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Note on an Application of the Tilting Plate Method of Mach Number Variation for Wind Tunnel Tests at Low Supersonic Speeds

By

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Note on an application of the tilting plate method of Mach number variation for wind tunnel tests at low supersonic speeds

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SUMMARY

When a flat plate mounted in the working section of a supersonic wind tunnel is inclined at an angle to the stream, there exists a region above the surface of the plate in which the Mach number is constant and different from the main stream value. In limited circumstances this region may be used as the test section and it is possible, by varying the angle of the plate, to obtain a continuous variation of test Mach number with the one fixed tunnel nozzle. This method of Mach number control can be particularly useful for making wind tunnel tests near M = 1.0.

The report describes an application of the method to a study of internal flow problems of side intakes at transonic speeds in a small supersonic tunnel. By arrangements involving the use of three or four tunnel nozzles, a continuous Mach number range from 0.5 to 1.6 is made available, apart from a gap between 0.97 and 1.04.

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1 Introduction

The use of a tilting plate for obtaining a continuous variation of Mach number in a supersonic wind tunnel has been described by Drougge[1]. The principle of the method is illustrated in Fig.1. A flat plate, with sharp leading edge, is installed in the working section, spanning the tunnel and close to the bottom liner. For a given angle of the plate to the tunnel stream, providing the shock at the plate leading edge is attached, a region of uniform Mach number exists between the surface of the plate and the wave fronts formed by the shock at the leading edge, the shock or expansion at the trailing edge and the foremost disturbance emanating from the roof. This last may be either the reflection of the leading edge shock or, if the roof liner is cut away to avoid choking the tunnel, a disturbance from the end of the liner.

The Mach number in this uniform region - the test section - is determined solely by the Mach number of the tunnel nozzle and the angle between the plate surface and the tunnel stream. By adjusting the angle of the plate a continuous variation of test Mach number can be obtained. The arrangement is particularly useful for obtaining test Mach numbers near 1.0, using a nozzle Mach number of about 1.3.

This method is currently being used in the No. 2 $5\frac{1}{2}$" × $5\frac{1}{2}$" supersonic tunnel of the R.A.E., in a series of experiments designed to study the flow characteristics of side intakes for aircraft and missiles. The present note describes the details and working of the method in this particular application.

2 Test arrangement

The arrangement used is shown in Fig.2. Conditions are somewhat different from those of Drougge. Drougge's tunnel was 3.1" wide × 11.5" high and he used a plate 5.5" long. His test specimen was mounted near the middle of the tunnel, where the length of usable test section was only slightly less than the length of the plate at all Mach numbers.

Compared with this, the No.2 tunnel is at a disadvantage in being only $5\frac{1}{2}$" high. To give the same ratio of tunnel height to plate length as in Drougge's tests would require a plate only 2.6" long, which would be totally inadequate for the purpose. Fortunately the particular type of experiment allows a much larger plate to be used, for the following reasons:-

(a) The intake model is mounted on the surface of the plate and is therefore approximately 5" from the roof. This is almost equal to the corresponding distance in Drougge's arrangement.

(b) Since the study is confined to problems of internal flow, the interference shock from the roof can be permitted to fall on the plate, providing it does not lie ahead of the plane of entry of the intake model.

The actual plate used is 8" long and 3/16" thick. The upper surface is flat, the lower surface chamfered to a sharp leading edge. The leading edge angle is about 3°.

The plate is mounted with its leading edge about $\frac{1}{2}$" above the bottom liner of the tunnel. It is supported on screw threads near the front and rear, by means of which it can be rotated about any transverse axis. In practice it is found to be satisfactory to keep the front supports fixed and allow the leading edge to dip slightly as the trailing edge is raised.

The bottom liner is cut away underneath the plate. This prevents choking and allows a rapid transition to subsonic speeds. It is desirable for the leading edge of the plate to be slightly behind the plane of cut-off of the liner. An appreciable overlap results, at low Mach number, in choking of the flow beneath the plate and consequent detachment of the leading edge shock. Air then spills round the leading edge from the underside and may affect the distribution on the upper surface.

The upper liner extends downstream of the plane of the plate leading edge but is cut away ahead of the foremost plane in which the shock from the leading edge would otherwise meet it. The arrangements used with two tunnel nozzles, giving M = 1.5 and 1.3 respectively, are shown in Fig.3.

With the M = 1.5 nozzle, some difficulty was experienced in deciding on the best form for this upper liner. Three arrangements were tried, these being as follows:-

(1) liner cut off at end of nozzle, i.e. in plane of plate leading edge;

(2) with level extension, 3" long;

(3) with upward-sloping extension, 3" long, angle to horizontal about 8°.

The sketches in Figs. 4, 5, 6 show shock formations obtained with these arrangements, as observed by shadowgraph. In the first case (Fig.4), by 5° plate angle the interference shock had reached a position less than 3" from the leading edge of the plate. With the level extension (Fig.5), the shock was still behind the half-way position even at 7°. With the sloping extension (Fig.6), the interference shock from the trailing edge, at small plate angles, was further downstream than in the case of the level extension, but the expansion fan from the end of the nozzle proper was well forward on the plate. At 6° the roof boundary layer separated causing the interference shock to jump forward to within 3" of the plate leading edge.

Since the second arrangement (3" level extension) allowed an adequate (though not necessarily the maximum) angle range for the proposed tests, this arrangement was adopted without further development.

With the M = 1.3 nozzle, the disturbance from the end of the liner was relatively weak. A 2" level extension beyond the end of the nozzle proper was used at the outset. This gave adequate results and consequently no attempts were made to improve on it.

3 Calibration

3.1 Mach number range

Fig.7 shows the variation with plate angle, at two nozzle Mach numbers, of mean Mach number on the part of the plate surface which is inside the test section. The mean Mach number was obtained by pressure plotting the surface along the centre line. In each case the measured variation followed the theoretical curve closely, up to the point at which the tunnel choked. This was at $7\frac{1}{2}^{\circ}$ with the 1.5 nozzle (plate Mach number 1.23) and at $4\frac{1}{2}^{\circ}$ with the 1.3 nozzle (plate Mach number 1.04).

These calibrations were made using humid air, during a period of breakdown in the plant air-drying facilities. One result of this was that the M = 1.3 nozzle gave a Mach number of only 1.25 with the plate at zero angle. Later, using dry air, a check was made of initial Mach number and plate angle for tunnel choking with this nozzle. The results are plotted in Fig.7, and show that when the initial Mach number was 1.3 the maximum plate angle was $5\frac{1}{2}^{\circ}$, giving M = 1.05.

With the 1.5 nozzle, the humidity had a negligible effect on initial Mach number, but it may be noted that in later tests investigating the effect of blockage (section 3.2, Fig.9), plate angles in excess of $7\frac{1}{2}^{\circ}$ were obtained without the tunnel being choked.

Sketches appended to some of the points in Fig.7 show approximately the shock wave patterns in the working section. It can be seen that in both cases, just prior to tunnel choking, the foremost interference shock has advanced to about half-way position on the plate. This state of affairs was considered satisfactory for the particular experiments in hand.

3.2 Model blockage effect

In order to investigate the suitability, from a blockage aspect, of the proposed size of intake model, tests were made with a series of solid blockages of various sizes. The blockages consisted of straight bars, each 4" long and of constant square section; these were mounted in turn on the centre line of the plate, with the front face of the blockage 4" from the plate leading edge.

From observations of shadowgraph, the following zones of interference can be defined (these are illustrated in Fig.8):-

Zone 1: Interference shock or expansion (i.e. the foremost disturbance from the roof) does not meet plate, but would intersect disturbance from plate trailing edge (the intersection was not actually observed owing to the disturbances being weak). This is the condition applying in Drougge's experiment.

Zone 2: Interference shock meets plate behind front face of blockage. This is the most usual condition in the intake work.

Zone 3: Interference shock meets plate ahead of front face of blockage. The boundary between zones 2 and 3 defines the limit of acceptability for the intake tests.

Ranges of plate angle and test Mach number appropriate to these zones and to the ultimate condition of a choked tunnel are plotted in Fig.9. It will be seen that, taking the limit line to be the boundary between zones 2 and 3, a reasonably good working range is available. Thus, for example, with a model giving 1% blockage, a continuous Mach number variation from 1.5 down to 1.1 can be obtained using the two nozzles tested.

The working range of Mach number for a given nozzle can be extended upwards by inclining the plate to negative angles. This has been tried on occasion, and negative angles up to 2° (maximum increase in M over zero angle = 0.1) appear to give satisfactory results. Negative angles are not generally used, however, because of the increased difficulty of maintaining a satisfactory seal (i.e. negligible leak) at the edges of the plate.

1% is the order of blockage given by the intake models, so that 1.1 is the lowest Mach number that can be used conveniently with the standard 1.3 nozzle.* Still lower working Mach numbers can be obtained, however, by

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* The effective blockage varies, of course, with intake mass flow ratio. At full mass flow the estimated blockage is only about ½%.

starting from a lower Mach number with plate at 0°. Thus by tilting the upper liner of the 1.3 nozzle to provide an area ratio corresponding to $M = 1.2$, working Mach numbers down to 1.04 can be obtained with intake models installed. This modified nozzle is the arrangement actually used in the current programme when low supersonic speeds are required.

We note from Fig.9 that if it were necessary to prevent the interference shock falling on the plate (interference zone 1), the method would be of very little use with the present size of plate. A further point is that if a closed tunnel were used in place of the present half open configuration, zones 2 and 3 would probably hardly exist. Instead, the choking boundary would tend to coincide with the boundary of zone 1. Again it may be concluded that the present relative size of plate would be excessive.

3.3 Velocity distribution

Typical velocity distributions on the surface of the plate are plotted in Fig.10. Results are shown for three supersonic nozzles, giving overlapping Mach number ranges and covering altogether a range from 1.6 down to 1.04. The subsonic distributions are obtained by using a subsonic nozzle with the plate at zero incidence and varying the tunnel pressure ratio. In this way, Mach numbers from 0.5 to 0.97 have been obtained with good distribution.

Thus it is seen that, with the use of three or four nozzles, a continuous Mach number variation from 0.5 to 1.6 is available, apart from a gap between 0.97 and 1.04. For a study of the internal flow characteristics of intakes, the presence of this gap is of no serious consequence.

The standard of uniformity of the distributions shown is high enough for the purpose of the experiments in hand. It could probably be improved by more careful positioning of the plate fore-and-aft relative to the bottom liner.

3.4 Minimum pressure ratio of tunnel

It is of some interest to record the minimum total pressure ratio required to operate the empty tunnel in the half-open jet condition, i.e. with liners cut away for installation of the tilting plate. This is shown in Fig.11. The pressure ratio is that required to cause the tunnel shocks to jump from the ends of the liners to a position downstream of the working section. The results are compared with a curve, taken from ref.2, for the minimum pressure ratio required by the No.4 tunnel, of similar design but operating with a fully closed working section.

4 Concluding summary

The tilting plate method has been successfully applied to the study of intake flow problems at transonic speeds, using models of reasonable size in a $5\frac{1}{2}$" square tunnel. With the arrangements described, a continuous Mach number variation from 0.5 to 1.6 is available, apart from a gap between 0.97 and 1.04.

List of symbols

M = Mach number

p_o = total pressure upstream of tunnel nozzle

p_o' = total pressure downstream of tunnel diffuser

REFERENCES

No.	Author	Title, etc.
1	Drougge	A method for the continuous variation of the Mach number in a supersonic wind tunnel and some experimental results obtained at low supersonic speeds. Aeronautical Research Institute of Sweden - Report No. 29. 1949.
2	Lukasiewicz	Design and calibration tests of a 5.5" square supersonic tunnel. R & M 2745. February 1950.

Wt.2078.CP168.K3 - Printed in Great Britain.

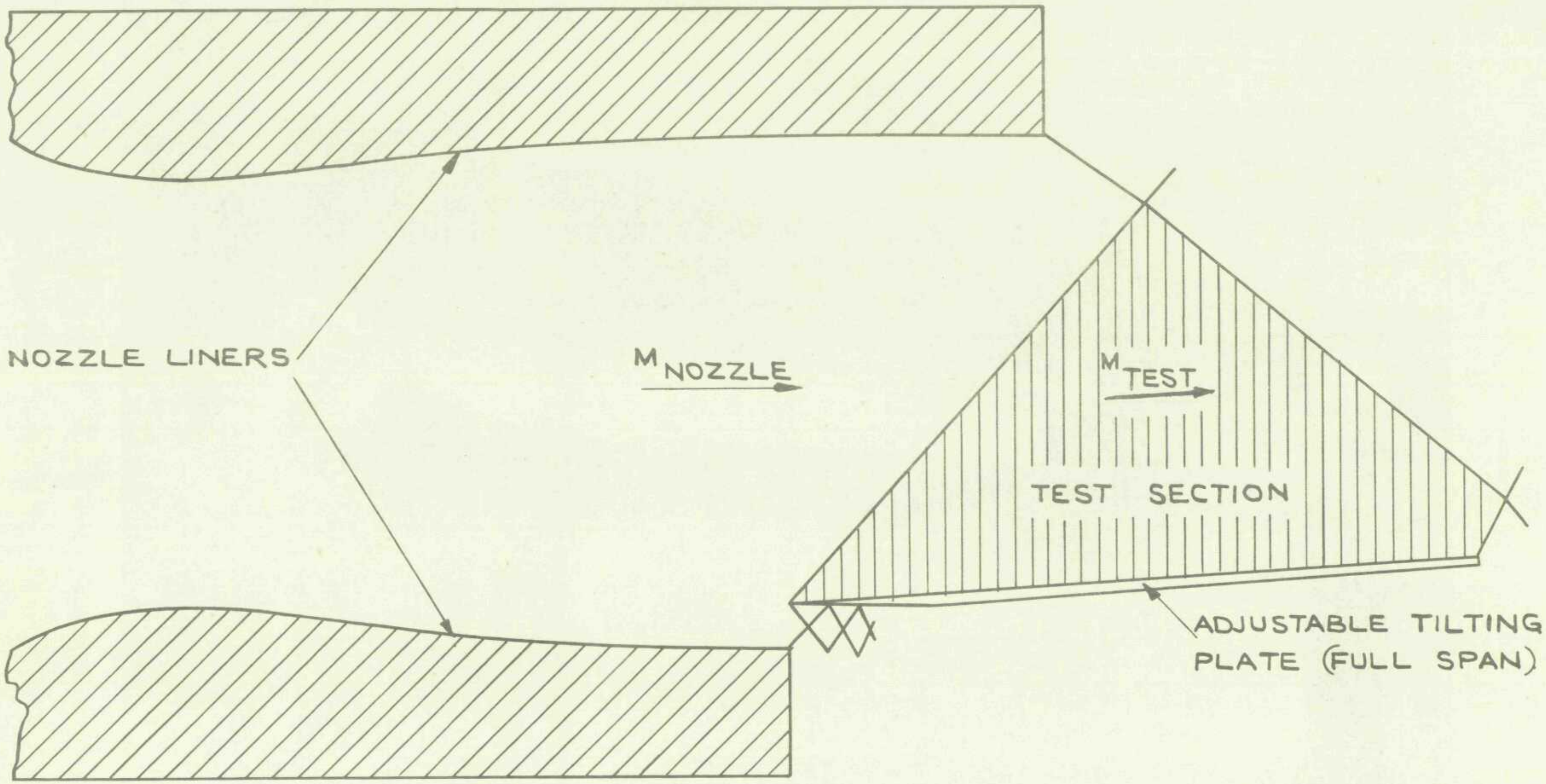


FIG 1. TILTING PLATE METHOD OF MACH NUMBER VARIATION IN A SUPERSONIC TUNNEL.

FIG.2

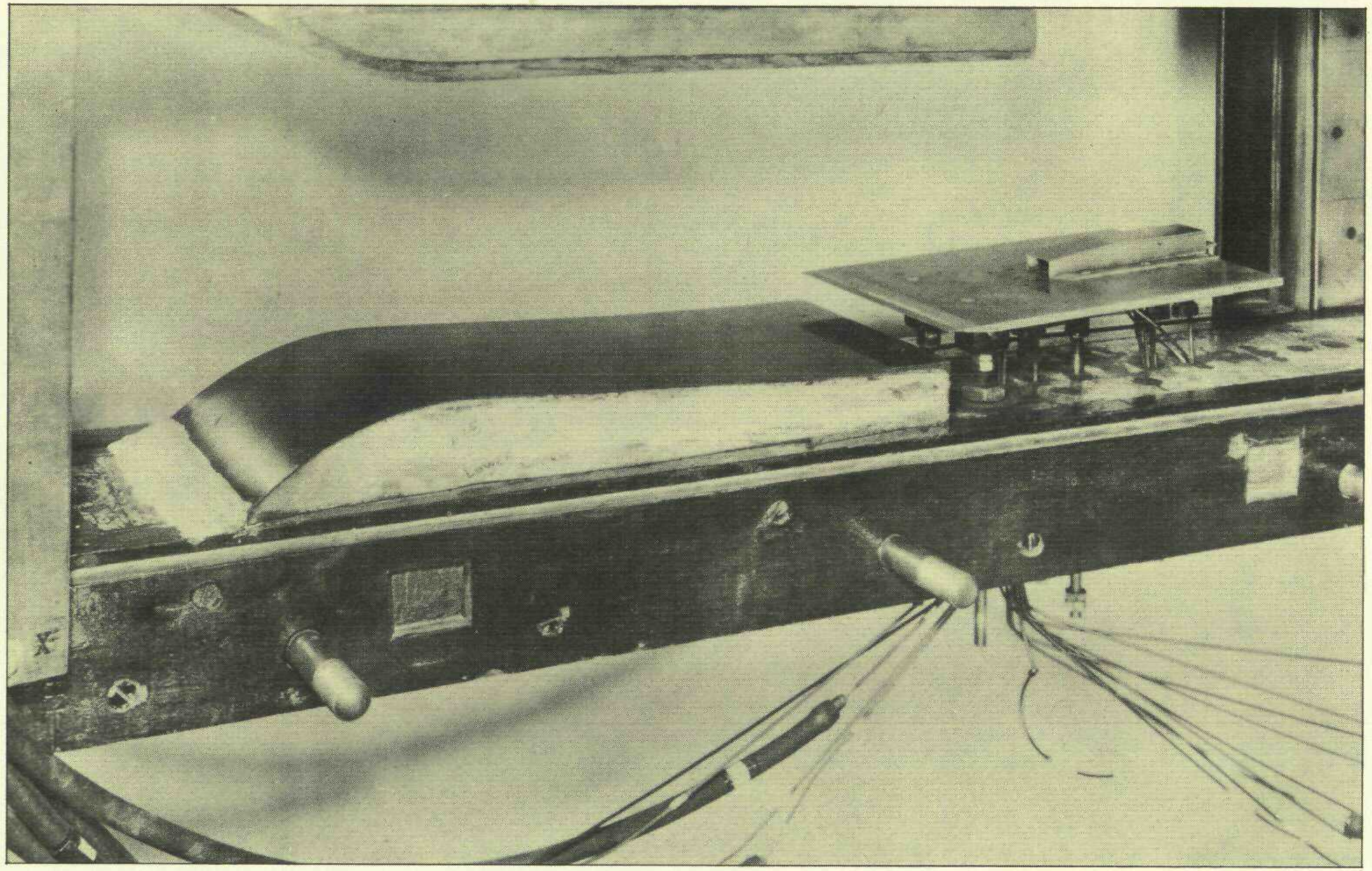
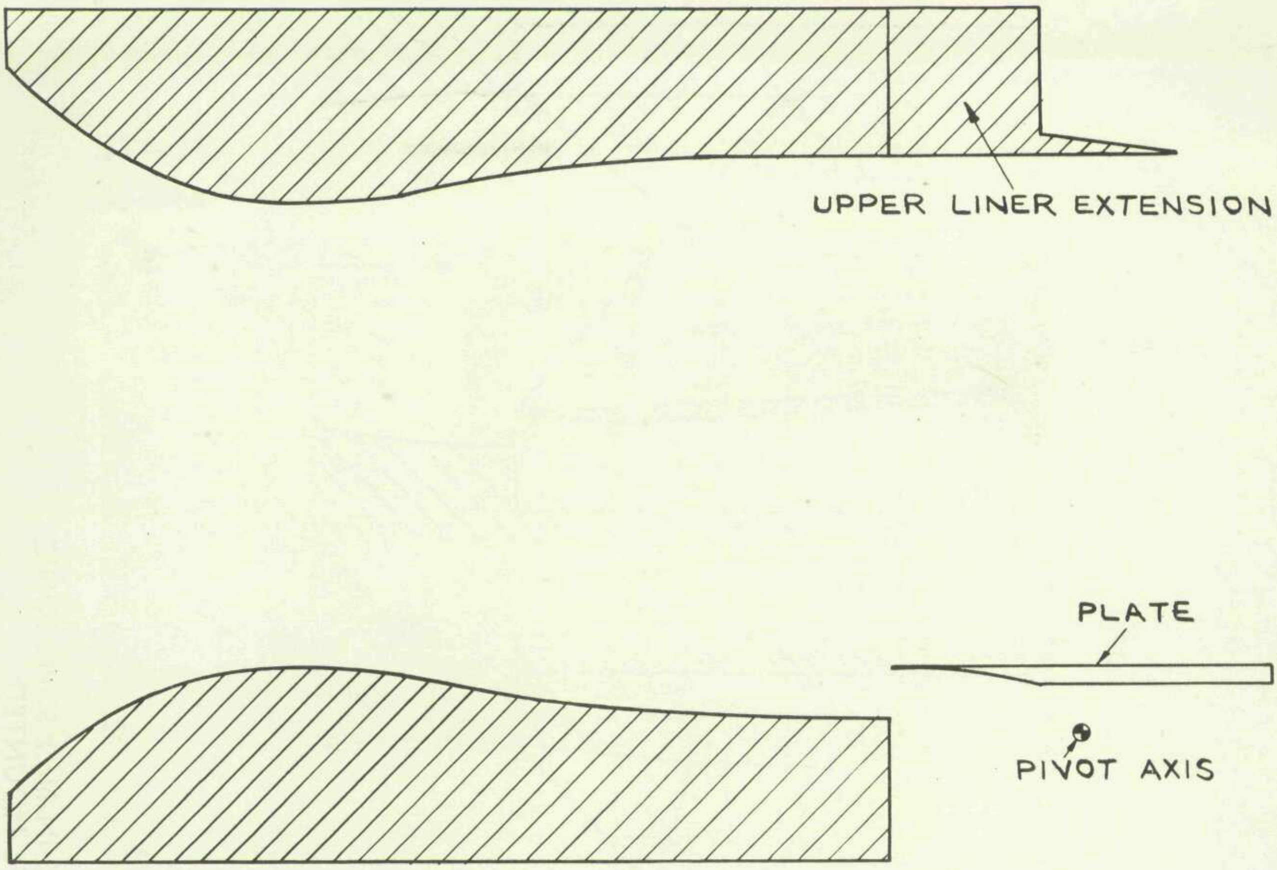
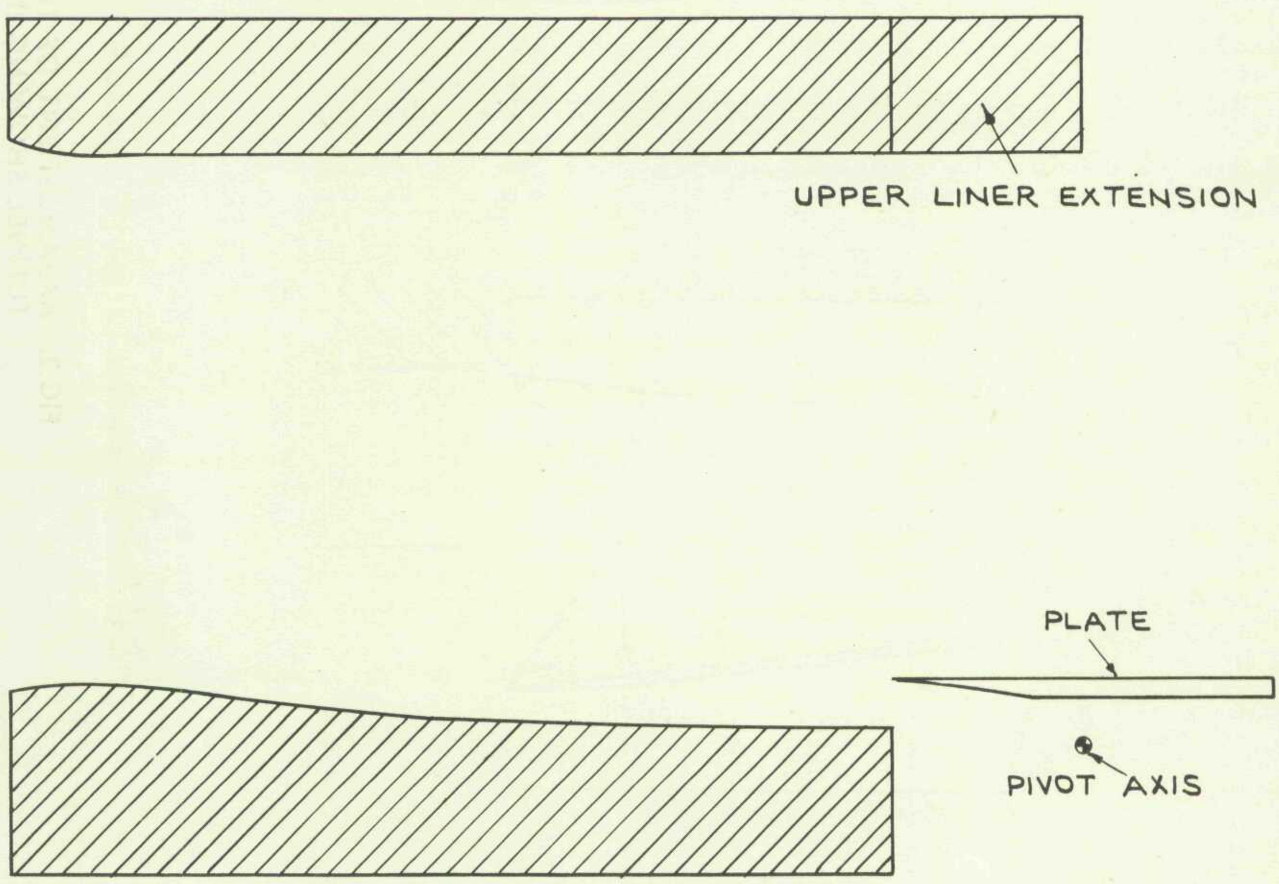


FIG.2. ARRANGEMENT OF TILTING PLATE IN No.2 SUPERSONIC TUNNEL SHOWING INTAKE MODEL MOUNTED



NOZZLE MACH NUMBER 1·5.



NOZZLE MACH NUMBER 1·3.

FIG 3. NOZZLE ARRANGEMENTS USED WITH TILTING PLATE.

FIG 4.

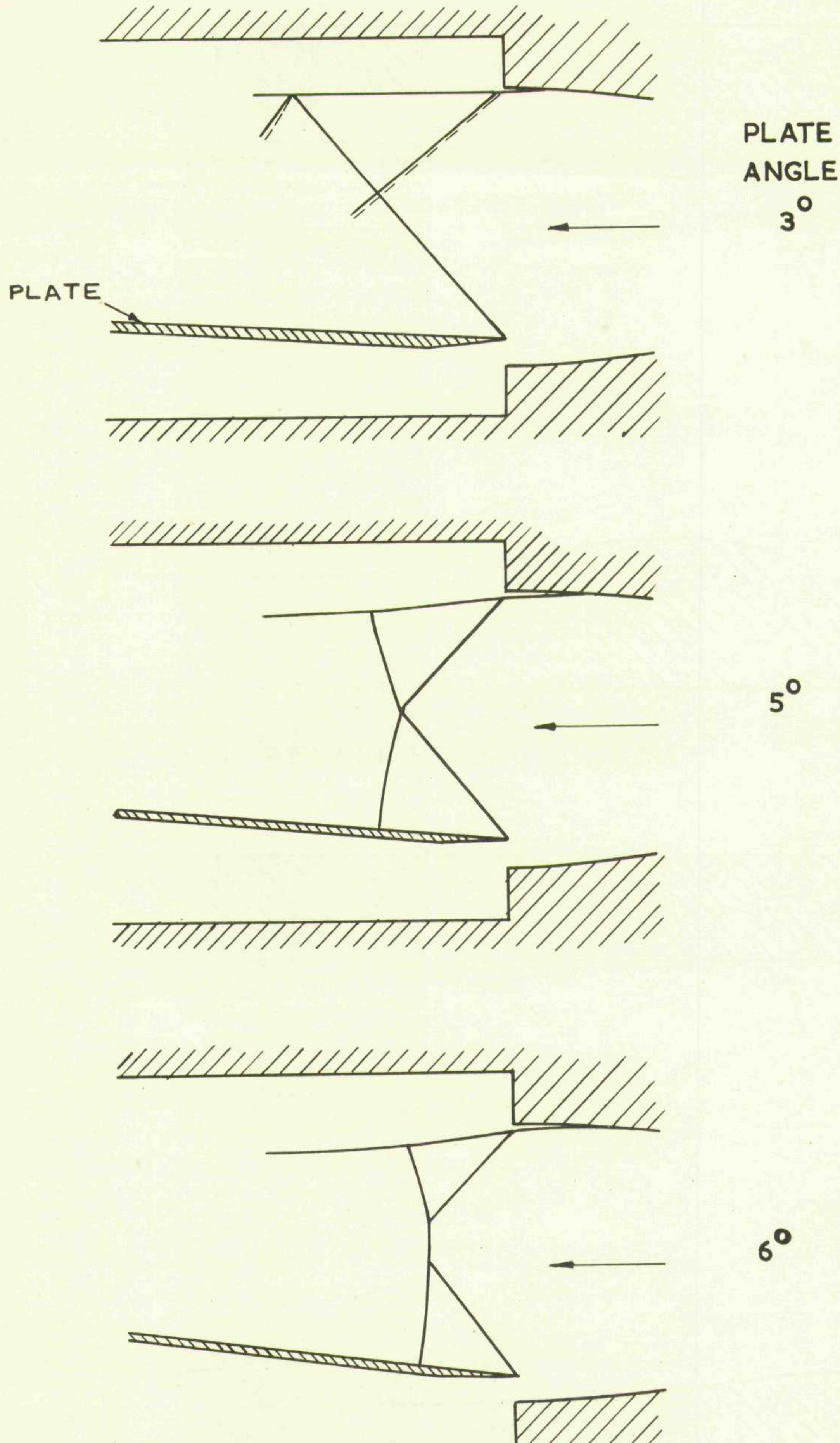


FIG 4. SHOCK FORMATIONS WITH M= 1·5 NOZZLE: UPPER LINER CUT OFF IN PLANE OF PLATE LEADING EDGE.

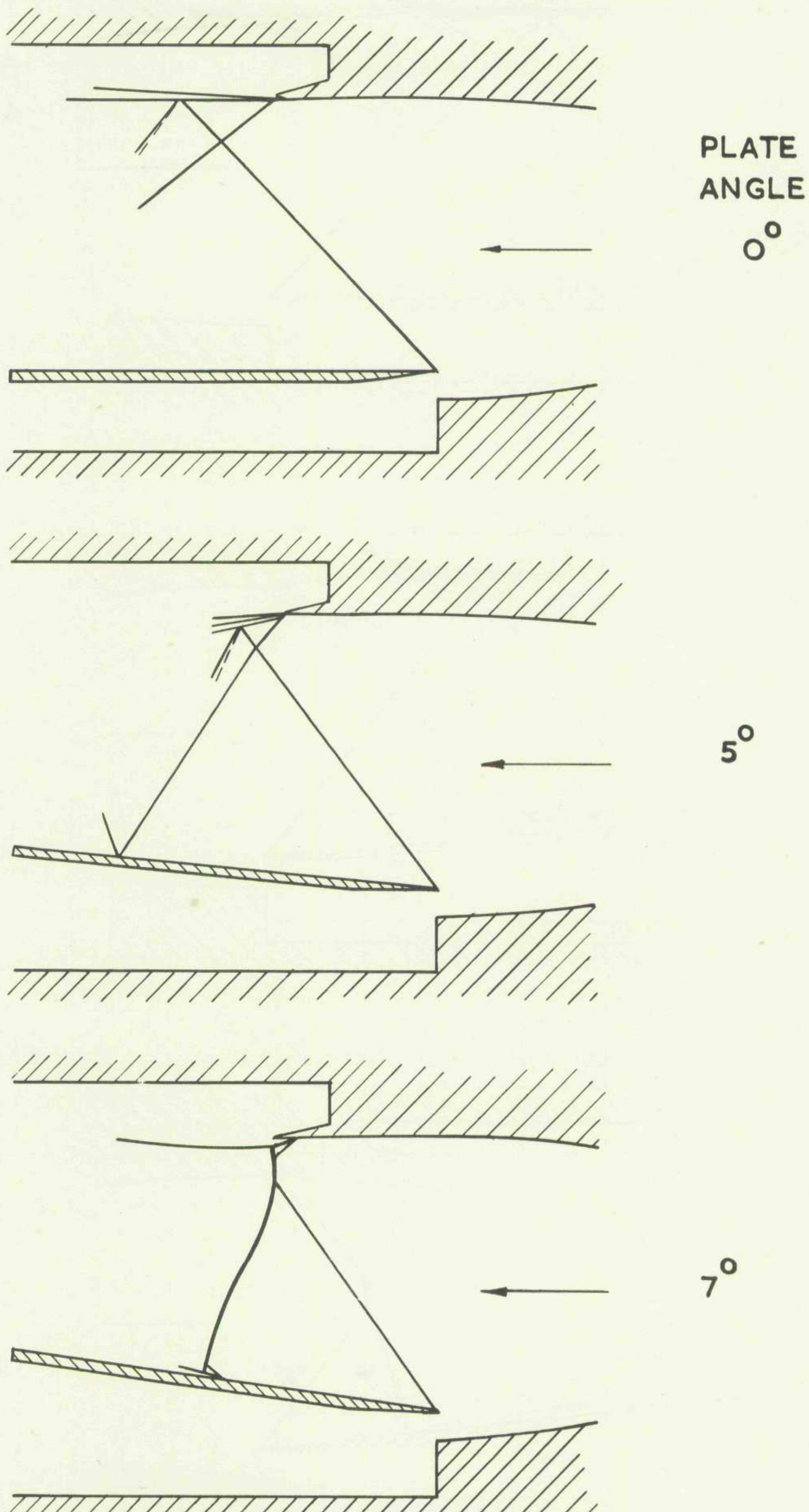


FIG. 5. SHOCK FORMATIONS WITH M= 1·5 NOZZLE: 3" LEVEL EXTENSION TO UPPER LINER.

(I.E. AS IN FIG. 3).

FIG 6

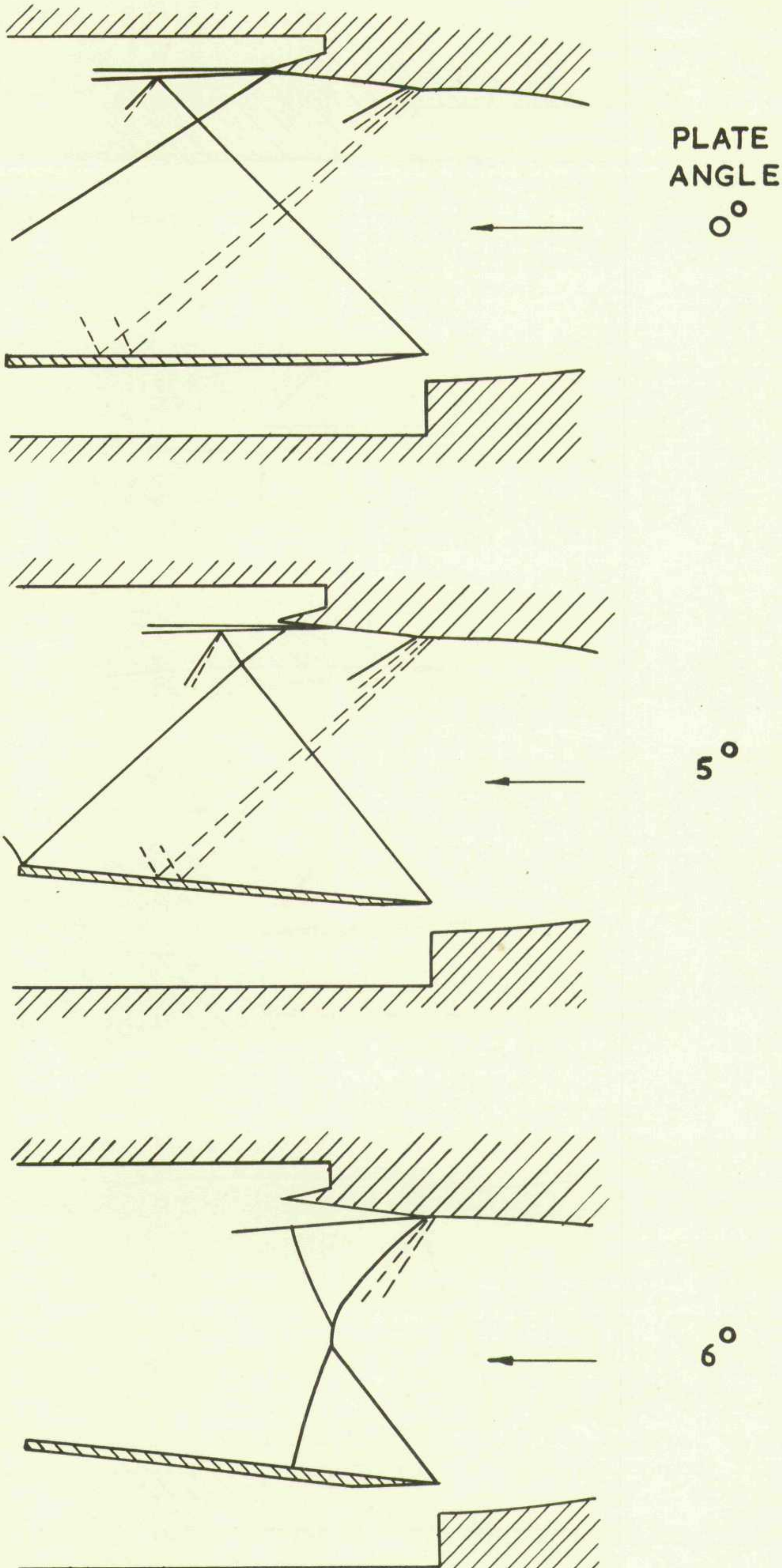


FIG 6. SHOCK FORMATIONS WITH M = 1·5
NOZZLE: 3" SLOPING EXTENSION TO
UPPER LINER.

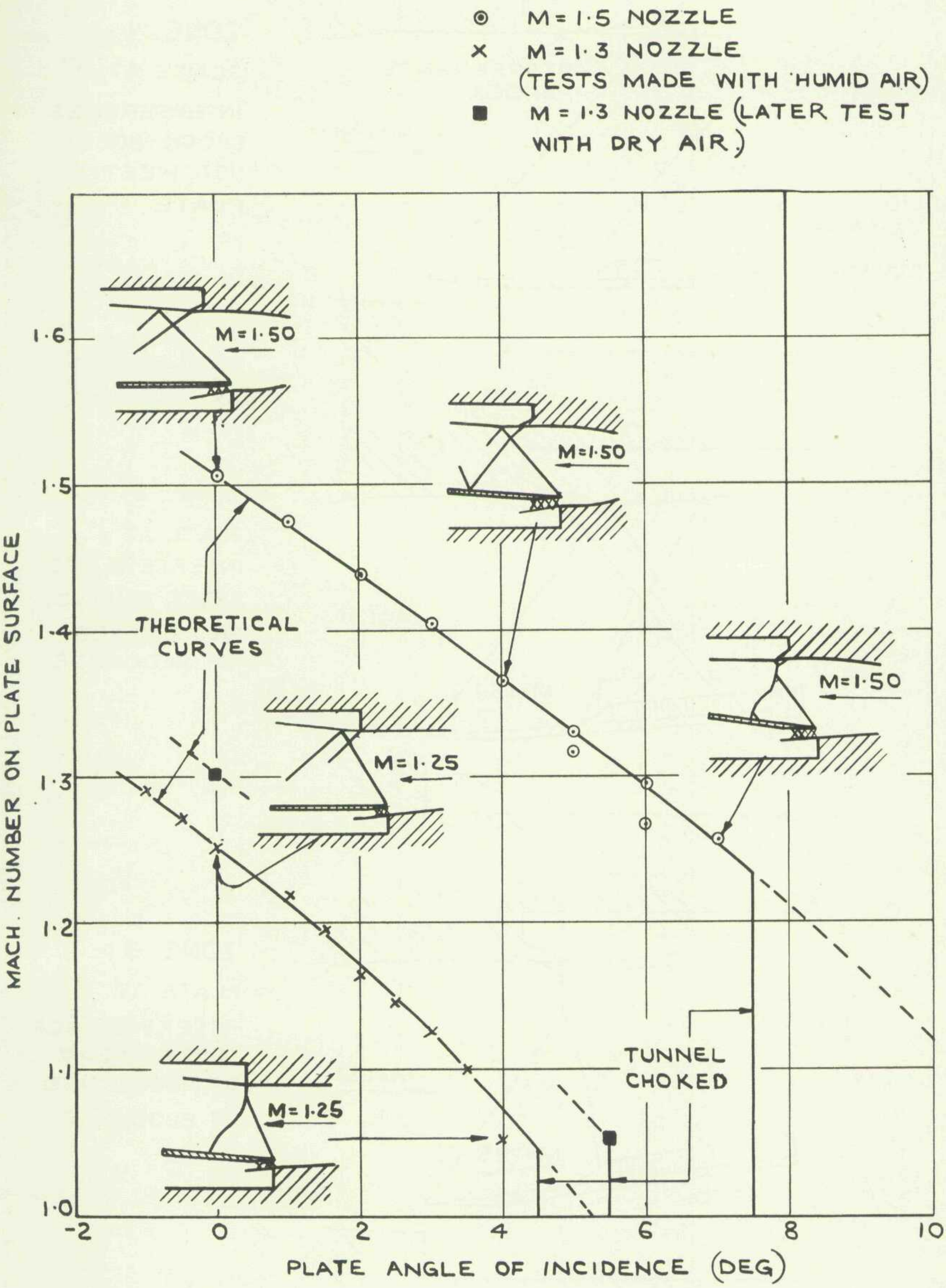


FIG 7. VARIATION OF PLATE SURFACE MACH NUMBER WITH PLATE ANGLE.

FIG 8

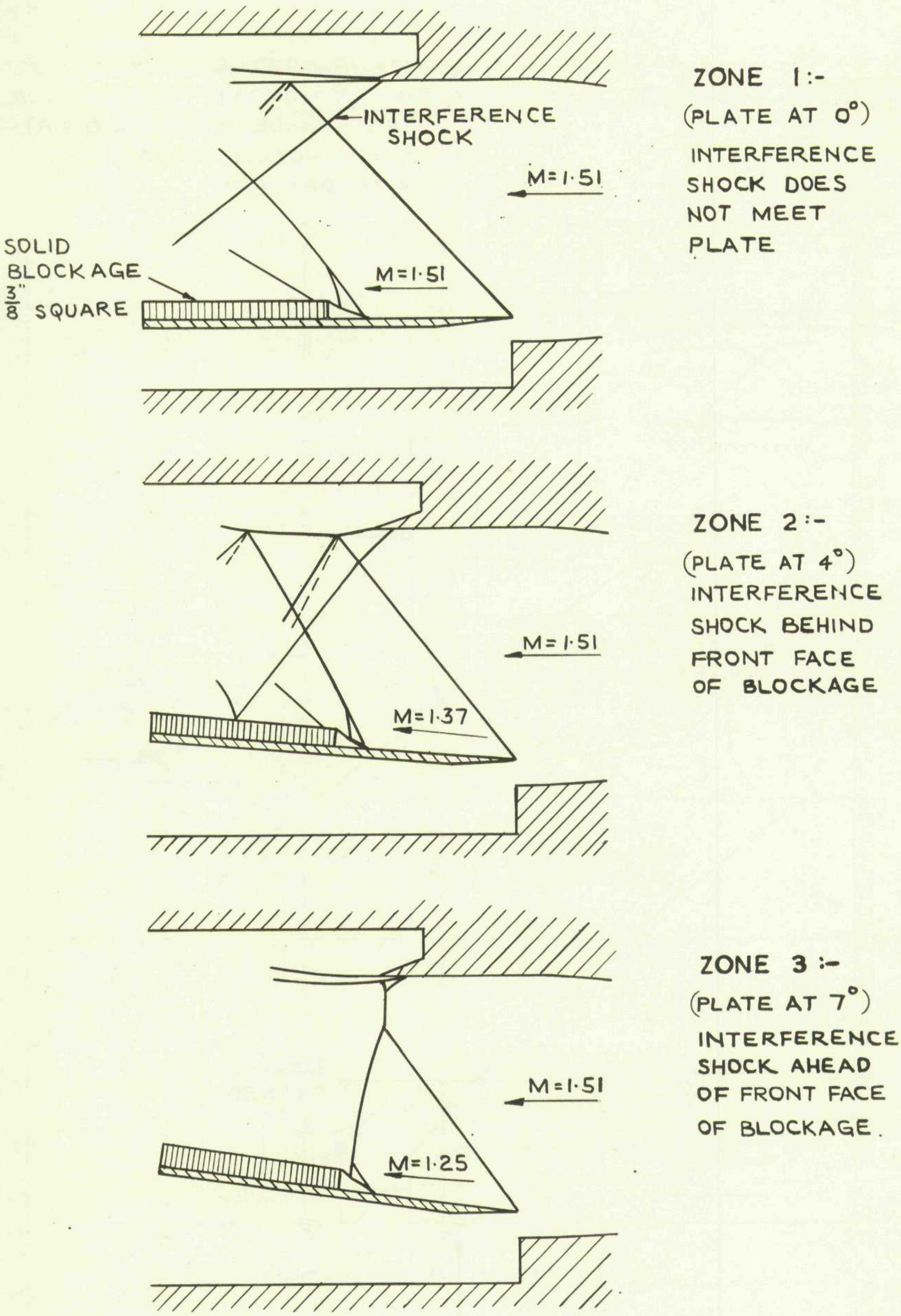


FIG 8. SHOCK FORMATIONS WITH M=1·5 NOZZLE & 3/8" SOLID BLOCKAGE SHOWING ZONES OF INTERFERENCE.

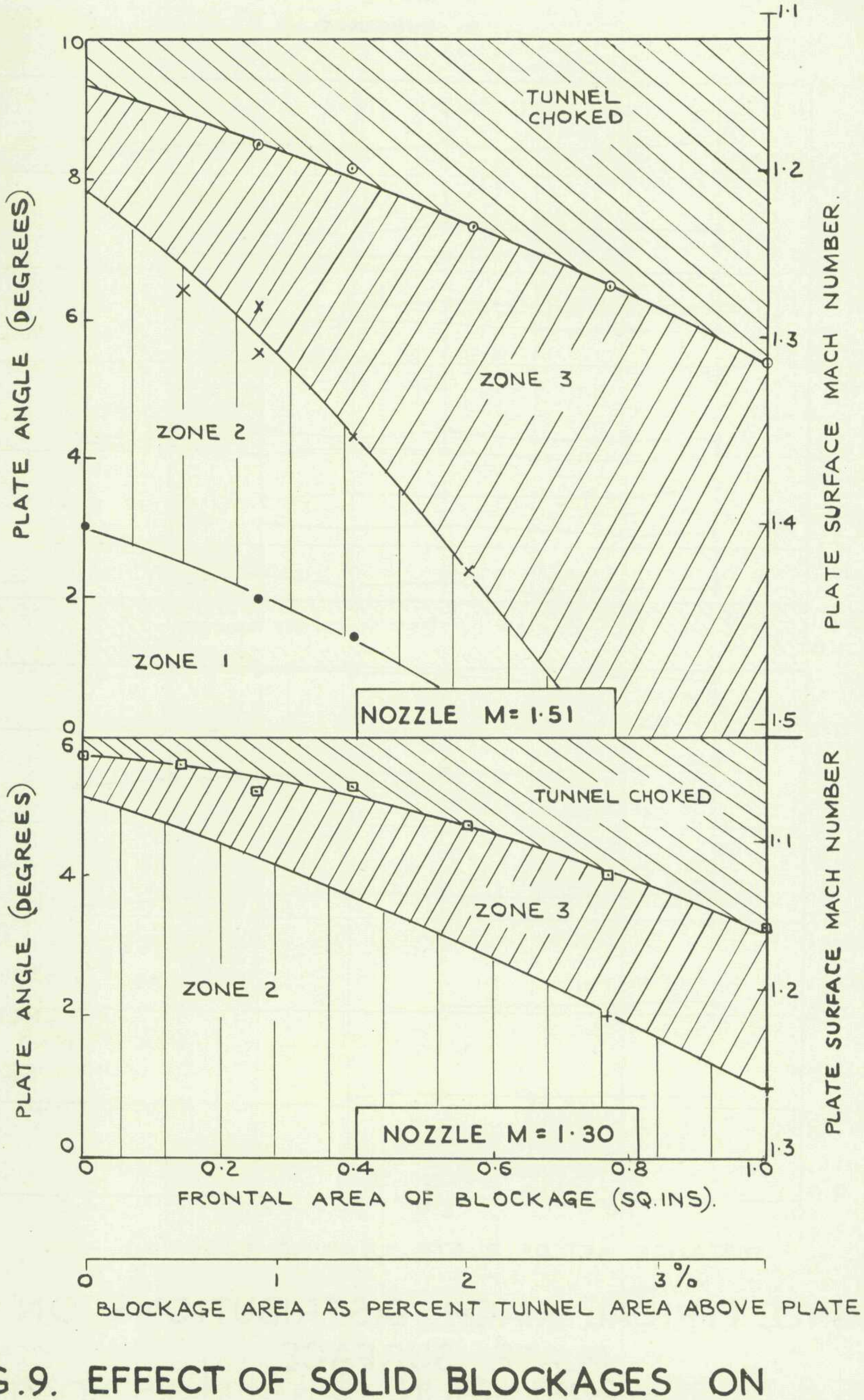


FIG. 9. EFFECT OF SOLID BLOCKAGES ON USABLE MACH. NUMBER RANGE: ZONES OF INTERFERENCE ARE AS DEFINED IN FIG. 8

FIG 10

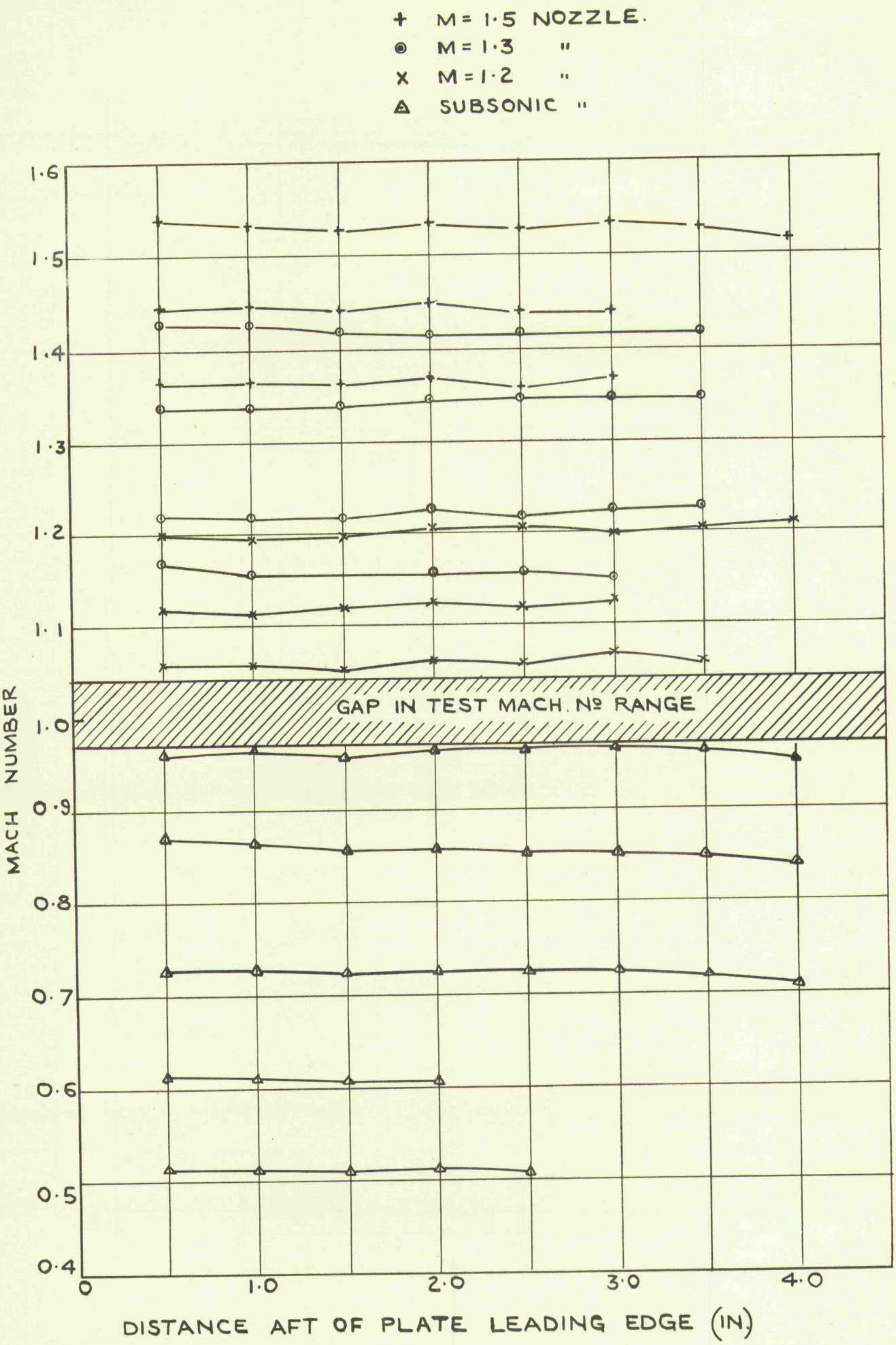


FIG.10. TYPICAL MACH DISTRIBUTIONS ON PLATE SURFACE.

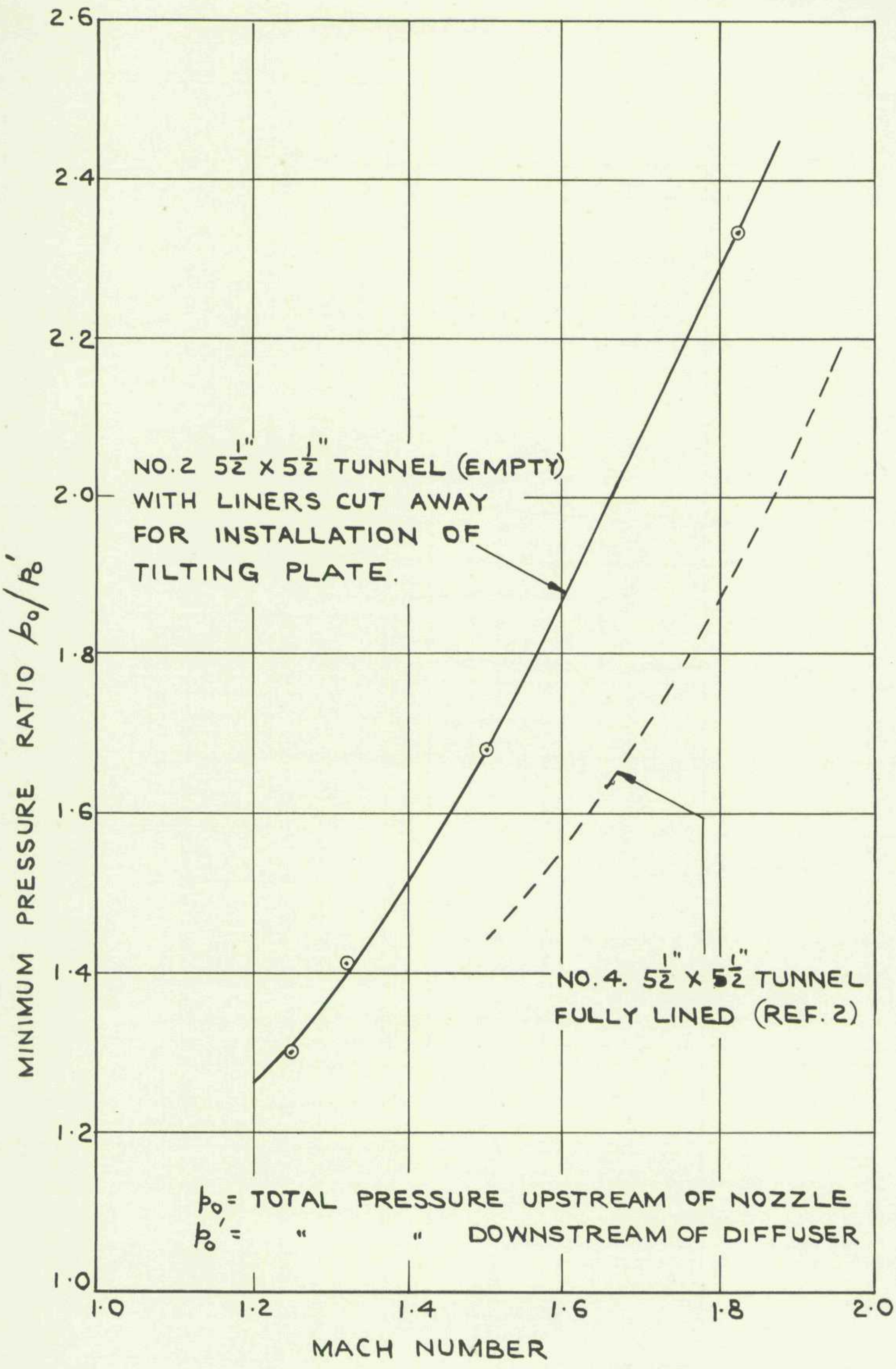


FIG. 11. MINIMUM PRESSURE RATIO REQUIRED BY No. 2. TUNNEL OPERATING WITH A HALF-OPEN JET.

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