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Model Tests on an Effuser Induction Scheme for operating a Transonic Wind Tunnel

by

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and
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SUMMARY

Model tests in a $^1/6$th scale rig on a proposed design for the 2 ft x $1\frac{1}{2}$ ft 'By-Pass' transonic wind tunnel are reported. To take advantage of the pressure ratio of 2.0 available at full scale, a two-dimensional supersonic nozzle, or "effuser", has been designed to expand the main stream from the working section up to a Mach number just above 2 at the point where it is vented to the plenum chamber, to induce re-entrant flow. The expansion is considerably larger than has been used in other known diffuser-suction wind tunnels, and appears to be capable of generating Mach numbers approaching 1.4 in the working section. The tunnel design may also be novel in that the model-support rig is to be situated upstream of the re-entry point.

The suction flow from the working section, and hence the tunnel Mach number, is to be regulated by re-entry doors. Characteristic curves of Mach number against door opening and overall pressure ratio were obtained. In addition the inflow through the doors was examined by Schlieren methods, using perspex-sided models, and extensive pressure plotting was carried out on the four effuser designs tested.

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LIST OF SYMBOLS

p	Static pressure
H	Stagnation pressure
B	Barometric pressure (i.e. tunnel outlet pressure)
M	Mach number
A/A^*	Stream tube area relative to a sonic throat
A	Cross sectional area in general
C,R,D,H	Suffixes referring to conditions in working section, at re-entry point (main stream flow), at re-entry point (inflow), and at hinge point respectively
Δ	Increase in boundary layer displacement area along working section (i.e. in displacement thickness X perimeter)
P	Pressure number (Reference 5).

1 Introduction

This report describes model tests leading to the design of an effuser-suction system for the 2 ft × $1\frac{1}{2}$ ft Transonic ('By-Pass') Tunnel which is at present being built in R.A.E. The tunnel is intended to make additional use of a 12 stage 8000 H.P. axial compressor, which was installed primarily to provide auxiliary suction for transonic operation of the 8 ft × 6 ft Wind Tunnel (the modified High Speed Wind Tunnel). By closing two valves, the full flow from this compressor can be directed through a by-pass line in which the new tunnel is to be situated. The maximum pressure ratio available from the compressor and the maximum volume flow at inlet pressure are about 3.5 and 4000 cu.ft/sec respectively. It was decided to make the throat size of the By-Pass Tunnel 2 ft × $1\frac{1}{2}$ ft, i.e. one-quarter of the corresponding linear dimensions of the larger tunnel. With this sized throat the maximum overall pressure ratio available is reduced to 2.0, but is still substantially greater than should be necessary for operating a diffuser-suction wind tunnel through the transonic range.

To take advantage of this large pressure ratio, a more elaborate suction scheme was tried out than had been used in other transonic tunnels of the same type. The conventional diffuser suction arrangement (Fig. 1) is that in which low pressures caused by expansion over a step at the downstream end of the working section induce flow through a transverse slot (possibly regulated by a flap) directly into the tunnel diffuser from a plenum chamber to which the working section is vented. In the system proposed for the By-Pass Tunnel, the expansion is to take place through a shaped nozzle or effuser which follows the working section, up to a Mach number a little over 2, at which point the low static pressure will be more effective in sucking a flow from the plenum chamber. At the same time it is desirable to be able to regulate the inflow and thus the tunnel Mach number mainly by the door position, holding pressure ratio fixed, since in this way stagnation pressure and Reynolds number can be kept approximately constant over the course of a series of Mach number changes.

In order to achieve the desired low pressures in the effuser it is necessary to ensure that the main tunnel shock wave system is located downstream of the flow re-entry point. It was found that this required careful shaping of the nozzle. The geometry of the re-entry region, which resembles an intake, also presented problems. Here two flows of different total heads are brought together, and shock waves originating from the mixing region were found to have a considerable effect on the efficiency of the induction process. In all, four effusers were tested in a 1/6th scale model rig before a satisfactory design was found. The effusers were extensively pressure-plotted, and the last two were built with perspex walls to allow a Schlieren examination of the re-entry region.

A design requirement of the tunnel is that the working section should be as nearly as possible a scaled-down replica of that in the 8 ft × 6 ft tunnel, which had already been designed on the basis of model tests described in Ref. 1. All the tests were carried out with a section slotted on all four walls, the side walls during some of the tests being of slotted glass as described in Ref. 2. No further tests on working section design were carried out, although it is possible that a design could have been found which would increase the maximum test. Mach number of the configuration above the limit of approximately 1.35 found in these tests*. The

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* By confining the suction to two walls only, as in several American diffuser-suction tunnels, the Mach number might have been increased, but at the expense of irregularities in distribution in the test section.

favourable Reynolds number effect in going to full scale should however give some improvement, and $M = 1.35$ is in any case well above the range at which the greatest changes in transonic flow take place.

2 Description of By-Pass Tunnel and Model Rig

2.1 General arrangement of tunnel

The general arrangement of the tunnel is indicated in Fig. 2. The working section is 54 in. long, and 24 in. × 18 in. in cross-section. It is followed by a 54 in. effuser of constant width (24 in.) expanding symmetrically in depth to approximately 30 in. and then by a constant-depth re-entry section in which the side walls are formed by doors of 18 in. chord, hinged vertically 32 in. apart along their downstream edges. Downstream of the hinge line is a slightly contracting section leading to the final diffuser via a second throat 32 in. × 27 in. in size. The whole tunnel from 33 in. upstream of the first throat to the second throat is enclosed in a 10 ft diameter plenum chamber. The working section is equipped with slotted glass side walls for Schlieren purposes, and with either perforated or slotted steel top and bottom walls. The first throat is 3 in. downstream of the beginning of the steel working section; slots and perforations commence at this station and close 3 in. ahead of the beginning of the effusor. A strut 1 in. thick with tapered leading and trailing edges, for supporting sting-mounted models, extends from $4\frac{1}{2}$ in. to 27 in. downstream of the working section - effusor junction, in the median vertical plane. The intended position for the C.G. of models is 16.2 ± 0.7 in. ahead of this junction.

2.2 Proposed method of operation

2.21 Generation of transonic flow

The Mach number in the working section is controlled, as in all transonic tunnels, by a suction flow through ventilated walls into a surrounding plenum chamber. At subsonic speeds the suction offsets the growth of the boundary layers on the walls, which would otherwise cause the working section to choke; at supersonic speeds it produces in addition an effective flow expansion, by removing some of the air passing through the throat.

The outflow takes place in the upstream part of the working section, where the static pressure in the tunnel is higher than that in the plenum chamber. Further downstream where uniform flow has been generated the pressures on either side of the ventilated walls are approximately equal. The outflow is balanced by an inflow from the plenum chamber at the effuser doors, where the static pressure of the main stream is now lower than that outside, as a result of the supersonic expansion in the effuser. The system is indicated in Fig. 3, which shows distributions of static pressure along the centre line at a number of test Mach numbers. The horizontal dashed lines show the plenum chamber pressure, and outflows and inflows are indicated by upward and downward arrows respectively.

The figure shows the effect of overall pressure ratio which is to fix the position of the system of oblique shock waves through which the supersonic flow breaks down in the initial part of the effuser. The longitudinal static pressure distribution is almost independent of pressure ratio but the lower the pressure ratio, the further forward the shock system occurs, and, in consequence, the higher is the pressure at the re-entry point. (In the figure, Mach number is plotted upwards and hence static pressure downwards).

2.22 Control of tunnel Mach number

The Mach number in the working section will be controlled both by the overall pressure ratio and by the amount of door opening. These controls are essentially independent, the pressure ratio determining the pressure at the inflow point, and the door opening determining the amount of inflow at a given pressure. The pressure ratio can be regulated up to the maximum of 2.0 either by means of a by-pass valve in a parallel line across the compressor, or by means of the rotor speed. The doors are to be motorised, and continuously controllable from the fully shut position up to an opening of 30°.

2.3 Test arrangements

The tests were carried out between July 1954 and April 1955 in the blowdown rig built for the tests of Ref. 1. This consisted of a $^{1}/6$th scale model of the proposed contraction, working section and diffuser, enclosed in a 27 in. diameter plenum chamber with Schlieren glass windows. The first throat was thus 4 in. x 3 in. in cross section. The drive was provided by the main reciprocating compressors used for evacuating the High Speed Tunnel, the outlet being to atmosphere. For the top pressure ratio of 2, the stagnation pressure was thus 2 atmospheres, which compares with the maximum of $^{2}/3$ of an atmosphere available in the By-Pass tunnel; the Reynolds number of the tests was thus between $^{1}/6$ and $^{1}/2$ of that attainable at full scale.

Pressure ratio was varied by adjusting the compressor outlet pressure by means of a bleed valve, and the diffuser doors could be put at any one of a number of fixed settings. In all the test results pressure ratio is given as $^{H}/B$. Here H is the compressor outlet pressure (i.e. the effective stagnation pressure upstream of the main shock system), and B is the barometric pressure.

3 Designs and performance of model effusers

3.1 Theoretical considerations

3.11 Design Conditions

The table below shows the conditions for which the successive effusors were designed. p, H, M, $^{A}/A^{*}$ are used for static pressure, total pressure, Mach number and stream - tube area relative to a sonic throat, respectively; suffixes C and R refer to conditions in the working section and in the main stream at the re-entry point. The area expansion of the effuser from inlet (i.e. the working section end) to the re-entry point is thus $^{A}R/A_C$. (The sonic throat corresponding to flow with Mach number M_R across an area A_R is smaller than the throat of the tunnel in the ratio $^{A^*}/A_C$; the remainder of the air passing through the throat of the tunnel is removed by working-section suction).

The ratio $^{p}R/p_C$ is the effective static/stagnation pressure ratio for the inflow at the doors, since p_C is the stagnation pressure in the plenum chamber; a nominal Mach number M_D for the inflow has been obtained from this ratio.

The door characteristics are plotted in the form of working section Mach number M_C against a non-dimensional door opening $^{A}D/A_C$. Here A_D is the area of door opening normal to the main-stream, and A_C the effuser inlet area (i.e. 12 square inches).

The table shows also the quantity $^{A}H/A_C$, where A_H is the cross-sectional area at the plane of the hinge lines.

TABLE I

Design conditions of supersonic effusors

(For symbols see section 3.11 above)

Model Number	Design Method	M_C	$\frac{A^*}{A_C}$	$\frac{p_C}{H}$	$\frac{A_R}{A_C}$	$\frac{A^*}{A_R}$	M_R	$\frac{p_R}{H}$	$\frac{p_R}{p_C}$	M_D	$\frac{A_H}{A_C}$	$\frac{A_D}{A_C}$ design
1	One dimensional theory-faired shape	1.200	0.971	0.412	1.283	0.756	1.684	0.208	0.503	1.041	1.478	-
2	Analytical-Atkins method	1.400	0.897	0.314	1.372	0.654	1.830 (wall) 1.905	0.166 (wall)	0.528	1.000	1.938	0.478
3	Graphical by characteristics (Sharp throat, minimum length)	1 401	0.897	0.314	1.760	0.509	2.176	0.097	0.309	1.411	2.388	0.433
4	Graphical by characteristics (Smooth entry, minimum length)	1.366	0.912	0.330	1.619	0.563	2.061	0.116	0.353	1.317	2.159	0.478

The theoretical pressure distributions along the centre lines and side walls of all four effusors, in their design conditions, are shown in Fig. 4.

3.12 Estimates of suction quantities

According to inviscid isentropic flow theory, the suction mass flow necessary to generate a Mach number M_C in the working section is a fraction $\left(\frac{A_C}{A^*} - 1\right)$ of the mass flow through the throat; in addition to this a further amount Δ/A^*, where Δ is the increase in boundary layer displacement area along the working section, must be removed. Assuming the boundary layer starts from the throat, Δ/A^* may be written as (Perimeter/Area) × δ_1, where δ_1 is the displacement thickness at the downstream end of the working section. From formulae for boundary layer growth on solid walls δ_1 has been estimated as approximately 0.021 in. in the conditions of the tests, and thus Δ/A^* as $14 \times 0.021/12 = 0.025$. This amount of boundary layer growth would correspond to choking in the absence of suction at the subsonic Mach number for which $A/A^* = 1.025$, namely $M = 0.835$. This is of the correct order, but an approximate curve of suction flow deduced from the door opening area (Fig. 5) suggests that a more accurate value for Δ/A^* is about 0.06, corresponding to choking without suction at $M = 0.75$. In fact the choking Mach number varied between 0.7 and 0.8 in the tests, increasing with increasing pressure ratio as a result of the accompanying increase in Reynolds Number.

3.2 Description of Effusors

3.21 Effuser 1 (Fig. 6)

The first effuser tested was designed to have a smooth Mach number distribution on the basis of one-dimensional theory, the overall expansion being sufficient to provide sonic inflow through the doors with $M_C = 1.2$ in the working section. The breadth was increased fairly sharply opposite the leading edge of the model-support strut to offset the solid blockage.

Re-entry doors were fitted in all four walls. The leading edges took the form of 30° wedges, and could be closed to a flush fit on corresponding wedges at the downstream end of the effusor. With the doors closed, the effusers walls formed a faired shape through the re-entry section, without the sudden increase in cross-section at the hinge line to allow for inflow volume which was provided in the later effusers.

The observed characteristics of the working section-effuser combination are shown in Fig. 11. The highest working section Mach number obtained was 1.28, with a pressure ratio of 2. As shown in the right hand diagram, increases in door opening A_D/A_C increased the Mach number up to a limit depending on the pressure ratio; but at all pressure ratios this limit was reached with A_D/A_C less than $\frac{1}{2}$ - further increases in A_D/A_C producing no gain in M_C. For a given A_D/A_C below this limit, the same M_C was obtained with either 2 or 4 doors open; thus there was no advantage in having 4 doors. Fig. 12 shows the Mach number distribution along a side wall at a number of pressure ratios. The distributions are affected by shock waves from the strut.

In all, the characteristics of this combination showed no great improvement over what could have been obtained with the more usual arrangement indicated in Fig. 1. This was attributed in part to the pressure difference $p_R - p_C$ being insufficient to induce a large re-entry flow, and in part to the wedge-shaped edges of the return doors, which produced shock losses due to the mixing of inlet and main stream flows at a finite angle.

3.22 Effuser 2 (Fig. 7)

It was next thought worthwhile to design a nozzle analytically to produce shock-free supersonic flow. It also seemed that stable re-entry conditions were more likely to be achieved if both the re-entrant and the main stream flows continued to expand supersonically for some distance downstream of the door opening. To secure this in the design conditions (M_C = 1.400, which was assumed to require A_D/A_C = 0.4775 with sonic inflow), the doors were shaped so that the static pressure distribution on the dividing streamline as computed for the inflow was the same as that computed for the main stream. The nozzle design was thus continued beyond the re-entry point, at which the Mach number at the wall was to be 1.830, up to a uniform parallel stream Mach number 1.963 at the hinge line. The analytical method of Atkin[3,4] in which a Busemann nozzle and a reversed Busemann nozzle are connected by a region of radial flow, was used to determine the effuser shape, and the bounding streamline of the main flow. Calculations for the inflow were done by one-dimensional theory.

Smooth entry flow was achieved by means of a feather edge at the downstream end of the effuser. The doors were fitted on the top and bottom walls only*.

With this arrangement the maximum working section Mach number was increased to M_C = 1.34. The characteristics of the section are shown in Fig. 13. The control by means of door opening is sensitive, as shown by the sharp rise in the curves of M_C against A_D/A_C, which are already close to their maxima at A_D/A_C = 0.2.

The distribution of Mach number along the centre line for a range of pressure ratios is shown in Fig. 14, and is seen to follow the design distribution fairly closely up to the point where the flow is broken down by the shock system.

3.23 Effuser 3 (Fig. 8)

The results obtained from Effuser 2 showed that the efficiency of the induction system had been considerably improved by the use of a theoretically shock-free nozzle shape and by the feather-edge intake. It appeared that further improvements in test Mach number might be obtained by carrying the expansion to a higher re-entry Mach number M_R. In the Atkin method M_R had been limited by the available length of nozzle (nozzles designed by the method being considerably greater in length than the minimum for a given expansion). A minimum length nozzle with a sharp throat was therefore designed graphically by the method of characteristics, as described by Temple[5], the construction being indicated in Fig. 10. The minimum length nozzle is obtained by means of a sharp throat, at which a Prandtl-Meyer expansion occurs abruptly** In Temple's notation the nozzle was designed for expansion from parallel flow at pressure number P = 991 (M_C = 1.401) to P = 969 (M_R= 2.177). The nozzle contour was constructed from straight-line segments in the flow direction at a series of consecutive mesh lines,

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* In the full scale tunnel the doors are to be in the side walls only; the model with top and bottom doors will, however, represent this adequately provided the main stream flow in the re-entry section is in fact uniform and parallel.

** This method can only be used when the initial uniform stream is supersonic, i.e. not for M = 1. A family of nozzles similar to that used here has been constructed by Shames and Seashore[6].

and the overall expansion ratio obtained in this way was within a fraction of one per cent of that deduced from one-dimensional isentropic flow tables.

The test results, shown in Figs. 15 and 16, are broadly similar to those obtained from Effuser 2. The main differences are (i) a slightly greater pressure ratio than hitherto was required to reach M = 1 in the working section; (ii) the Mach number was less sensitive to door opening than before, and the maximum Mach number, at pressure ratio 2.0, was slightly higher (M_C = 1.36) than before; (iii) with pressure ratio of 1.8 or more, the characteristic showed a decrease in M_C as the door-opening A_D/A_C was increased beyond about 0.35.

Schlieren studies of the flow in the vicinity of the doors, discussed more fully in Section 4, showed the last effect to be due to a change from subsonic to supersonic inlet flow with a resulting decrease in inlet volume.

A further effect not previously found was a choking at the downstream end of the working section at supersonic test Mach numbers, instead of a continuous expansion into the effuser. This was attributed to boundary layer separations at the sharp throat, and resulted in the effuser running in a slightly off-design condition, the expansion beginning at M = 1. (The effect on the working-section was a more serious disadvantage). The plot of centre line pressures (Fig. 16) at the design door setting shows premature shock formation ahead of the doors, and it was concluded that the expansion ratio was too great for the available pressure ratio.

3.24 Effuser 4 (Fig. 9)

This was designed by characteristics to have a smooth entry and an expansion ratio mid-way between those of effusers 2 and 3; in Temple's notation the pressure numbers of the initial and final parallel flows were taken as P = 992 (M_C = 1.366) and P = 972 (M_R = 2.059). The theoretical pressure distributions are shown in Fig. 4. They are compared with the observed centre line distribution together with the calculated distribution for a particular off-design case (P = 996, M_C = 1.218) in Fig. 18.

The characteristics of the working section-effusor combination are shown in Fig. 17. The maximum Mach number with a pressure ratio of 2.0 was 1.34* as for effuser 2, but in this case there was no tendency for the Mach number to decrease with excessive door opening, the inflow being subsonic under all conditions. At the higher pressure ratios the curves of M_C against A_D/A_C are still increasing at A_D/A_C = 1, and the slope of the characteristics at all pressure ratios is less than the corresponding slope for effusers 2 and 3. Thus tunnel control by means of door-opening should be more accurate with this design, and the upward trend in the characteristics at all door-openings indicates that higher Mach numbers could be generated if the working section were suitable.

4 Schlieren studies of re-entry flow

The last two effusers were made with plane sides of $\frac{1}{2}$ in. perspex sheet to permit Schlieren examination of the re-entry region. Flow photographs from effuser 4 under a variety of conditions are shown in Figs. 20 and 21.

Figs. 20(b) to (d) show the effect of changes in pressure ratio on the flow with a fixed door opening. Fig. 20(a) is taken with wind off to show markings on the perspex which are common to all the photographs. At the two lower pressure ratios (Figs. 20(b) and (c)) the inflow is subsonic, and the slip plane separating it from the main flow

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* The working section in this series of tests was slightly changed by the introduction of local divergence over the rear inch, and exact comparisons of Mach number are not possible.

is forced inwards, the resulting rise in pressure causing a large λ-shock wave in the main stream. At $^H/_B = 1.98$ (Fig. 20(d)) however, the main stream remains supersonic through the re-entry section and the low pressures along the slip plane induce supersonic inflow as shown by the shock wave in the inflow stream originating at the feather edge.

Figs. 21(a) to (d) show the effect of changes in the door opening at an approximately constant $^H/_B = 1.95$. For this series of photographs a horizontal knife edge was used, to show density changes between planes parallel to the stream. The first photograph $^{A_D}/_{A_C} = 0.24$ shows almost the same pattern as that of Fig. 20(d). With the horizontal knife edge the slip plane is clearly visible, and a shock induced separation on the door can also be seen. In the three succeeding photographs the inflow has become subsonic as a result of the increase in door opening, and the slip plane is displaced inwards, causing again the λ-shock pattern in the main flow. At the same time a subsonic boundary layer separation from the nose of the door has taken place, possibly because the diffusion angle between the door and the slip plane is too severe. Later tests suggested that this separation could be postponed by means of a bulbous fairing on the outside of the leading edge, such as is indicated in Fig. 9.

From this series of photographs it appears that the opening of the doors has two opposing effects: (i) an increased inflow volume can be accommodated, and (ii) the constriction caused by the diffusion of the incoming air alters the shock pattern in such a way as to reduce the negative pressure available for inducing the inflow. The characteristics of M_C against $^{A_D}/_{A_C}$ shown in Figs. 11, 13, 15 and 17, indicate the balance between these effects which has actually been achieved.

Flow photographs markedly similar to these are presented by Holder, Chinneck, and Gadd in Ref. 7. In their investigation an injected stream of controllable Mach number was induced to flow between a solid wall and a parallel uniform supersonic stream. When the injected stream was supersonic Holder, Chinneck and Gadd obtained a flow virtually identical to that of Fig. 21(a), including in particular the "lip shock" from the feather edge and its reflection from the wall. Comparison in the subsonic case is more difficult as in the NPL tests the free stream flow was unaffected by the inflow. However in these tests as in the present ones, the slip plane retained its form without excessive mixing for a considerable distance, even when bounded on one side by a subsonic stream.

5 Conclusions

Model tests have shown it possible to operate a transonic wind tunnel up to Mach numbers of 1.35 or more by suction induced into a supersonic nozzle, downstream of the working section through a surrounding plenum chamber. The optimum nozzle design appears to be one for which the main stream flow in the re-entry region is uniform and parallel; this requires a two-dimensional nozzle designed by the method of characteristics. With an overall pressure ratio of 2.0 for the tunnel, the optimum nozzle expands the flow to a uniform Mach number of 2; a larger expansion produces premature flow breakdown by means of shock waves ahead of the re-entry point.

With overall pressure ratio fixed, the tunnel Mach number can be controlled accurately by varying the opening of doors which permit inflow to the effusor. These doors must have hinges offset in such a way as to allow room for the inflow to remain parallel to the main stream for some distance. Schlieren studies of the re-entry flow show that it is governed by a complicated interaction with the shock pattern in the main stream.

A scaled-up version of the final effuser tested, number 4, appears suitable for use in the 2 ft × 1½ ft transonic (By-Pass) Tunnel. With favourable scale effect this should enable test Mach numbers of nearly 1.4 to be obtained in the working section. These are substantially higher than have hitherto been obtained in diffuser-suction transonic wind tunnels; moreover in the present case supersonic flow in the working section is generated by suction through all four walls, instead of through two as is more usual. The design is believed to be novel in securing the flow expansion downstream of the working section by means of a shaped nozzle, and also in that the inflow re-enters the tunnel downstream of the model support rig.

6 Acknowledgement

The graphical construction of the nozzles for effusers 3 and 4 was done by Mr. J.A. Beasley.

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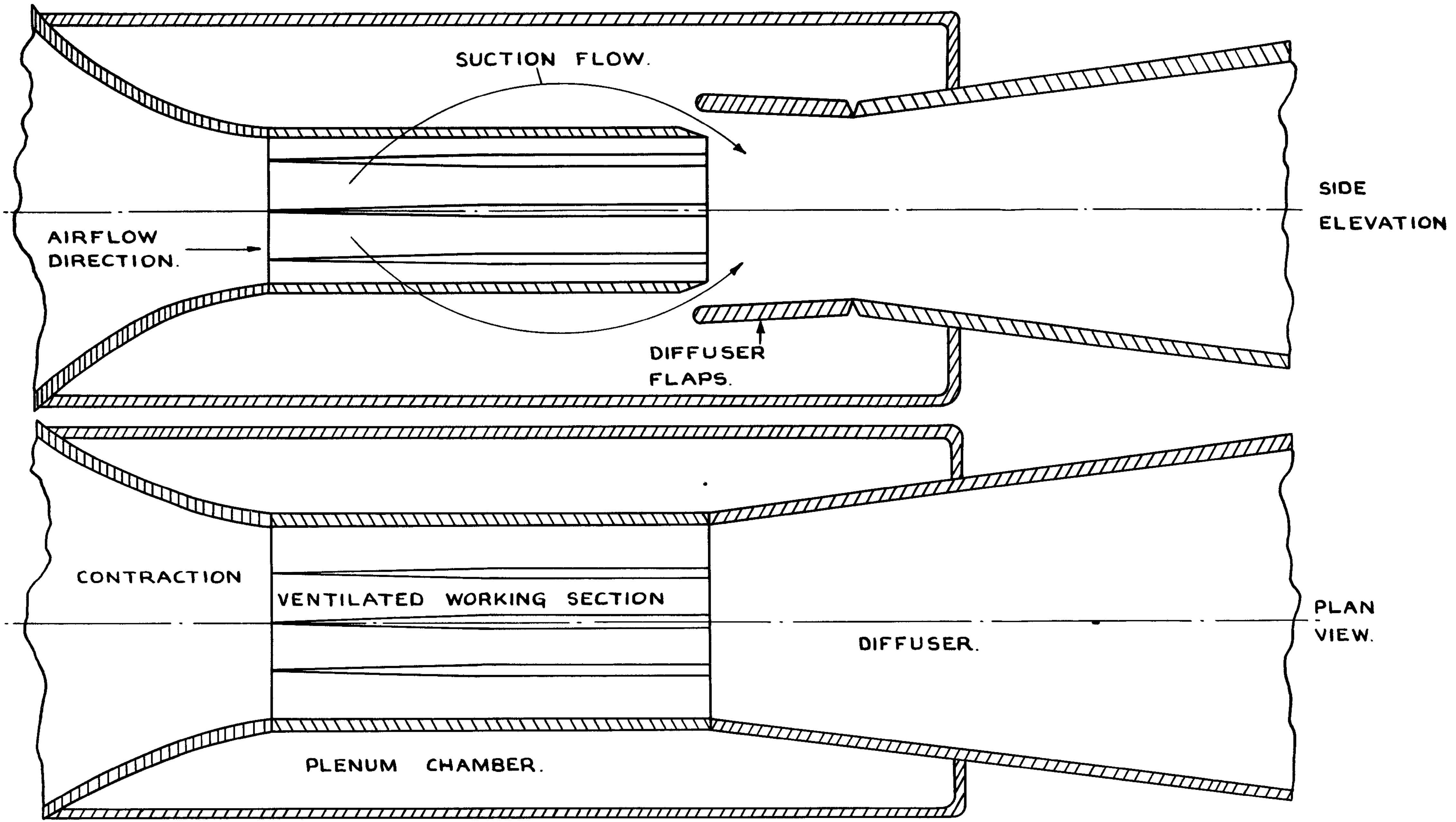
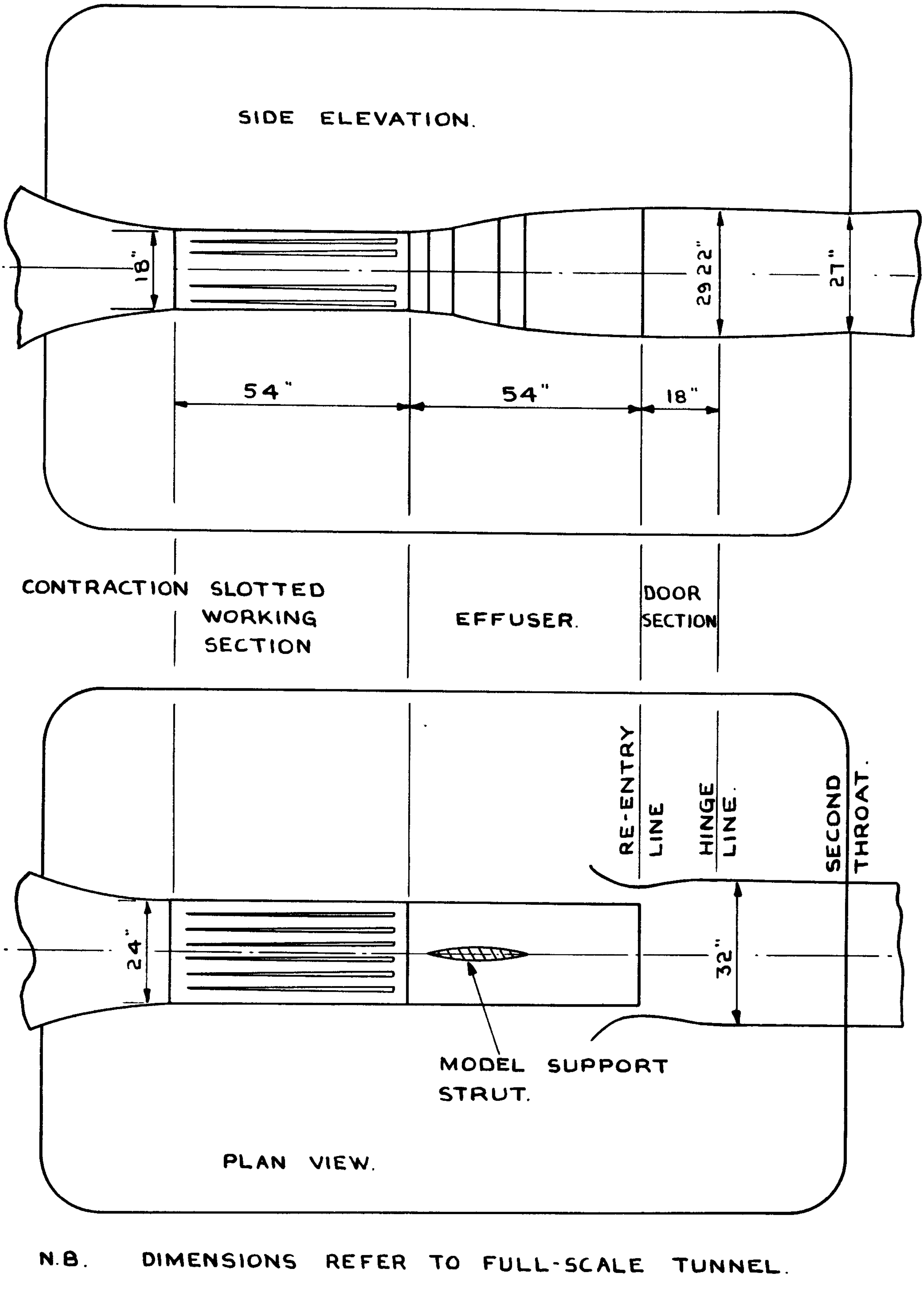
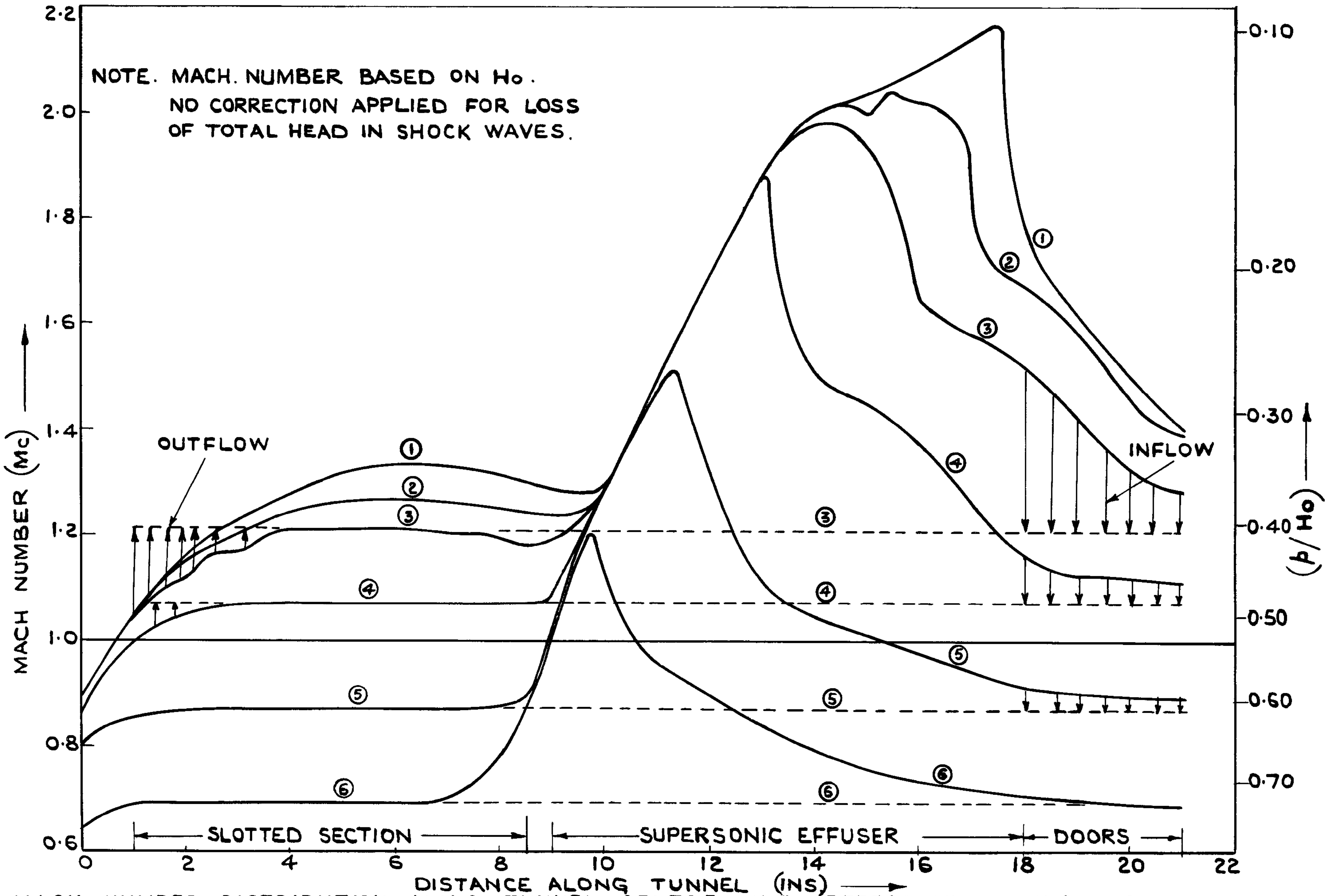


FIG. 1. TYPICAL ARRANGEMENT OF A DIFFUSER-SUCTION TRANSONIC WIND TUNNEL.



N.B. DIMENSIONS REFER TO FULL-SCALE TUNNEL.

FIG. 2. GENERAL ARRANGEMENT OF 2 FT. X $1\frac{1}{2}$ FT. (BY-PASS) TUNNEL.


NOTE. MACH. NUMBER BASED ON Ho.
NO CORRECTION APPLIED FOR LOSS
OF TOTAL HEAD IN SHOCK WAVES.

CURVE	Mc	H/B
1	1.33	2.00
2	1.26	1.87
3	1.22	1.71
4	1.08	1.53
5	0.88	1.35
6	0.71	1.20

FIG. 3. MACH NUMBER DISTRIBUTION ALONG TUNNEL CENTRE LINE – EFFECT OF VARYING PRESSURE RATIO
DOOR OPENING FIXED AT $\frac{A_D}{A_C} = 0.43$ (EFFUSER 3).

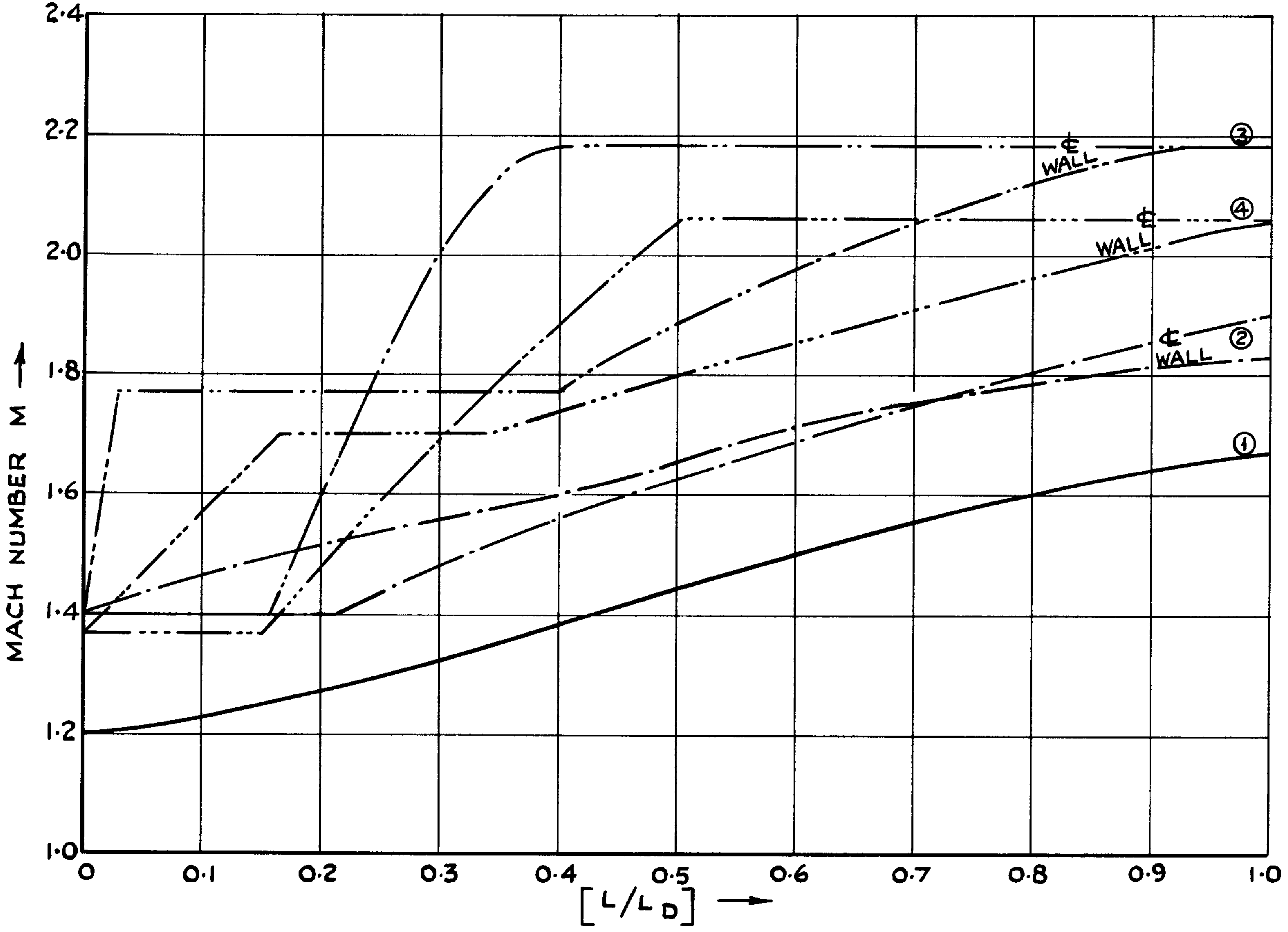


FIG. 4. COMPARISON OF THEORETICAL MACH NUMBER DISTRIBUTIONS FOR FOUR EFFUSERS.

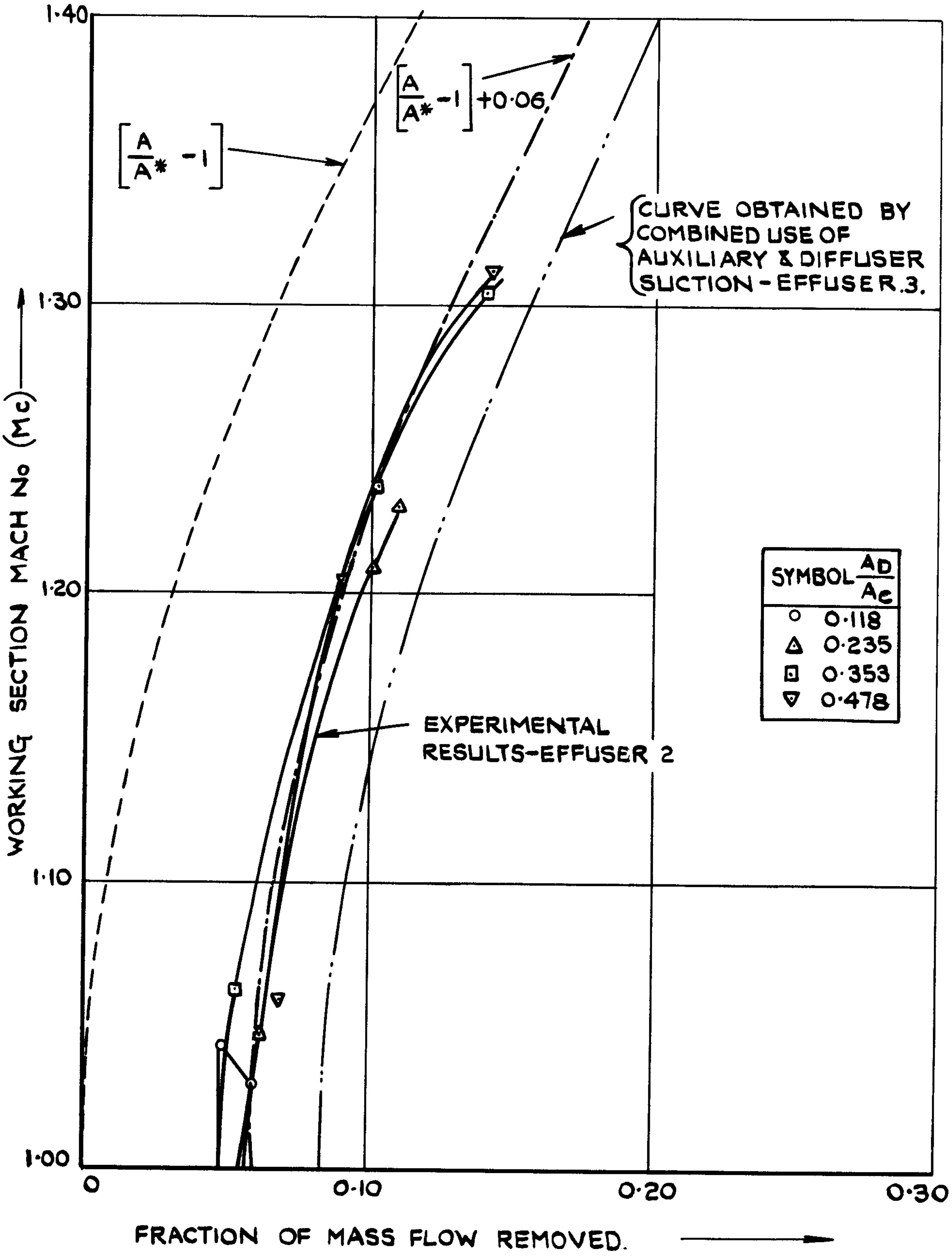


FIG.5. SUCTION CURVES FOR WORKING SECTION DERIVED FROM TESTS IN EFFUSERS 2 AND 3

NOTE: FIGURES 6-9 SHOW ONE RE-ENTRY DOOR OPEN AND ONE CLOSED TO INDICATE BOTH POSITIONS. IN PRACTICE THEY ARE OPENED SYMMETRICALLY.

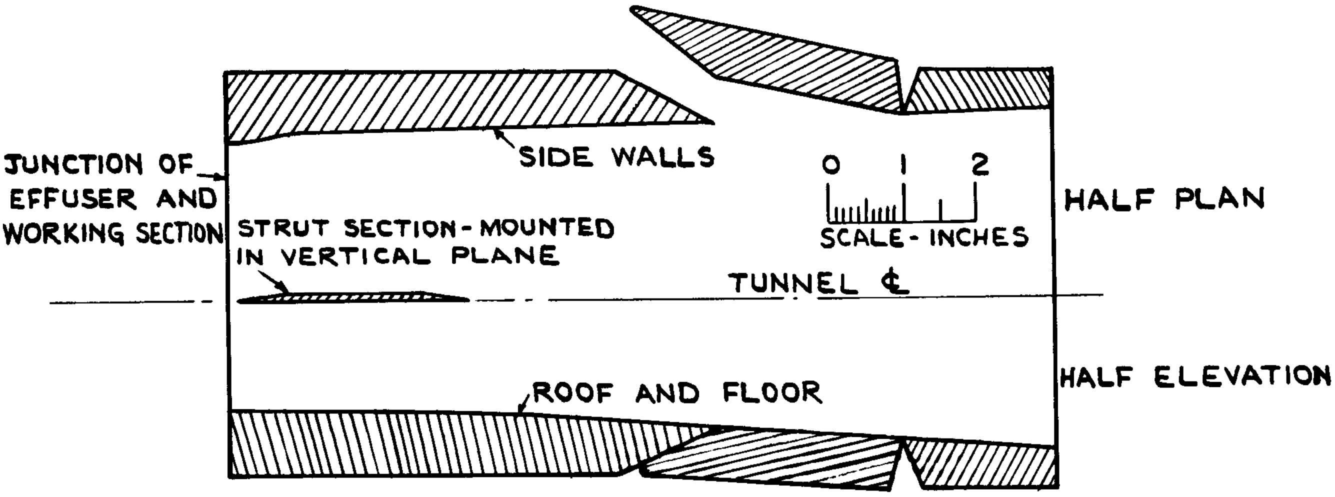


FIG.6. VERTICAL AND HORIZONTAL CROSS-SECTIONS OF EFFUSER I

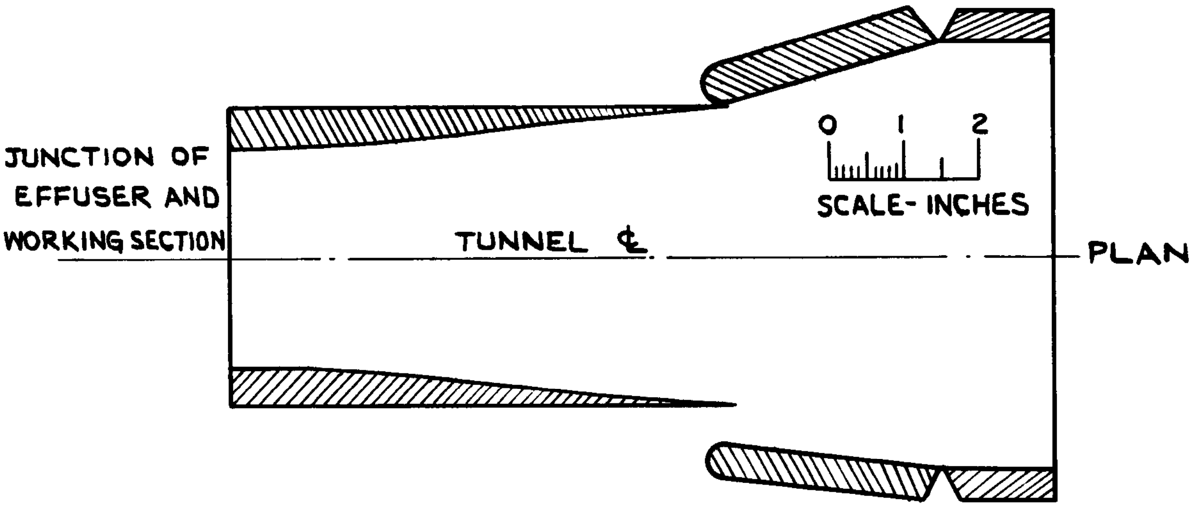


FIG 7. CROSS SECTION OF EFFUSER 2.- CHANNEL WIDTH-4·167".

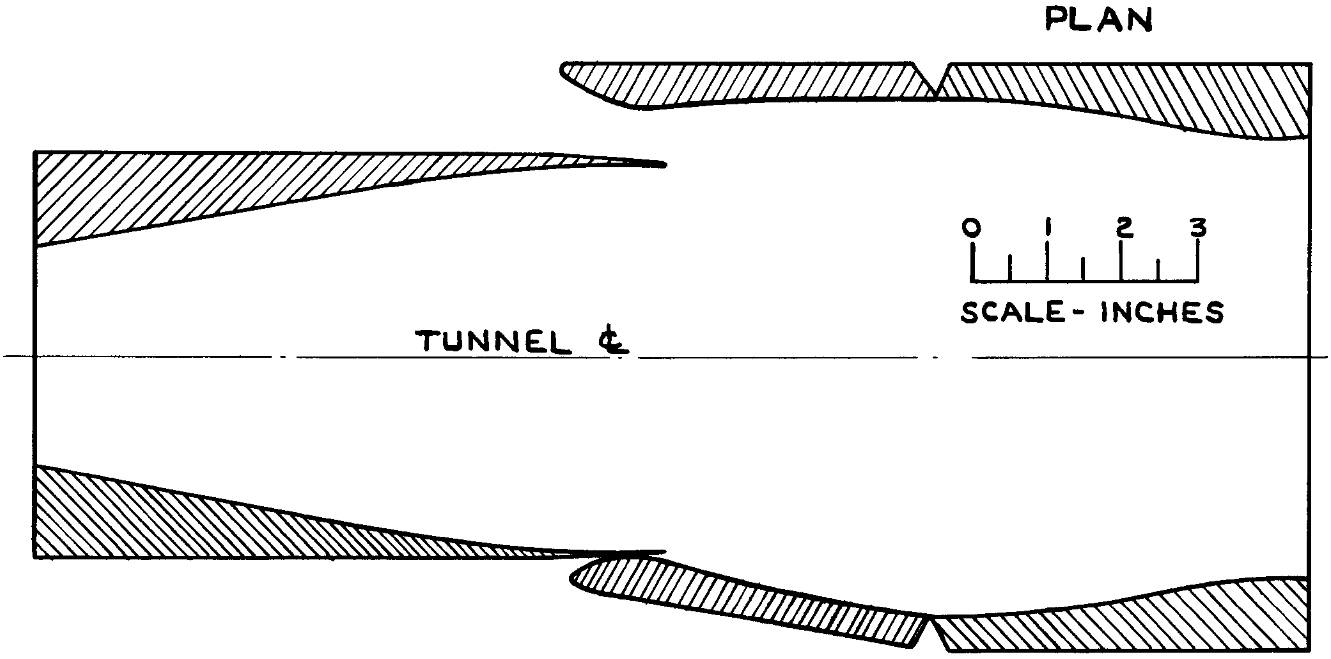


FIG 8. SECTION OF EFFUSER 3 - CHANNEL WIDTH 4·167".

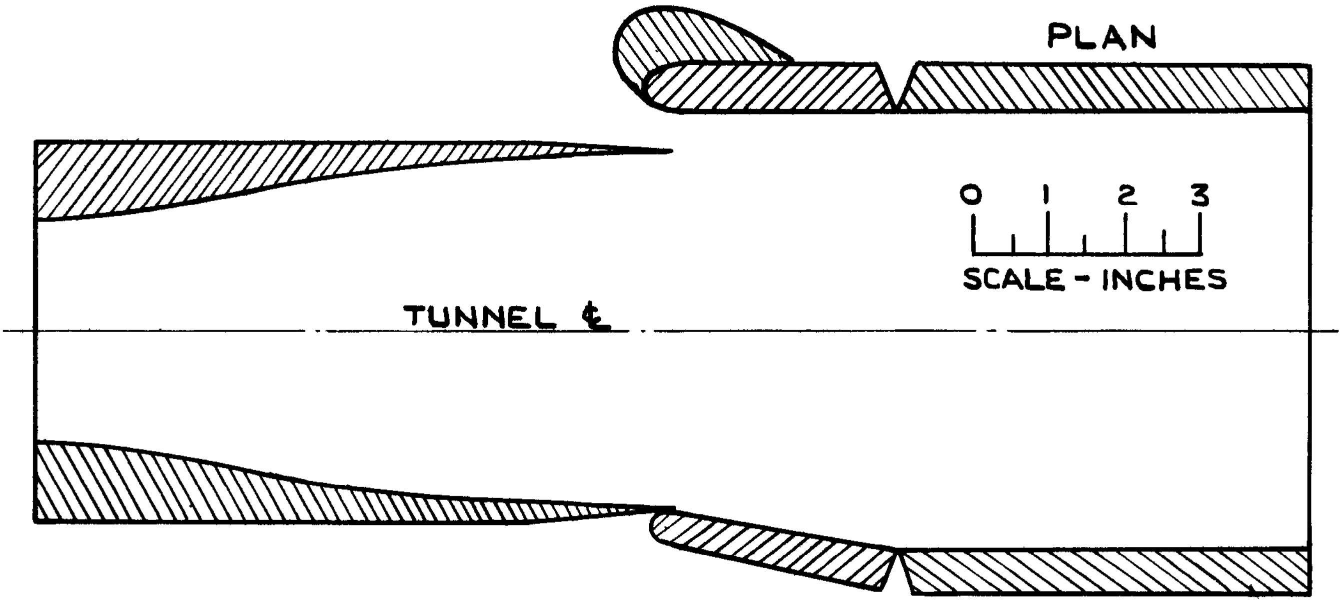
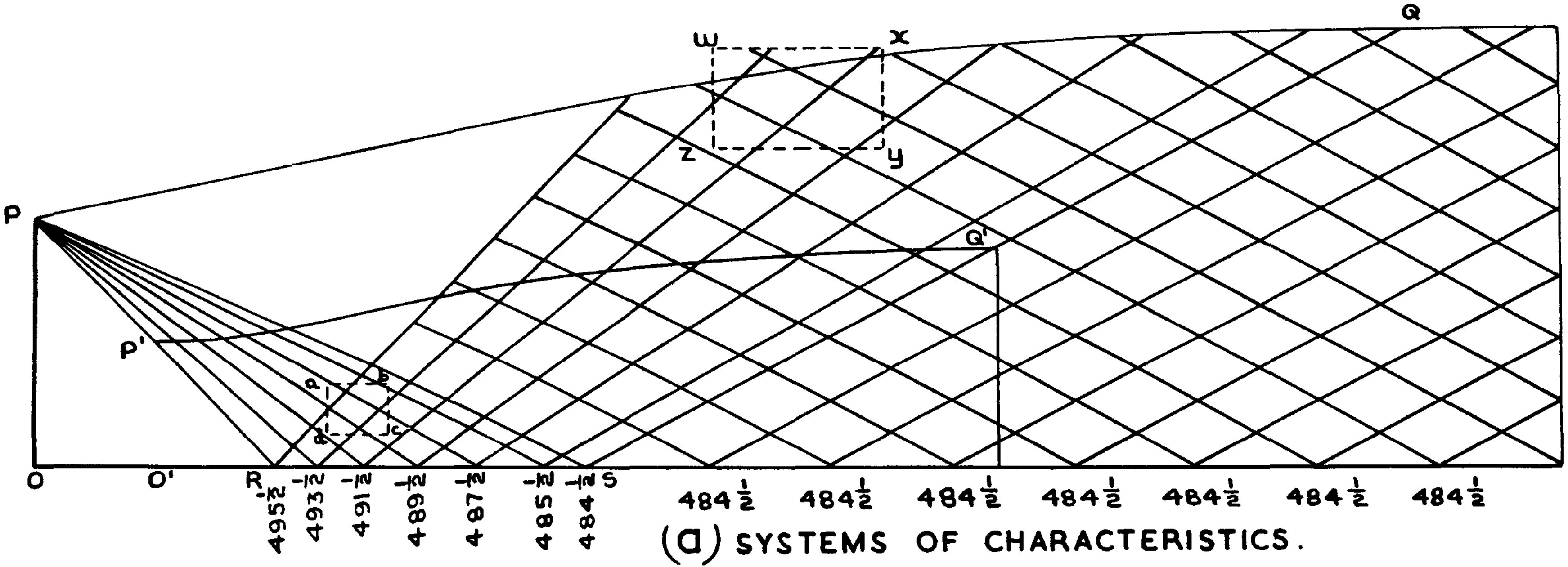
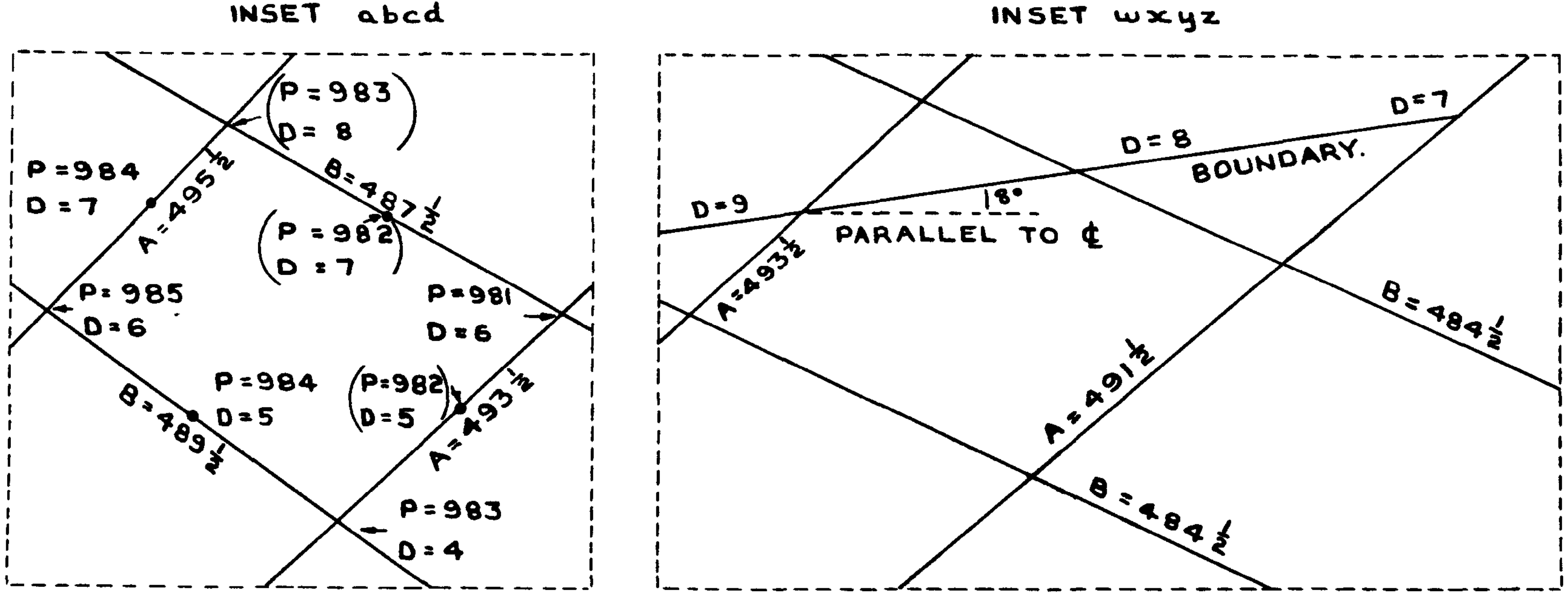


FIG. 9. SECTION OF EFFUSER 4 - CHANNEL WIDTH 4·167".



(a) SYSTEMS OF CHARACTERISTICS.



(b) CONSTRUCTION OF ELEMENTARY RECTANGLE.

(c) CONSTRUCTION OF STREAMLINE BOUNDARY.

FIG. 10 (a, b & c) CONSTRUCTION OF SHARP-EDGED (MINIMUM LENGTH) NOZZLE BY METHOD OF CHARACTERISTICS.

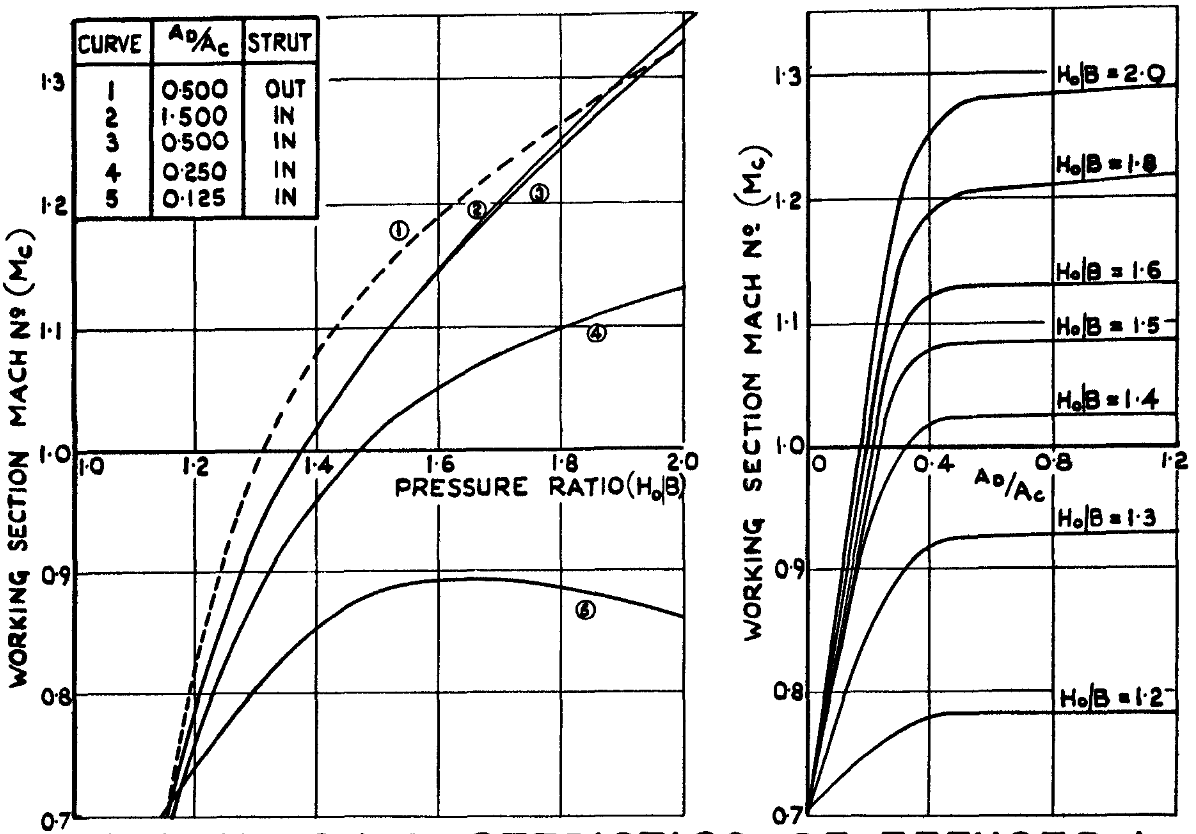


FIG. 11. CHARACTERISTICS OF EFFUSER 1. (INCIDENCE STRUT IN POSITION)

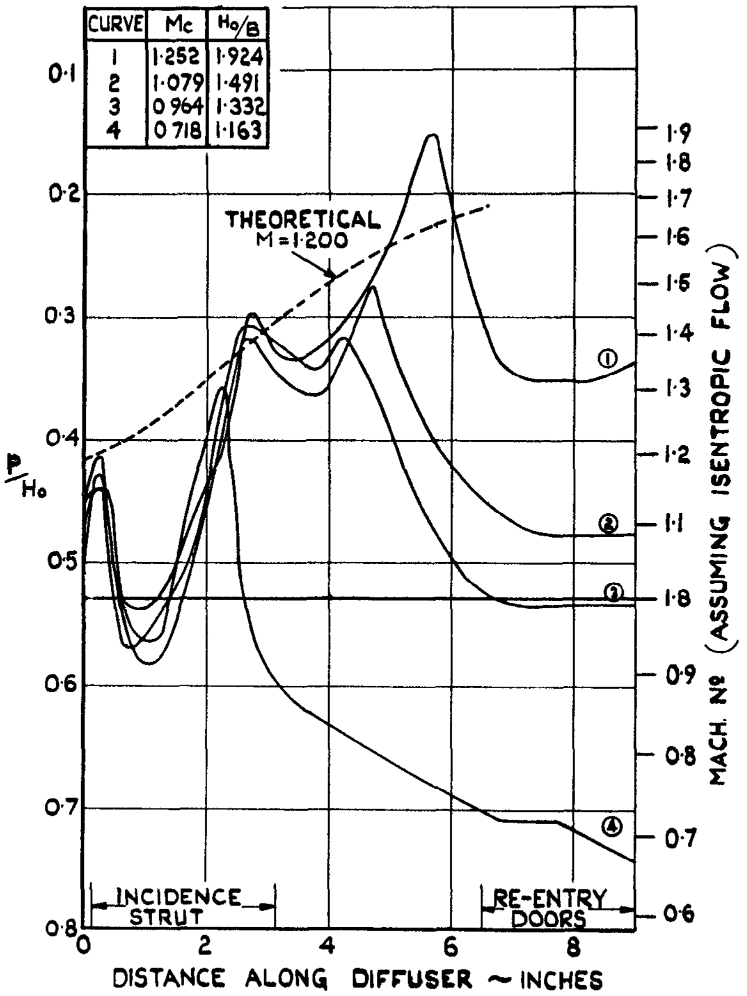


FIG. 12. CENTRE-LINE PRESSURE DISTRIBUTION IN EFFUSER 1: INCIDENCE STRUT IN POSITION $(A_D/A_C = 0{\cdot}5)$

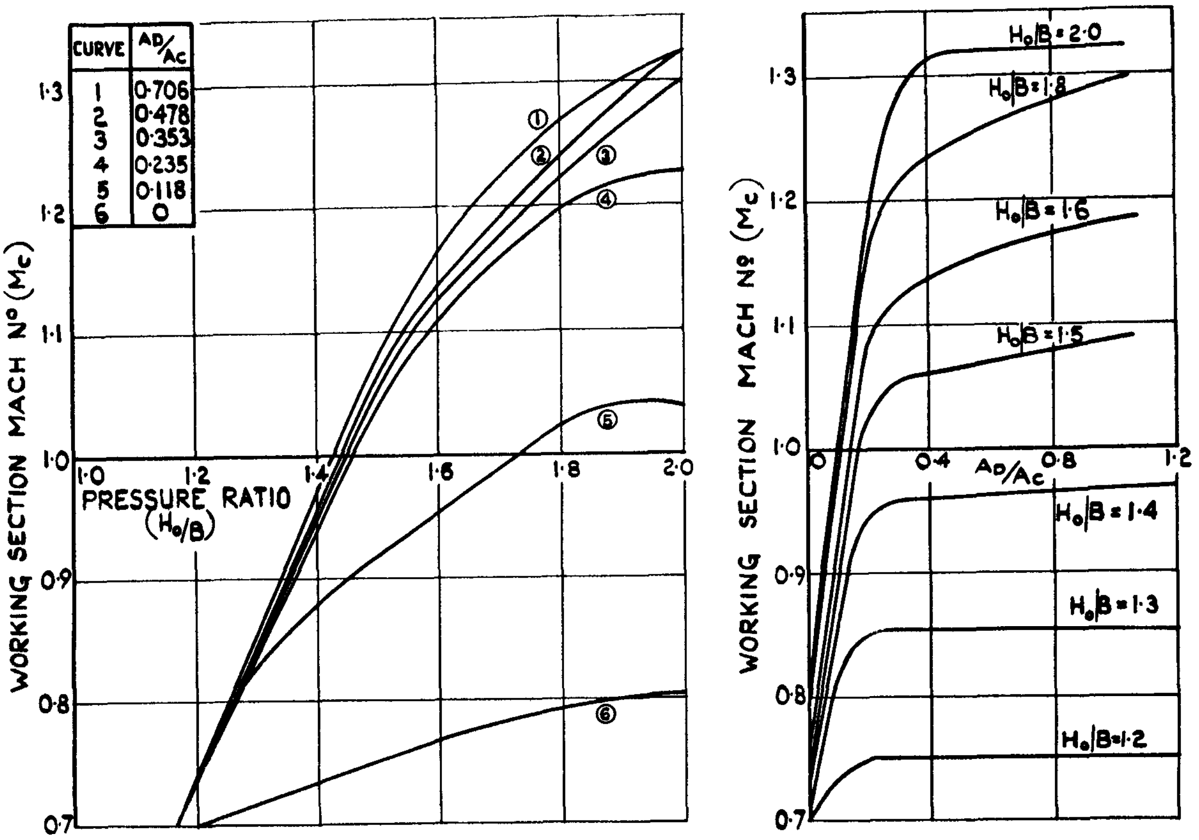


FIG. 13. CHARACTERISTICS OF EFFUSER 2.

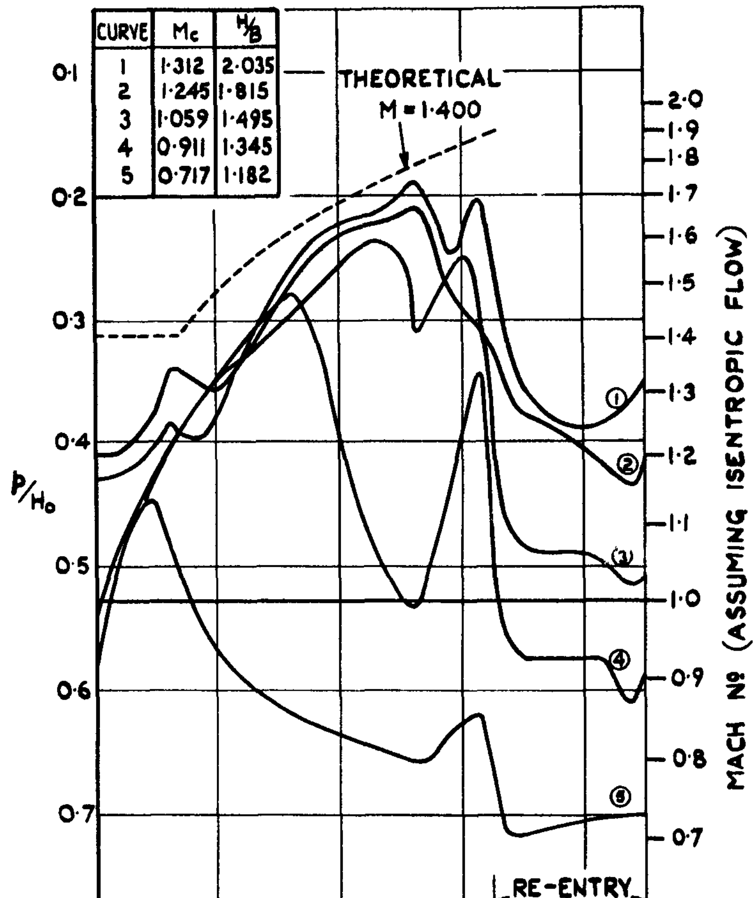


FIG. 14. CENTRE-LINE PRESSURE DISTRIBUTION IN EFFUSER 2 $(A_D/A_C = 0{\cdot}478)$.

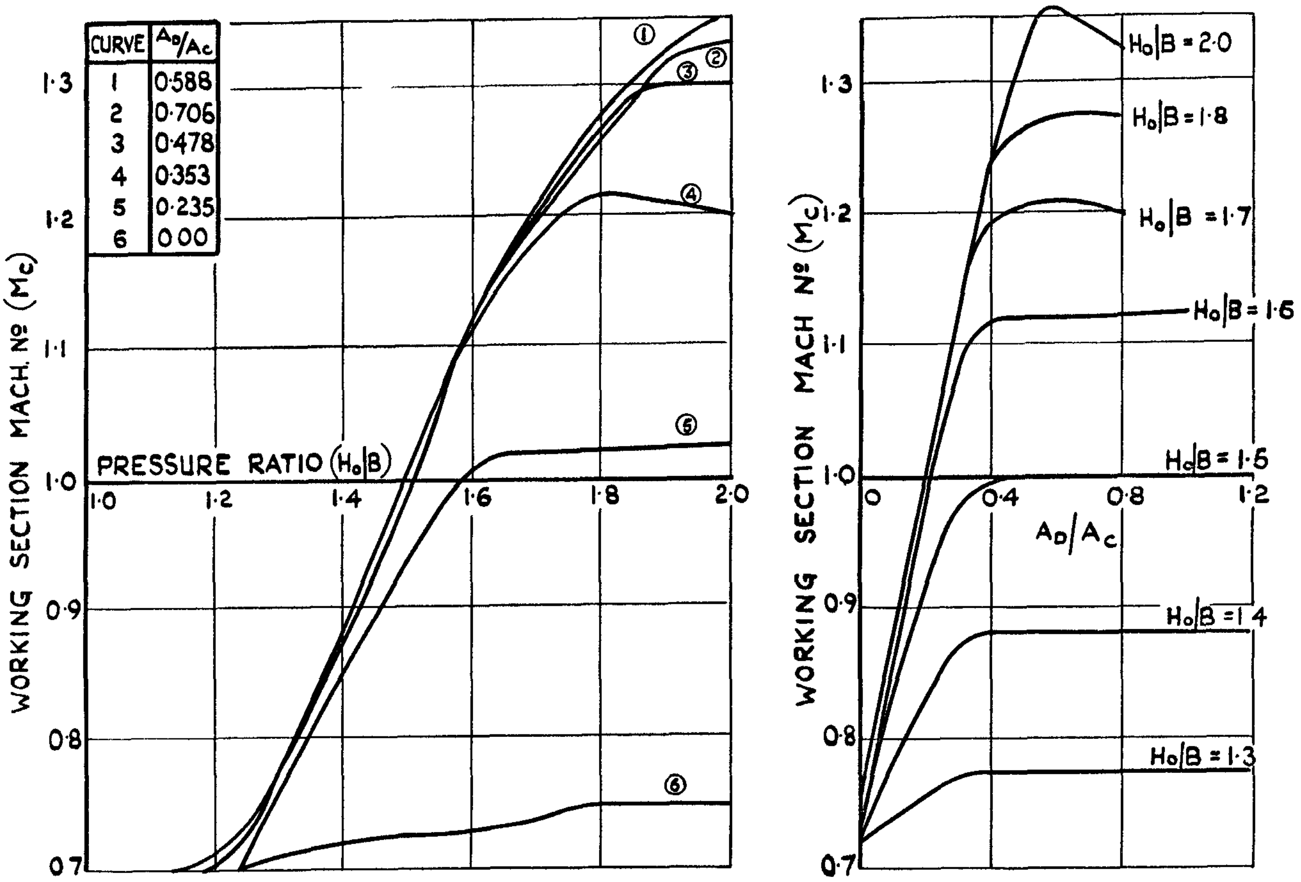


FIG. 15. CHARACTERISTICS OF EFFUSER 3.

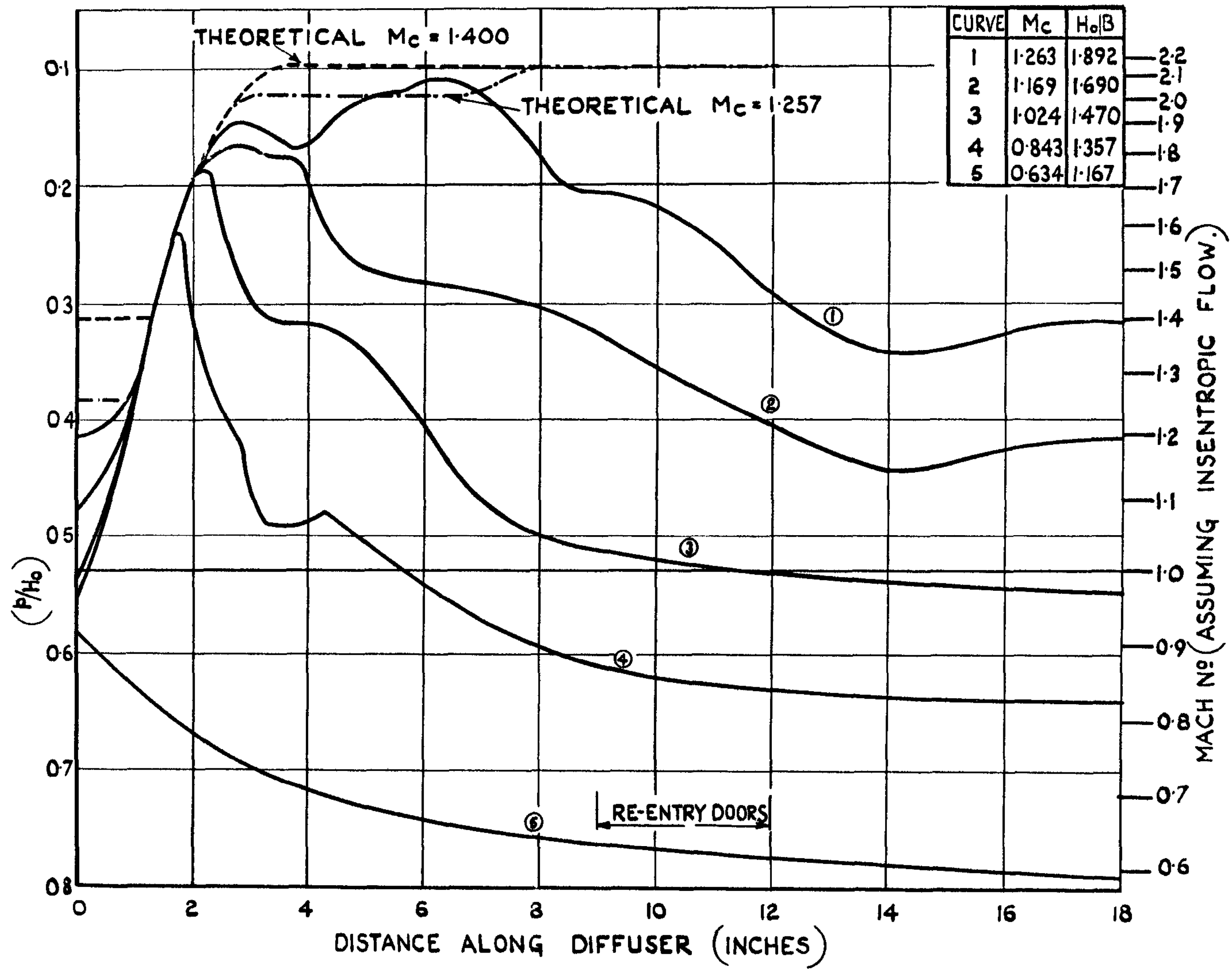


FIG. 16. CENTRE-LINE PRESSURE DISTRIBUTION IN EFFUSER 3 $(A_D/A_C = 0{\cdot}478)$.

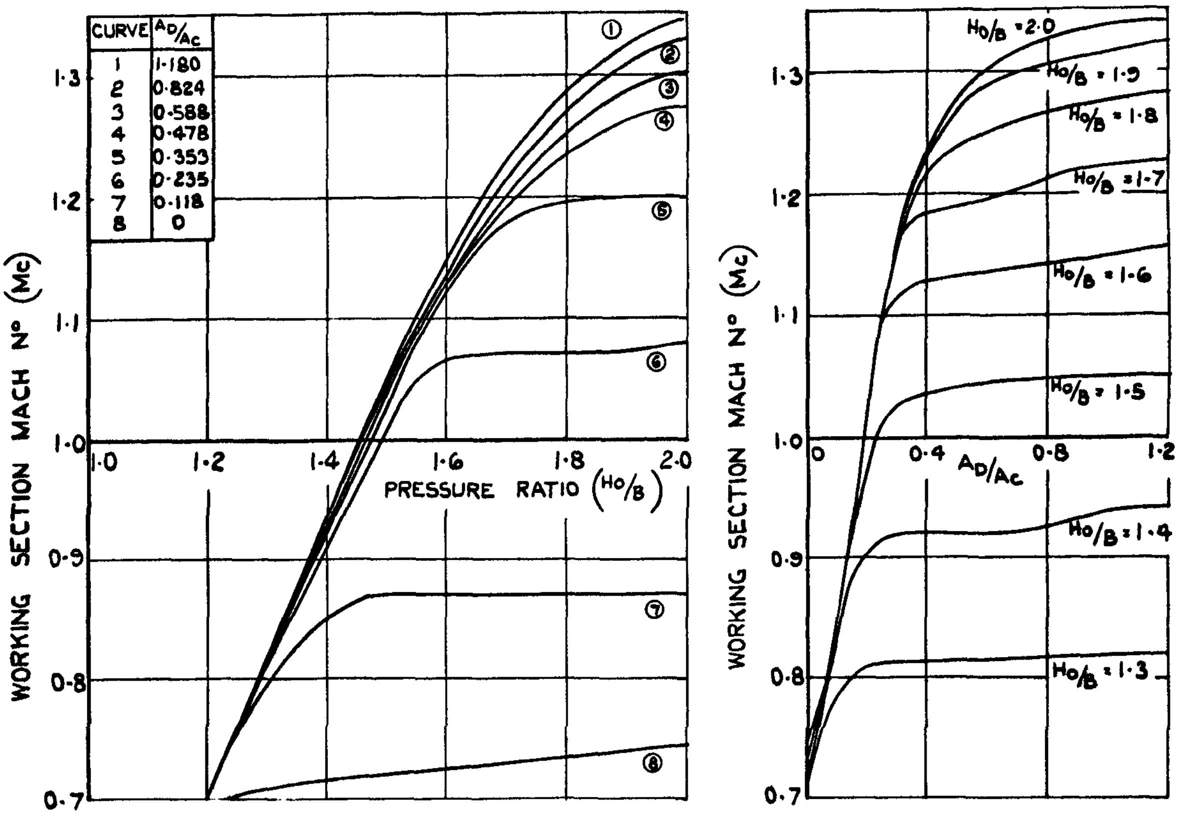


FIG. 17. CHARACTERISTICS OF EFFUSER 4

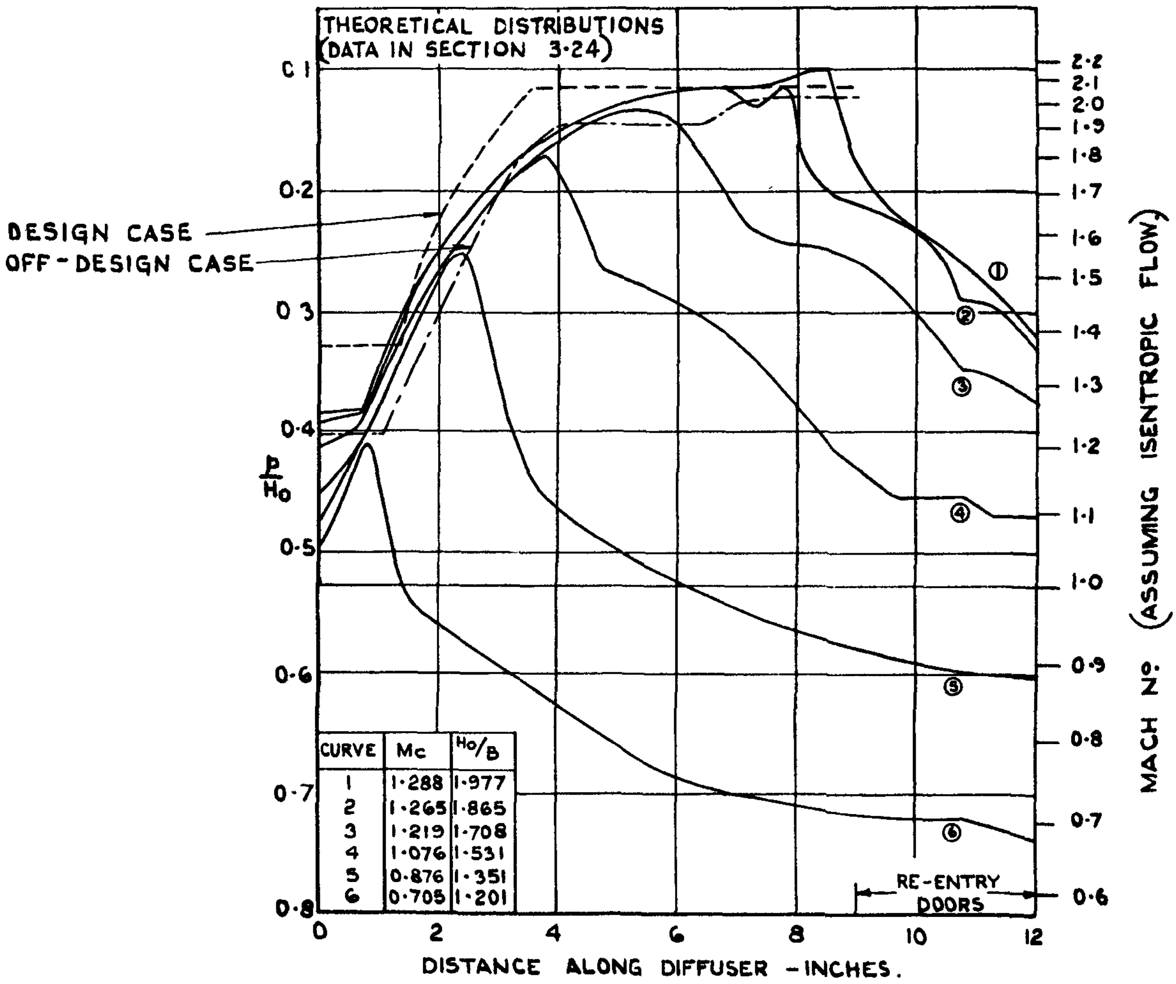
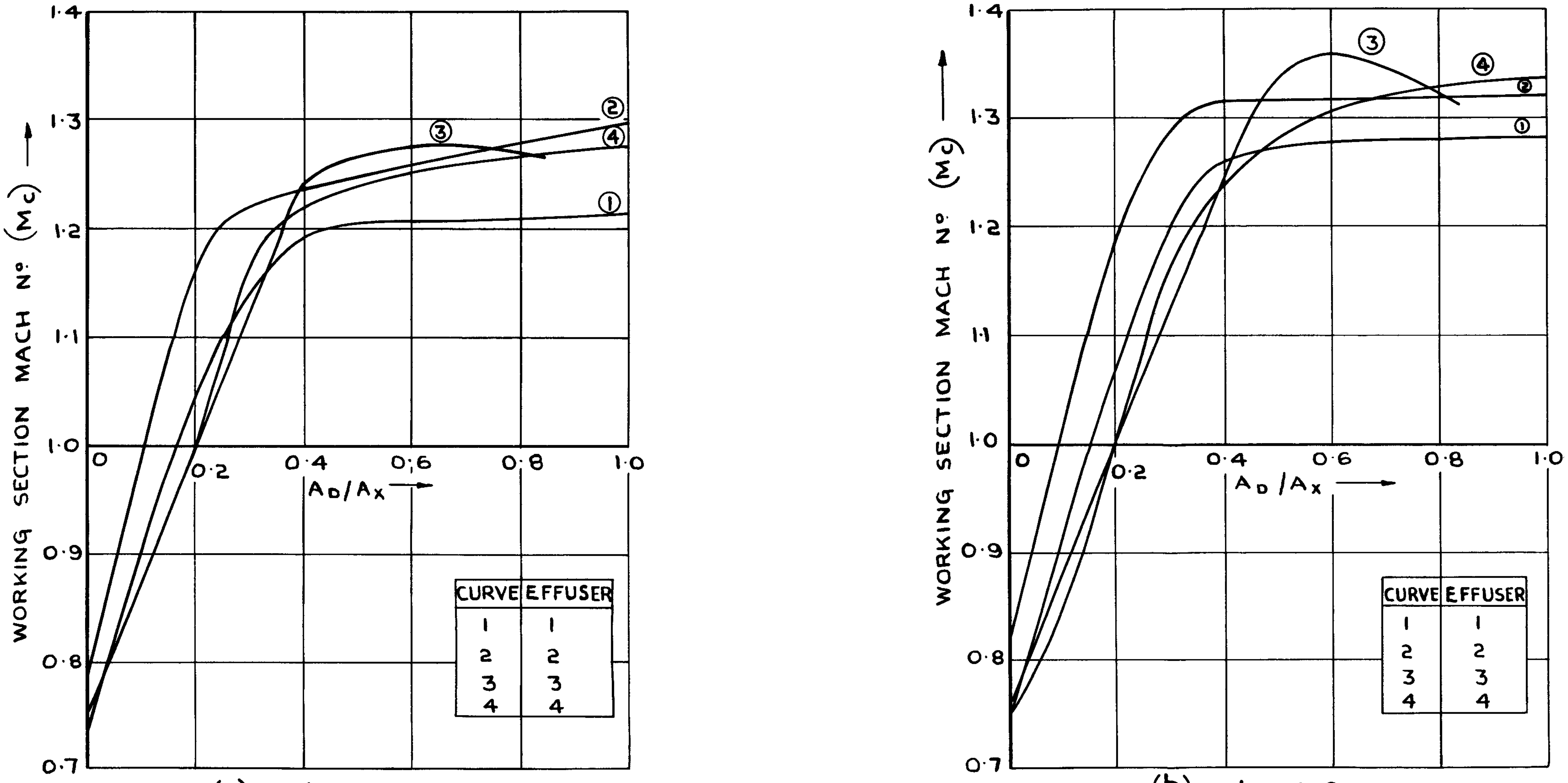


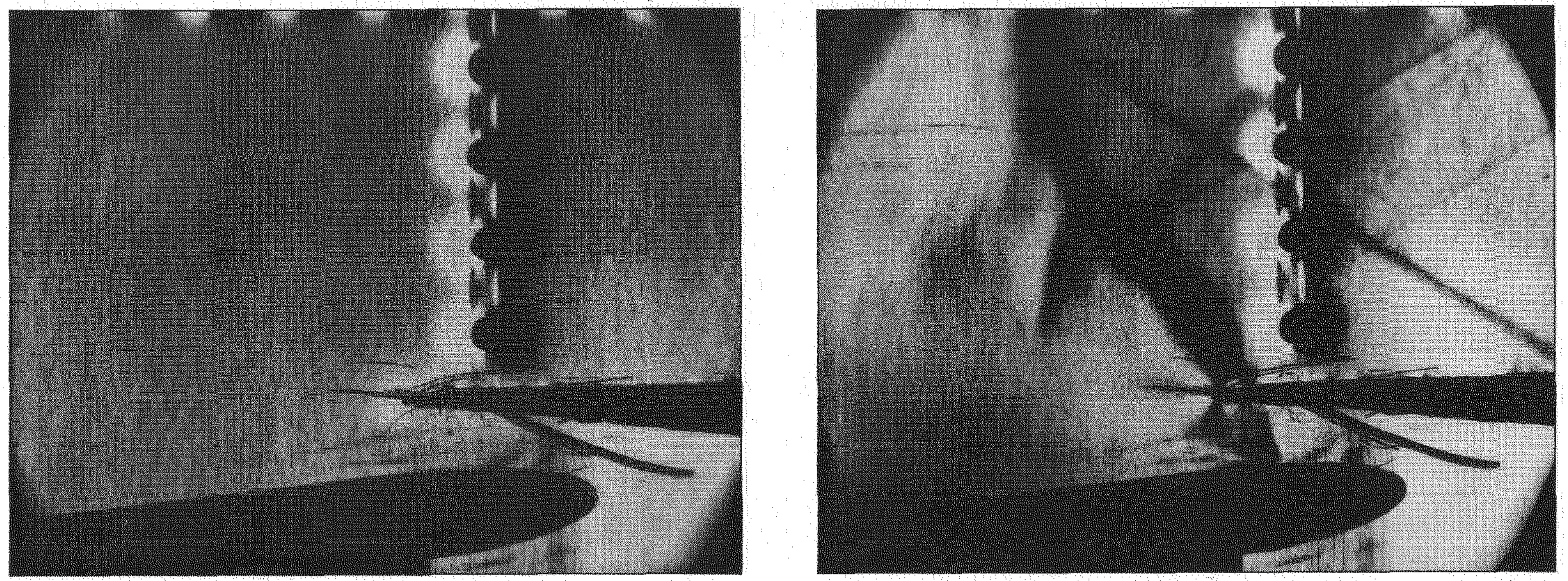
FIG. 18. CENTRE-LINE PRESSURE DISTRIBUTION IN EFFUSER 4 $\left(A_D/A_C = 0{\cdot}478\right)$



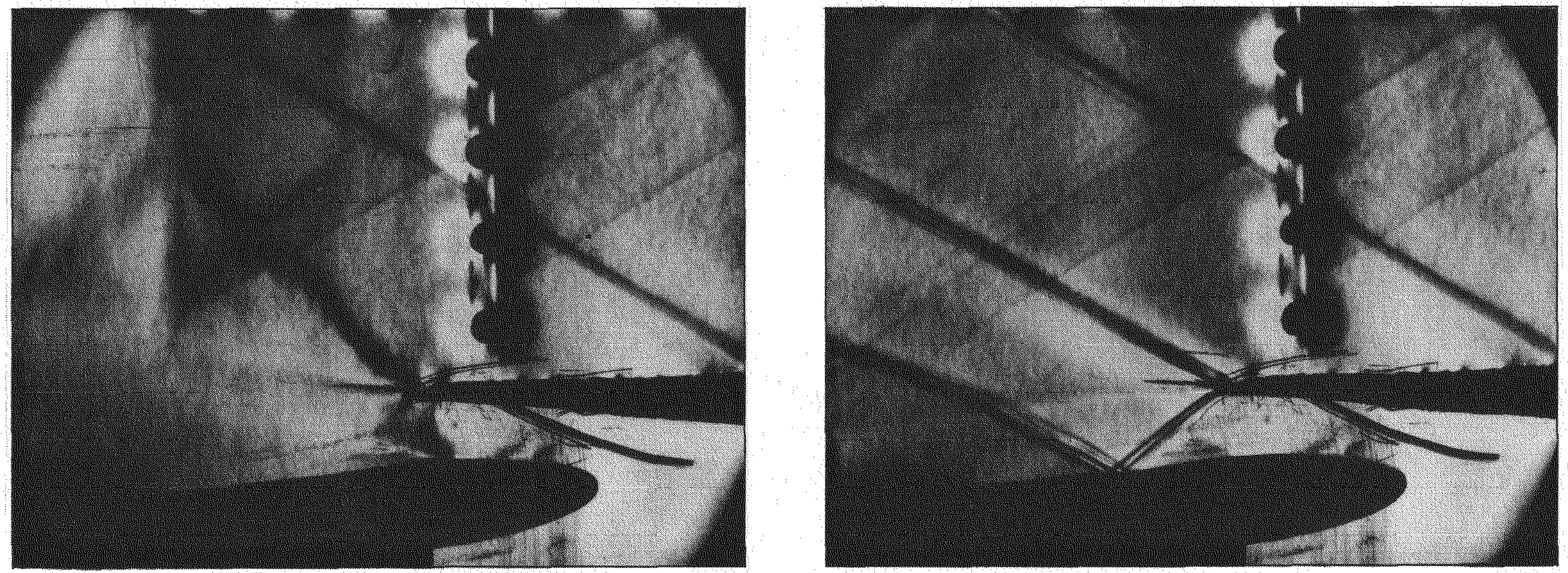
(a) Ho/B = 1.8

(b) Ho/B = 2.0

FIG. 19. (a & b) COMPARISON OF MACH NUMBER-DOOR OPENING CHARACTERISTICS AT FIXED PRESSURE RATIO FOR ALL FOUR EFFUSERS.

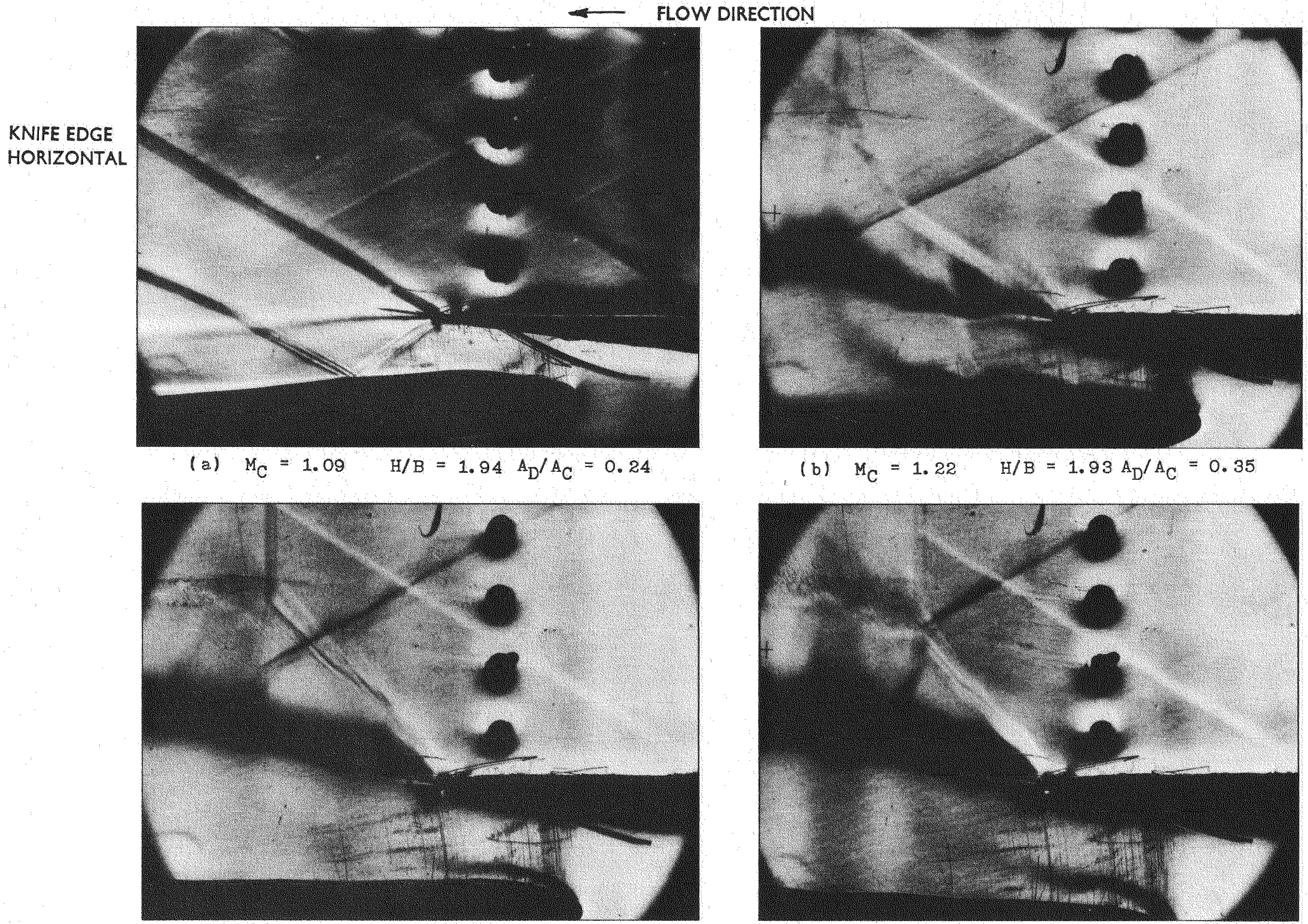


(a) WIND OFF (b) $M_C = 1.12$ $H/B = 1.68$



(c) $M_C = 1.11$ $H/B = 1.74$ (d) $M_C = 1.10$ $H/B = 1.98$

FIG.20. EFFECT OF PRESSURE RATIO ON EFFUSER SHOCK PATTERN DOOR OPENING (A_D/A_C) CONSTANT



(a) $M_C = 1.09$ $H/B = 1.94$ $A_D/A_C = 0.24$

(b) $M_C = 1.22$ $H/B = 1.93$ $A_D/A_C = 0.35$

(c) $M_C = 1.28$ $H/B = 1.93$ $A_D/A_C = 0.48$

(d) $M_C = 1.30$ $H/B = 1.95$ $A_D/A_C = 0.60$

FIG.21. EFFECT OF DOOR OPENING (A_D/A_C) ON EFFUSER SHOCK PATTERN - PRESSURE RATIO CONSTANT

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