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By

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14th May, 1953

SUMMARY

Tests have been made with lateral strips fixed to the back of the slotted walls of the N.P.L. 9 in. × 3 in. High-speed Wind Tunnel to find whether such strips would have a serious effect on the flow. The strips gave rise to shock waves at the beginning of the slotted section at supersonic speeds but the strength of these shock waves could be greatly reduced by displacing the strips a small distance from the wall. Observations of the flow round a two-dimensional 10% thick RAE 104 aerofoil showed that the strips had an effect similar to that of reducing the ratio of open to total area.

The results obtained were used to prepare a preliminary design which incorporated slots in the existing flexible walls of the N.P.L. 20 in × 8 in. High-speed Wind Tunnel. A model of this design, which included all the obstructions behind the walls, was then tested in the 9 in. × 3 in. tunnel and modifications were made to improve the flow. When sufficient cut-away was provided in the lateral strips, which would in the 20 in. × 8 in. tunnel be fixed to the wall to transmit the motion of the adjusting micrometers, a reasonably uniform flow was produced. Observations made for the RAE 104 aerofoil showed that, for the particular ratio of open to total area used, the tunnel would behave similarly to an open jet of the same dimensions, and that shock waves produced at the lateral strips by the outflow opposite the aerofoil would not interfere with the conditions at the surface of the aerofoil.

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1. Introduction

A scheme was proposed by for increasing the maximum Mach number of the N.P.L. 20 in. × 8 in. High-speed Wind Tunnel[1,2] by incorporating longitudinal slots in the existing flexible walls. It was suggested that, with the slots covered, the flexible walls could still be used to minimize wall interference for the same range of Mach number as at present (i.e., 0.3 to 0.9) but that, with the slots open, the maximum Mach number would be increased by a worthwhile amount, possibly even to a value above 1.0.

The various parts of the mechanism necessary to operate the flexible walls would obstruct the flow in the chambers behind the slots. It was decided therefore, before embarking on a major modification to the working section of the 20 in × 8 in. tunnel, to investigate the effect of such obstructions in the existing slotted-wall working section of the 9 in × 3 in. High-speed Wind Tunnel. The object was to find how serious their adverse effect would be on the performance of the tunnel and whether the effect could be minimized by alterations to the obstructions.

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It was felt that the most serious effects would be caused by the metal strips - called 'top-hat pieces' because of their cross-sectional shape - actually fixed to the back of each flexible wall. The first tests were therefore made with slotted walls which had lateral strips fixed to them to simulate these 'top-hat pieces'. These were followed by tests on a model of the actual arrangement proposed for the 20 in × 8 in. tunnel. The 'top-hat pieces' of this model were modified in the light of the earlier experiments and all the other obstructions necessary for the operation of the flexible walls were represented.

It was in fact found that a reasonably uniform flow could be obtained in the working section by making small modifications to the 'top-hat pieces' and that the maximum Mach number was well above 1.0. Although it is not now intended to adopt this scheme - interchangeable liners are to be used instead - an account of the work is given because it may well bd of interest if other slotted-wall tunnels have to be designed with some obstructions behind the walls.

Part I of this report is an account of the work with lateral strips as the only obstructions and Part II describes the tests on the complete model.

PART I

Tests made with Lateral Strips as the Only Obstructions

2. Description of the Walls used

Two sets of walls were used, those designated D and H by Holder, North and Chinneck[3]. The details of the walls are given in Table I and a sketch of the general arrangement is shown in Fig.1.

Table I

Wall	Width of each slot (inches)	Number of Slots	Ratio of Width to Depth of Slots	Ratio of Open to Total Area
D	0.038	9	0.30	0.114
H	0.060	2 (additional slots in expansion)	0.48	0.040

These walls were chosen because wall H gave negligible blockage over much of the subsonic range although its top speed was only just supersonic and wall D gave a smooth distribution of Mach number at a reasonable supersonic speed.

The lateral strips were of 3/32 in. square section and 3 in. long. They were fixed to the outer surfaces of the walls with Durofix, seventeen being applied to each wall. Their positions corresponded to the positions of the 'top-hat pieces' of the flexible walls of the 20 in. × 8 in. tunnel.

3. Effect of the Lateral Strips on Tunnel Performance

(a) Empty Tunnel

At subsonic speeds the empty tunnel pressure distributions showed no substantial change from those obtained without lateral strips[3]. (Figs. 2 and 4)

At supersonic speeds a centred expansion occurred at the beginning of the slotted section causing an outflow through the slots into the chamber behind them. The presence of the lateral strips in this outflow caused a series of weak shock waves in the main stream (Fig.6a). The change in static pressure in passing through one of these shock waves was approximately 2%. As the outflow occurred only at the beginning of the slotted section the shock waves were produced from only the first three strips. They were reflected from the opposite wall but suffered attenuation and were almost unobservable at a distance downstream from the beginning of the slots of about one and a half tunnel heights.

The tunnel speed was measured at a pressure hole in one wall about half a tunnel height from the beginning of the slots. At this distance the acceleration of the air near the wall due to the centred expansion was complete.

The presence of the strips lowered the maximum supersonic Mach number; walls D gave a maximum Mach number of 1.17 without strips and 1.14 with strips; the corresponding figures for walls H were 1.08 and 1.06.

The first strip on the lower wall of walls D was then displaced from the wall by its own thickness, i.e., 3/32 in. It was found that the shock from this strip was eliminated, (Fig.6b), presumably due to the whole of the outflow being able to pass between the strip and the under surface of the wall.

(b) <u>RAE 104 Aerofoil in the Tunnel</u>

A 10% thick 2 in. chord RAE 104 aerofoil with ten* 0.010 in. diameter pressure holes on its surface was placed at 0° in the centre of the tunnel and approximately $1\frac{1}{2}$ tunnel heights from the beginning of the slots. This position corresponded to that of aerofoils under test in the 20 in. × 8 in. tunnel.

The pressures at the slotted walls of the tunnel are shown in Figs. 3 and 5. It will be seen that the differences in pressure distribution due to the presence of the strips were more marked with the aerofoil in position than with the empty tunnel. The maximum Mach number obtained with walls D was 1.15 which compared with 1.12 obtained with the same walls and aerofoil in the absence of the strips. Wall H would no longer run at a supersonic speed the maximum Mach number dropping from 1.06 in the absence of strips to 0.93.

The effect of the strips on the pressures on the surface of the aerofoil is shown in Figs. 7 and 8. With walls D the effect at subsonic speeds below M = 0.85 was small there being only a very slight variation over the rear half of the aerofoil. At speeds above M = 0.85 the pressures were in general slightly higher than when no strips were present, the difference becoming greater with increase of free stream Mach number. With walls H the pressures were in general higher than when there were no strips present for values of the free stream Mach number below 0.9. For the two top tunnel speeds the pressures on the aerofoil remained essentially the same and unchanged from the no strips condition, although the top speeds were different in the two cases. This was presumably due to the insensitivity of the pressure distribution on a two-dimensional aerofoil near Mach numbers of unity.

The pressure distribution about an aerofoil of the same section and chord length has been obtained in the 20 in. × 8 in. tunnel for a range of subsonic speeds[4]. In Figs. 9 and 10 the free stream pressure coefficient p_o/H_o (p_o, H_o are the static and stagnation pressures respectively in the free stream), has been plotted against the value ('True' p_o/H_o) obtained in Ref.5 which gave the same local pressure coefficient at a particular chordwise position on the surface of the aerofoil. Also shown are the experimentally obtained curves for open and closed tunnels of the same dimensions[3] and the mean curves for the walls without strips[3]. It will be seen that the points for walls D with lateral strips lie scattered about the original line which is indistinguishable from that of the open jet. The points for walls H, which originally gave no blockage correction, have been moved nearer to the line obtained for the closed tunnel.

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*Two of these holes were at the same chordwise position, one on each surface, so that the aerofoil could easily be set to zero incidence relative to the airstream.

The alteration, due to the presence of the strips, in the ratio of open area to total area over the wall length from one chord in front of the aerofoil to one chord behind it was 0.114 to 0.100 for walls D and 0.040 to 0.035 for walls H. Theory[5] and experiment[3] have shown that when the area ratio is small the blockage effect is very much more sensitive to changes in area ratio than when it is large. This would explain the shift in the mean blockage curve for walls H and the apparent insensitivity of walls D.

The strips might also have produced shock waves opposite the aerofoil when a local supersonic outflow through the slots occurred. Such shock waves if they had hit the aerofoil might have been expected to produce kinks in the pressure distribution curves. No such kinks were observed (Figs. 7 and 8) and observation of the flow with a schlieren system showed that the shock waves, when produced at the wall, were propagated too far downstream to hit the surface of the aerofoil and passed through its wake sufficiently far downstream to have no effect at the aerofoil.

PART II

Tests made with a Model of the Arrangement Proposed for the 20 in. × 8 in. Tunnel

4. Description of the Proposed Walls for use in the 20 in × 8 in. Tunnel

It was shown in Part I of this report that the shock wave produced by a lateral strip behind a slotted wall due to its interference with the outflow through the wall could be suppressed by displacing the strip so as to allow a gap between it and the wall. In the proposed slotted-flexible walls the function of the lateral strips, or 'top-hat pieces', would be to transmit the motion of the adjusting micrometers to the flexible walls and to hold together the longitudinal strips comprising the walls. They would thus have to be attached to the back of each longitudinal strip but could be cut away behind and near the edge of the slots. It was hoped that this would provide sufficient space for the air from the main stream to pass unobstructed into the chamber behind the walls. It was proposed to cut the slots in the 'top-hat pieces' only slightly larger than the slots in the walls (Fig.12), so as to keep the 'top-hat pieces' as stiff as possible.

To find out whether such an arrangement would be satisfactory it was decided to build a model of the proposed walls and to test it in the 9 in. × 3 in. tunnel. The walls of this model would not be flexible but the 'top-hat pieces' and adjusting micrometers would be represented.

5. Description of the Model Walls Tested in the 9 in. × 3 in. Tunnel

The general assembly of one of the walls is shown in Fig.11a and the details of a portion of the back of the wall showing the model 'top-hat pieces' in Fig.11b. The walls themselves were made from 1/16 in. thick brass strip. There were seven strips in each wall giving a ratio of open area to closed area of 0.125. The strips were mounted between two wooden blocks the upstream block being faired into the 16:1 contraction of the tunnel circuit and the downstream block being faired into the diffuser. For the first 18.54 in. of the slotted section the width of the tunnel increased from 7.34 in. by 0.016 in. per inch to allow for the growth of the boundary layer. The walls then diverged at a total angle of $12\frac{1}{2}^{\circ}$ until they blended into the tunnel circuit at the downstream wooden block. The chamber behind each wall was 1.54 in. deep at the beginning of the slotted section.

The 'top-hat pieces' were represented by solid strips with slots cut in them fixed to the rear of each wall by small metal screws. To each 'top-hat piece', (with the exception of the two extreme downstream ones where the space was insufficient), was attached a model of the swivel mechanism connecting the 'top-hat piece' to its adjusting micrometer. This micrometer was represented by a spigot which was attached to the wood forming the outer side of the chamber behind the walls. Two of these assemblies were made of brass throughout; the remainder were made from wood. Pressure holes were provided in the central strip of each wall.

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6. Observations with the Empty Tunnel

The flow was examined optically and it was found that at supersonic speeds shock waves were generated from the positions of all the 'top-hat pieces'; those from the first three on each wall being very much stronger than those further downstream. Fig.14a shows the pattern observed at the beginning of the slotted section at the top speed of the tunnel. The slots in the first 'top-hat piece' on each wall were then enlarged, the lower ones being widened (Fig.13b) and the upper ones deepened (Fig.13c). Fig.14b shows the shock wave pattern observed after these modifications had been made. It will be seen that the strength of the shock wave was reduced in both cases but that the widening of the slot was more beneficial than the deepening of it. Not only was the shock wave associated with the widened slot much weaker than before modification but the shock wave associated with the next 'top-hat piece' on this wall was also much reduced. This was presumably because the direction of the outflow through the widened slot was not altered much and most of it passed underneath the second 'top-hat piece'.

The slots in the first 'top-hat piece' on the lower wall, i.e., the ones that had been widened, were then deepened (Fig.13d) but no further improvement of the flow was detected (Fig.14c).

Smoothing of the join between the metal strips and the wooden contraction produced a further improvement in the flow pattern (Fig.14d).

The slots in all the 'top-hat pieces' were widened. Fig.15, which is a composite picture, shows the flow pattern in the working section of the tunnel at its top speed. It will be seen that shock waves were still produced at the position of each of the 'top-hat pieces' but their strength was small and much of the disturbance probably arose from the heads of the screws holding the 'top-hat pieces' to the walls.

Axial pressure distributions compiled from a series of traverses with a static tube are shown in Fig.16. At subsonic speeds the pressure was very level throughout the parallel portion of the working section but there was some variation of pressure with axial position at supersonic speeds. However this variation was no worse than that reported for any of the slotted walls used in Ref.3, and it is known that this kind of variation can be remedied by tapering the entry to the slots. It will be seen that the shocks visible in Fig.15 produced no discontinuities in the axial pressure distribution. The pressures measured at the walls are shown in Fig.17. It will be seen that they were very even throughout the parallel portion of the working section as might be expected since the walls are very near a constant-pressure boundary.

7. Observations with the RAE 104 Aerofoil in the Tunnel

The RAE 104 aerofoil used in Part I of this report was placed in the tunnel about $1\frac{1}{2}$ tunnel heights from the beginning of the slots. Pressures on the aerofoil surface and at the slotted walls of the tunnel were measured for several wind speeds with the aerofoil at incidences of 0°, $\pm 2^\circ$ and $\pm 4^\circ$. By combining the results obtained at positive and negative incidences the pressure distribution curve for each surface could be defined at nine chordwise positions. Toepler schlieren photographs were taken at 0°, $+2^\circ$ and $+4^\circ$.

The pressures measured at the slotted walls are shown in Figs. 18-20, the pressures on the surface of the aerofoil in Figs. 21, 23 and 25, and the schlieren photographs in Figs. 22, 24 and 26. Also shown in Figs. 21, 23 and 25 for the lower tunnel speeds are the pressure distributions for the aerofoil of the same section and the same chord length tested in the 20 in. × 8 in. tunnel. These distributions were obtained by interpolation from the results given in Ref.5.

It will be seen that the aerofoil pressure distribution obtained in the slotted tunnel at a particular Mach number corresponded to that which would have been obtained at a lower Mach number in the 20 in. × 8 in. tunnel. This may more clearly be seen in Fig.27 where the free stream pressure coefficient p_o/H_o has, as in Figs. 9 and 10, been plotted against the value ('True' p_o/H_o) obtained in

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the 20 in. × 8 in. tunnel which gave the same local pressure coefficient at a particular point on the surface of the aerofoil. It will be seen that the behaviour of the slotted tunnel approximated closely to that of the open jet, of approximately the same dimensions, tested in Ref.3. This was to be expected for a tunnel with this area ratio from the results given in Ref.3.

The photographs of the flow around the aerofoil show some unusual features when the tunnel speed is supersonic. The change of velocity distribution produced by inserting the aerofoil distorted the shock waves visible in Fig.15 and produced a pattern of the type shown in Fig.22 for $\alpha = 0^\circ$, $M = 1.025$. As however the pressure distribution on a two-dimensional aerofoil is insensitive to changes of Mach number near unity nothing unusual may be seen in the pressure distributions for these cases.

In some cases a shock wave occurred where the supersonic outflow through the slots opposite the aerofoil was obstructed by one of the 'top-hat pieces'. This may be most clearly seen for the case $\alpha = 4^\circ$, $M = 1.050$, (Fig.26), where the outflow opposite the lifting surface is large and the shock wave appears as a white line running diagonally across the top right hand corner of the photograph.

It will be seen that in this case, and in others where it occurred, the shock wave was propagated too far downstream to reach the aerofoil surface at any point and that it did not exert any noticeable effect through the wake.

8. Conclusions

(a) The Effect of Lateral Strips Fixed to the Outer Surfaces of Slotted Walls

Lateral strips on the outer surfaces of the slotted walls produced weak shock waves in the initial portion of the main stream when it was supersonic due to the outflow through the slots. These shock waves died out after about $1\frac{1}{2}$ tunnel heights from the beginning of the slots. They could be avoided by providing a gap between the strips and the outer surface of the walls. The top speed of the tunnel was found to be slightly lower than it was before the strips were fixed in position. Observations of the flow round a two-dimensional RAE 104 aerofoil showed that for a wall with a basic ratio of open to total area of 0.114 little change occurred in the blockage, but for a wall with a ratio of 0.040 the change was quite large, the blockage tending towards that for a closed tunnel of the same dimensions.

(b) The Behaviour of the Model of the Proposed 20 in. × 8 in. Tunnel Walls

The original slots in the 'top-hat pieces', which were only slightly wider than the slots in the tunnel walls, were found to be insufficient to allow unrestricted passage to the outflow of air through the tunnel slots at supersonic speeds and shock waves were formed in the main stream. These shock waves were considerably reduced in strength by widening the slots in the 'top-hat pieces'; deepening of the slots did not produce such a large beneficial effect.

When the slots in all the 'top-hat pieces' had been widened the tunnel ran satisfactorily, the axial pressure distribution being reasonably uniform throughout the parallel portion of the working section at subsonic speeds. At supersonic speeds the pressure distribution was no longer uniform but the axial variation was no worse than that of any of the slotted walls tested by Holder et al.[3] Moreover this variation could have been lessened by tapering the entry to the slots.

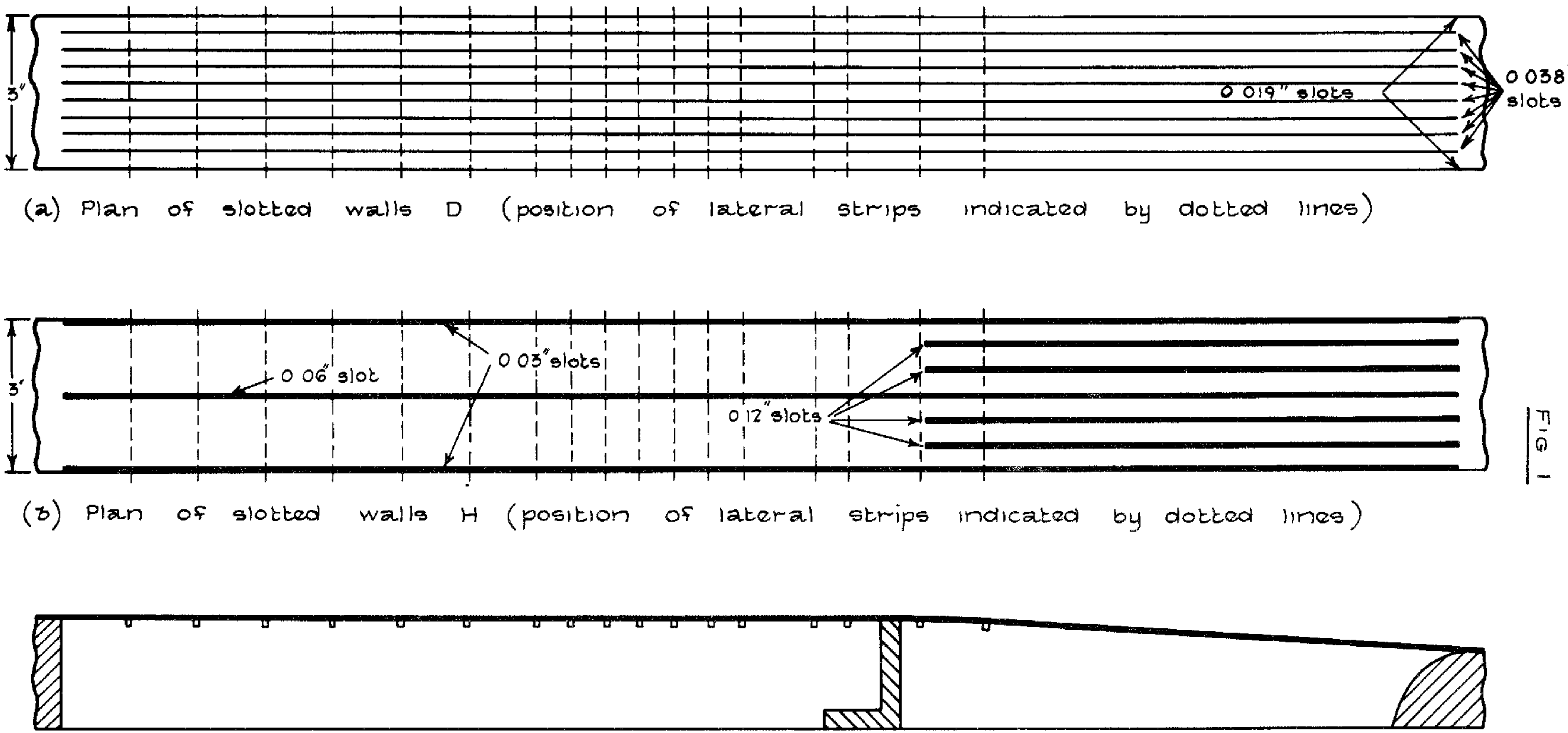
Observations of the flow round the RAE 104 aerofoil showed that, with the area ratio chosen, the blockage approximated to that which would be expected for an open jet of the same dimensions. Shock waves produced at the walls by the interference of some of the 'top-hat pieces' with the outflow opposite the aerofoil in all cases passed behind the aerofoil and did not affect the pressures on the surface of the aerofoil.

References/

References

No.	Author(s)	Title, etc.
1	J. A. Beavan and G. A. M. Hyde	Interim report on the rectangular high-speed tunnel including some pitot traverse measurements of drag of the aerofoil E.C.1250. R. & M.2067. February, 1942.
2	C. N. H. Lock and J. A. Beavan	Tunnel interference at compressibility speeds using the flexible walls of the rectangular high-speed tunnel. R. & M.2005. September, 1944.
3	D. W. Holder, R. J. North and A. Chinneck	Experiments with slotted and perforated walls in a two-dimensional high-speed tunnel. R. & M. 2955. 14th November, 1951.
4	E. W. E. Rogers A. Chinneck and R. F. Cash	The comparison of results obtained at high subsonic speeds on two aerofoils having the same section but different chord. A.R.C. 13,628 29th December, 1950.
5	R. C. Tomlinson	The theoretical interference velocity on the axis of a two-dimensional wind tunnel with slotted walls. 22nd August, 1950.

FIG 1



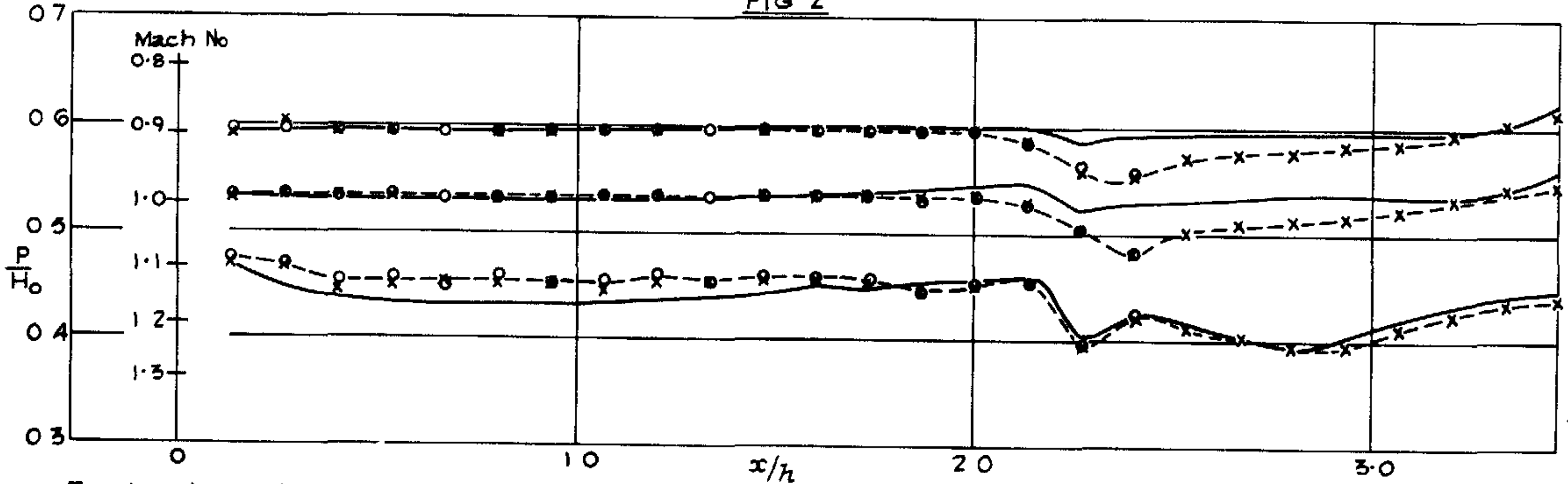
(a) Plan of slotted walls D (position of lateral strips indicated by dotted lines)

(b) Plan of slotted walls H (position of lateral strips indicated by dotted lines)

(c) Elevation of slotted walls showing lateral strips in position

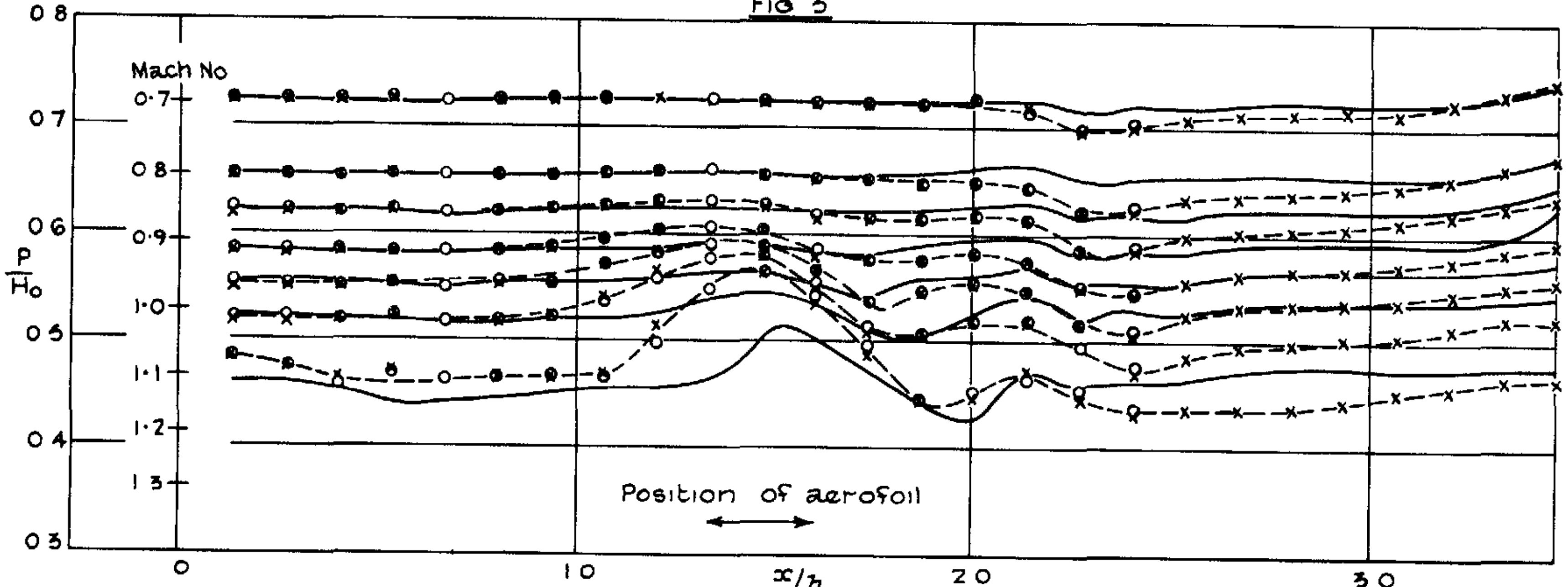
Details of the walls used in the preliminary tests

FIG 2



Empty tunnel pressure distributions along slotted wall D, Area ratio 0 114

FIG 3

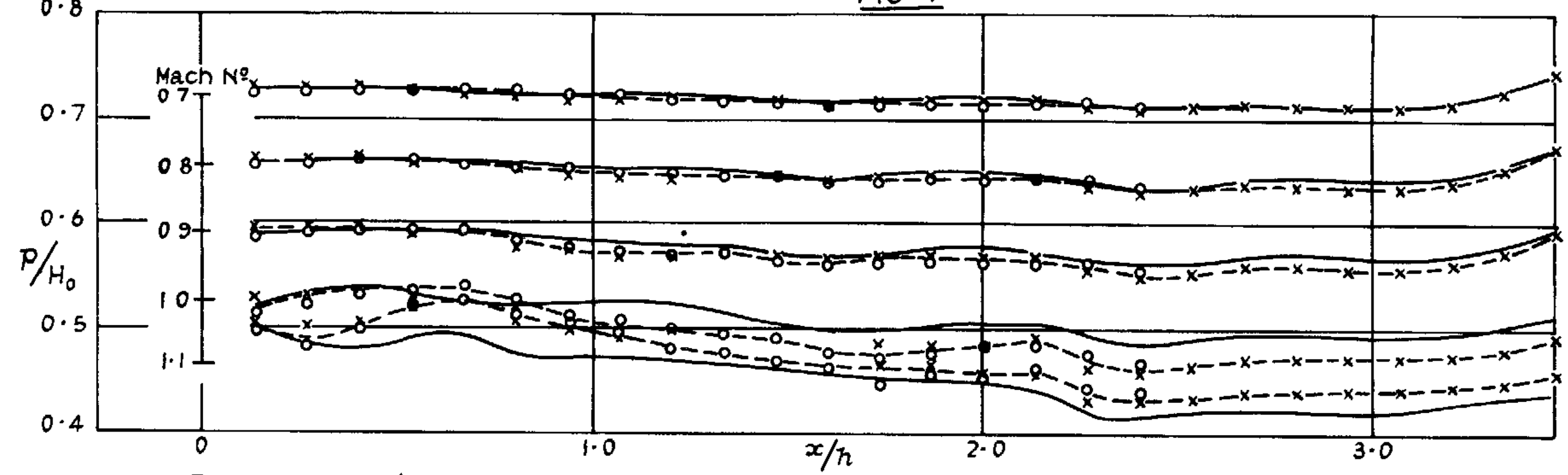


Wall pressures with R A E 104 aerofoil at $\alpha = 0°$ Walls D, Area ratio 0·114

——— Without lateral strips
– – – With lateral strips
o Upper wall
x Lower wall

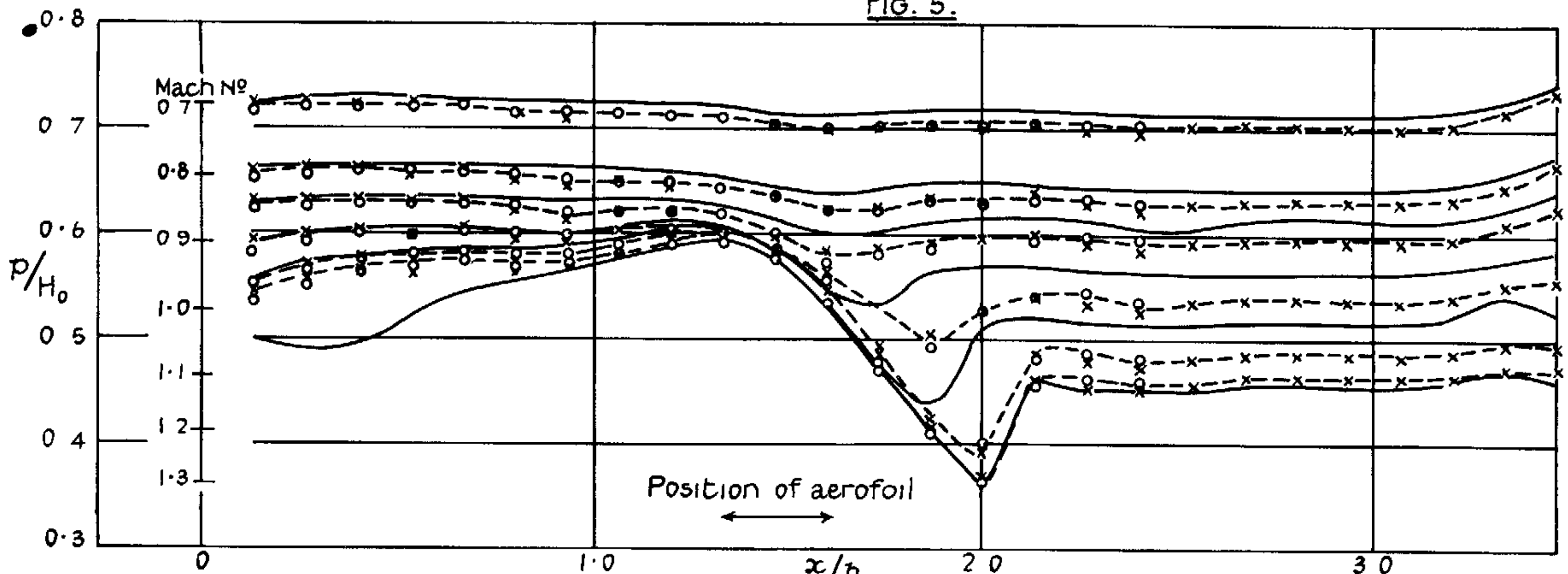
FIGS 2 & 3

FIG 4



Empty tunnel pressure distributions with slotted wall H ; area ratio 0 040

FIG. 5.

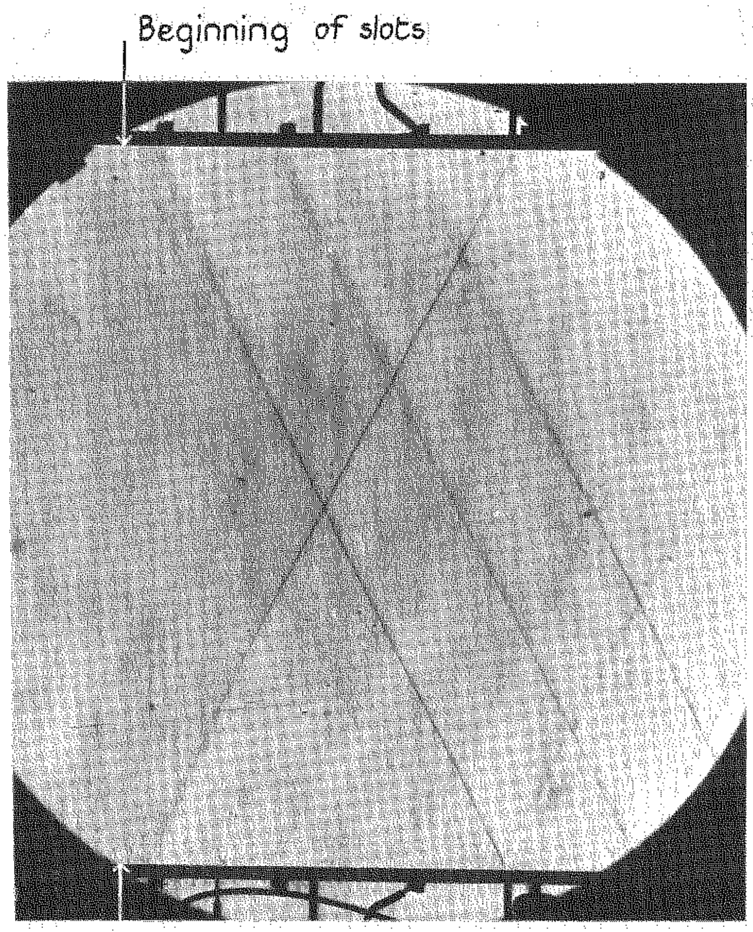


Wall pressures with R.A.E 104 aerofoil at $\alpha = 0$. Walls H Area ratio 0 040

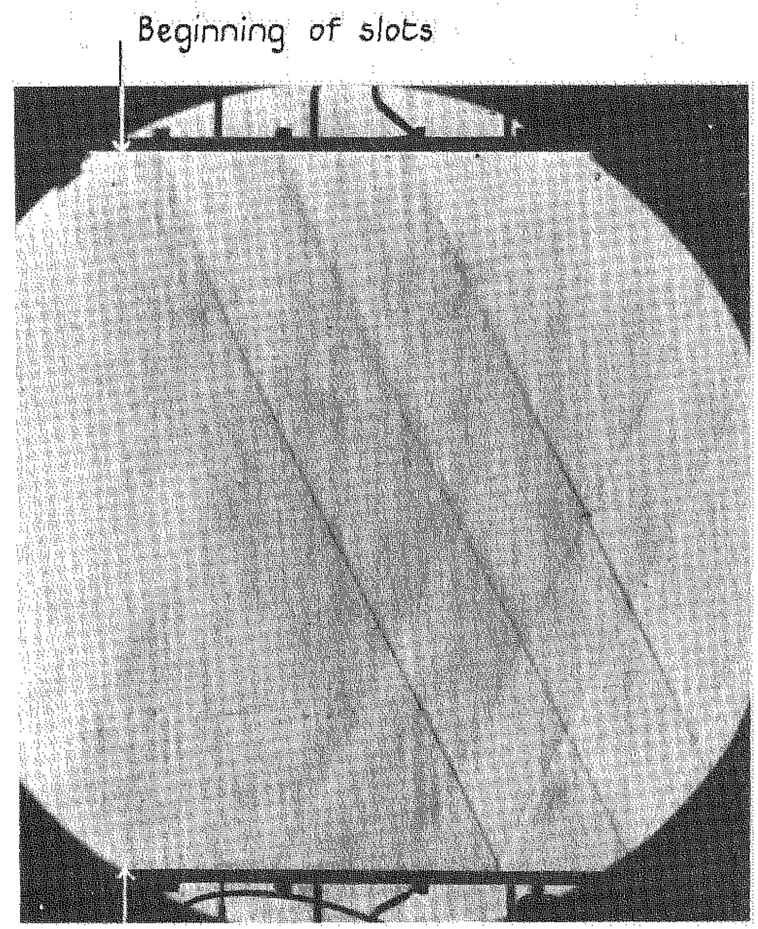
—— Without lateral strips
- - - With lateral strips
o Upper wall
x Lower wall

FIGS 4 & 5

Fig. 6.



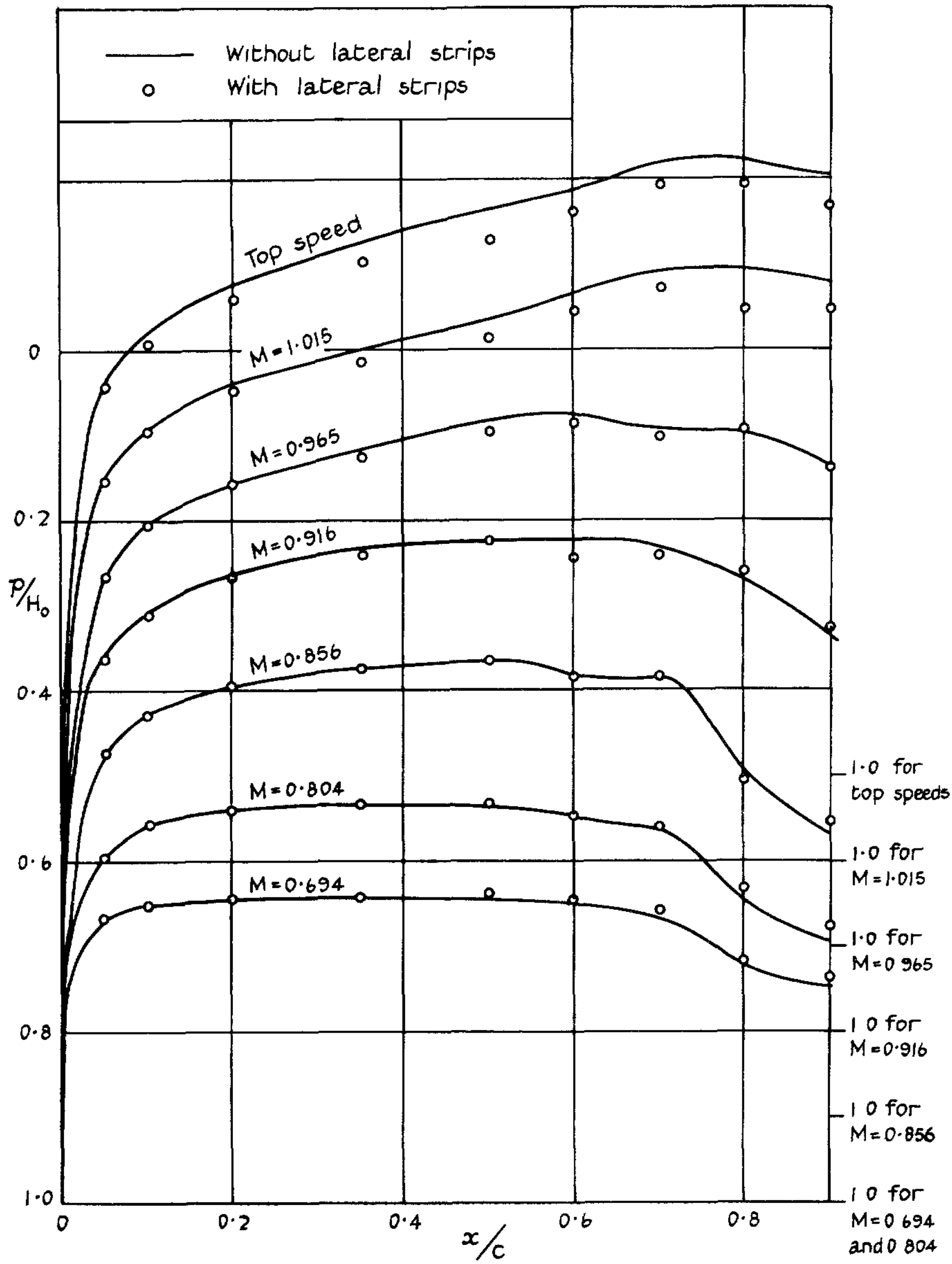
(a) All strips fixed closely to the under surfaces of the walls.



(b) The first strip on the lower wall displaced downward by its own thickness ($^3/_{32}$ inch).

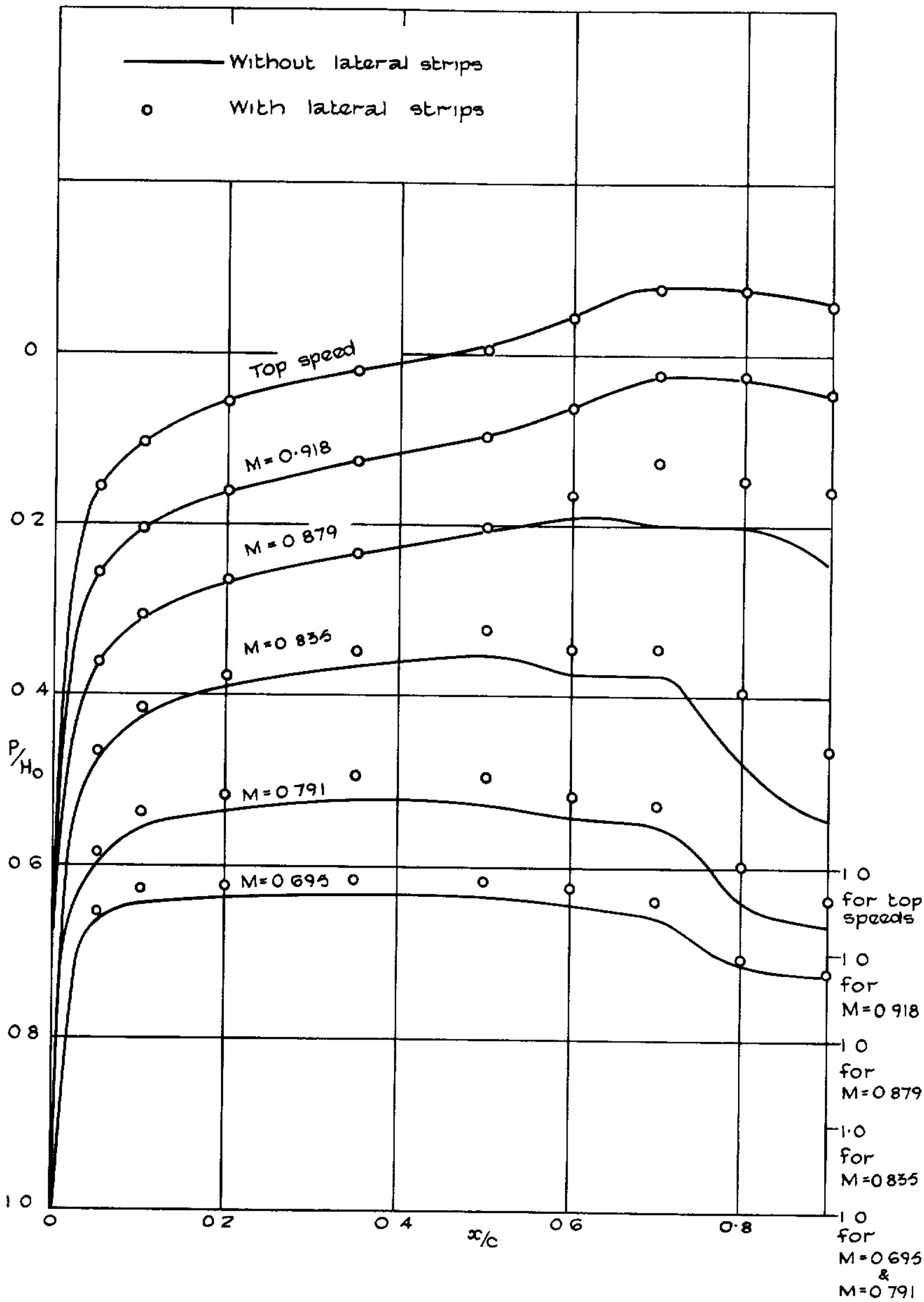
Photographs of the flow at the beginning of the slotted section of the tunnel with lateral strips fixed to the under surfaces of the walls D.

FIG 7



Local static pressure at the surface of the R.A E 104 aerofoil at 0° incidence Walls D

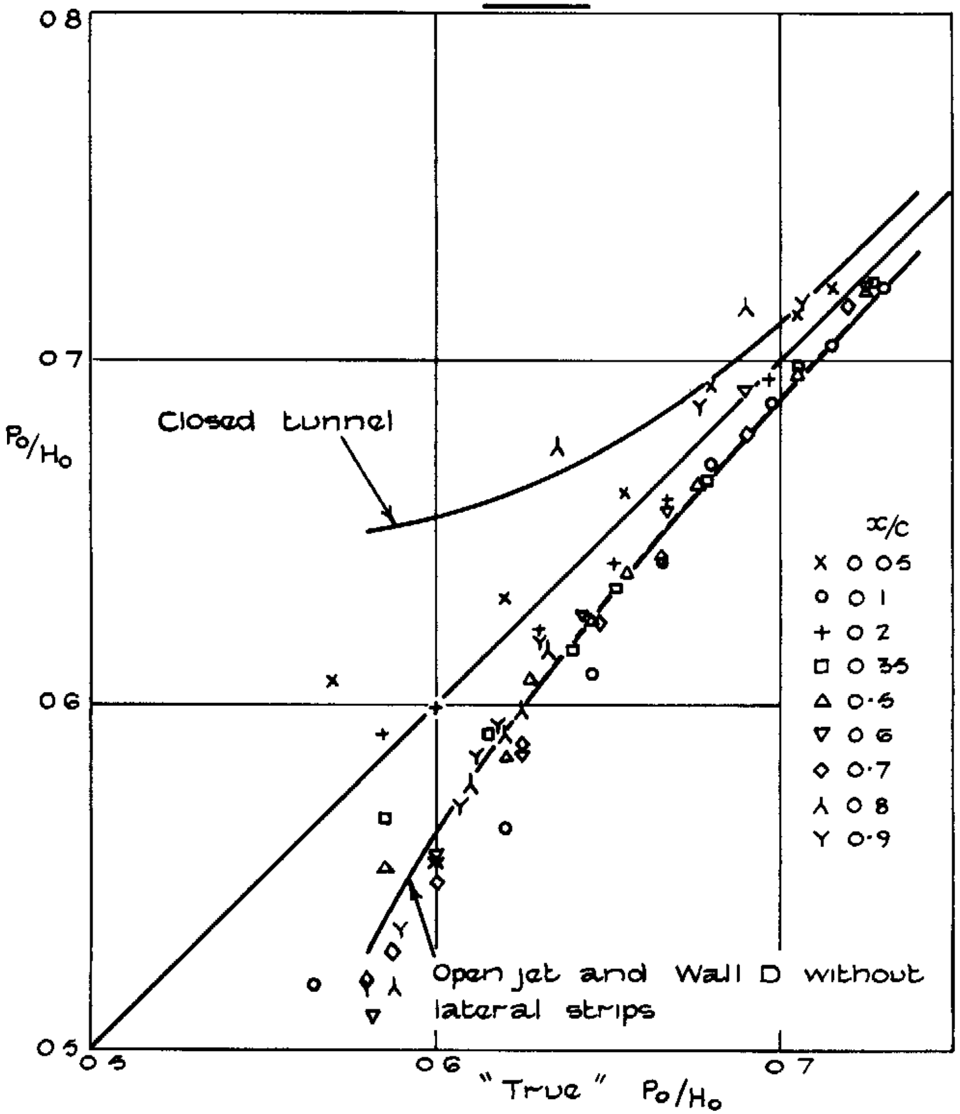
FIG 8



Local static pressure at the surface of the RAE 104 aerofoil at 0° incidence Walls H

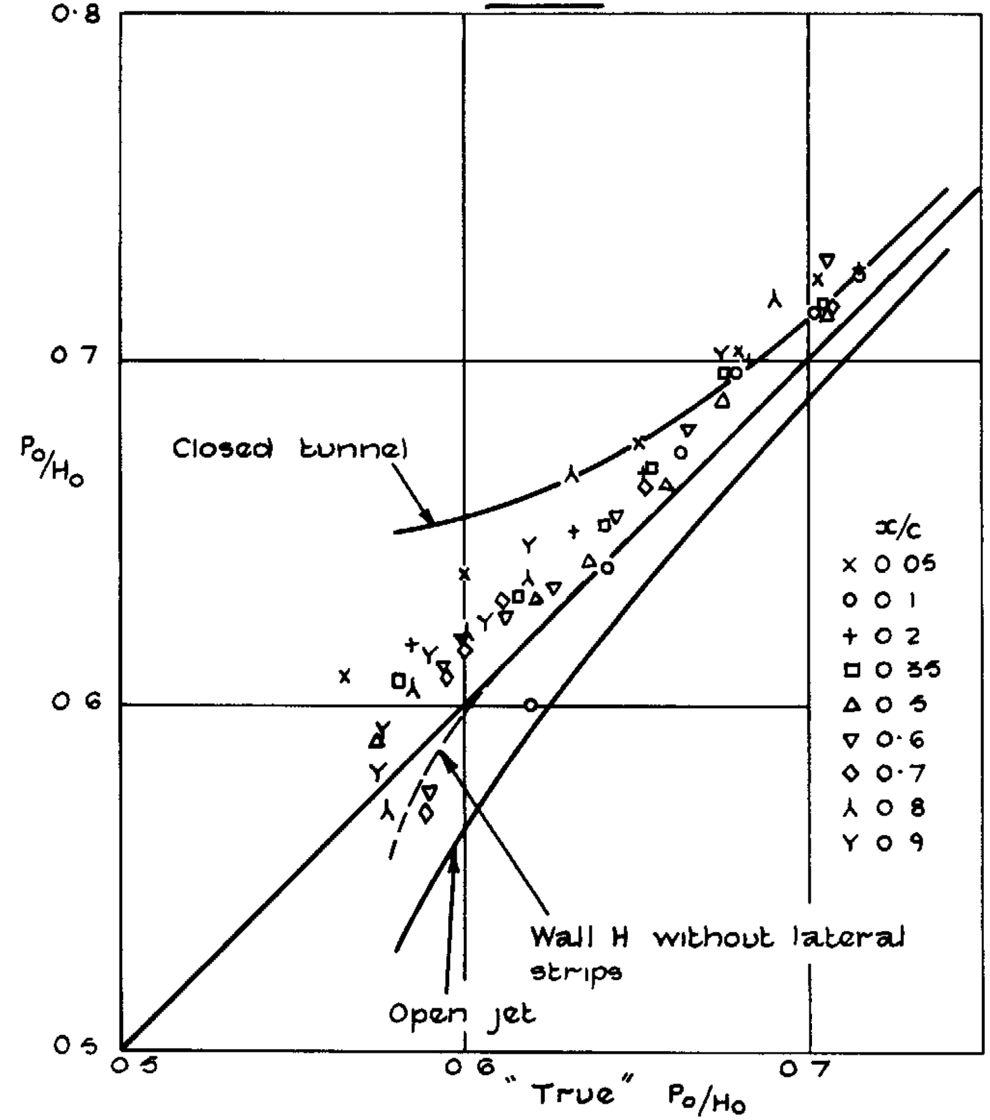
FIGS 9 & 10

FIG 9



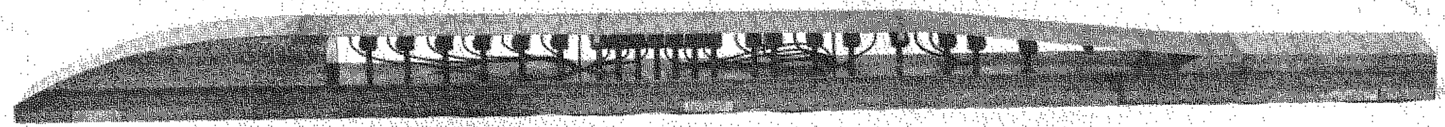
Blockage diagram for walls D with lateral strips

FIG 10

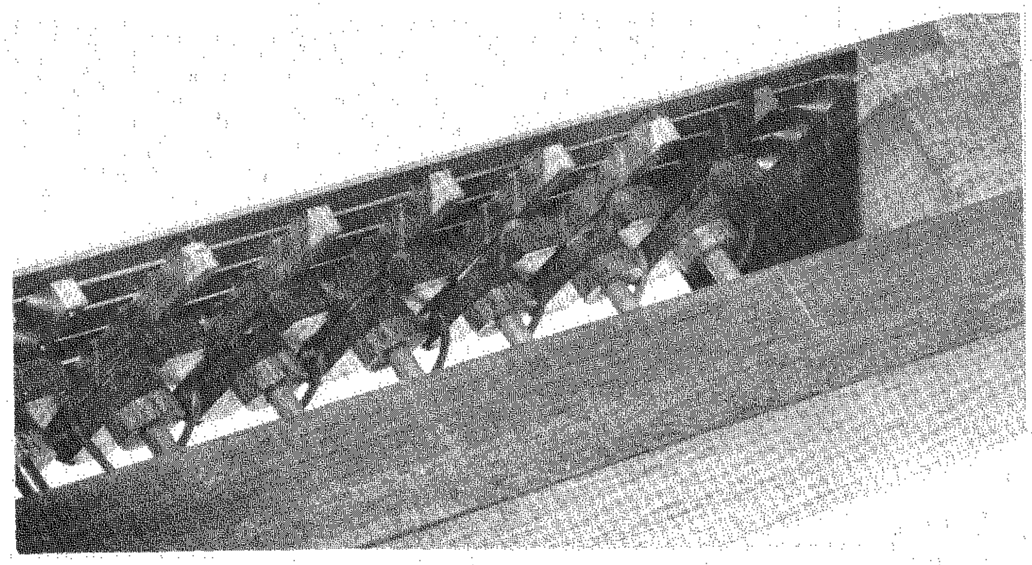


Blockage diagram for walls H with lateral strips

FIG. 11.



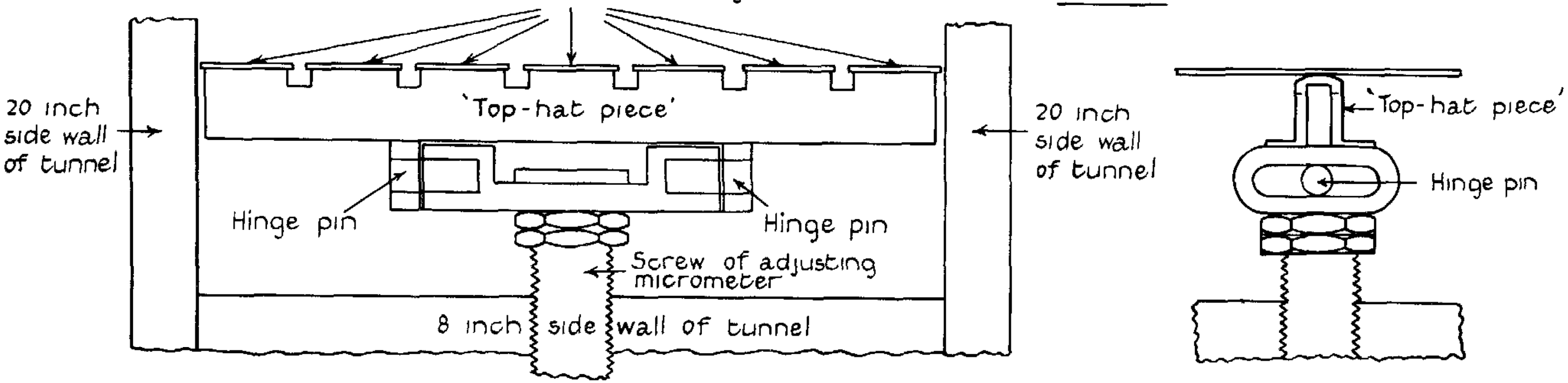
(a) General view of the model.



(b) View showing details of the 'top-hat pieces' and the micrometer assemblies.

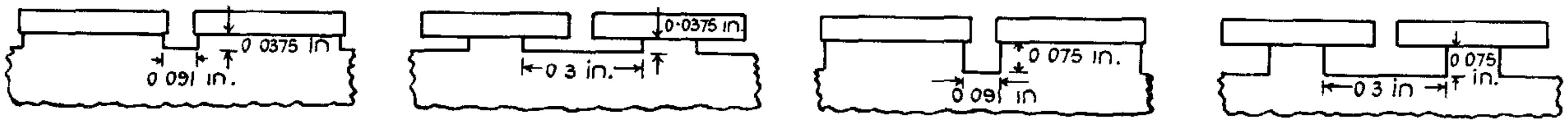
Photographs of the model of one of the proposed slotted walls for the 20" x 8" tunnel.

FIG 12.



Proposed arrangement of the micrometer adjusting mechanism for the slotted-flexible walls in 20 inch x 8 inch tunnel.

FIG 13



(a) Original dimensions. (b) Slot widened (c) Slot deepened (d) Widened slot deepened.

Modifications to the slots in the 'top-hat pieces' of the model of the proposed 20 inch x 8 inch slotted-flexible walls.

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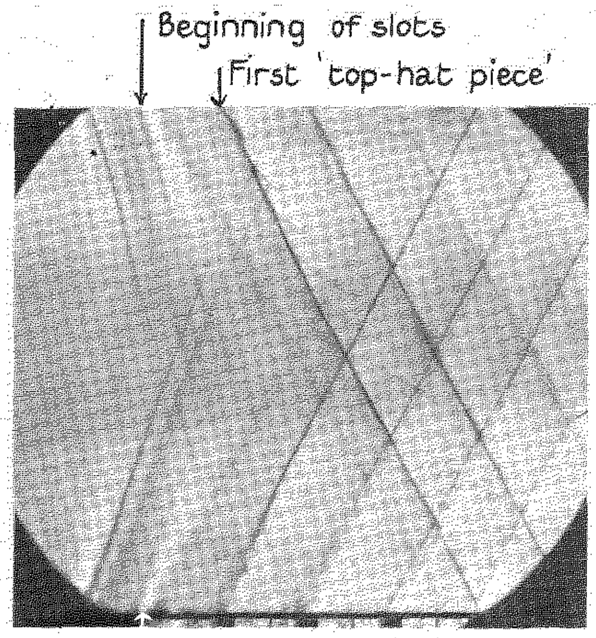
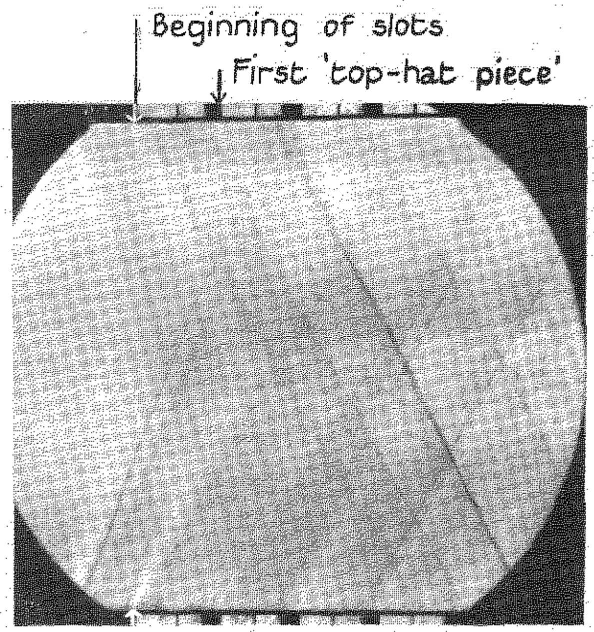
FIGS 12 & 13

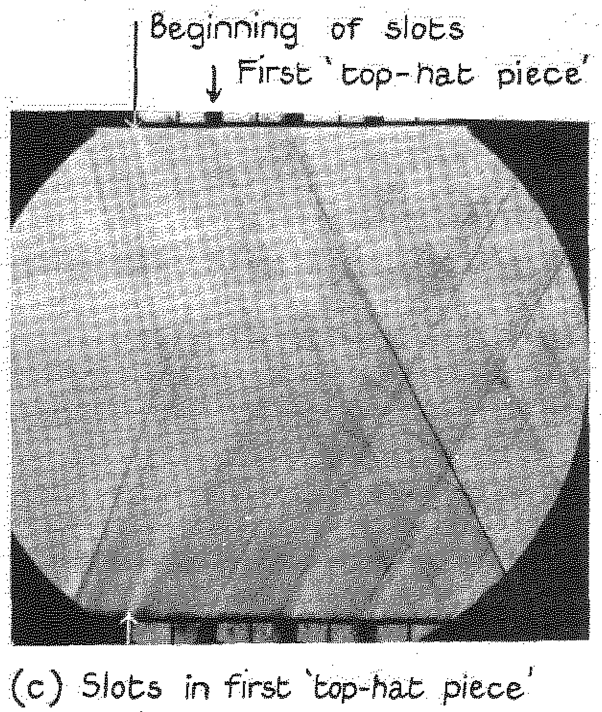
FIG. 14.



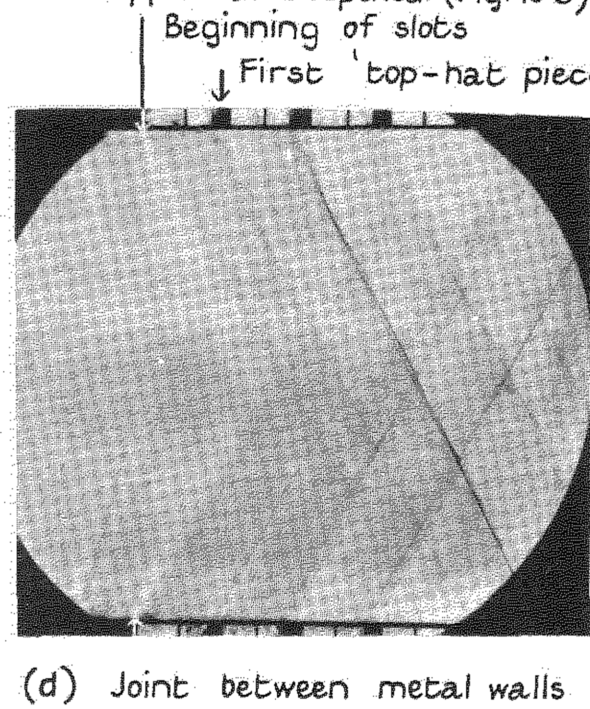
(a) Initial conditions (Fig. 13 a)



(b) Slots in first 'top-hat piece' behind lower wall widened (Fig. 13 b) slots in first 'top-hat piece' behind upper wall deepened (Fig. 13 c).



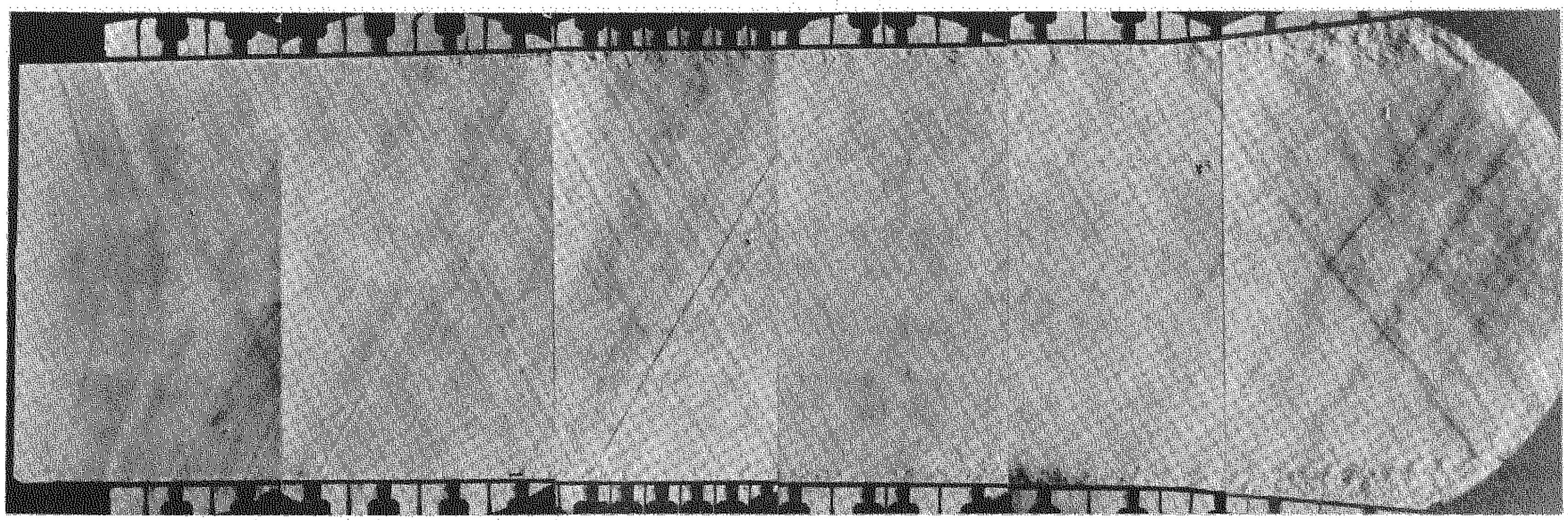
(c) Slots in first 'top-hat piece' behind lower wall widened and deepened (Fig. 13 c).



(d) Joint between metal walls and wooden intake smoothed.

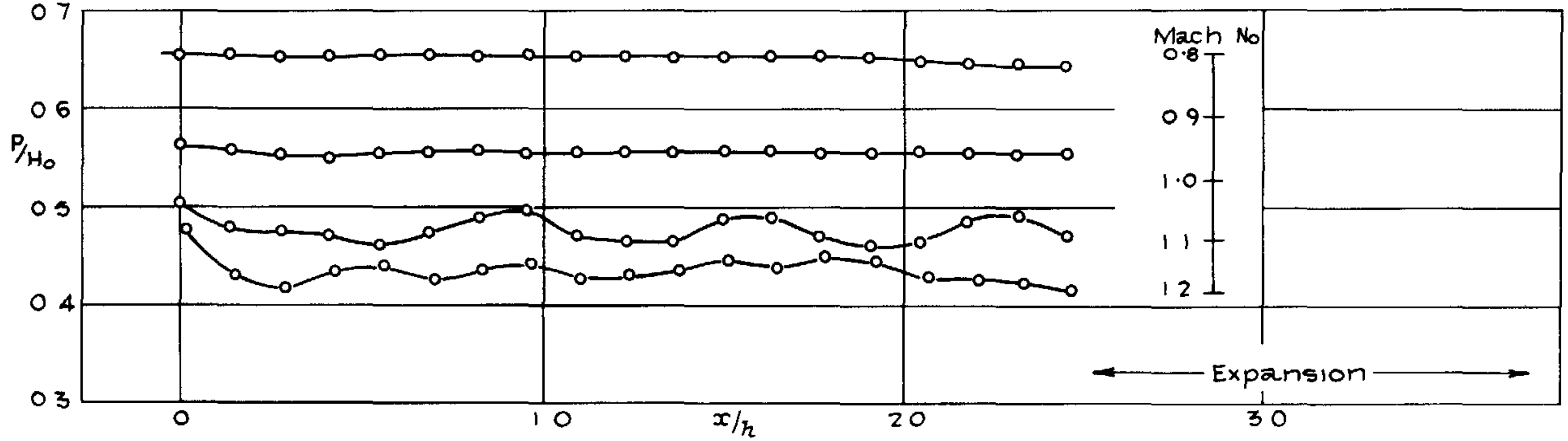
Schlieren photographs showing the effect of varying the conditions near the beginning of the slots of the proposed 20 inch x 8 inch slotted-flexible walls at the top speed of the tunnel, M = 1·17.

FIG. 15.



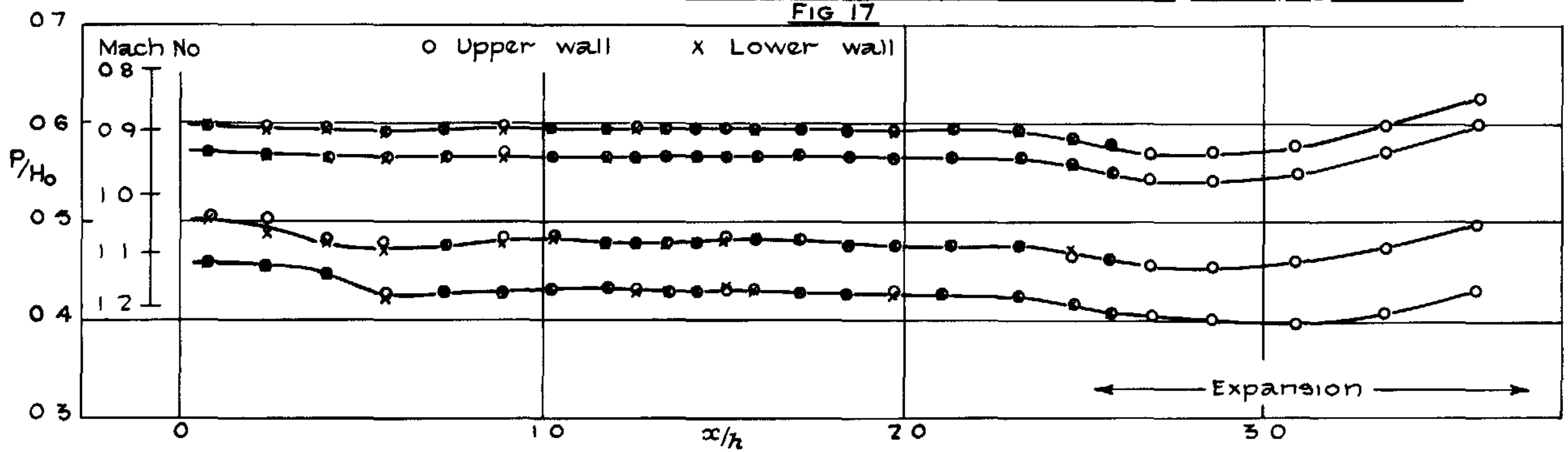
Composite schlieren photograph of the flow in the final model of the 20 inch x 8 inch slotted-flexible walls at the top speed of the tunnel, M = 1·17.

FIG. 16



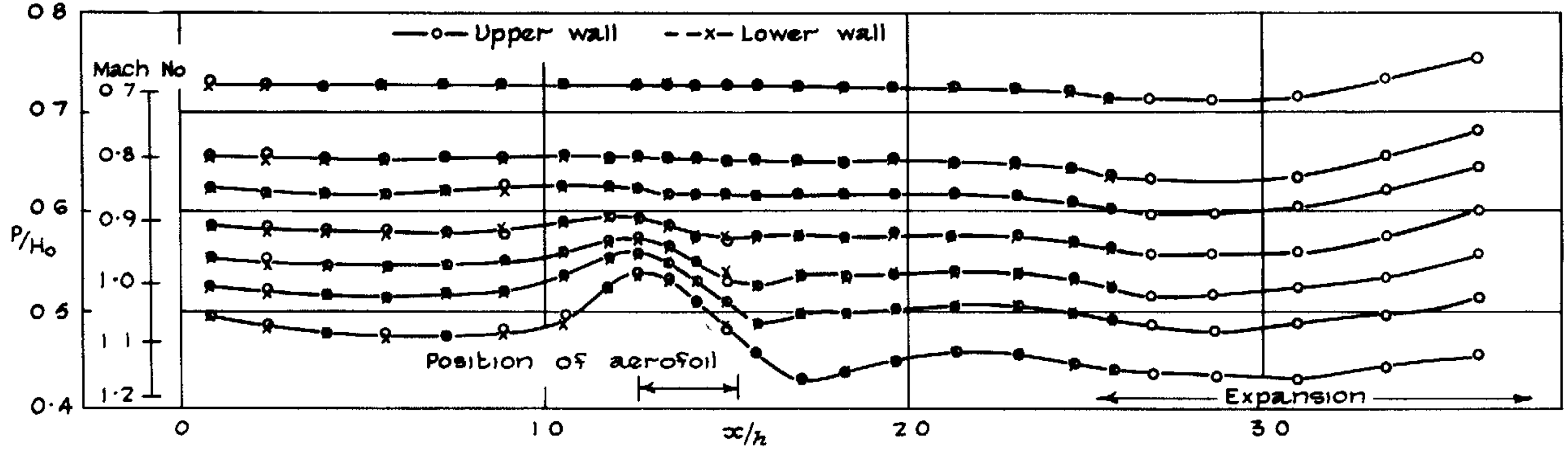
Static pressure distributions on the axis of the final model; Empty tunnel

FIG 17



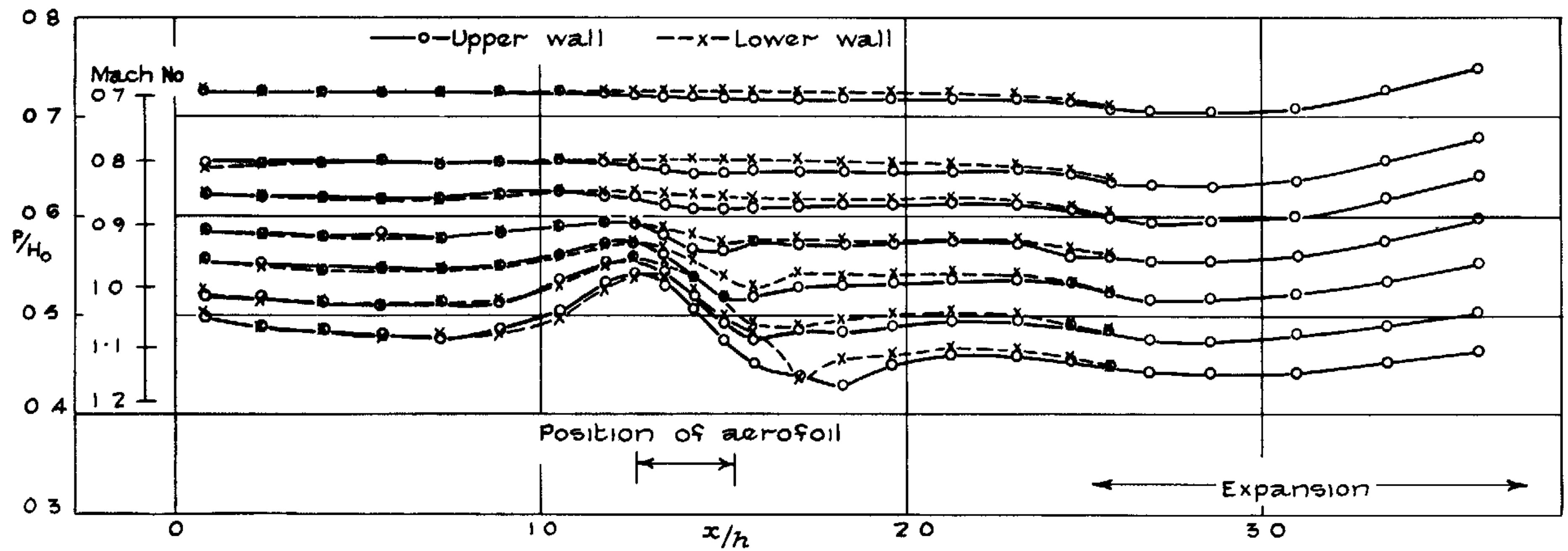
Static pressure distribution along the slotted walls of the final model, Empty tunnel

FIG. 18



Static pressure distribution along the slotted walls of the final model RAE 104 at 0°

FIG 19



Static pressure distribution along the slotted walls of the final model RAE 104 at +2°

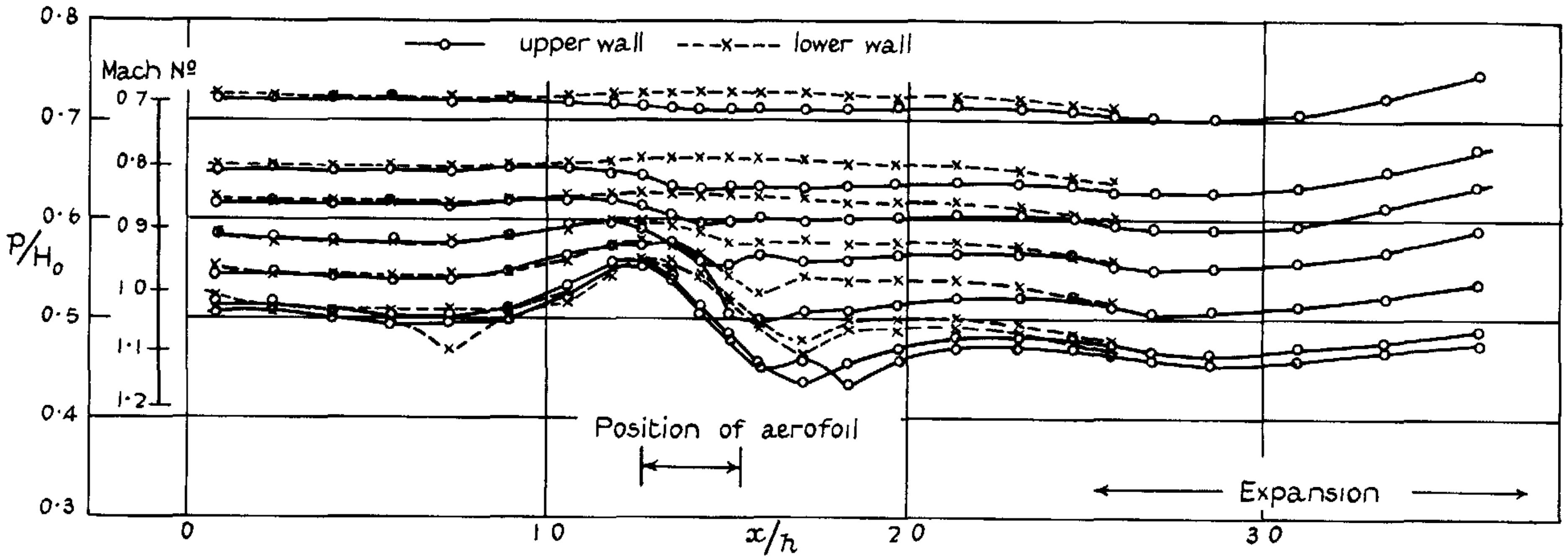
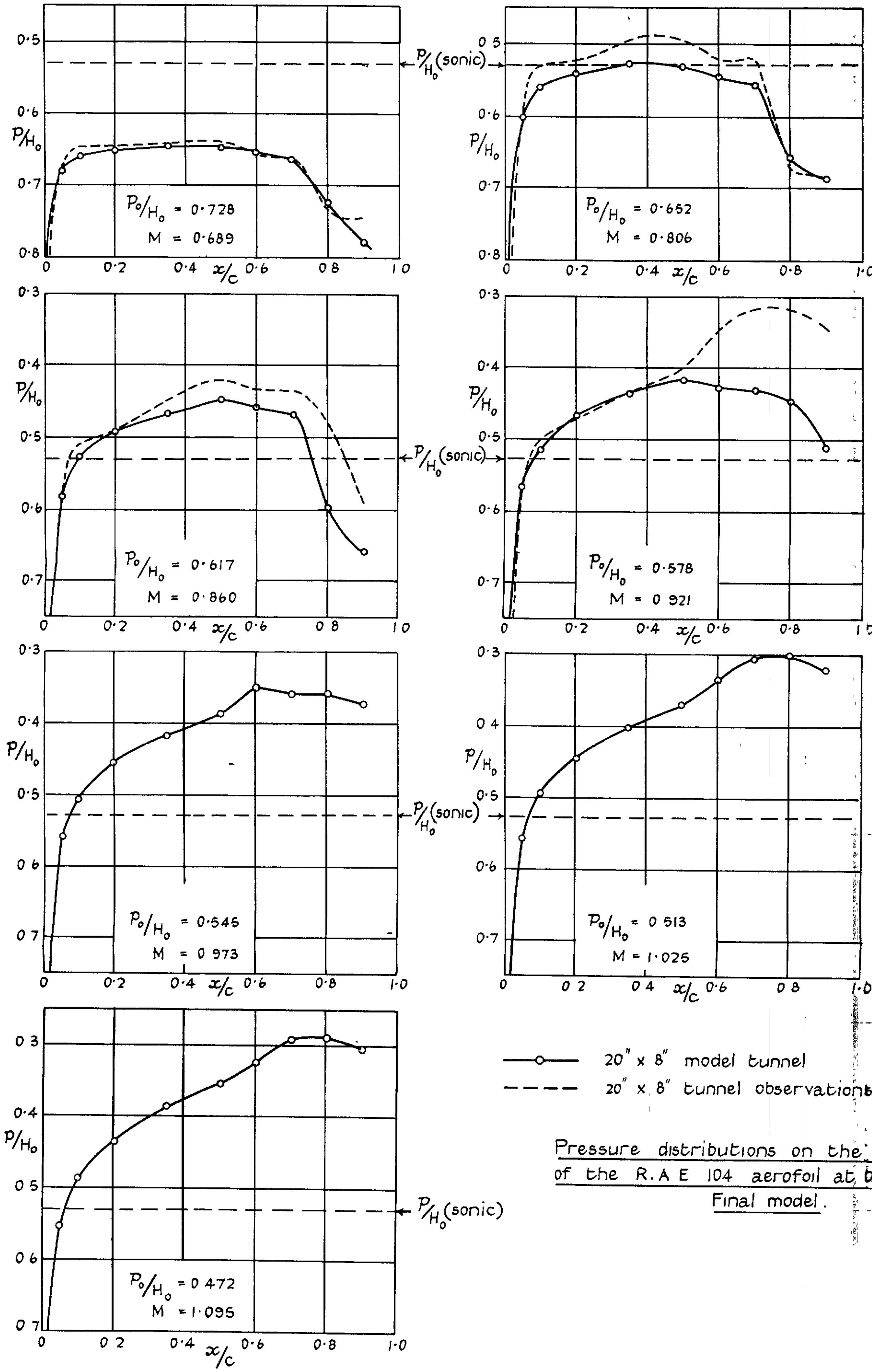


FIG 20

Static pressure distribution along the slotted walls of the final model

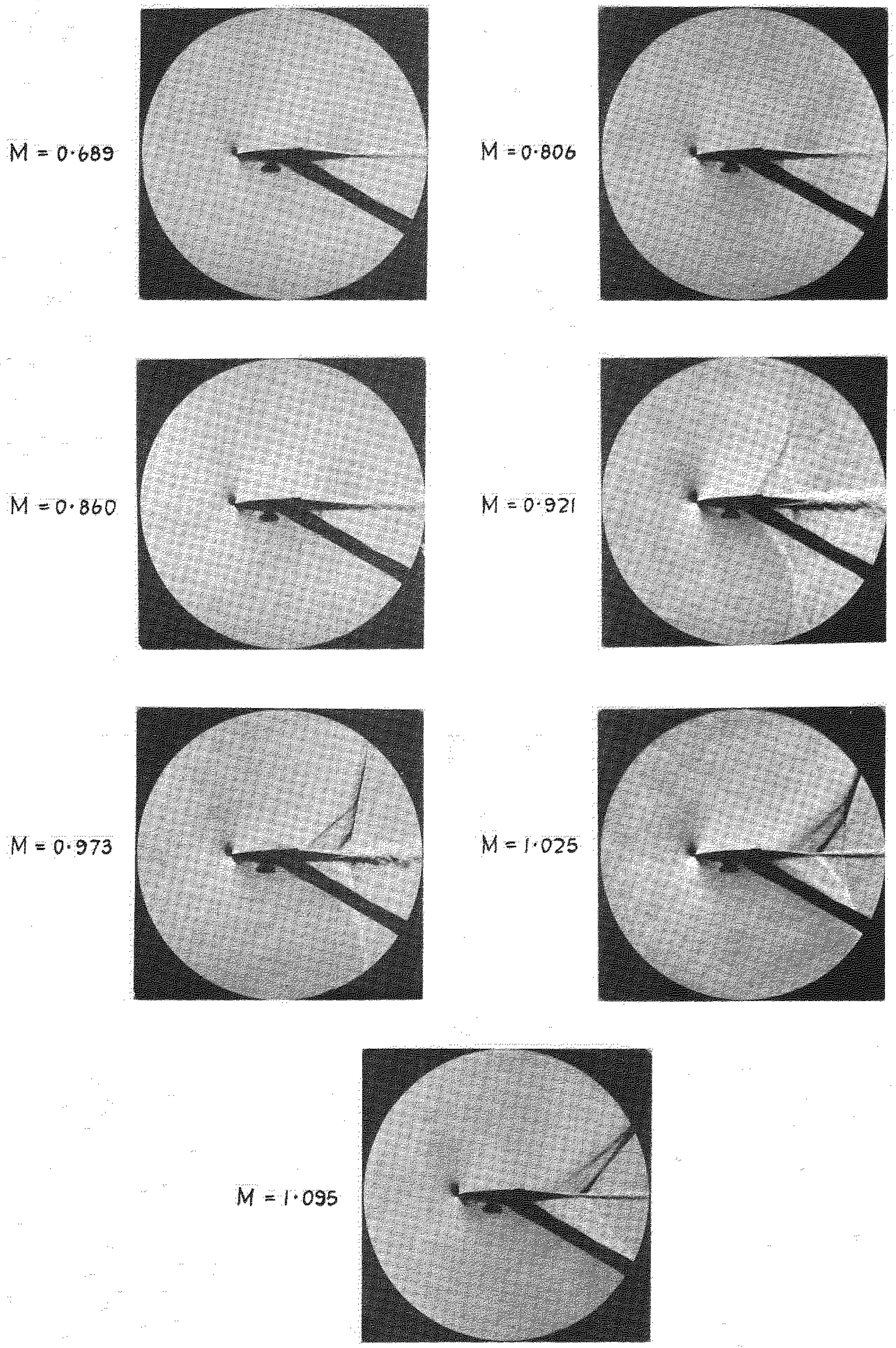
R A E 104 at +4°



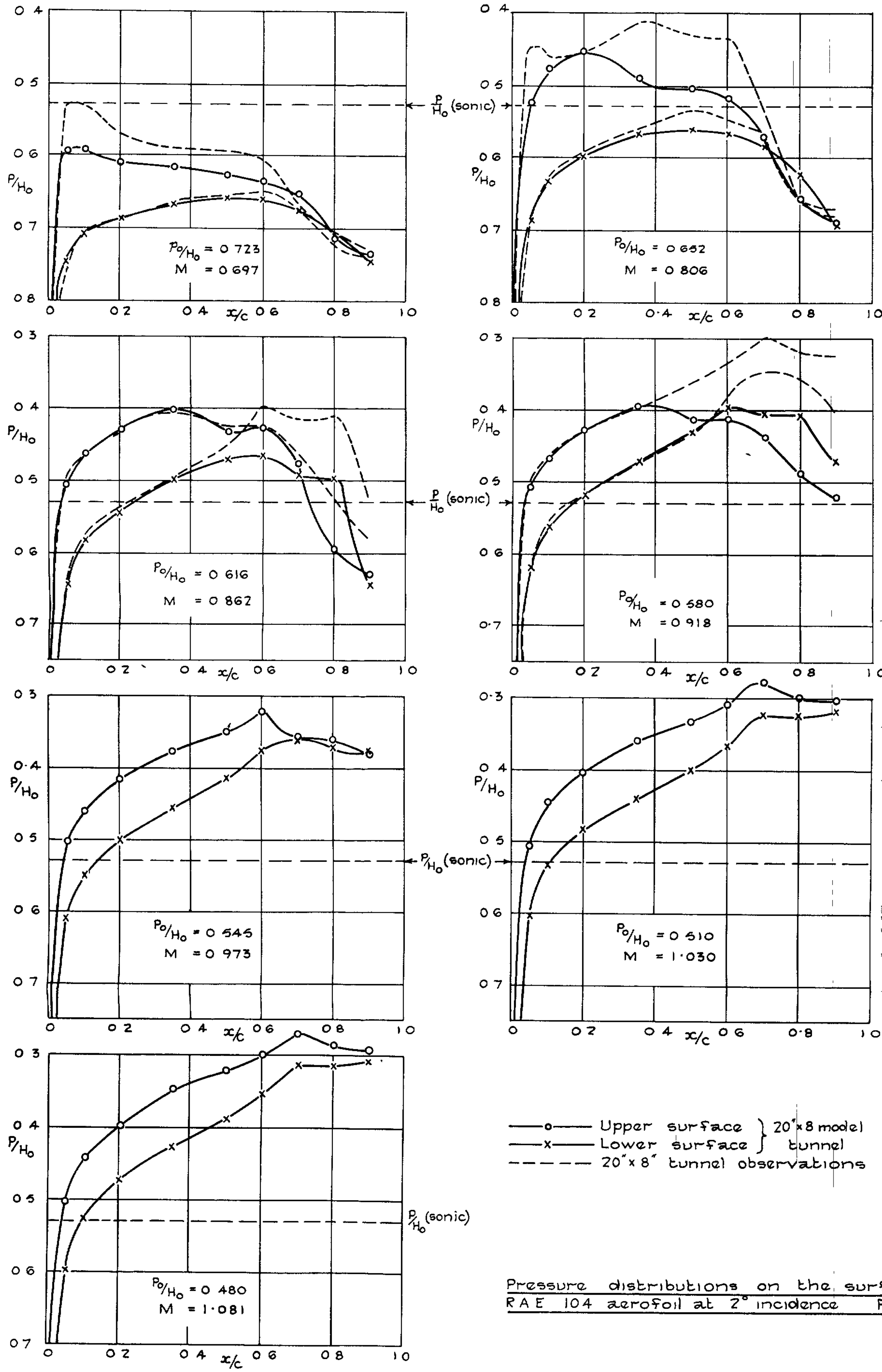
Pressure distributions on the surfaces of the R.A.E 104 aerofoil at 6° incidence.
Final model.

FIG. 21

FIG. 22.



Schlieren photographs of the flow round the R.A.E. 104 aerofoil at 0° incidence. Final model.

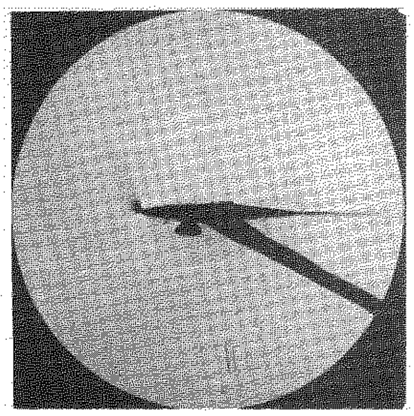


Pressure distributions on the surface of the RAE 104 aerofoil at 2° incidence Final model

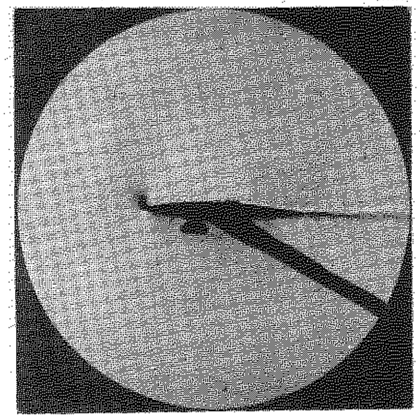
FIG 23

FIG. 24.

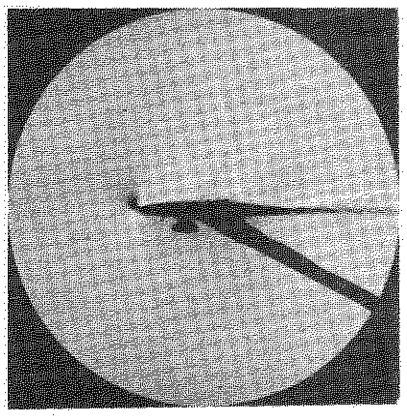
M = 0·697



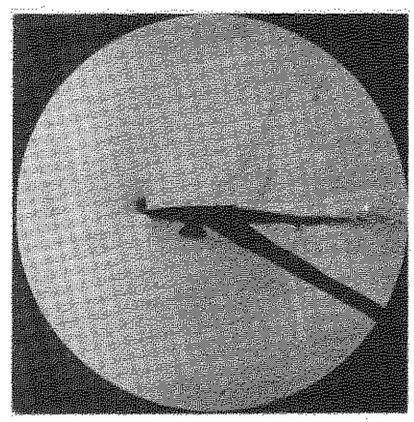
M = 0·806



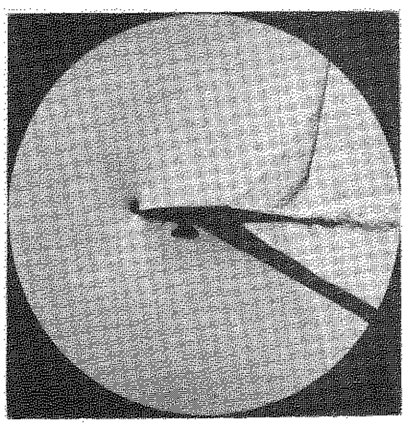
M = 0·862



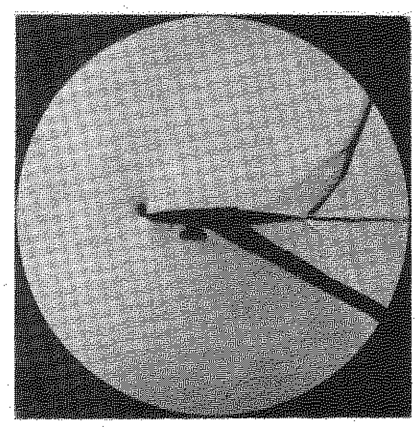
M = 0·918



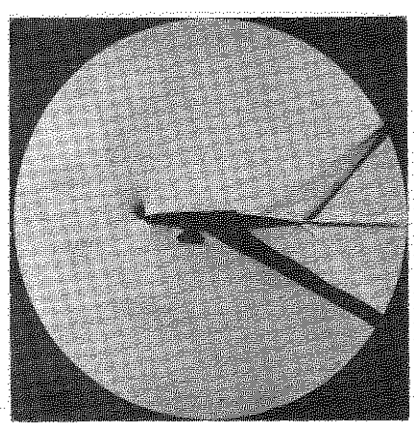
M = 0·973



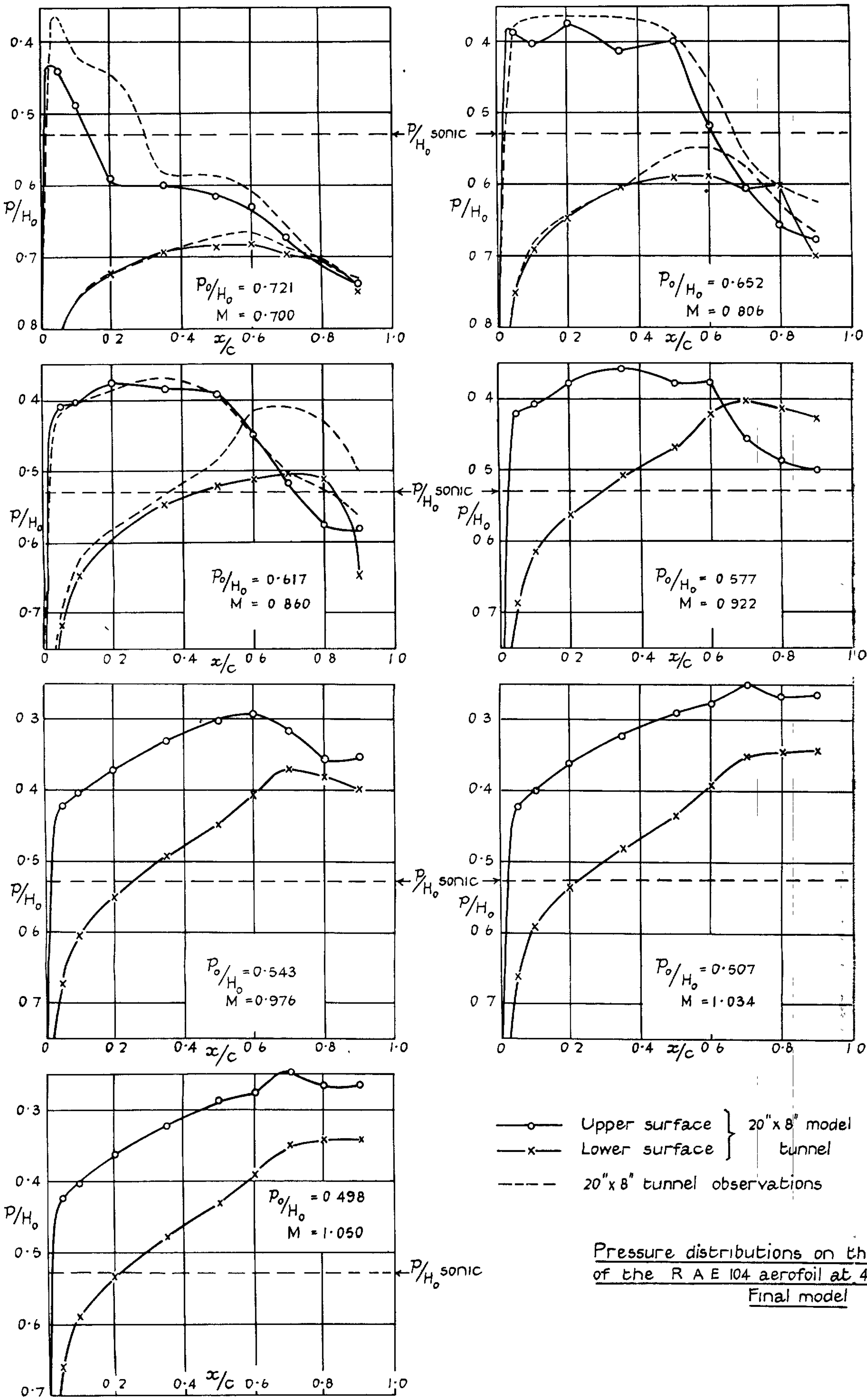
M = 1·030



M = 1·081



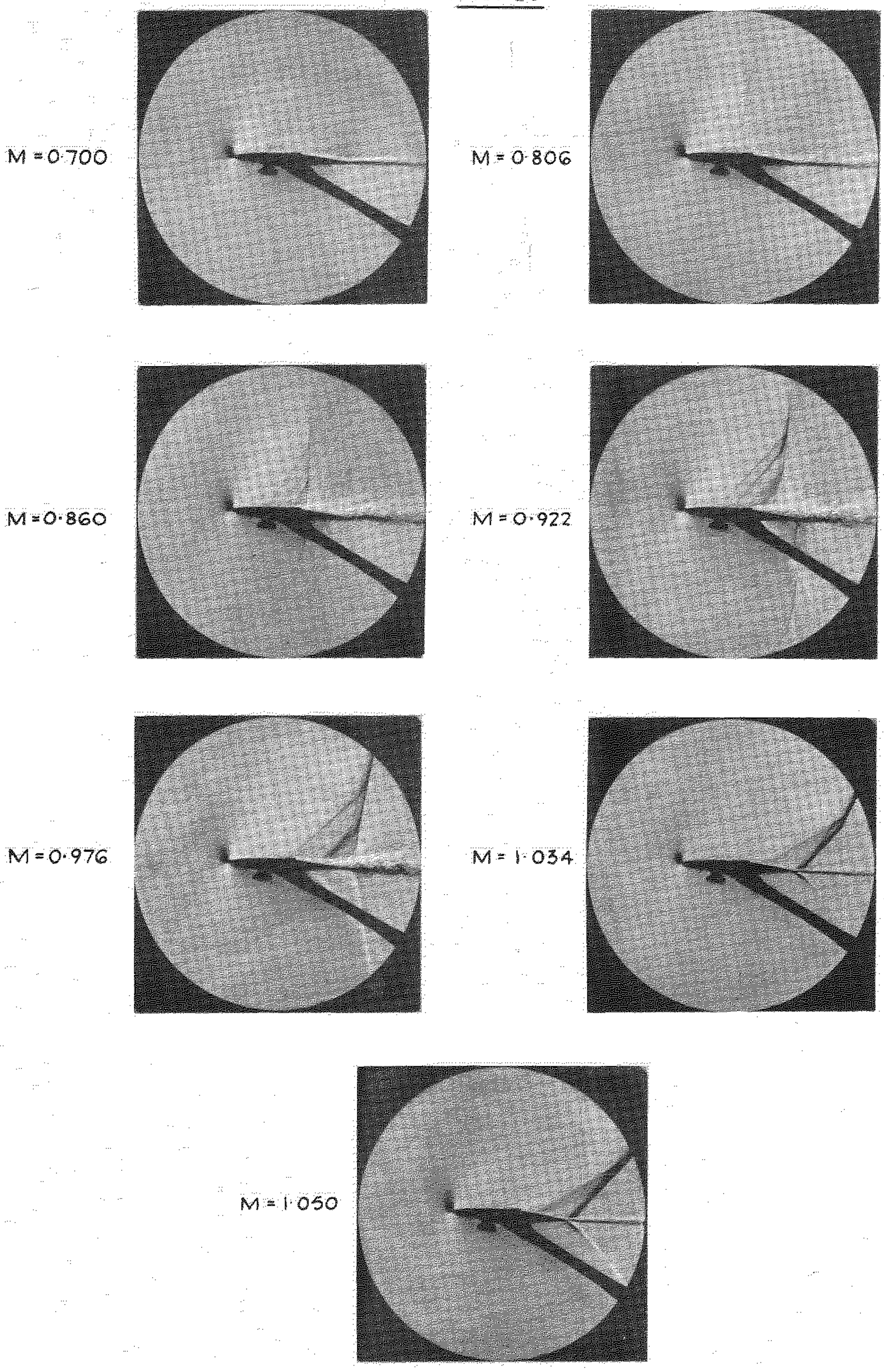
Schlieren photographs of the flow round the R.A.E. 104 aerofoil at 2° incidence. Final model.



Pressure distributions on the surfaces of the R A E 104 aerofoil at 4° incidence.
Final model

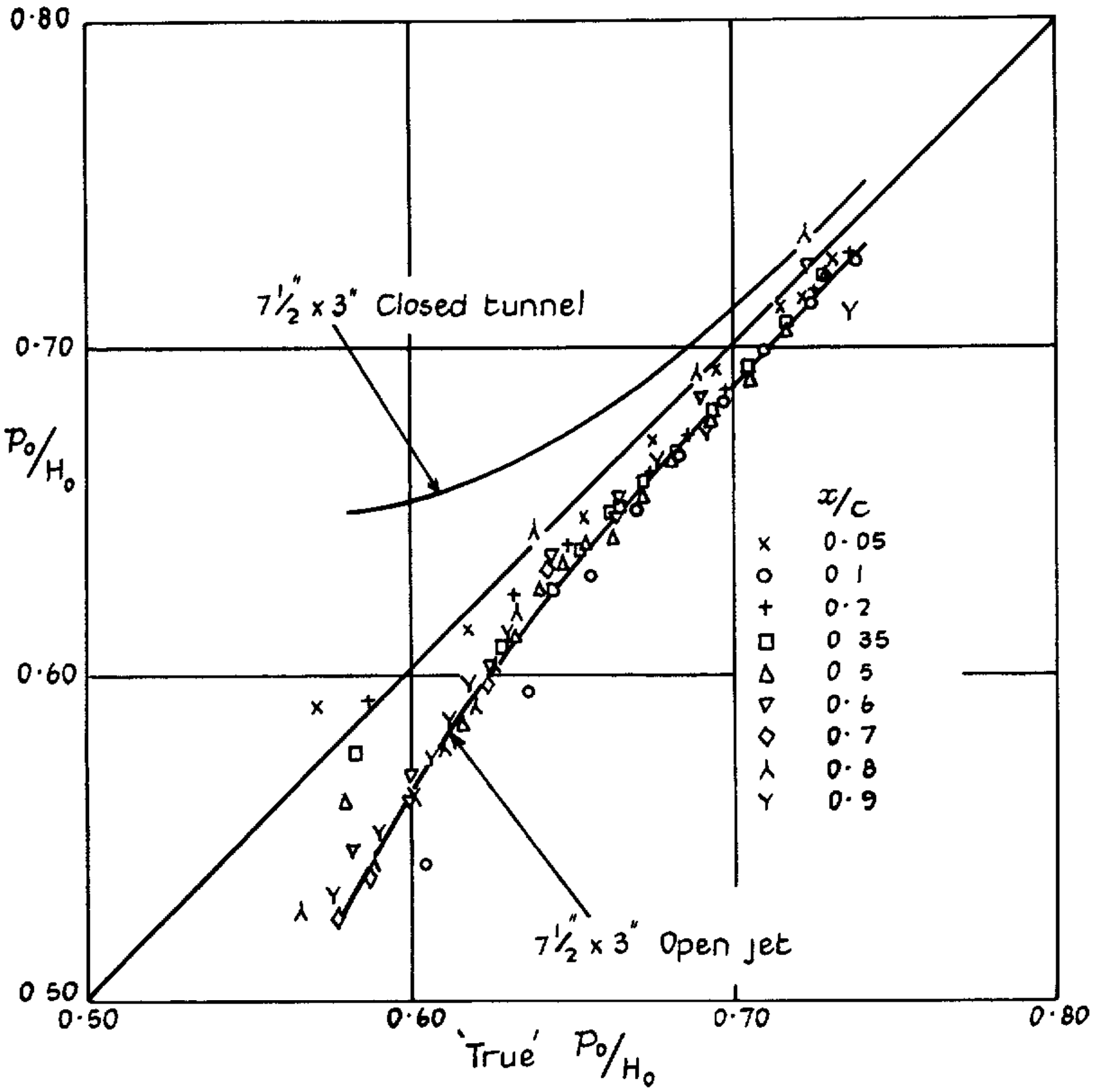
FIG 25.

FIG. 26



Schlieren photographs of the flow round the R.A.E. 104 aerofoil at 4° incidence. Final model.

FIG 27.



Blockage diagram for the final model.

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