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Some Characteristics of Rectangular Multi-Shock and Isentropic External Compression Intakes at a Mach Number of 2.9

by

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SOME CHARACTERISTICS OF RECTANGULAR MULTI-SHOCK AND ISENTROPIC EXTERNAL COMPRESSION INTAKES AT A MACH NUMBER OF 2.9

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SUMMARY

Pressure recovery and mass flow have been measured for a number of rectangular air intakes having single-shock, multi-shock and isentropic external compression surfaces at a Mach number of 2.9 and Reynolds number of 2.25×10^5 (based on entry height). For one intake having a multi-shock compression surface the effect of throat boundary layer bleeds on the variation of pressure recovery with mass flow was investigated.

Measured pressure recoveries varied from 5% to 20% below the calculated shock wave recovery value when employing the maximum permissible amount of internal contraction (i.e. that which will just allow the intake to 'start'). Variation of the internal contraction was found to have an appreciable influence on pressure recovery. With the best throat boundary layer bleed tested, the pressure recovery was increased by 10% over that without bleed.

Measured pressure recoveries have been used to calculate thrusts for comparative hypothetical ramjets. These have been combined with calculated external cowl drags for the different configurations to produce specific fuel consumption values for a given thrust minus drag.

Replaces R.A.E. Tech. Note No. Aero 2786 - A.R.C.23,440.

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1 INTRODUCTION

The use of quasi-two-dimensional centrebody intakes has been considered for engine installations in either the wing or the fuselage for flight speeds in the region of M = 3. Compared with the amount of research devoted to the performance of axi-symmetric centrebody intakes the attention paid to the rectangular type has so far been fairly small. The present investigation was therefore planned to determine the performance which could be expected from external-compression rectangular intakes with various forms of compression surface and degrees of external compression.

More specifically it was required to determine:-

(a) for a given cowl shape (hence a given external drag if the intake were operating without spillage) the influence of the particular form of compression surface (i.e. isentropic or multi-shock) pressure recovery;

(b) for a given compression surface, the effect of internal contraction of the duct downstream of the entry plane and the effect of internal cowl shape (for a given internal contraction) on pressure recovery (both these parameters having been shown to be important in axi-symmetric centrebody intakes);

(c) the best compromise between conflicting requirements of high pressure recovery and low drag, consequent upon adopting increasing amounts of external compression and hence flow deflection at the entry plane.

To give an indication of where an optimum configuration might lie, simple calculations of thrust minus drag and specific fuel consumption for hypothetical ramjet engines have been made.

Tests were made with single-oblique-shock, multi-shock and isentropic compression surfaces designed for a number of cowl shapes, the initial internal angles of the cowls ranging from 0° to 22.5°. The compression surfaces were designed to have all the shocks from the centrebody intersecting at the cowl lip and to have the maximum permissible internal contraction (see footnote on page 5) corresponding to the appropriate entry Mach number.

2 DESCRIPTION OF APPARATUS

2.1 General arrangement

All the tests were made in the $5\frac{1}{2}$" × $5\frac{1}{2}$" No.4 Supersonic Tunnel at the R.A.E. Farnborough, at a mean Mach number of 2.9. A general view of the experimental arrangement is shown in Fig.1. The model was screwed on to a sting which could be moved so that incidence was varied between +6° and -3°. Control of intake mass flow was provided by translating a wedge in the model exit plane. The position of this wedge could be adjusted from outside the tunnel.

The vertical position of the base plate in the model could be adjusted so that entry area remained the same (1.1" wide × 1.0" high) for each cowl. The centrebodies were attached to this base plate.

2.2 Centrebodies

The centrebodies were designed with either 8° or 12° initial angles, with the exception of one single wedge centrebody which had an angle of 18°. For convenience these compression surfaces are designated by the initial wedge angle and the number of oblique shocks; e.g. the compression surface made up of three wedge angles and having an initial angle of 8° is referred to as the 8°, three-shock centrebody. The second and following wedge angles on the multi-shock compression surface were chosen such that the theoretical static pressure ratio across each oblique shock was just less than 1.8. This was done to prevent boundary layer separation at each junction.

The isentropic centrebodies had initial wedge angles equal to those chosen for the multi-shock wedges i.e. 8° and 12°.

Each centrebody was designed to focus the oblique wedge shocks on the cowl lip at $M = 2.9$ and to give the maximum allowable internal contraction for starting*. The amount of external compression was chosen - with one exception - such that the Mach number at the cowl lip was approximately 0.1 greater than the shock detachment Mach number. In the one exceptional case (8° isentropic) the external compression reduced the lip Mach number to the shock detachment value. Under design conditions the rate of internal contraction and the subsequent initial rate of diffusion were the same for each model. In the main part of the subsonic diffuser section of each intake the total angle of divergence was either 6° or 9° approximately. To investigate the efficiency of the subsonic diffusion process one multi-shock model was designed such that this angle could be increased to 21°.

One multi-shock centrebody was designed with a boundary layer bleed located at the intake throat. This coincided with a position just downstream of the intersection of the cowl lip shock with the compression surface (see Fig.2). The bleed spanned the compression surface and both flush and forward facing bleeds were tried. The effect of varying the bleed size was also investigated. Fig.2 contains sketches of the different bleed configurations.

The actual centrebodies used are shown in Fig.3 (note that vertical and horizontal scales are different) together with the corresponding theoretical pressure recoveries and internal contraction ratio C_r, with the 'design' cowls. Duct area distributions are shown in Fig.4 for each compression surface with its 'design' cowl.

2.3 Cowls

Six cowls were designed having different initial internal angles viz $\eta_i = 0^{\circ}, 5^{\circ}, 10^{\circ}, 15^{\circ}, 17^{\circ}$ and 22.5° (Fig.3). The exterior profile was a straight line for ease of manufacture and the included angle at the lip was approximately 5°. Each cowl is referred to by its initial internal angle.

2.4 Side plates

Side plates were used for each model; these were swept back at an angle corresponding to the initial shock angle for each compression surface. The angle of chamfer on the outside edge was made smaller than

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*Maximum allowable contraction is based on throat area found by assuming that a normal shock occurs in the entry plane of the intake at the appropriate compression-surface Mach number and that the flow behind the shock is accelerated isentropically to $M = 1.0$ at the throat. The contraction ratio is then defined as the ratio of this throat area to the net area in the intake plane perpendicular to the mean direction of flow.

the shock detachment angle for the free stream Mach number component normal to the sweptback edge. Because this angle was small (3°) a double chamfer was used.

3 PROCEDURE AND ANALYSIS OF RESULTS

With each model, measurements of static pressure were made in the constant area section just upstream of the exit plugs, for mass flow variations ranging from the supercritical state to the unstable flow regime. Two wall static holes and a central static tube were used for these measurements.

Since the exit from the model was choked for all mass flows through the intake, the value of static pressure in the constant area section, together with values for the relevant constant area and exit area, was sufficient to determine both mean pressure recovery and mass flow.

As each centrebody could be used with any of the cowls, the effects of varying internal contraction on the pressure recovery could be investigated. The range of internal contraction was extended by moving individual centrebodies axially by a small amount relative to the cowl.

The majority of the tests were made at zero incidence. Transition was promoted on each centrebody by a narrow strip of sellotape positioned close to the leading edge.

With the boundary-layer-bleed model, the flow through the various bleeds was allowed to exhaust back into the tunnel stream from underneath the model.

4 PRESSURE RECOVERY AND MASS FLOW RESULTS

4.1 Compression surfaces with their 'design' cowls

Under these conditions each intake has the maximum permissible internal contraction and hence (by comparison with results for axi-symmetric intakes) it should give its best performance.

The variation of pressure recovery with mass flow obtained with each compression surface is shown in Figs.5 to 8. As will be seen the values of critical flow pressure recovery $(P_f/P_\infty)_{crit}$ are significantly lower than the theoretical shock pressure recoveries and this difference shows a sharp increase as the compression surface changes from single-shock to multi-shock or isentropic. Thus the losses other than shock losses,

$$\frac{\Delta P_f}{P_\infty} = \left(\frac{P_f}{P_\infty}\right)_{theo} - \left(\frac{P_f}{P_\infty}\right)_{measured} ,$$

amount to about 0.05 for single-shock models but increase to 0.17 to 0.22 for multi-shock and isentropic models. These results are similar to those obtained in Ref.1, also on rectangular intakes, but with an entry height/width of 2.3 and at a Reynolds number approximately twice that of these tests.

Maximum mass flow ratios as measured are appreciably below the theoretical maximum value 1.0. This result can be accounted for on the basis of schlieren observations which showed that the initial wedge shock was always at a slightly greater angle than the theoretical value and hence some spillage occurred over the cowl and around the sweptback side-plates. Examples are to be found in the photographs shown in Fig.9. It is not understood why this should be so. A check on the accuracy of the method of measuring mass flow was provided by converting one model into a pitot type intake with which the occurrence of full mass flow could readily be determined from schlieren observations. The mass flow was measured by the present method and also by using a twenty-tube pitot rake in the model exit flame. The results are shown in Fig.10 where both methods are seen to agree reasonably with theory. The error in mass flow is thus likely to lie within ±2%.

Intakes with compression surfaces which induced a large amount of flow turning e.g. the 12°, three-shock centrebody designed for the 17° cowl and also the 8°, four-shock centrebody, appeared to have been over-contracted internally. Schlieren photographs showed that the cowl shock remained slightly detached even under supercritical flow conditions. This result was probably caused by boundary layer separation in the vicinity of the shoulder of the centrebody.

4.2 Effect of changes in subsonic diffuser

The 8°, three-shock centrebody intake was tested with three different angles of divergence in the subsonic diffuser, viz. 6°, 9° and 21°. The results are shown in Fig.11. Little change was produced in the final pressure recovery by going from the 9° diffuser to one with 6° divergence but there was a significant fall-off (12%) with the short 21° diffuser. A difference in maximum mass flow was obtained between one configuration and the other two; this is thought to have occurred because of a slight change in side plate setting.

4.3 Effect of throat boundary layer bleed on pressure recovery

As described in section 2.2 a centrebody similar to the 8°, three-shock centrebody was tested with the boundary layer bleeds shown in Fig.2.

The variations in pressure recovery with mass flow obtained with different bleeds and without bleed are compared in Fig.12. A significant improvement in maximum pressure recovery is obtained with each bleed and there is little difference between the results obtained with the best flush and the best forward facing bleeds. The improvement in pressure recovery is obtained by removing comparatively small amounts of flow through the bleeds i.e. 1 to 3% of intake mass flow. Figs.12(a) and (b) indicate that increases in pressure recovery for critical flow conditions may quickly reach a peak for small amounts of bleed flow and then decrease as the bleed flow is further increased. Evidence of a similar result is contained in Ref.2.

The highest pressure recovery is given by the bleed configuration shown in Fig.2(f) and although it is difficult to believe strictly the indication of the mass flow measurements that the bleed flow was negligible in this case, nevertheless it is clear that the bleed flow was small, i.e. of order 1% - 2% of intake flow.

4.4 Effects of internal contraction on pressure recovery

Internal contraction was varied in two ways, (a) by fitting a given centrebody with different cowls and (b) by moving the centrebody forwards or backwards with respect to the cowl by small amounts.

Even with maximum centrebody movement the initial wedge shock did not fall inside the cowl lip. The results obtained in this way are shown in Figs.13(a) to (e) where the percentage loss in pressure recovery below the theoretical shock value is plotted against internal contraction ratio for each compression surface. The conditions which lead to values of contraction ratio in excess of unity arise with certain of the off-design wedge positions, when the cross-sectional area inside the cowl increases immediately downstream of the entry plane but then remains constant for a comparatively large distance downstream before increasing further. The area in this constant area section has been taken as the 'throat' area for the calculation of contraction ratio.

For all the compression surfaces the results plotted in Fig.13 appear to lie reasonably well on straight lines of approximately the same gradient (the equations to each of the lines through the points was found by the method of least squares). Unfortunately the simple empirical method of Ref.3 for axi-symmetric intakes, which correlates the effects of internal contraction and flow turning angle at the cowl lip, does not achieve the same good collapse of results for these rectangular intakes. This may be owing to irregular variations in subsonic diffuser area distribution (brought about when different cowls and centrebody positions are used to vary internal contraction ratio) and perhaps more significantly to varying end-wall effects.

These latter effects are not present of course for axi-symmetric intakes but may be quite important. They will obviously depend on the pressure gradients and total pressure rise induced by the external shock system on the end-walls and on the aspect ratio w/h_t at the intake throat section.

The general dependence of losses other than shock losses on flow turning angle at the cowl lip is illustrated in Fig.14 where the results obtained for design configurations are plotted.

5 THRUST AND DRAG CALCULATIONS

Thrust and drag calculations were made (using the experimentally obtained values for pressure recovery at the critical flow condition) for all the 'design' combinations of compression surface and cowl, except those that were known to be over-contracted.

The following assumptions were made:-

(i) Matched engine and intake airflows were assumed, in the stratosphere, with the intake operating at its critical flow condition.

(ii) All the intakes were assumed to be operating without supersonic forespillage, i.e. $(A_\infty/A_{en}) = 1.0$, and the measured pressure recoveries obtained for $(A_\infty/A_{en})_{max} = 0.9$ to 0.95 were assumed to apply.

(iii) The convergent-divergent exit nozzle was expanded in each case to an area equal to the maximum intake area A_{max}.

(iv) The entry area was taken as constant and hence the cowl projected area (and A_{en}/A_{max}) varied with cowl shape. To make the cowl drags consistent, the external surface of the cowl was assumed to have an elliptic profile with a fineness ratio, L/r_{max}, of 3.0 and the same initial angles as the actual cowls used in the experiments.

The calculation of thrust and specific fuel consumption (s.f.c.) are based on curves given in Ref.4.

The results of these calculations are shown in Table 1 below, where values of s.f.c. are given for a fixed value of thrust minus drag ($C_T - C_D = 0.75$).

TABLE 1

Values of s.f.c. for constant thrust minus drag ($C_T - C_D = 0.75$) obtained for various intake configurations

Compression surface and cowl	$\eta_o q$	s.f.c.
18° single-shock ; 15° cowl	0.0294	3.674
12° two-shock ; 0° cowl	0.0241	3.311
8° three-shock ; 5° cowl	0.022	2.882
8° three-shock ; 10° cowl	0.023	2.882
8° four-shock ; 22.5° cowl	0.0233	2.882
8° isentropic ; 5° cowl	0.0218	2.860

The first conclusion from these results is that increasing the complexity of the external shock system results in significant decreases in s.f.c. It is interesting to note that this can occur for cases having similar external drag, i.e. 12° two-shock with 0° cowl and 8° isentropic with 5° cowl.

The second indication appears to be that gains in pressure recovery by using more external compression (c.f. 8° isentropic 5° cowl, 8° three-shock 10° cowl and 8° four-shock 22.5° cowl) are fairly well counterbalanced by the accompanying increases in drag.

More evidence would have been collected if most of the higher cowl-angle configurations were not over-contracted and hence not represented in these calculations. Thus the low drag configurations, where the external multi-shock or isentropic compression is limited by shock attachment considerations at the cowl undersurface, give very much the same results (on an equal thrust minus drag basis) as high drag configurations where the external compression is not so limited.

The values of C_T and C_D are based on the A_{max} value of the actual models and as these are somewhat arbitrary the effect of changing the A_{max} value has been investigated. Changing A_{max} changes the cowl drag but also alters the amount of expansion through the exit nozzle and hence affects the thrust. Fig.15 shows appreciable changes of $C_T - C_D$ and s.f.c. with A_{en}/A_{max} for a particular intake. Fig.16 however shows that for a constant $C_T - C_D$ the curve of s.f.c. versus A_{en}/A_{max} is fairly flat and only small changes in s.f.c. result from fairly large changes in area ratio. In Table 2 below s.f.c. results are quoted for $C_T - C_D$ of 0.75 and with $A_{en}/A_{max} = 0.7$; this shows that there is no significant change in the order of merit obtained in Table 1.

TABLE 2

Values of s.f.c. for constant values of $C_T - C_D$ (= 0.75) and A_{en}/A_{max} (= 0.7) obtained for various intake configurations

Compression surface and cowl	$\eta_c q$	s.f.c.
18° single-shock ; 15° cowl	0.031	3.29
12° two-shock ; 0° cowl	0.025	2.94
8° three-shock ; 10° cowl	0.026	2.85
8° three-shock ; 5° cowl	0.029	2.80
8° four-shock ; 22.5° cowl	0.025	2.79
8° isentropic ; 5° cowl	0.028	2.77

6 SUMMARY OF RESULTS AND CONCLUSIONS

(1) Experimental pressure recoveries were from 0.05 to 0.22 lower than the corresponding calculated shock pressure recoveries.

(2) No change in pressure recovery was recorded on increasing the slope of the centrebody from 6° to 9° in the subsonic diffuser for a particular intake configuration. When the diffuser angle was increased from 9° to 21°, an additional loss of 0.05 in pressure recovery was measured.

(3) A particular throat boundary layer bleed increased the pressure recovery of a three-shock compression surface by 10%. Other throat bleeds gave somewhat smaller increases.

(4) The adoption of the theoretical maximum internal contraction for all the compression surfaces with their 'design' cowls led in practice to over-contraction with three of the centrebodies. These were the isentropic, three and four-shock compression surfaces with the largest amounts of external compression.

(5) Internal contraction (up to the maximum for 'starting') had an appreciable effect on pressure recovery. The pressure recovery varied linearly with internal contraction ratio for each compression surface. The flow turning angle at the cowl lip also appeared to have an appreciable effect on losses other than shock losses. Attempts to use a general correlation derived previously for axi-symmetric intakes (which relates changes in loss associated with either flow turning or internal contraction to Mach number in front of the final normal shock) have been unsuccessful; probably owing to variation in end-wall effects and to non-representative area variations in the subsonic diffusers.

(6) Calculations of the specific fuel consumption for a given thrust minus drag for hypothetical ramjet engines using these intakes show little variation as either external compression increases or the form of this compression (for a given final angle of deflection from the free stream direction) changes.

NOTATION

P	total pressure
η	internal cowl angle
A	intake area
L	horizontal distance between the cowl tip and its "highest point"
h_{max}	maximum height of the intake
C_r	A_t/A_i internal contraction ratio
η_c	combustion efficiency
q	fuel air ratio

Suffixes

f	intake plane in the measuring section
t	plane in the throat of the intake
i	intake entry plane perpendicular to the mean direction of flow
en	entry plane
∞	free stream conditions

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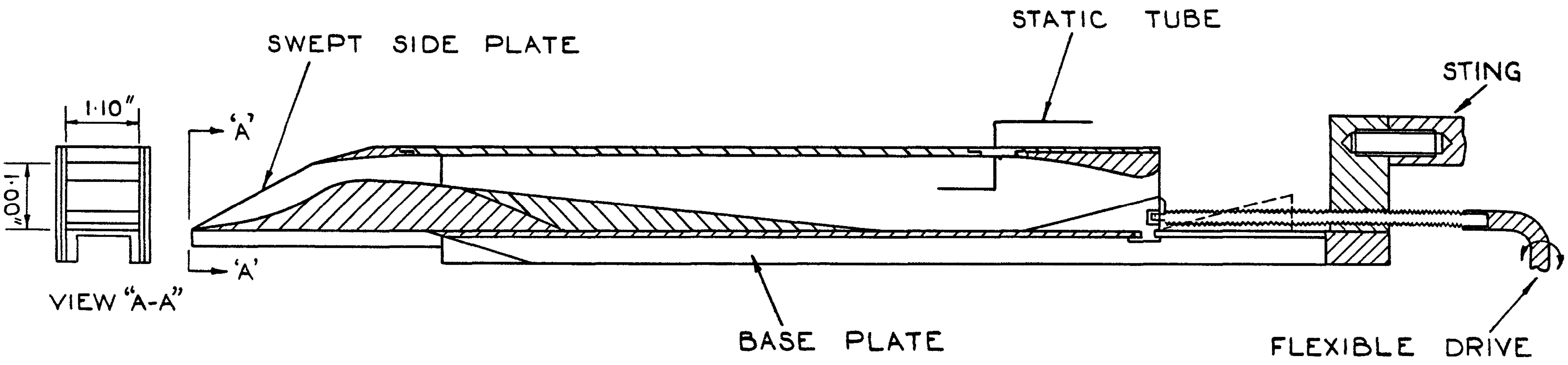


FIG. 1. GENERAL ARRANGEMENT OF MODEL.

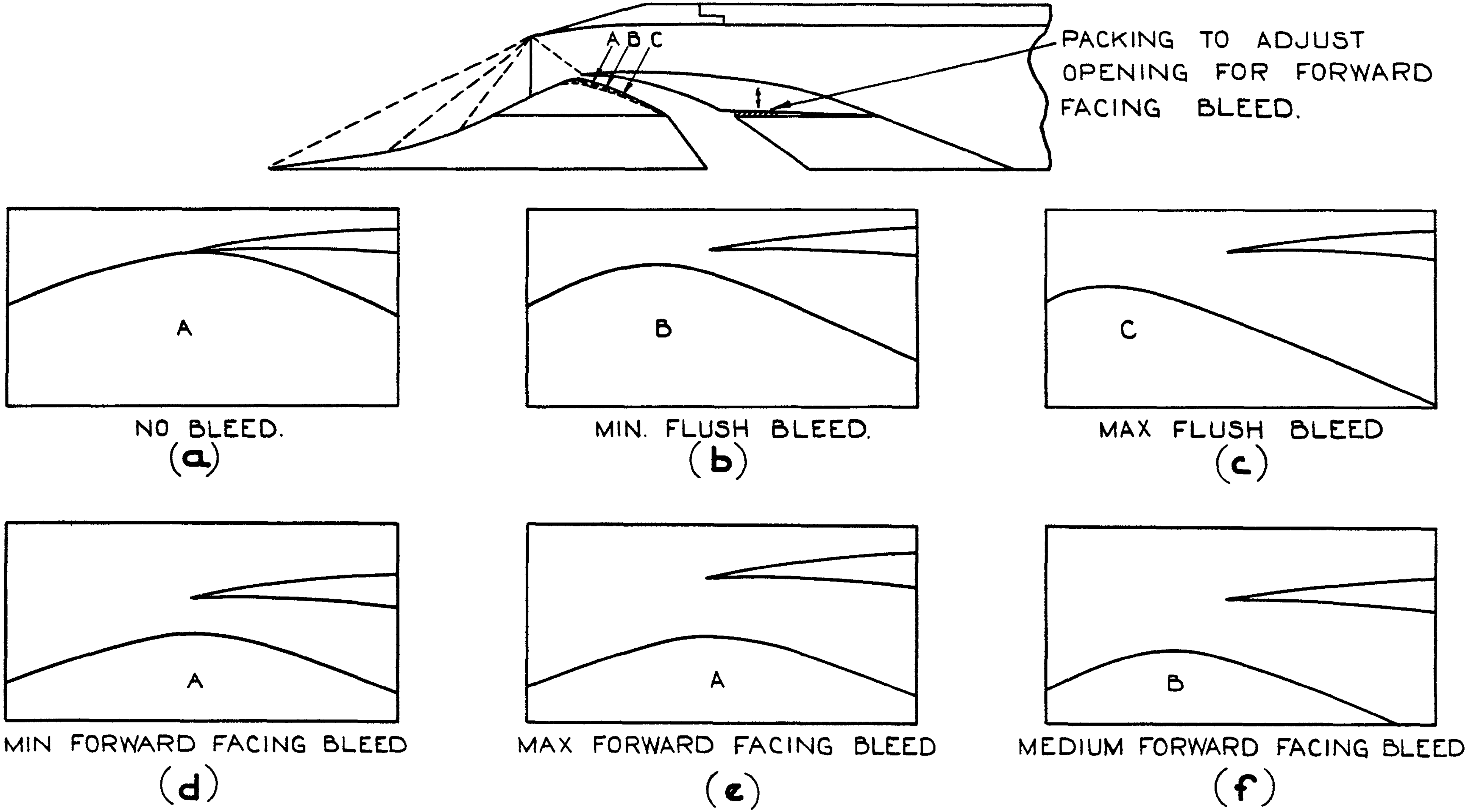


FIG. 2. GENERAL ARRANGEMENT OF INTAKE WITH THROAT BOUNDARY LAYER BLEED AND THE BLEED CONFIGURATIONS USED.

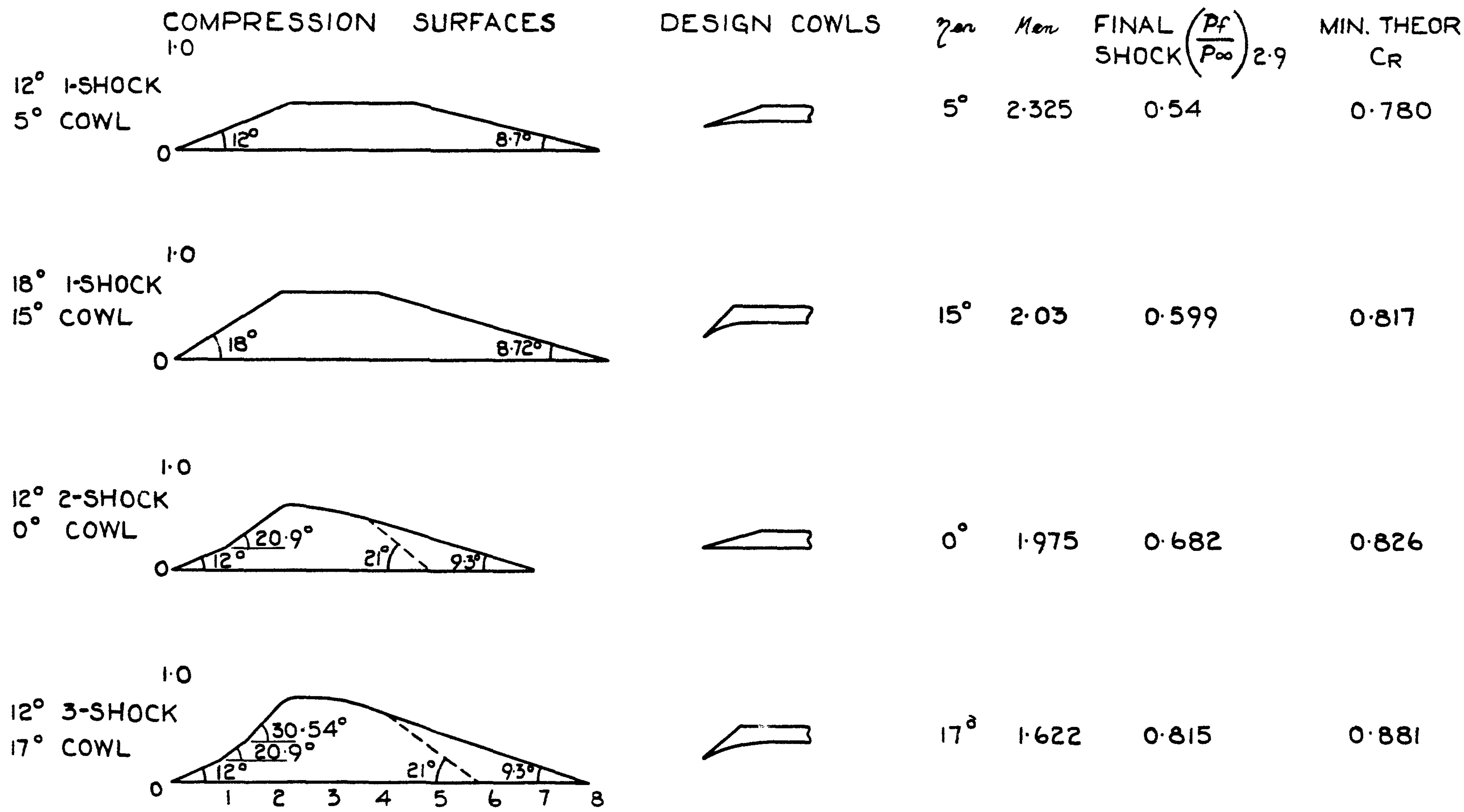


FIG 3(a). DETAILS OF THE COMPRESSION SURFACES

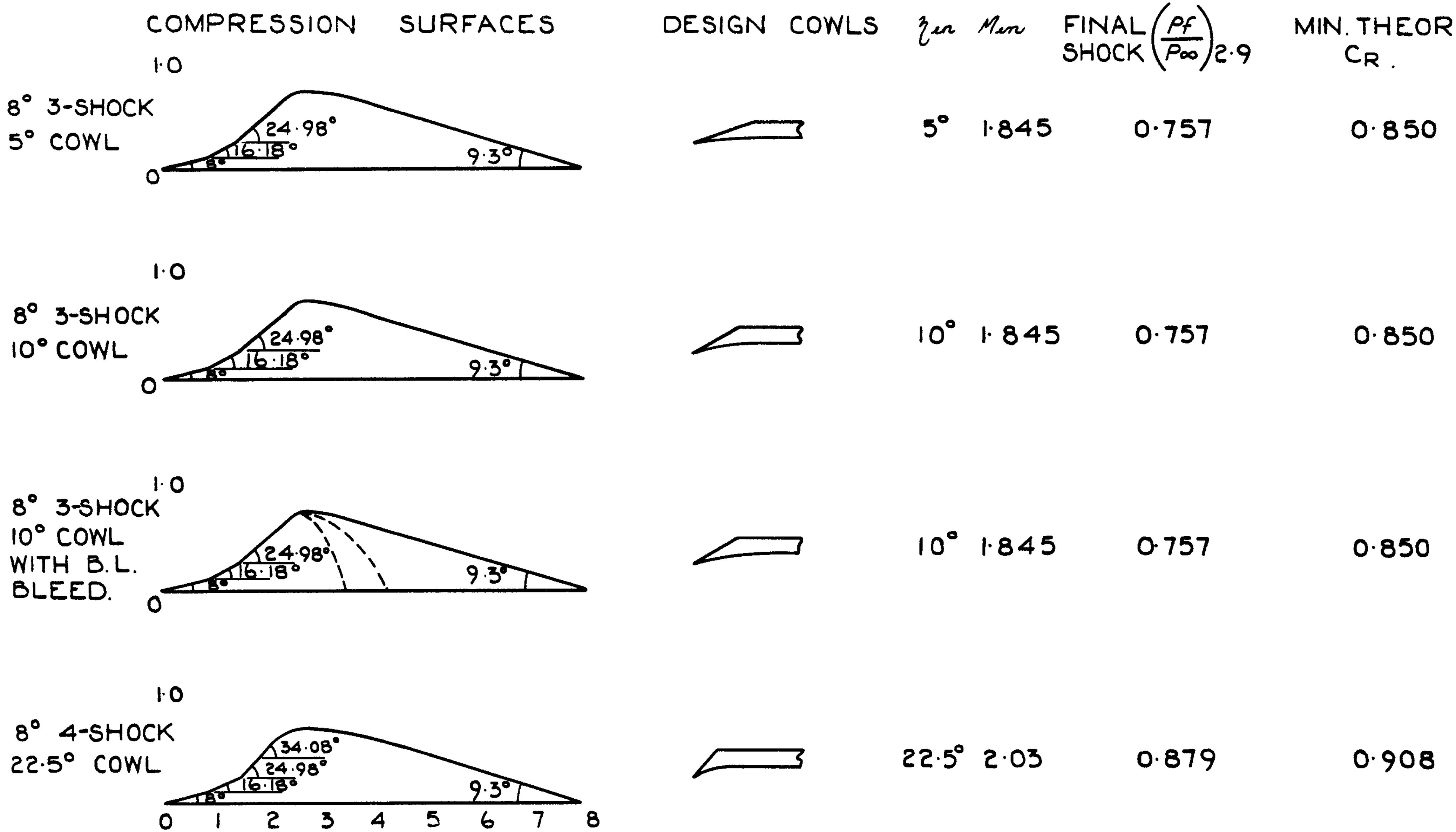


FIG. 3(b). DETAILS OF THE COMPRESSION SURFACES

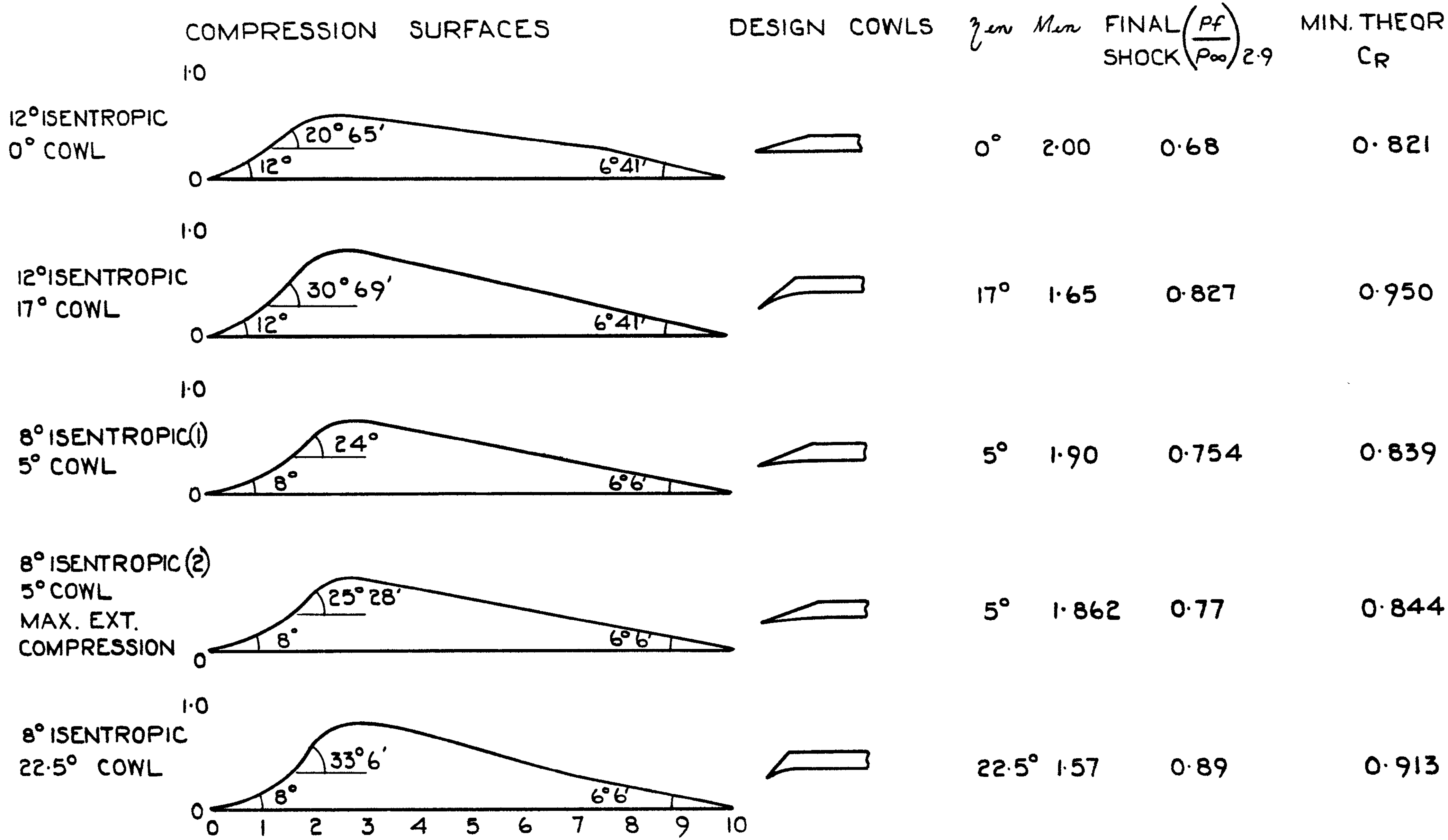


FIG. 3(c) DETAILS OF THE COMPRESSION SURFACES.

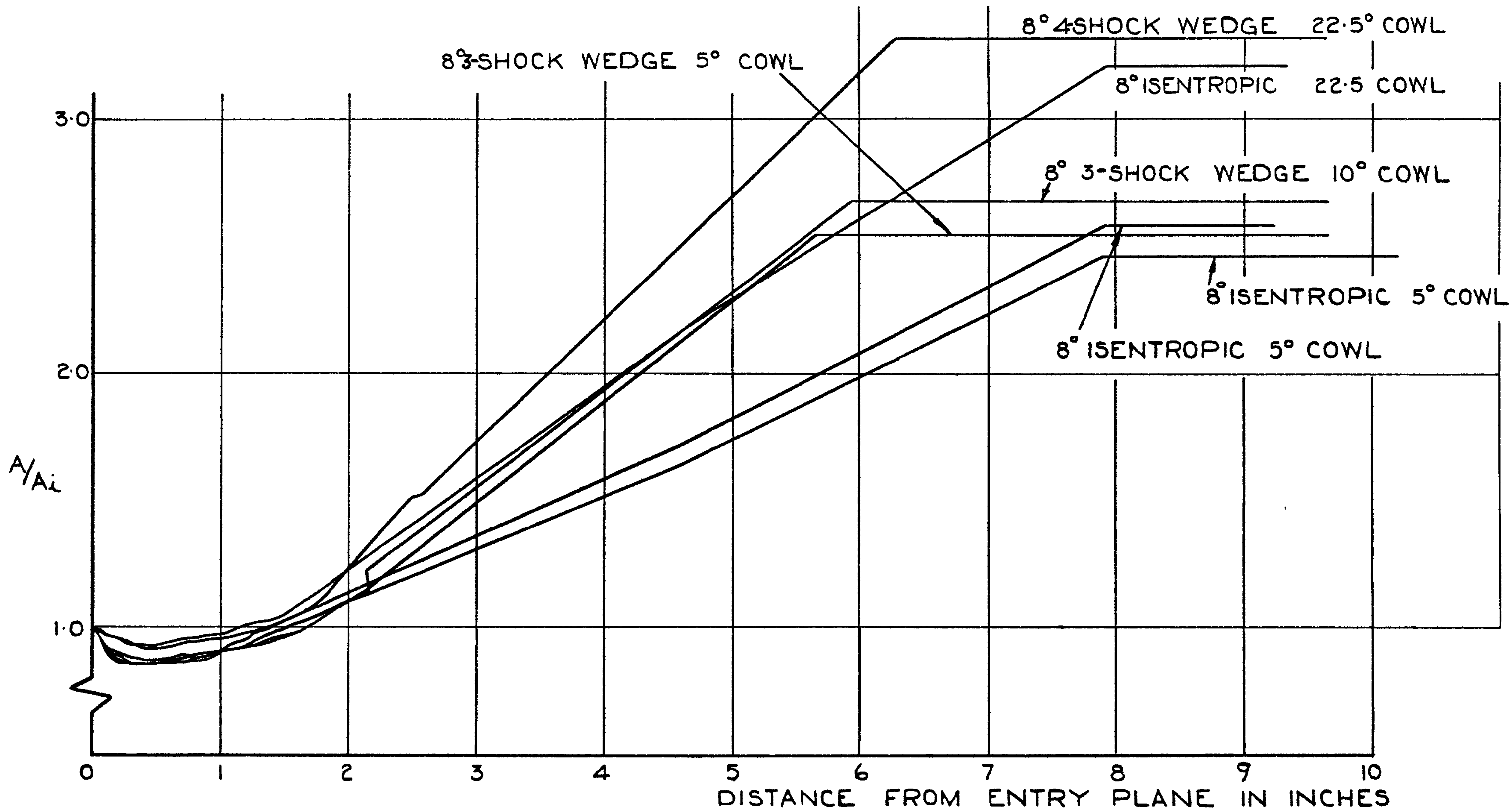


FIG. 4(a) INTAKE AREA DISTRIBUTIONS

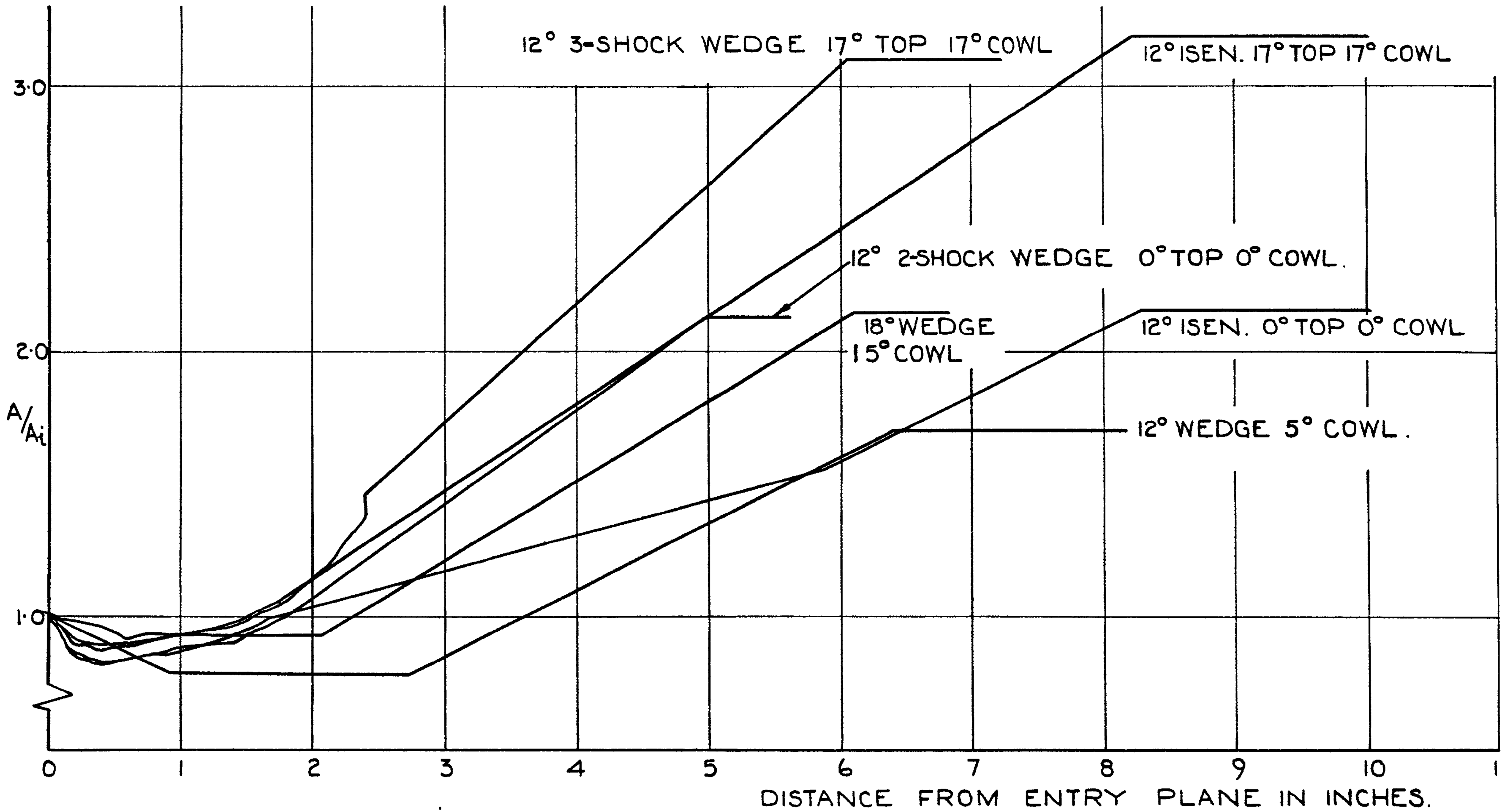
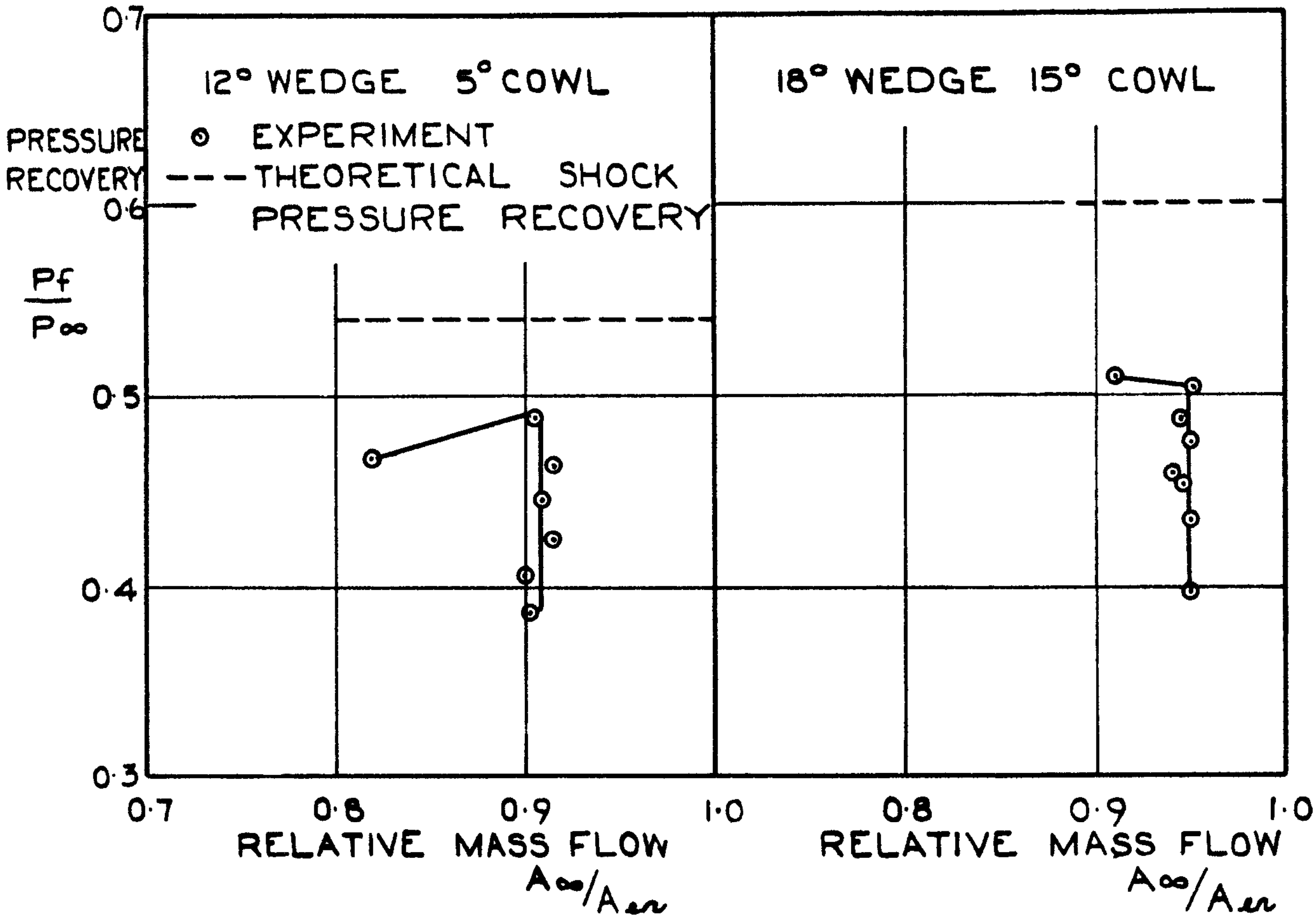
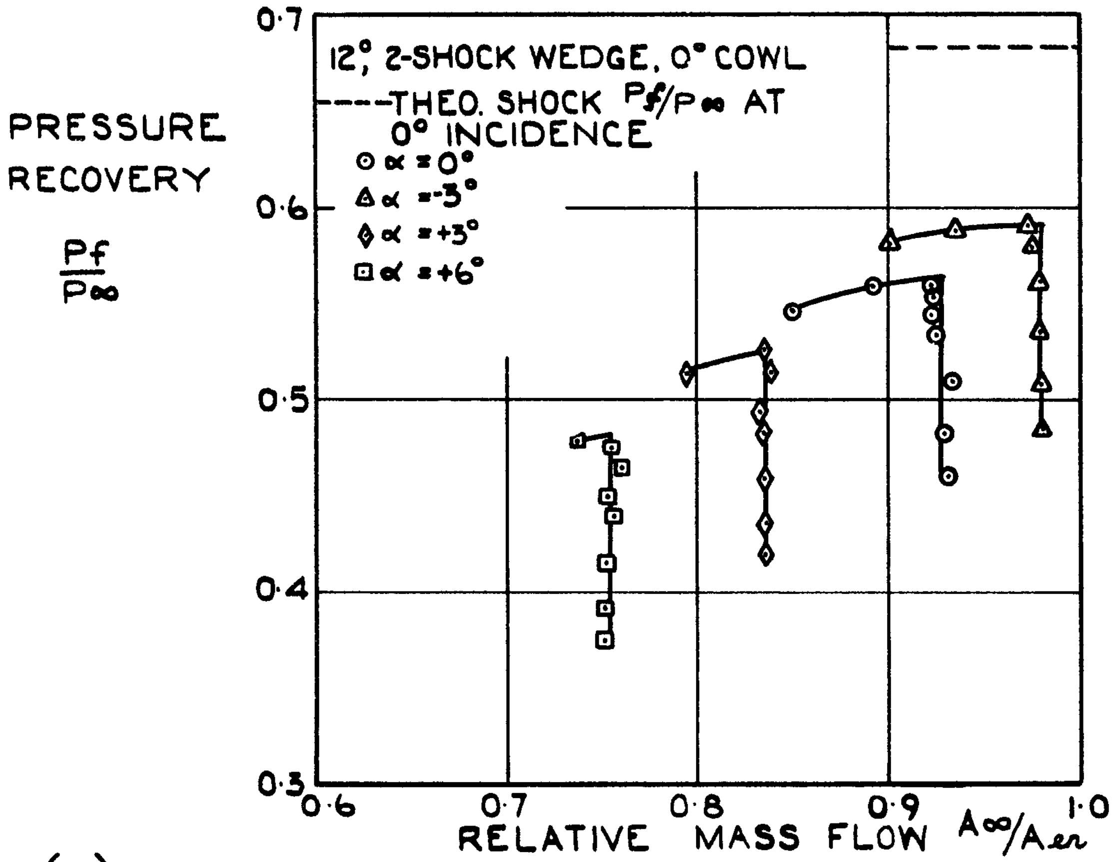


FIG. 4(b) INTAKE AREA DISTRIBUTIONS.



(a) SINGLE-SHOCK COMPRESSION SURFACES.



(b) TWO-SHOCK COMPRESSION SURFACES

FIG. 5(a&b). INTAKE PRESSURE RECOVERY FROM SINGLE & TWO-SHOCK COMPRESSION SURFACES WITH THEIR DESIGN COWLS.

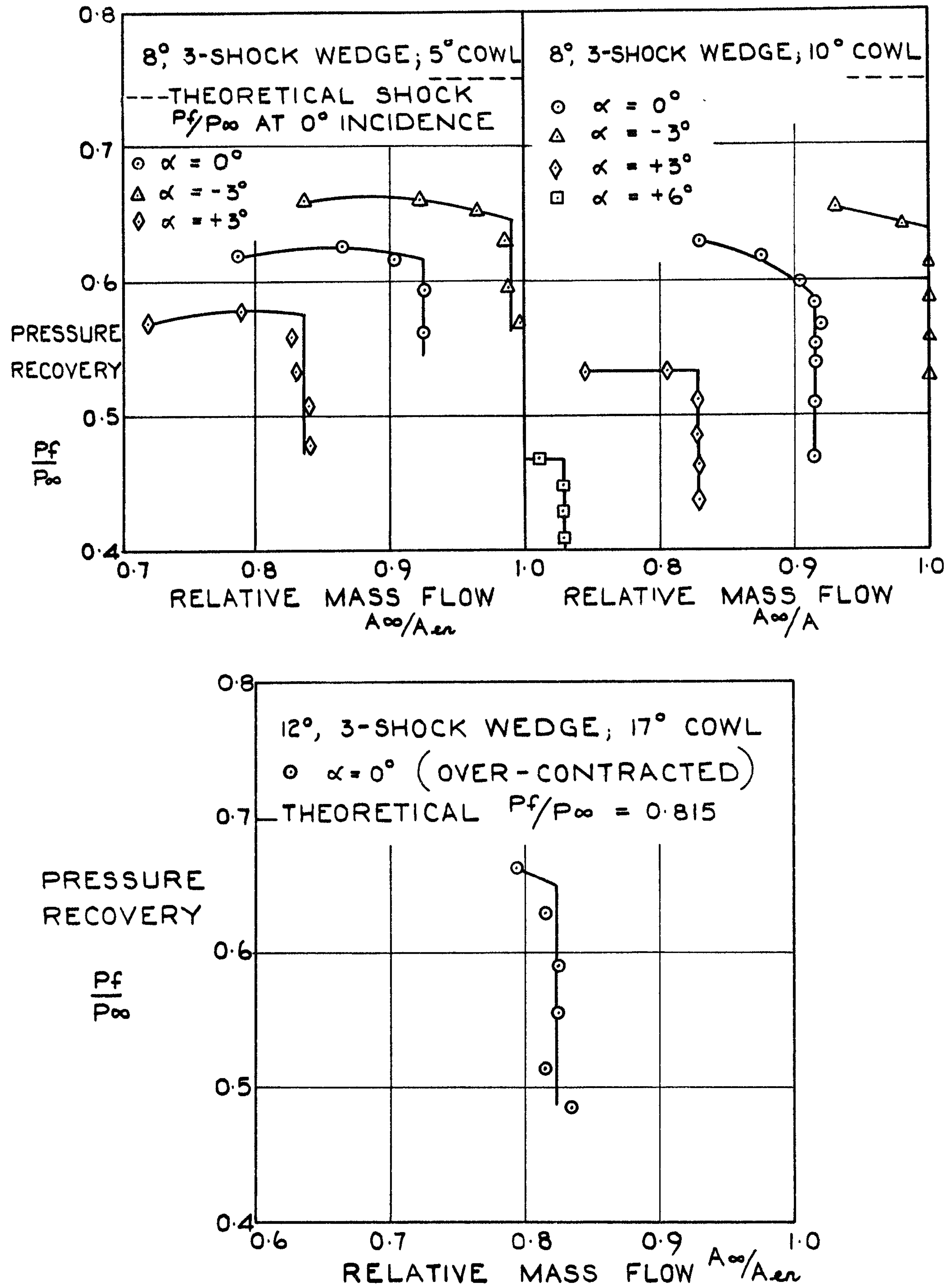
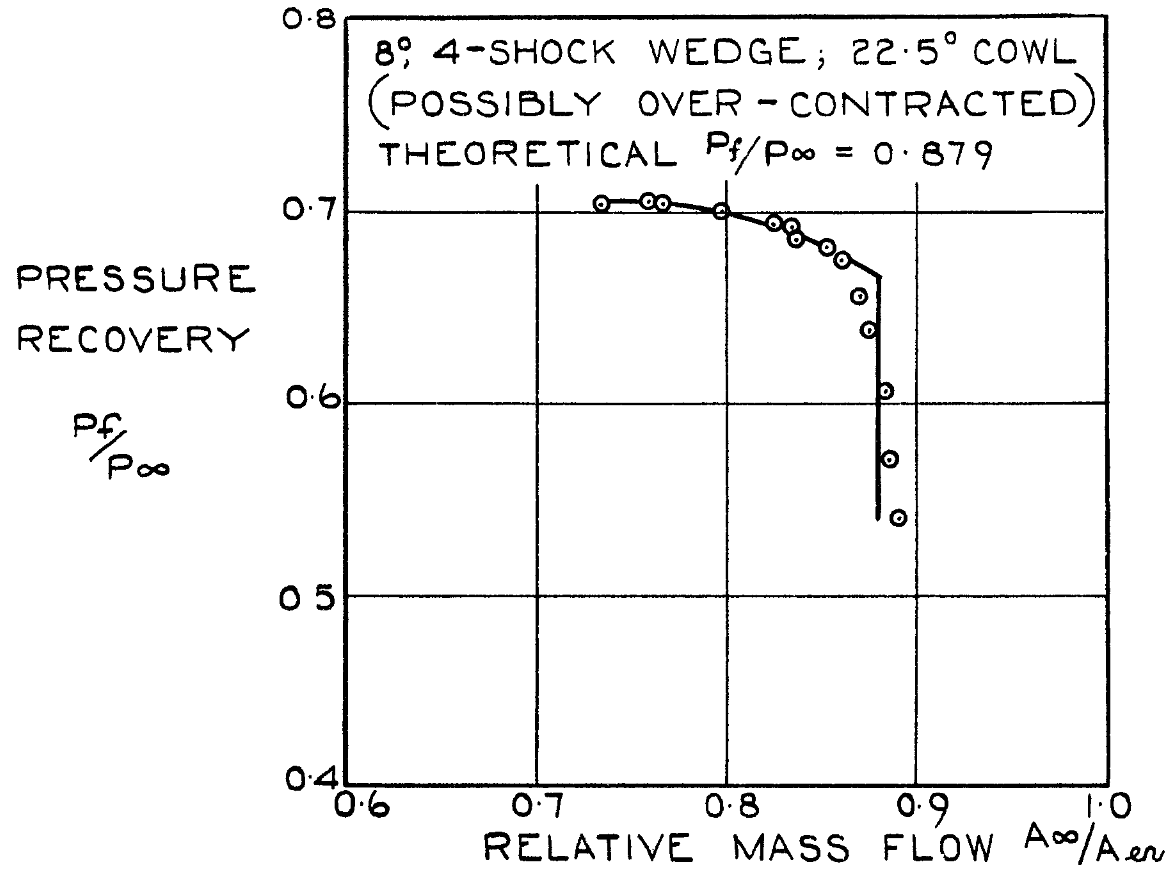
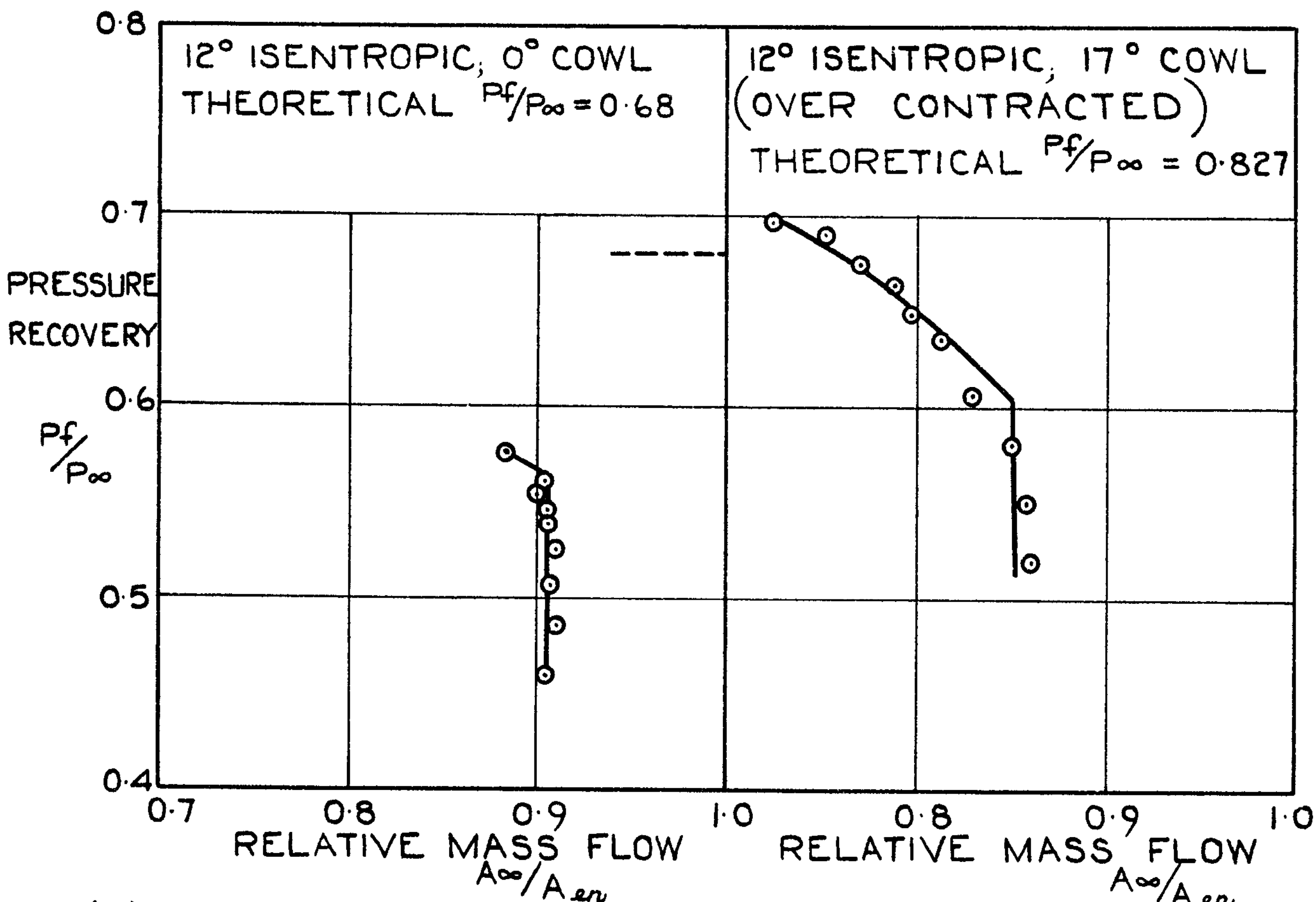


FIG. 6. INTAKE PRESSURE RECOVERY FROM THREE–SHOCK COMPRESSION SURFACES WITH THEIR DESIGN COWLS.

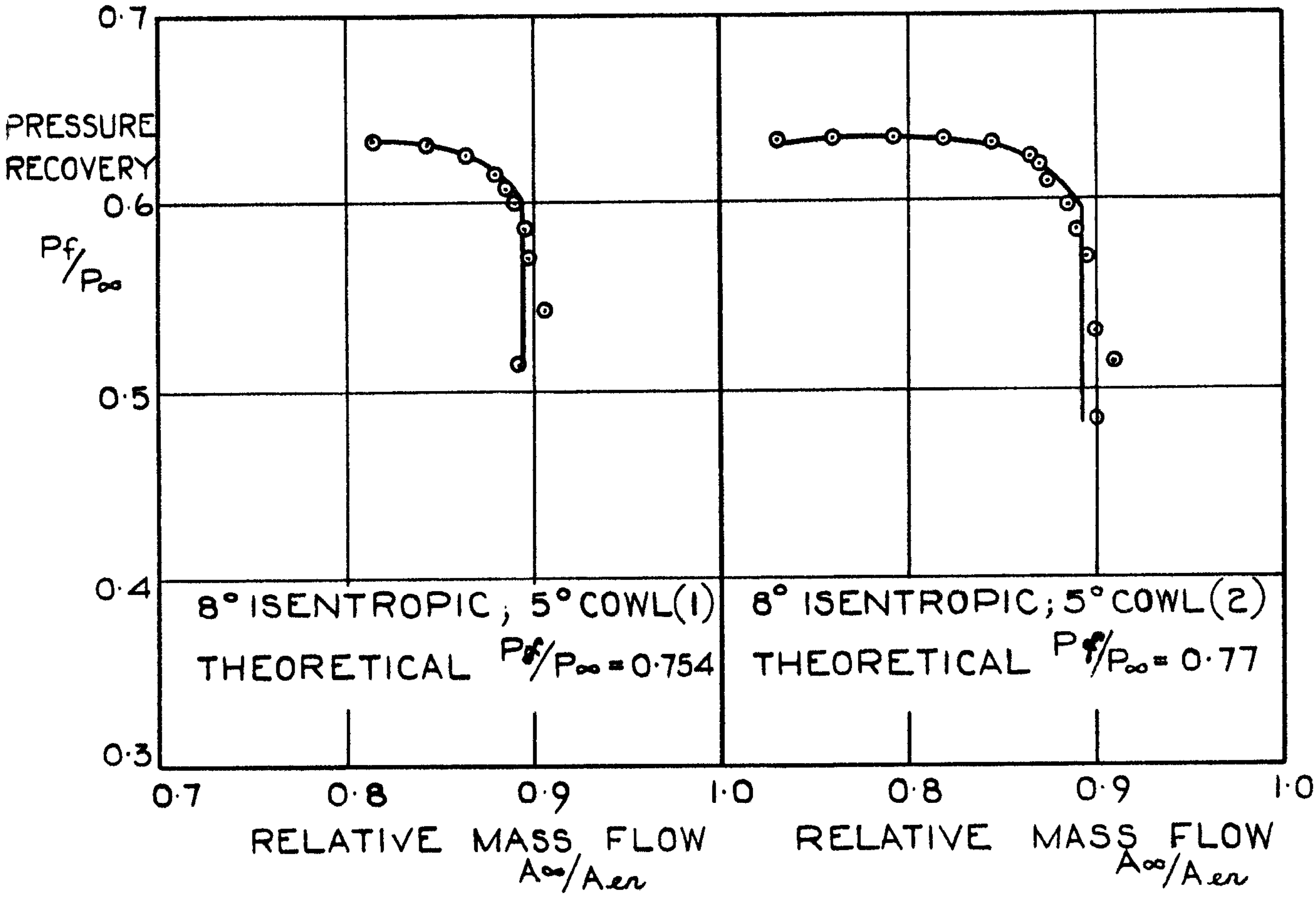


(a) FOUR-SHOCK COMPRESSION SURFACES



(b) ISENTROPIC COMPRESSION SURFACES

FIG. 7 (a & b) INTAKE PRESSURE RECOVERY FROM FOUR-SHOCK & ISENTROPIC COMPRESSION SURFACES WITH THEIR DESIGN COWLS.



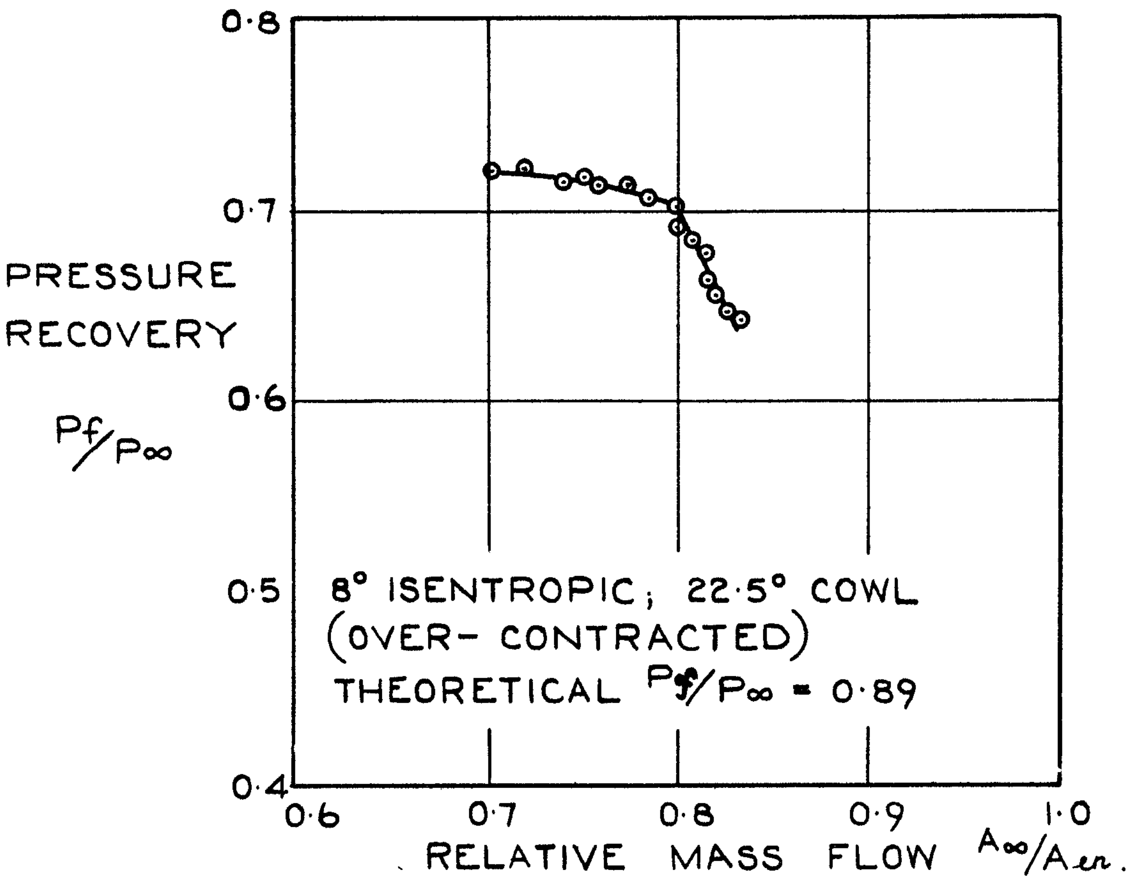
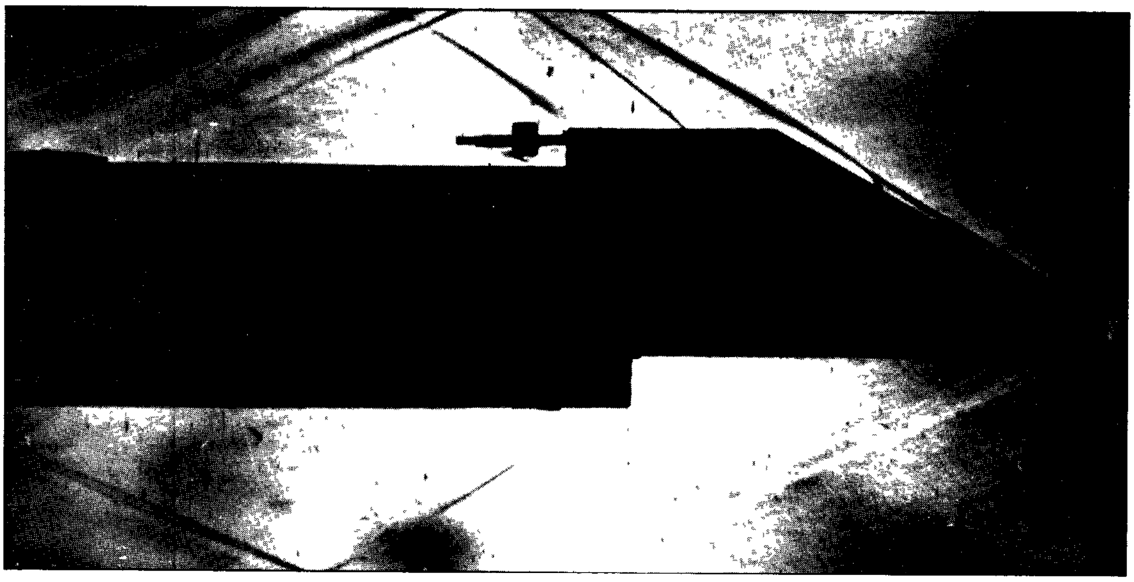
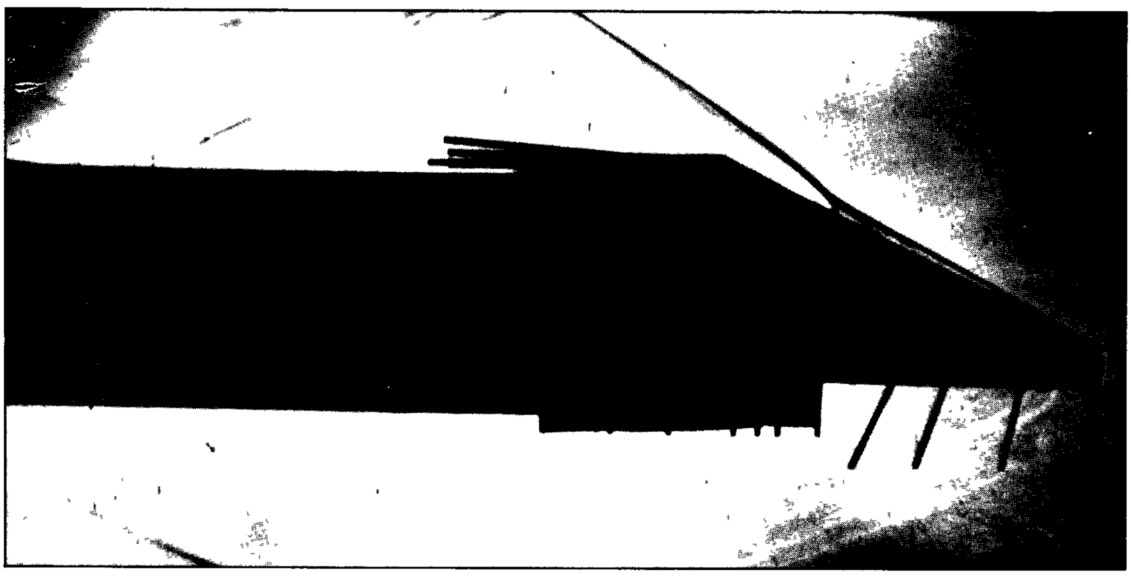


FIG. 8. INTAKE PRESSURE RECOVERIES FROM ISENTROPIC COMPRESSION SURFACES WITH THEIR DESIGN COWLS.



12° SINGLE-SHOCK WEDGE



8° FOUR-SHOCK WEDGE

FIG.9. DIFFERENCE BETWEEN ACTUAL SHOCK ANGLES AND THE THEORETICAL SHOCK ANGLE OF THE SWEPT BACK SIDE PLATES

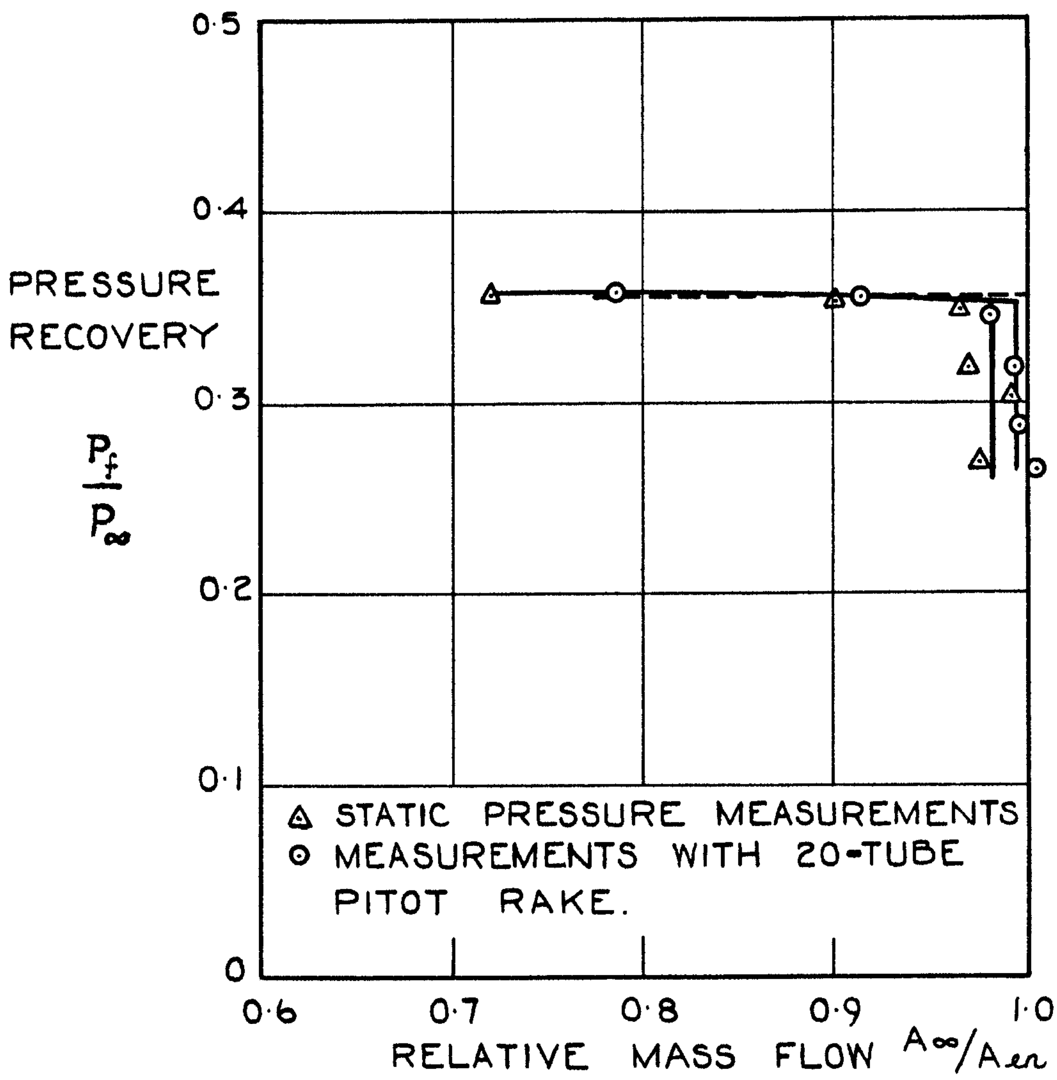


FIG. 10. MASS FLOW THROUGH A PITOT INTAKE WITH CHOKED EXIT BY TWO INDEPENDENT METHODS OF MEASUREMENT.

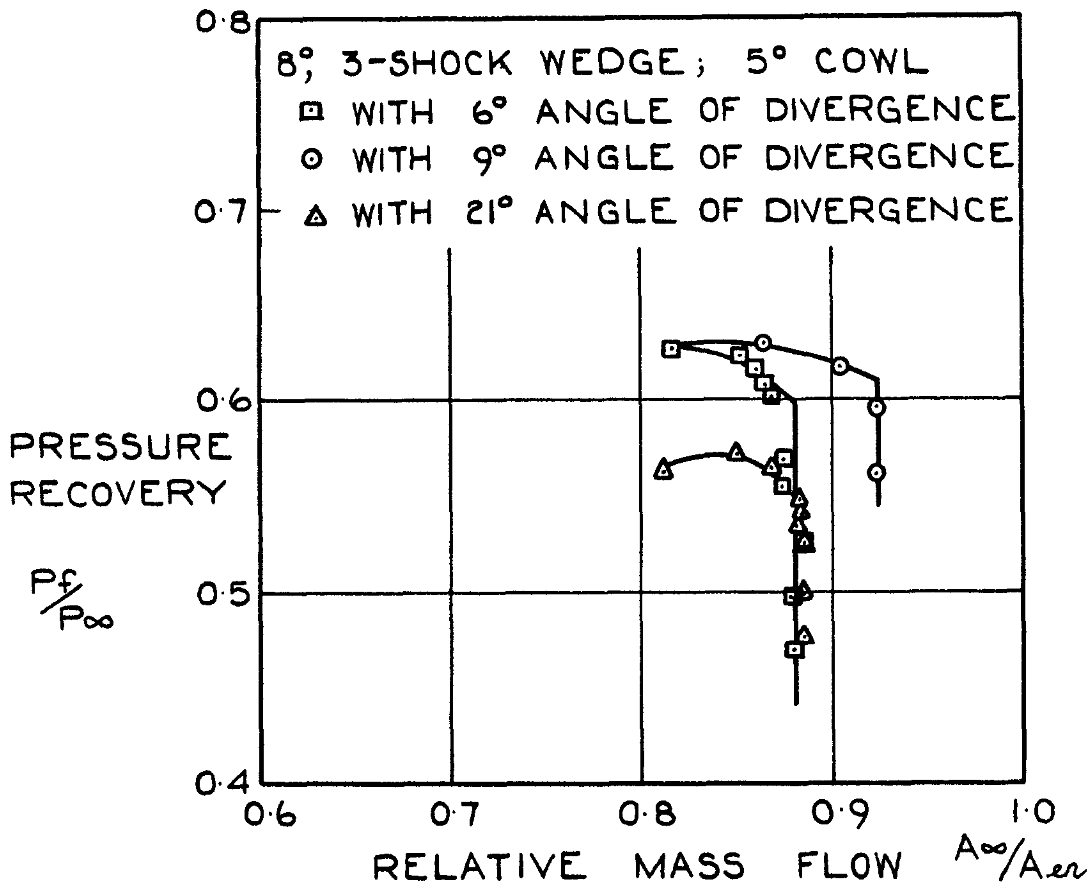


FIG.11. EFFECT OF CHANGES IN THE SUBSONIC DIFFUSER ON PRESSURE RECOVERY

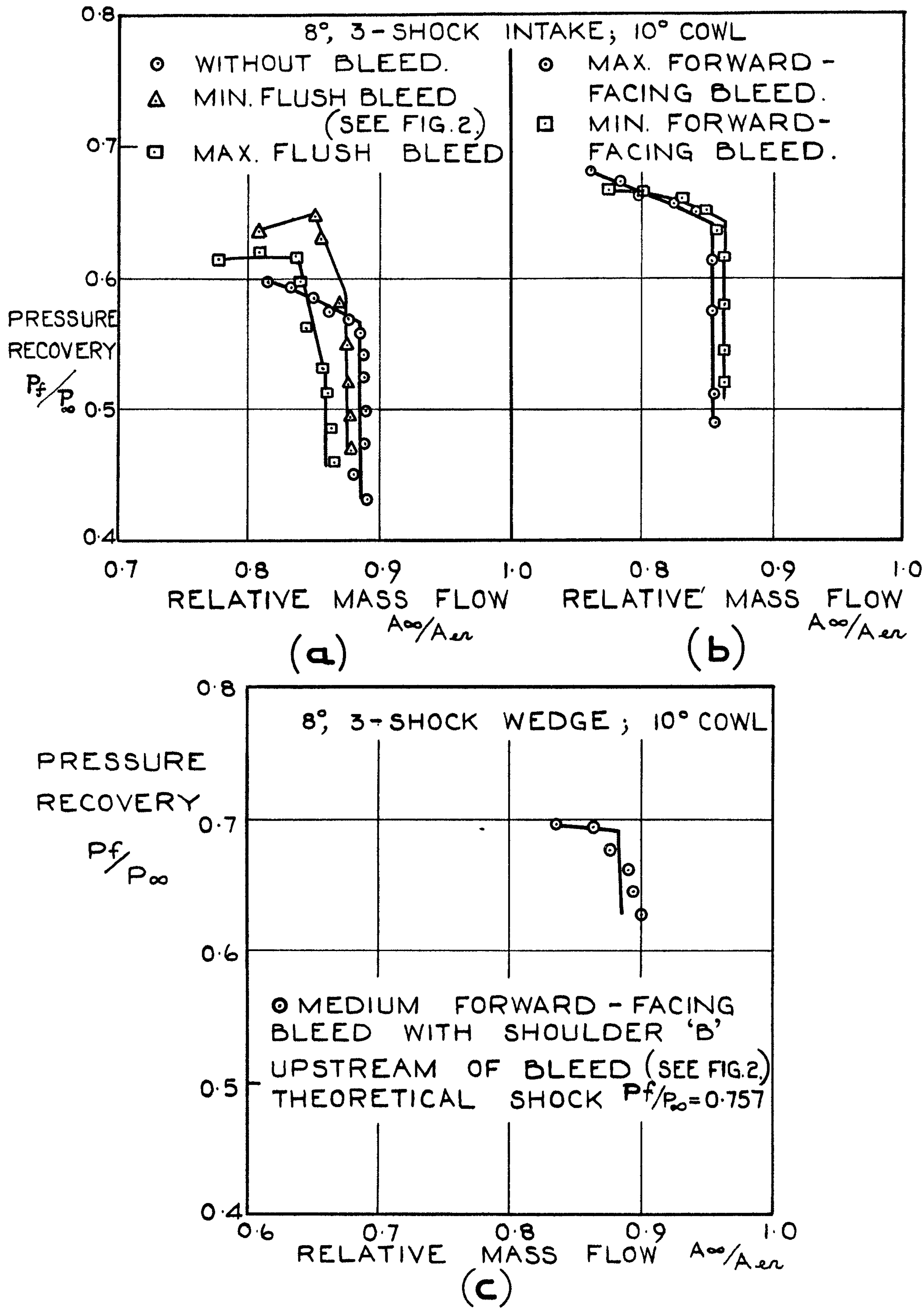


FIG. 12. (a, b & c.) INFLUENCE OF THROAT BOUNDARY LAYER BLEEDS ON P_f/P_∞ MEASURED WITH 3-SHOCK INTAKE WITH MAXIMUM INTERNAL CONTRACTION.

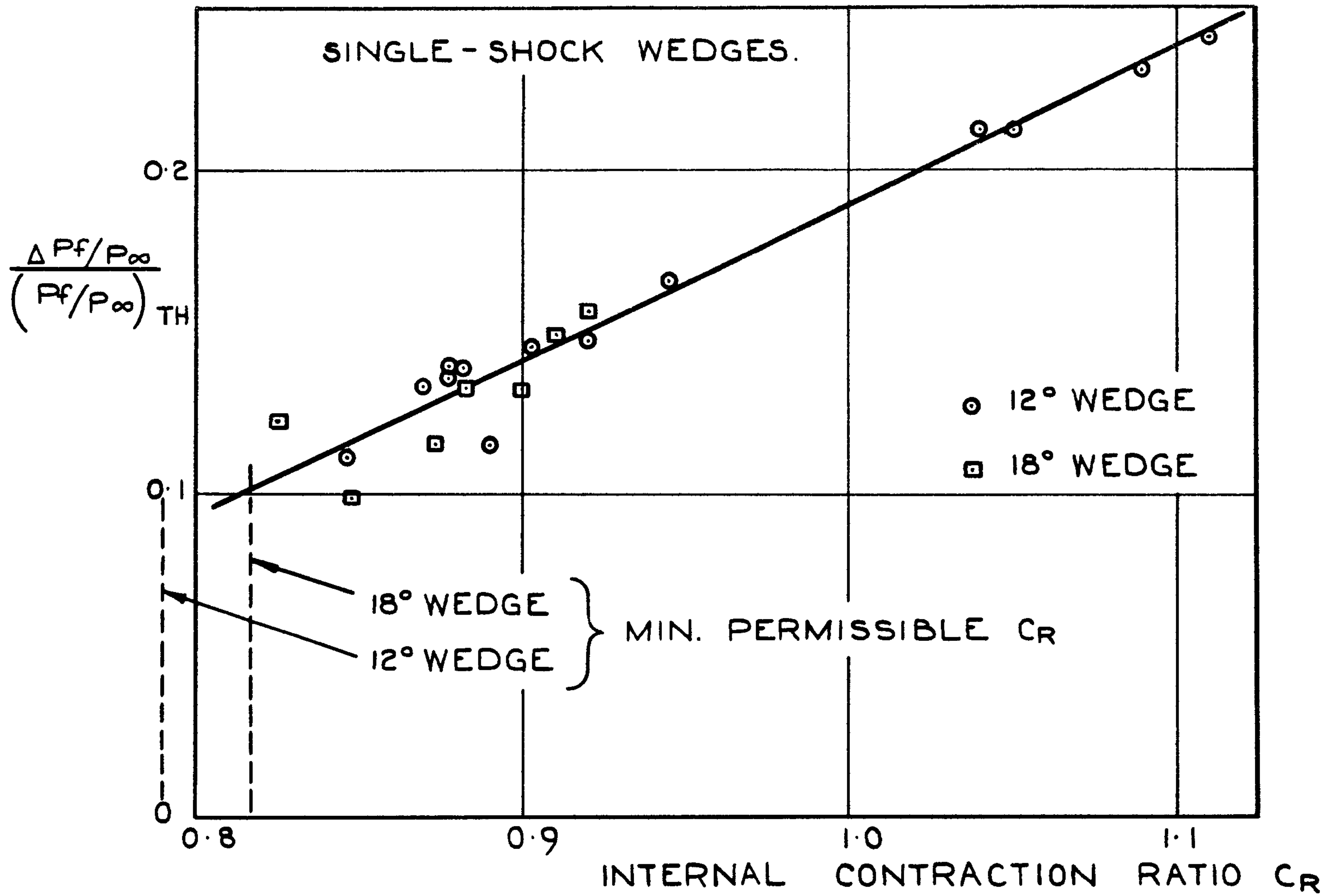
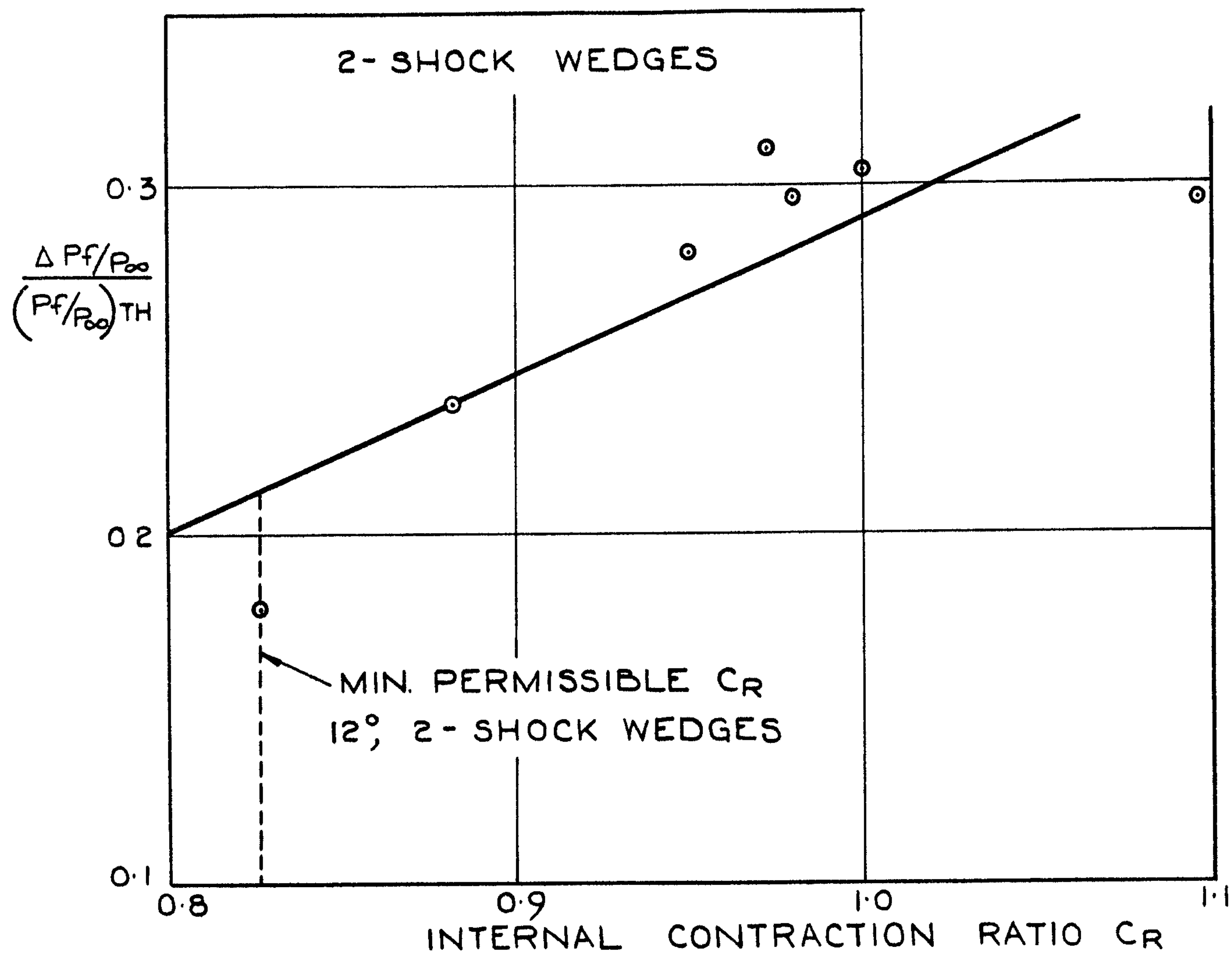


FIG. 13 (a) THE EFFECT OF INTERNAL CONTRACTION RATIO ON PRESSURE RECOVERY OBTAINED WITH VARIOUS COMPRESSION SURFACES.



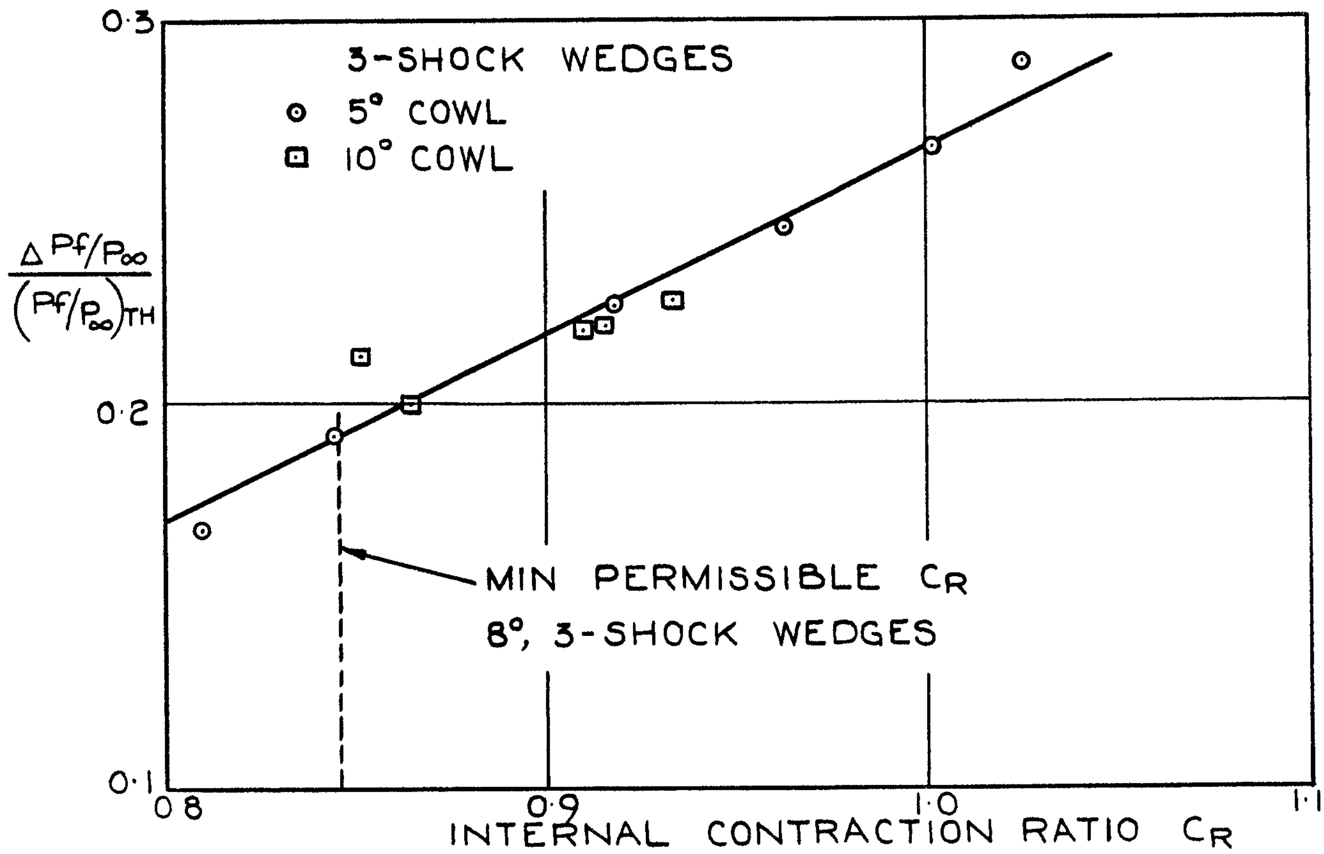


FIG. 13.(b & c) THE EFFECT OF INTERNAL CONTRACTION RATIO ON PRESSURE RECOVERY OBTAINED WITH VARIOUS COMPRESSION SURFACES.

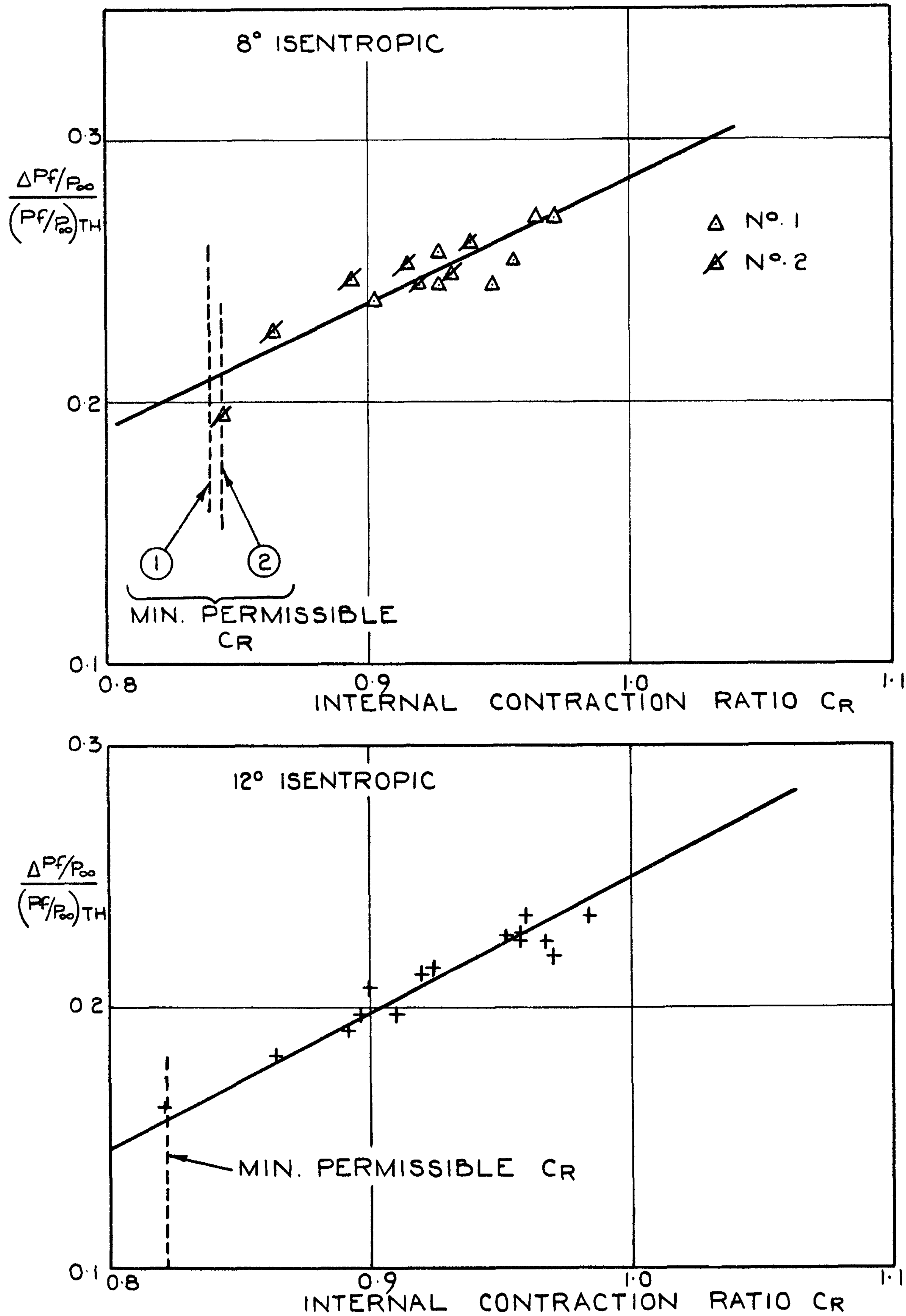


FIG. 13.(d & e) THE EFFECT OF INTERNAL CONTRACTION RATIO ON PRESSURE RECOVERY OBTAINED WITH VARIOUS COMPRESSION SURFACES.

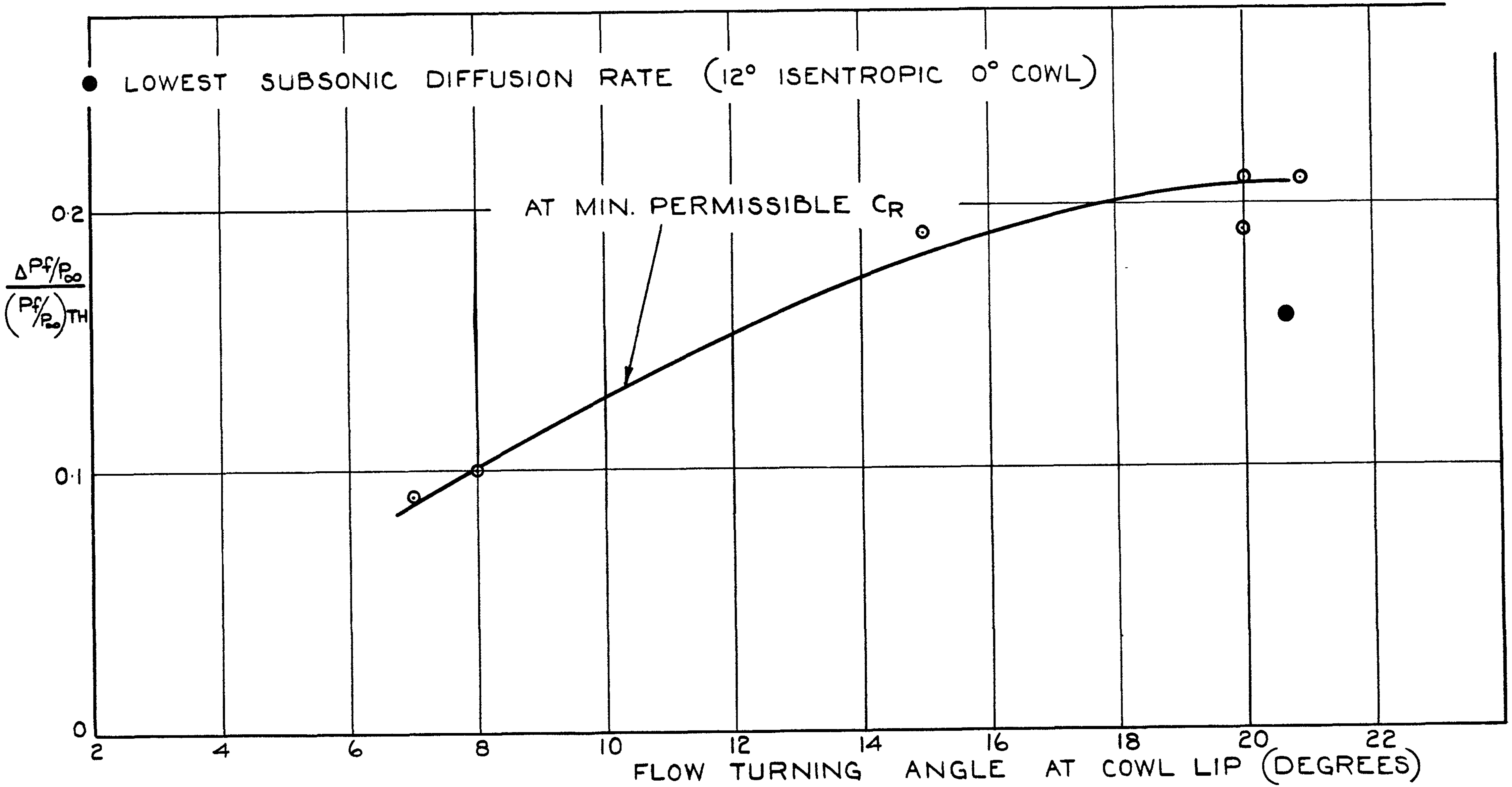


FIG. 14. EFFECT OF FLOW TURNING ANGLE AT COWL LIP ON LOSSES OTHER THAN SHOCK LOSSES.

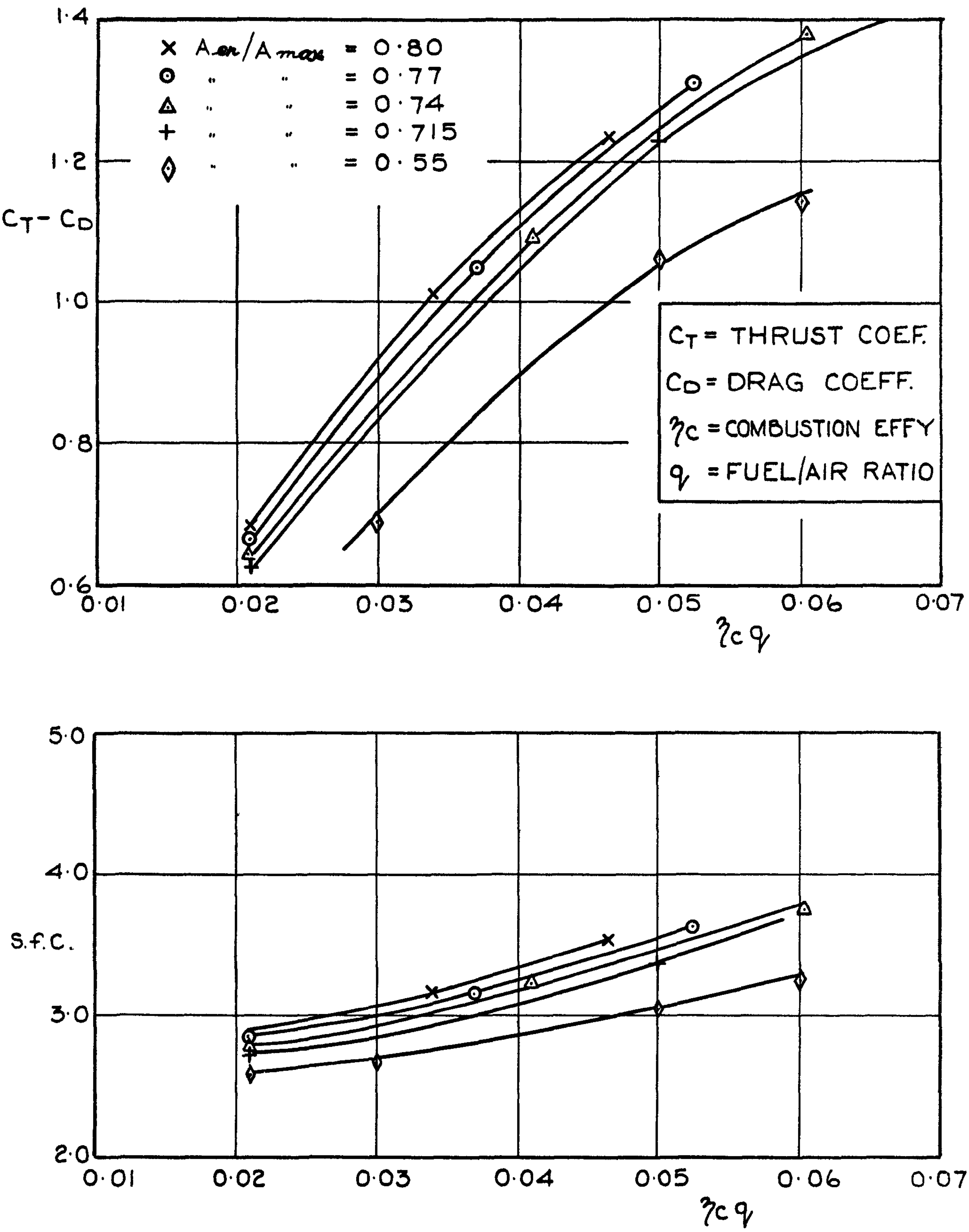


FIG. 15. VARIATION OF THRUST MINUS DRAG AND SPECIFIC FUEL CONSUMPTION FOR INTAKES HAVING DIFFERENT RATIOS OF A_{ENTRY} TO A_{MAX} & CONSTANT PRESSURE RECOVERY OF 0·615.

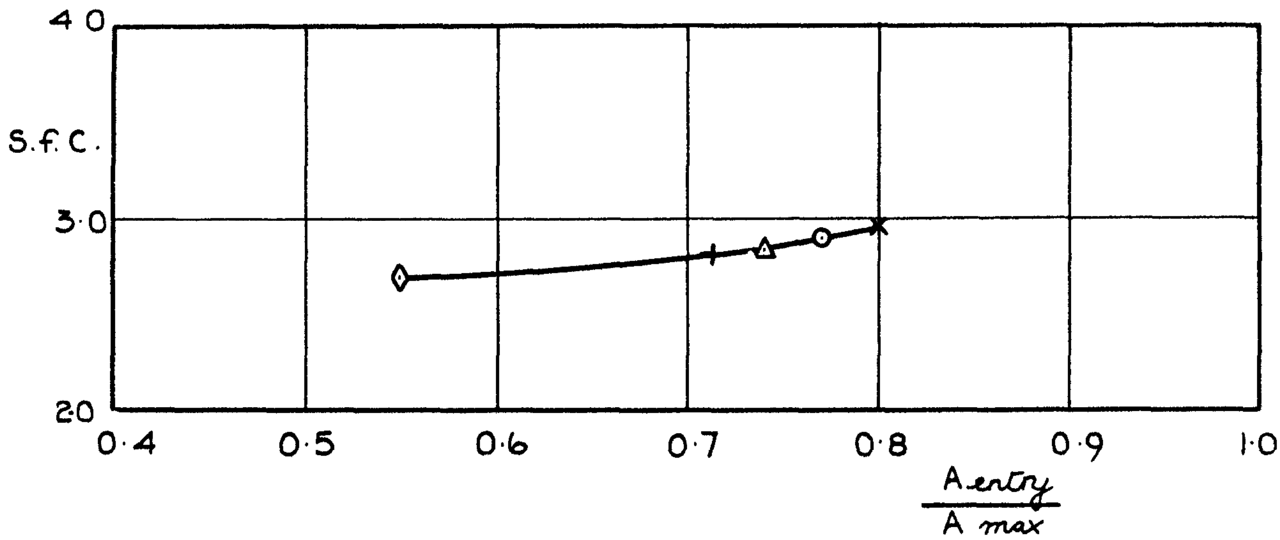


FIG. 16. VARIATION OF SPECIFIC FUEL CONSUMPTION WITH AENTRY / AMAX FOR $(C_T - C_D) = 0{\cdot}75$ FROM FIG. 15.

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533.697.2/3 :
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SOME CHARACTERISTICS OF RECTANGULAR MULTI-SHOCK AND ISENTROPIC EXTERNAL COMPRESSION INTAKES AT A MACH NUMBER OF 2.9. Dutton, R.A. and Goldsmith, E.L. September, 1961.

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Measured pressure recoveries varied from 5% to 20% below the calculated shock wave recovery value when employing the maximum permissible amount of internal contraction (i.e. that which will just allow the intake to 'start'). Variation of the internal contraction was found to have an appreciable influence on pressure recovery. With the best throat boundary

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layer bleed tested, the pressure recovery was increased by 10% over that without bleed.

Measured pressure recoveries have been used to calculate thrusts for comparative hypothetical ramjets. These have been combined with calculated external cowl drags for the different configurations to produce specific fuel consumption values for a given thrust minus drag.

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