DISTRIBUTIONS ARE THE MEAN VALUES OF COLUMNS A, B, C, D.
+ VERTICAL DISTRIBUTIONS ARE THE MEAN VALUES OF ROWS 1, 2, 3, 4.

$$D^* = \frac{P_{TOT_{MAX}} - P_{TOT_{MEAN}}}{P_{TOT_{MEAN}}} \%$$

TOTAL PRESSURE DISTRIBUTIONS AT THE EXIT FROM THE SUBSONIC DIFFUSER.

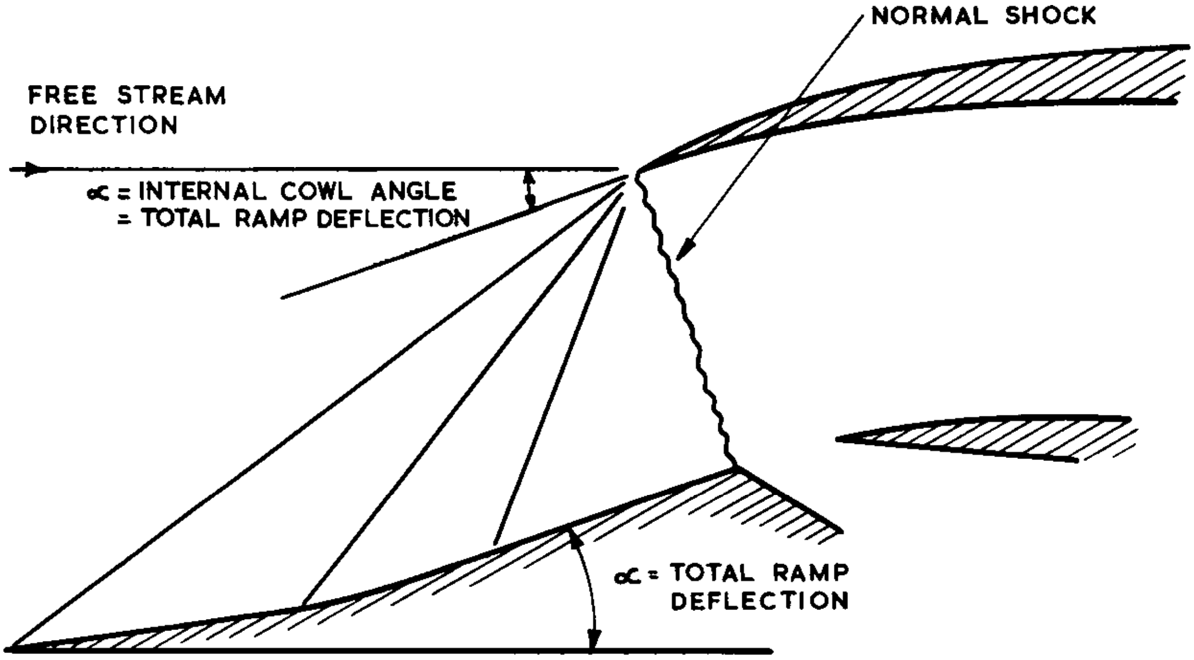
FIG. 11



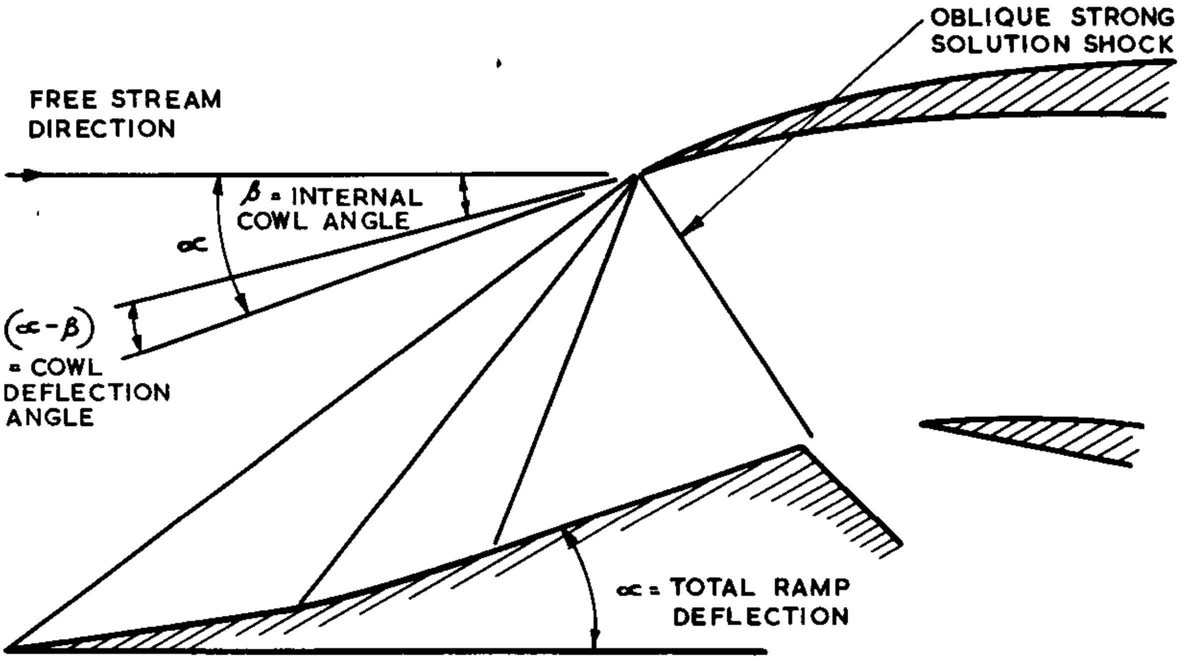
A COMPARISON WITH OTHER WORK.

(FREE STREAM MACH NUMBER = 2·0)

FIG. 12.



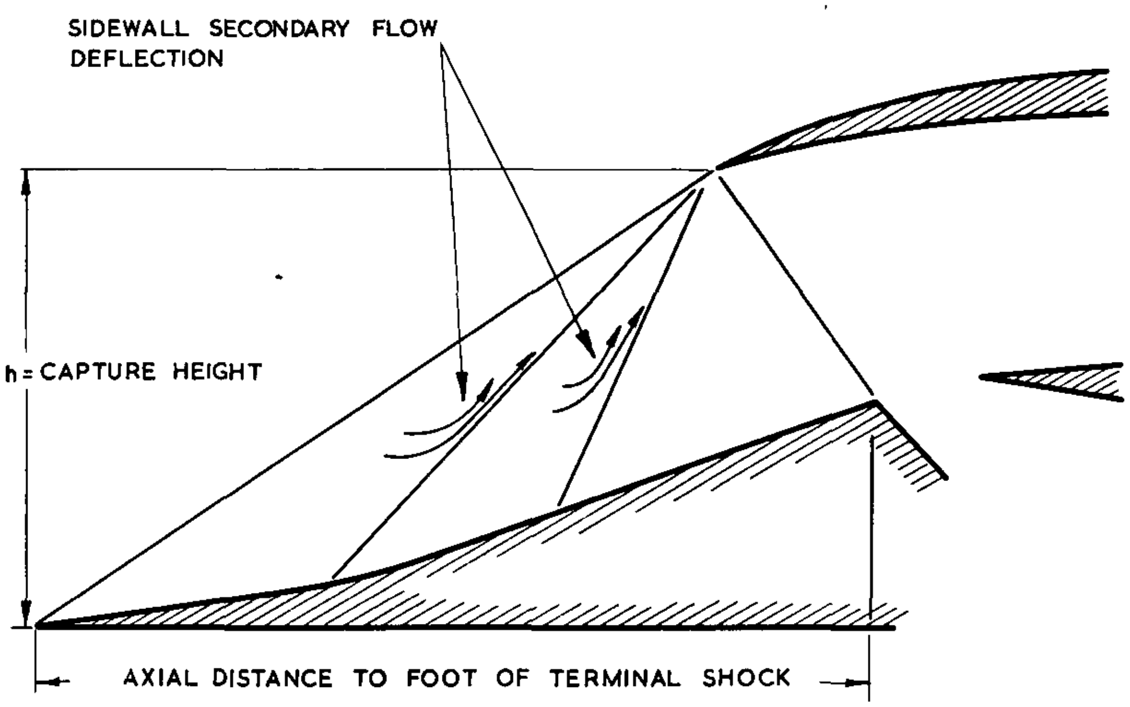
(a) WITHOUT COWL DEFLECTION



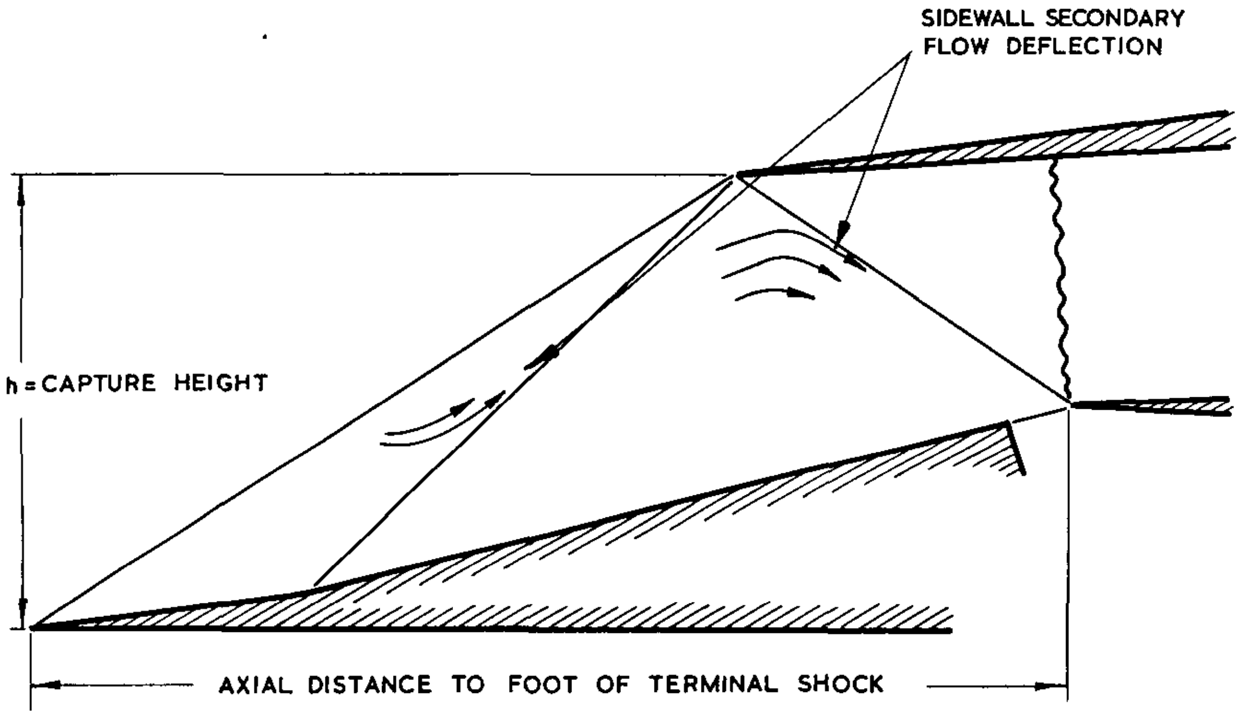
(b) WITH COWL DEFLECTION

EXTERNAL COMPRESSION INTAKES

FIG.13



(a) EXTERNAL COMPRESSION INTAKE



(b) COMBINED EXTERNAL / INTERNAL COMPRESSION INTAKE

EXTERNAL AND COMBINED/EXTERNAL INTERNAL COMPRESSION INTAKES

D 86673/1/129528 K4 5/67 CL

A.R.C. C.P. No. 937 533.697.2:620.1
September, 1963
Neale, M. C. and Lamb, P. S.

TESTS WITH A TWO-DIMENSIONAL INTAKE HAVING ALL EXTERNAL COMPRESSION AND A DESIGN MACH NUMBER OF 2.0

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