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by

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A SIMPLE FLEXIBLE SUPERSONIC WIND TUNNEL NOZZLE FOR THE RAPID AND ACCURATE VARIATION OF FLOW MACH NUMBER

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SUMMARY

The design of a simple, variable-geometry nozzle for a supersonic wind tunnel is described. The method of construction enables the Mach number of the flow to be continuously and accurately altered while tests are proceeding. Although designed to be incorporated as part of a flight simulator, the installation is suitable for normal wind tunnel testing especially where tests at a particular Mach number are essential.

The results of the calibration of the flow in a small scale test section are given. The tests show that it is possible to obtain a standard of flow throughout the working section similar to that obtained with fixed nozzle installations.

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CONTENTS

1 INTRODUCTION

Beecham, in Ref.1, suggests that the separate roles of the wind tunnel and the computer could profitably be integrated to form a closed-loop, flight-dynamic simulator. He proposes that the forces acting on the wind tunnel model at any instant should be measured and the model orientation to the wind kept consistent with that in full scale, three dimensional flight. By this means the behaviour of models from a given initial set of conditions would be directly determinable, and the boundaries of stability readily obtained. This proposal is currently being implemented in the R.A.E. 18" × 18" supersonic wind tunnel.

To simulate fully all conditions of flight it is desirable to vary the Mach number of the flow in the wind tunnel sufficiently quickly and accurately to conform with the motion given by the computer, such as deceleration of a missile after boost burn out or changes due to drag. If uniform flow is to be retained however, the Mach number of the flow in a supersonic wind tunnel can only be satisfactorily altered by changing the profile of the convergent-divergent nozzle upstream of the working section. The problem is therefore to construct a nozzle, the profile of which can be continuously and rapidly varied and which will, at all settings, produce a uniformity of flow acceptable for force measurements on models. For simplicity these changes of geometry should be effected by a single actuator.

In the past, many attempts have been made to design adjustable nozzles. The difficulty is to maintain the very accurate profiles necessary throughout the Mach number range in order to obtain a uniform flow throughout the working section. One satisfactory solution is that described in Ref.2 where the nozzle consists of fixed parallel side walls between which are mounted upper and lower flexible plates forming the convergent-divergent nozzle. The flexible plates are each supported by 30 hydraulic jacks which can be controlled to deform the plates to a predetermined profile. The installation produces excellent flow characteristics in the working section throughout the Mach number range, but is complicated and costly, since the rate of extension of each jack differs and has to be carefully related by hydraulic motors and valves controlled electrically by means of punched paper tapes of standard teleprinter type, one tape for each jack.

This report describes a new solution to the problem of deflecting a flexible plate which enables the Mach number to be continuously and rapidly altered whilst still retaining an accuracy of flow comparable with that of the multi-support system of Ref.2.

2 PRINCIPLE OF THE SWINGING LINK AND FLEXIBLE PLATE

In common with Ref.2 it is assumed that the nozzle will consist of two thin metal sheets which may be flexed into the required profiles without developing excessive stresses. The hydraulic jacks are however replaced by a number of swinging links of fixed lengths. The principle is shown diagrammatically in Fig.1. The flexible plate is connected to a fixed frame by a number of swinging links r_A, r_B etc. The lengths of the links and positions of the pivot centres are chosen so that as the end of the plate is moved in a streamwise direction the plate flexes into the curves of a family of profiles designed to produce uniform Mach number distributions.

With the simple swinging arm linkage suggested here it is possible to generate three such prescribed profiles. In principle more profiles could be fitted with more complicated linkages and slides but the mechanical problems to be overcome would be considerably greater.

Referring to Fig.1 it is assumed that the curves marked M = 1.5, 1.9 and 2.3 represent profiles which will result in flow at the lower, middle and upper Mach numbers of the range of supersonic flow to be covered. With the linkage considered here it is evident that once one point on each of the three profiles has been selected to represent the connecting point of one of the links to the plate, then the rest of the linkage is uniquely determined for given spacing of the hinges on the flexible plate. Although in principle the selection of these initial three points is apparently arbitrary it is found that mechanical considerations limit the freedom of this choice, since fouling between links, and excessive link length, have to be avoided.

Once the initial link and its connecting points, to the plate, say A, A_1 and A_{11} of Fig.1, have been chosen then the positions of connecting points B, B_1 and B_{11} for the next link can be obtained by assuming a discrete spacing between plate fixing points. This spacing will depend on allowable deflections of the plate between links due to different pressure on either side of the plate when the wind tunnel is operating. Points B, B_1 and B_{11} now specify the length of link r_B and the position of the fixed pivot bearing p_B.

By continuing this process, a series of links can be determined which will flex the plate to the correct profiles at the three chosen Mach numbers. As the change from one chosen profile to another occurs smoothly and concurrently over the whole plate it is to be hoped that at intermediate positions, the profile will be close to the appropriate profile at that Mach number setting and the flow characteristics in the working section acceptable.

For a constant working section size the profiles at the downstream end would of course have to converge to the same straight line parallel to the stream direction. To fulfil this condition would require links of infinite length in the region of the working section. To avoid this difficulty it is necessary to relax very slightly the restriction on the working section dimensions, permitting a small variation with Mach number. Use can be made of the fact that the rate of growth of the boundary layer increases with Mach number and that in allowing for the displacement thickness the profiles may thus be sufficiently displaced.

The above principles have been used to design the small scale nozzle described in the remaining paragraphs.

3 $1\frac{1}{2}" \times 5\frac{1}{2}"$ VARIABLE MACH NUMBER SUPERSONIC WIND TUNNEL

One of the unknown factors affecting the acceptibility of the design is the accuracy of the flow at nozzle settings other than at the three design profiles. To obtain this data and to prove the functioning of the multi-link system, a small scale test nozzle was built to replace the working section of the $5\frac{1}{2}" \times 5\frac{1}{2}"$, No.2 supersonic wind tunnel at R.A.E., Farnborough.

The nozzle profiles used were scaled from those given in Ref.3 for the 8 ft × 8 ft supersonic wind tunnel at Bedford after correcting for differences in boundary layer thickness. Since the ratio of nozzle length to working section height is greater for the Bedford tunnel the height of the scaled working section was reduced to 3 inches. At a later stage in the design it was decided that only one half of the nozzle should be constructed and a reflection plate fitted along the tunnel centre line, consequently the working section was finally reduced to $1\frac{1}{2}" \times 5\frac{1}{2}"$.

Due to the small scale of the installation, some difficulties were experienced in the design and manufacture which should be less troublesome in a larger installation. The three main problems were :-

(i) Fixing pivot bearings as close as possible to the surface of a very thin flexible plate without damaging the surface finish or causing appreciable local increases in plate stiffness.

(ii) Sealing the nozzle where the thin plate slides against the side walls.

(iii) Manufacturing the link lengths to the accuracy required in view of the size of the installation.

The final design is shown in detail in Fig.2 and a photograph in Fig.3. The range of Mach number covered was 1.5 to 2.3 to correspond to that of the No.19 R.A.E. supersonic wind tunnel in which the full scale nozzle is to be installed. The scale model was designed to operate with atmospheric stagnation pressure.

The flexible plate is 22 SWG (0.028 inch) stainless steel sheet to specification DTD 166, which has a 0.1% proof stress of 40 tons in^{-2}. The thickness of the plate is such that the combined stresses due to bending, pressure and pretensioning do not exceed 22 tons in^{-2}. The spacing of the bearing pivot blocks on the plate is designed so that the deflection of the plate between pivots due to the different pressure on either side is less than 0.001 inch.

The nozzle is designed so that the back face of the flexible plate is vented to the lowest pressure generated on the operative face, viz. that in the working section; thus should leakage occur between the plate and the side walls, the flow would be outwards from the nozzle. Since the greatest pressure difference occurs upstream of the throat, reducing to zero in the working section, the effects of any leakage on the flow uniformity should, in any case, be slight. This arrangement has the further advantage that the deflections due to pressure difference across the plate are reduced in the region close to the working section.

However, to minimise any leakage a flexible moulded rubber strip, Fig.4, is fixed to the edges of the plate to form a seal between the sliding plate and the fixed side walls of the tunnel. The shape of the seal is designed so that only the 'horns' touch the side walls during assembly. With the air flowing the pressure difference which occurs between the inner and outer faces of the plate, presses the horn tightly into the corner thus forming an airtight seal with no measurable effect on the uniformity of the flow. To reduce friction when operating the strip is lubricated with a smear of silicon grease.

The Mach number is adjusted by a hand wheel on a screwed rod which controls the longitudinal position of the plate. On the full scale installation it is intended that this hand wheel should be replaced by a hydraulic jack. The plate is tensioned by a pneumatic jack attached to a pivot block at the upstream end of the plate, the pressure in the jack being sufficient to return the plate against the pressure loads, friction in the pivot bearings and friction between the sealing strip and the sidewalls. The jack is coupled to a reservoir of relatively large volume so that the pressure and therefore tension, is kept approximately constant during the full movement of the plate.

At the junction of the flexible plate and the fixed contraction, the longitudinal movement of the plate is accommodated within a slot formed by a large block and a tapered cover plate supported on distance pieces. Since it was not possible to curve the three profiles into one slot position without sudden changes in curvature, the block containing the slot is itself pivoted, so that it could adjust itself to conform to the slope of the plate. On assembly, the gap between the pivoted block and a fixed frame was measured at several nozzle settings and a cam plate and follower made to fit between them, Fig.5. The follower was attached to the moving part of the nozzle so that as the plate slides, the pivoted block is forced to the appropriate position and supported against the pressure difference on the faces of the plate.

4 CALIBRATION OF THE NOZZLE

The flow in the nozzle was calibrated at several nozzle settings extending over a Mach number range of from 1.5 to 2.3. Measurements of static pressure from upstream of the throat to the working section were obtained from holes positioned at 0.75 inch intervals along the centre-line of the reflection plate. The Mach numbers deduced from these measurements and a measurement of the total head upstream are given in Fig.6.

The uniformity of the flow within the working section was examined by means of 5 hole yawmeters of the type described in Ref.4. Measurements were obtained at positions approximately $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ of the working section height and width at 0.2 inch intervals longitudinally. The variations in Mach number, sidewash and downwash for 5 nozzle settings are given in Figs.7, 8 and 9. The results shown are typical of the results at other nozzle settings and probe locations.

Schlieren photographs of the flow in the tunnel are shown in Fig.10. These show a shock wave in the working section originating 0.75 inch from the end of the flexible liner. The shock wave is due to a 0.002 inch deformation of the plate at the last link position. Since the shock wave is almost at the end of the working section, and the reason for its origin is known, rectification of the error was deferred until after the nozzle was calibrated and the feasibility of this type of construction assessed.

Fig.7 shows that, except for the higher Mach numbers, the velocity of the flow increases slightly with distance. This is due to the variation of the rate of the growth of the boundary layer on the reflection plate with Mach number, for which the position of the plate could be designed to be correct at one Mach number only.

When a complete installation consisting of two flexible plates is constructed, the fixed reflection plate will not be present and the problem of the changing boundary layer thickness will not arise. Considering therefore the flow ahead of the shock wave due to the plate kink, and ignoring this steady rise in Mach number with distance, it can be observed that the local fluctuations in Mach number are roughly ± 0.010 compared to ± 0.006 for the 8 ft x 8 ft Bedford tunnel. Since errors of ± 0.003 inch in link length occurred during manufacture the results are as good as could be expected.

The sidewash variations, Fig.8, are satisfactory and the effects can clearly be seen of the growth of the boundary layer on the sidewalls which cause the port and starboard flows to be turned inwards by roughly 0.1 degree. The downwash variations, Fig.9, are larger than desirable and are almost certainly due to the errors in link length which occurred during manufacture.

One of the unknown features of the design, and one which required investigating, was the extent to which irregularities in the flow increase when the nozzle profile is set to some position other than at one of the three chosen profiles. It is pleasing to record that for the range of Mach number covered with this installation, no recognisable increases in fluctuations occur at off-design settings.

The mechanical operation of the variable nozzle proved to be trouble free and the Mach number could be varied over the whole range within seconds. Repeatability of results was excellent, the air jack tensioning system removing all effects of backlash in the linkages.

5 MANUFACTURING PROBLEMS

During the manufacture and assembly of the nozzle, two design features were noted which require consideration for future installations.

A sketch of the method of construction of the links is shown in Fig.11. It is seen that three link plates are used at each station. Each link plate was originally made from a single piece of steel and the bearing holes jig drilled. Because of the length to be drilled, difficulty was experienced in maintaining parallel holes and eventually the plates were split into two parts, as shown, and the bearing grooves milled. On assembly it was found that errors in link length were still present and it is evident that it would have been preferable to manufacture individual links for each bearing block, the links being jig drilled or made adjustable, set and locked.

The centres of the rear row of bearing blocks on the flexible plate are positioned considerably higher from the surface than the remainder. Since it is through these bearings that the load is applied to move the plate, an undesirable bending moment is introduced. Bending is however prevented by arms extending forward to locate on the pivot rod of an upstream row of bearings. Nevertheless a slight error in assembly has resulted in deformation of the plate and the formation of a shock in the working section. It is essential in future installations to ensure that the centres of the bearings are as close as possible to the surface of the plate.

6 CONCLUSIONS

Experiments with a small-scale model of a variable-Mach-number nozzle have been successful. The nozzle, constructed of a flexible plate deformed by a number of swinging links of varying length attached to a fixed frame, can be rapidly yet accurately varied to produce flow at any desired Mach number between the design limits. The tests show that a standard of flow throughout the working section similar to that of other variable nozzles with more elaborate mechanisms can be obtained provided the component parts are manufactured to the required accuracy.

NOTE: The principle of construction described in this report is the subject of Patent Application No. 49443/64.

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No.	Author	Title, etc.
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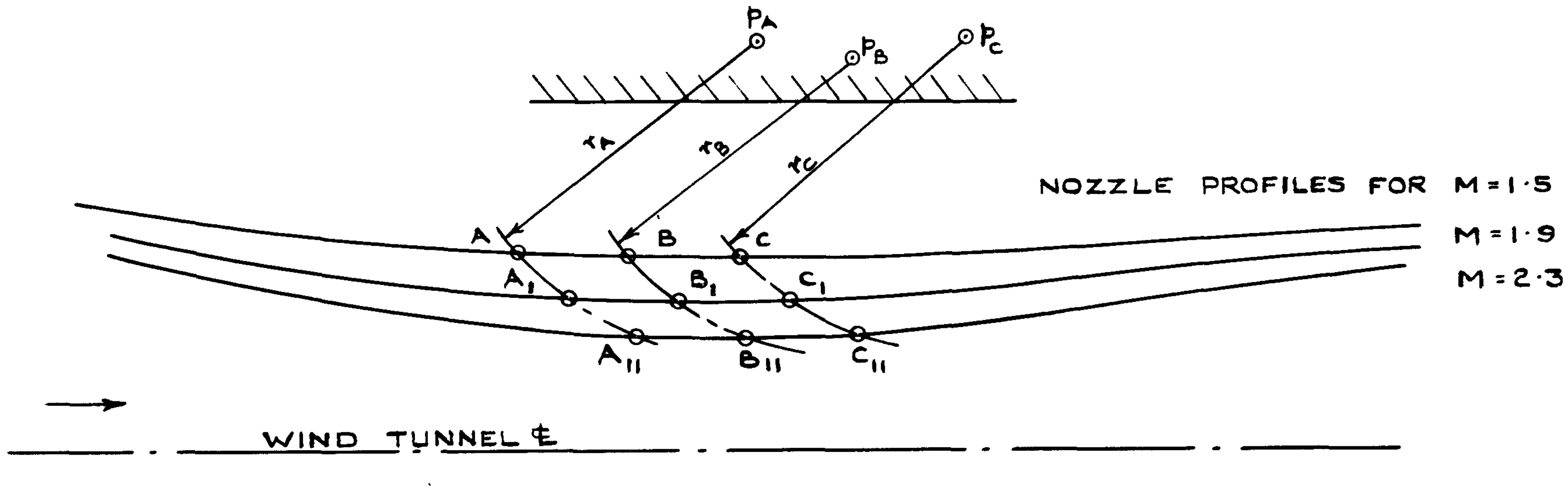


FIG. I PRINCIPLE OF THE MULTI-LINK FLEXIBLE WALL NOZZLE.

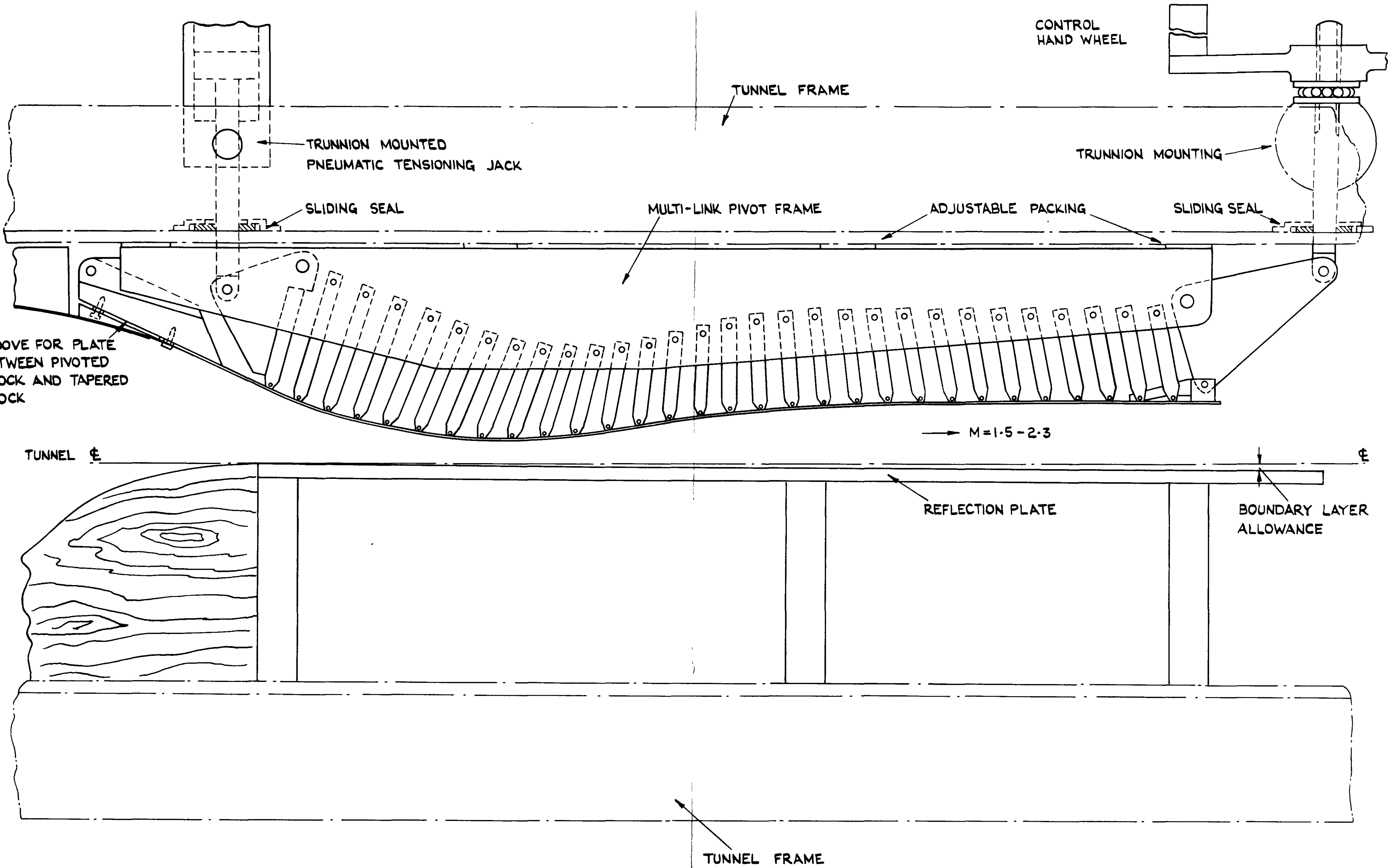


FIG. 2 FLEXIBLE NOZZLE FOR $1\frac{1}{2}$ in x $5\frac{1}{2}$ in WORKING SECTION

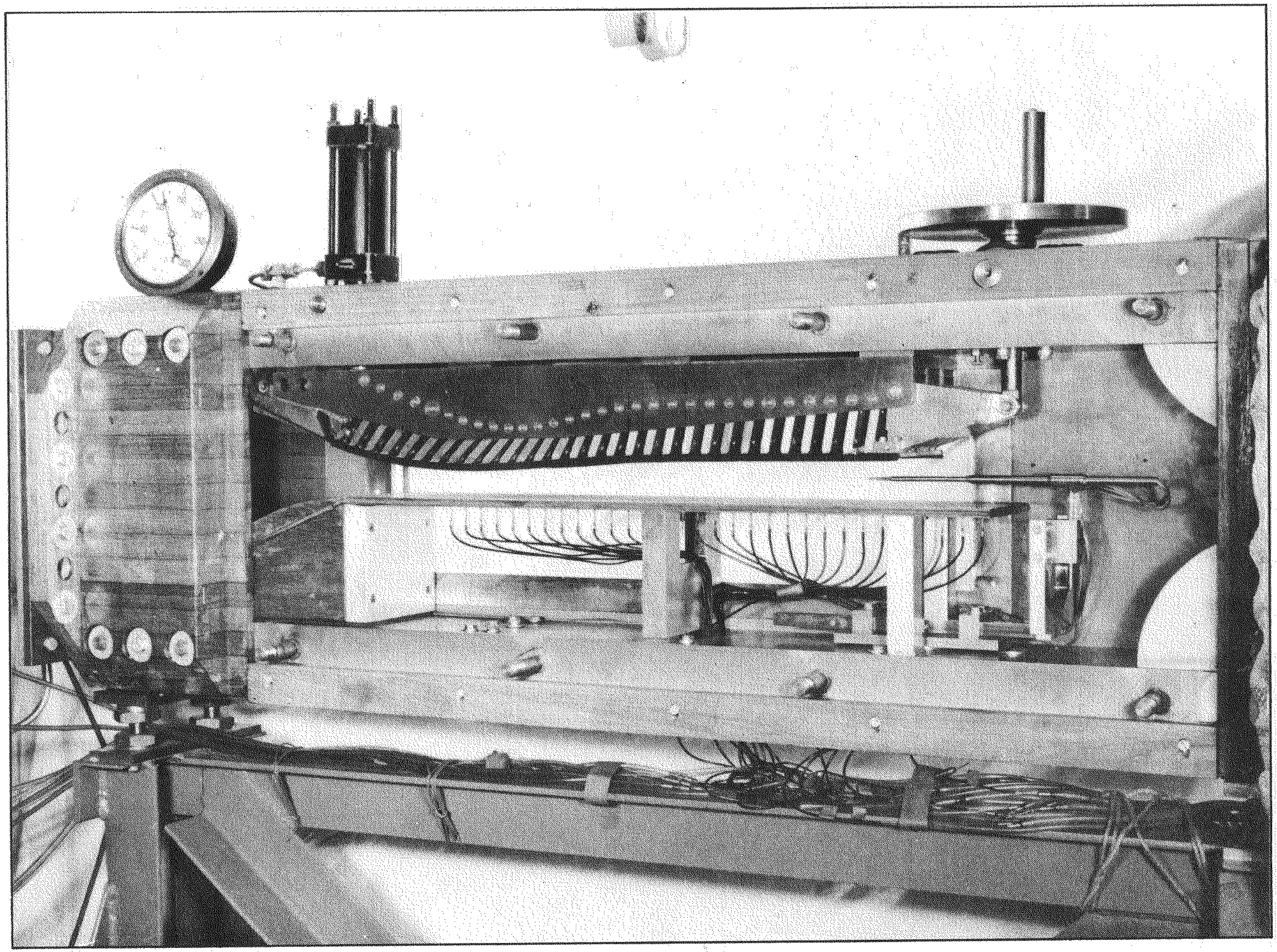


Fig.3. $1\frac{1}{2}$ins x $5\frac{1}{2}$ins wind tunnel installation

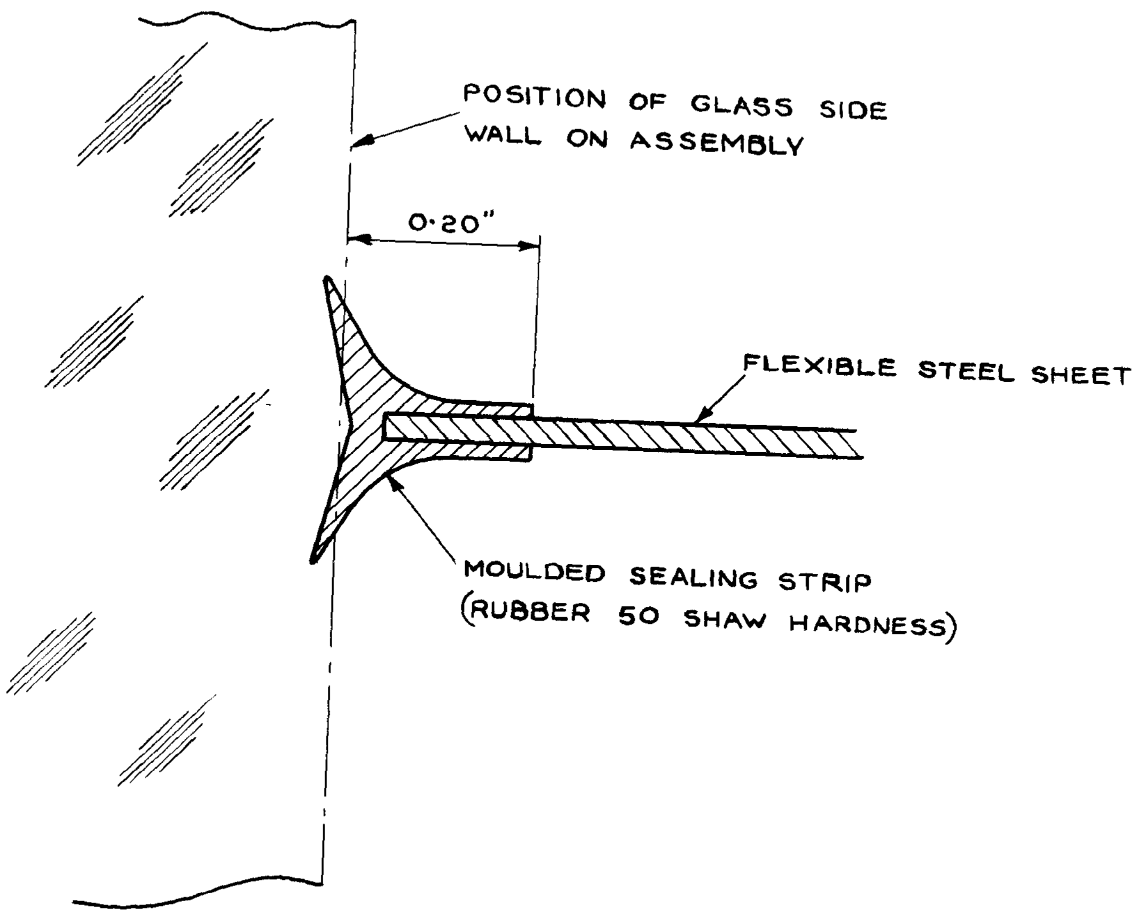


FIG. 4 EDGE SEAL FOR FLEXIBLE PLATE

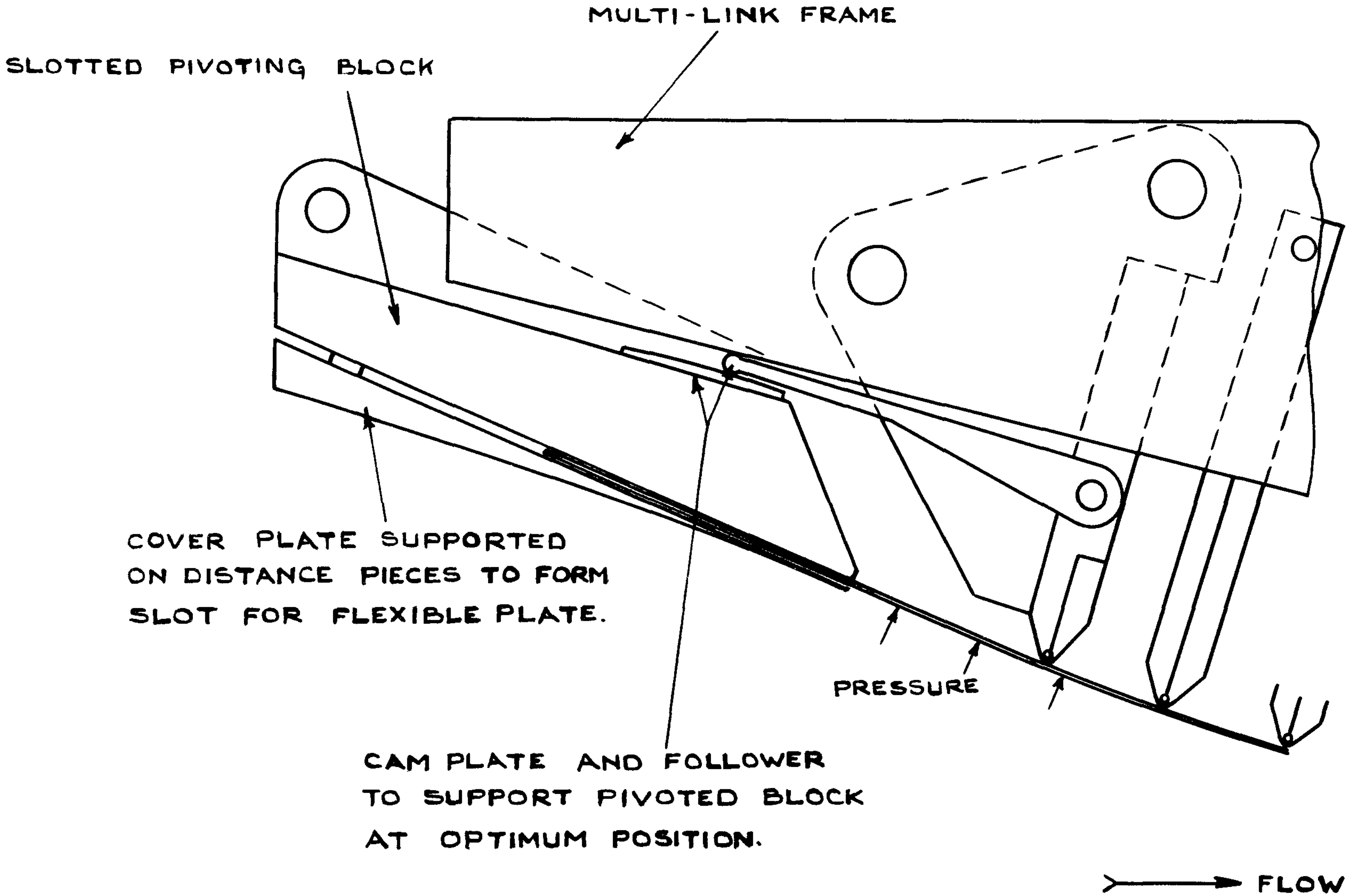


FIG.5 CAM AND FOLLOWER FOR SUPPORTING SLOTTED PIVOTED BLOCK.

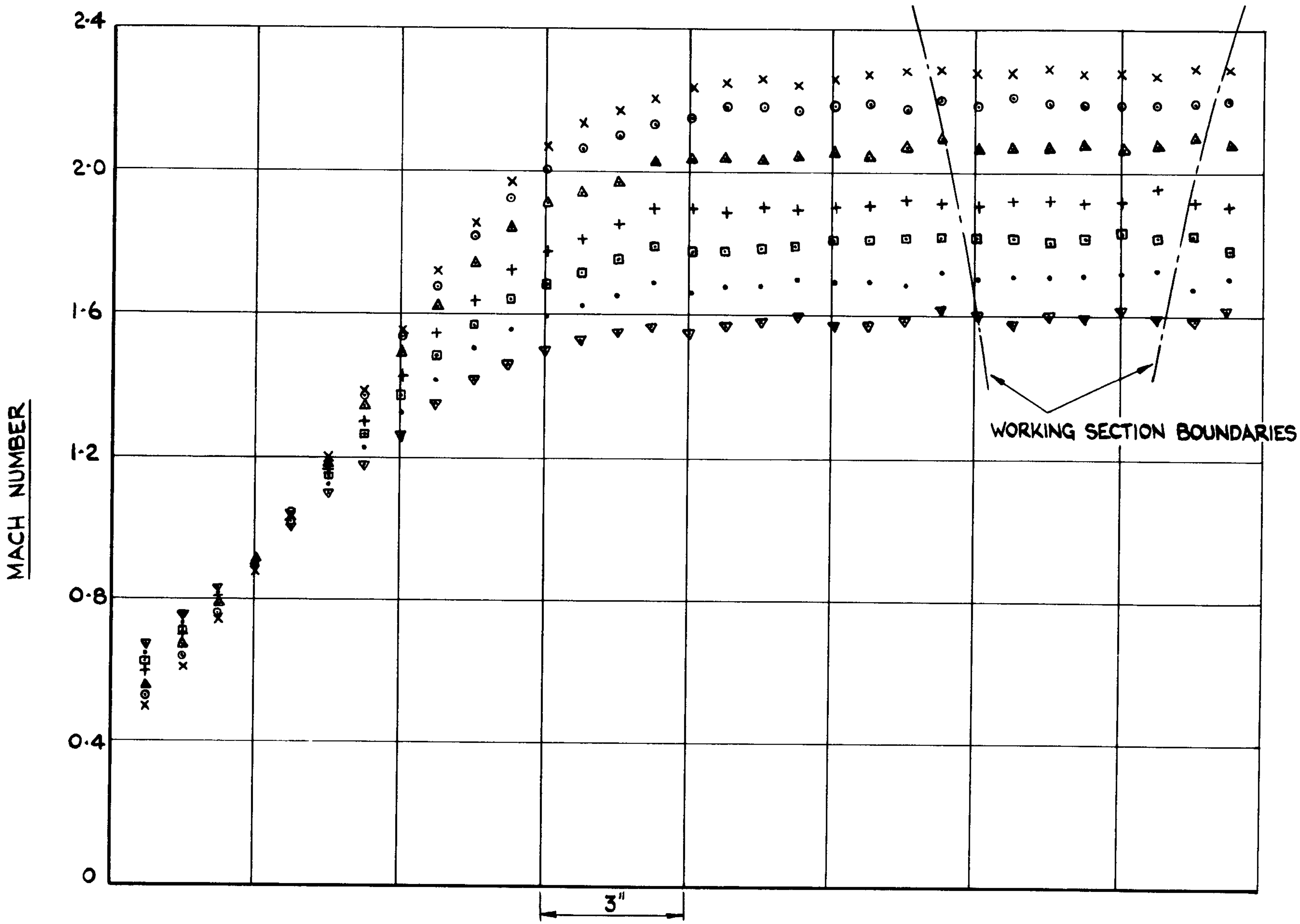


FIG. 6 CENTRE LINE MACH No. DISTRIBUTION FROM STATIC PRESSURE MEASUREMENTS ON REFLECTION PLATE

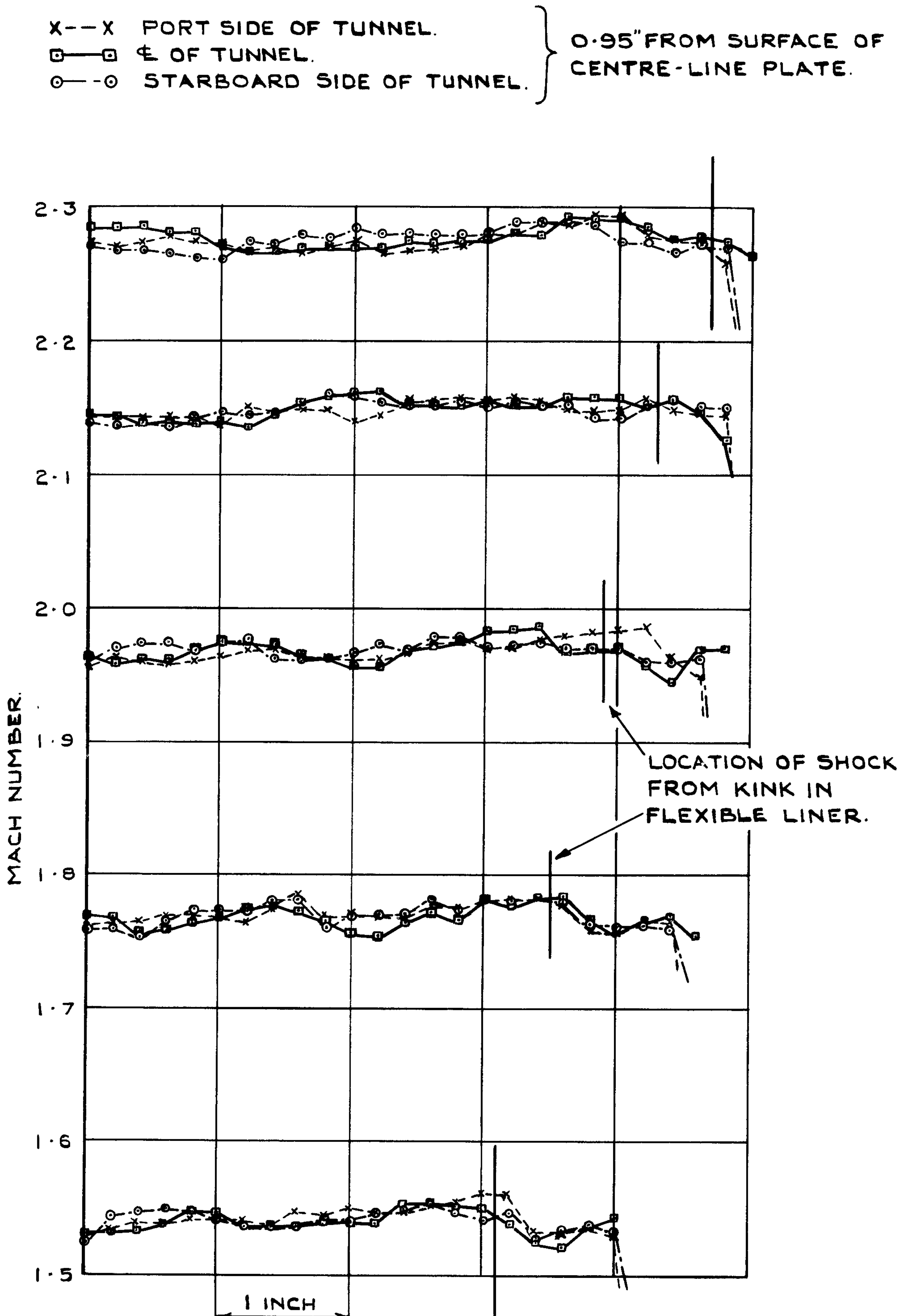


FIG. 7 DISTRIBUTION OF VELOCITY

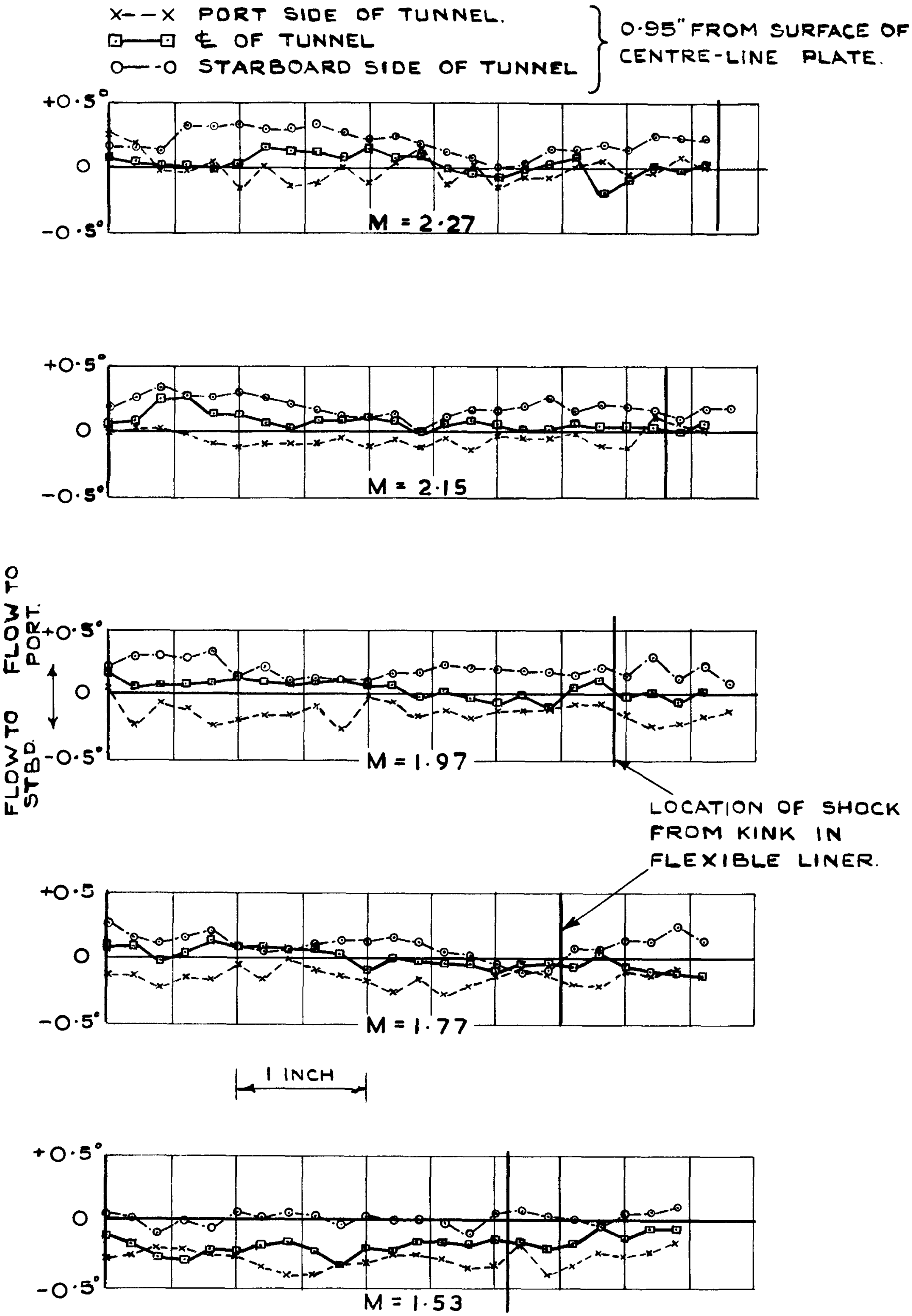


FIG 8. DISTRIBUTION OF SIDEWASH

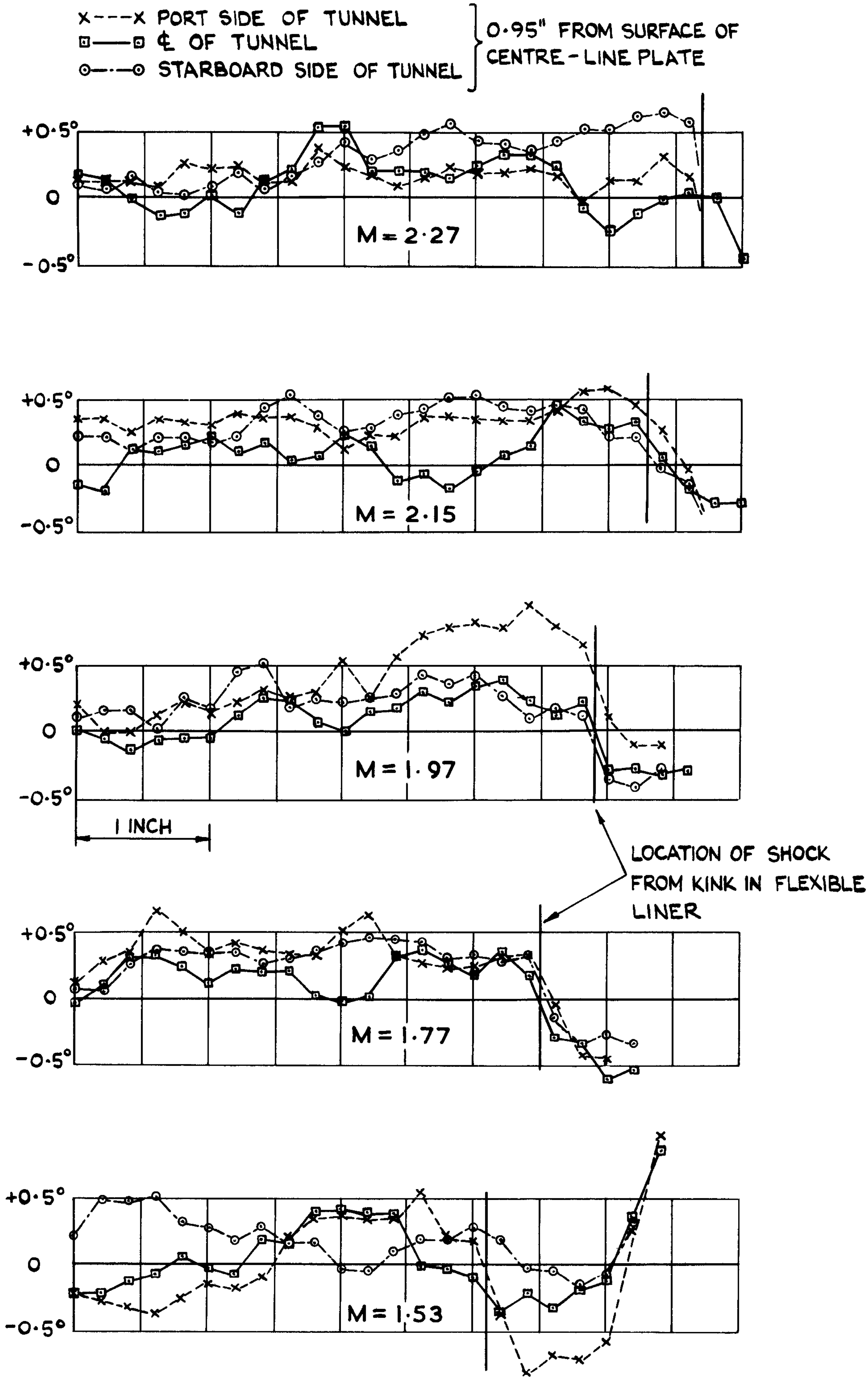
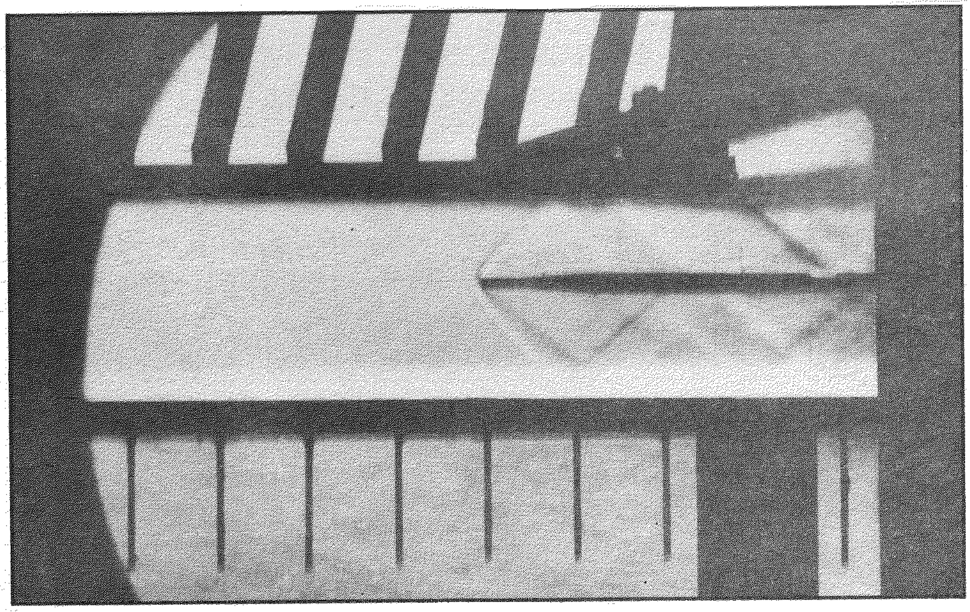
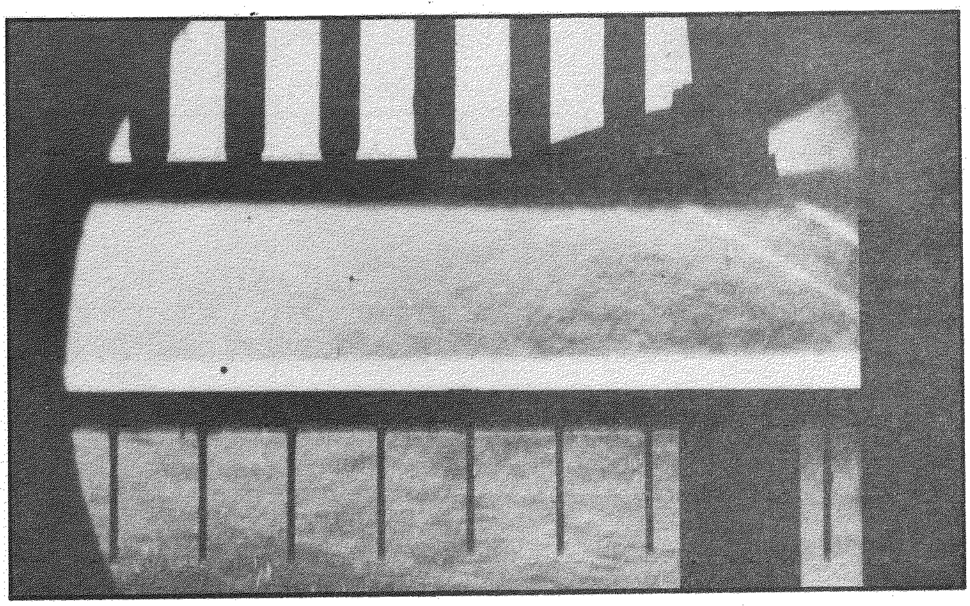


FIG. 9 DISTRIBUTION OF FLOW DOWNWASH

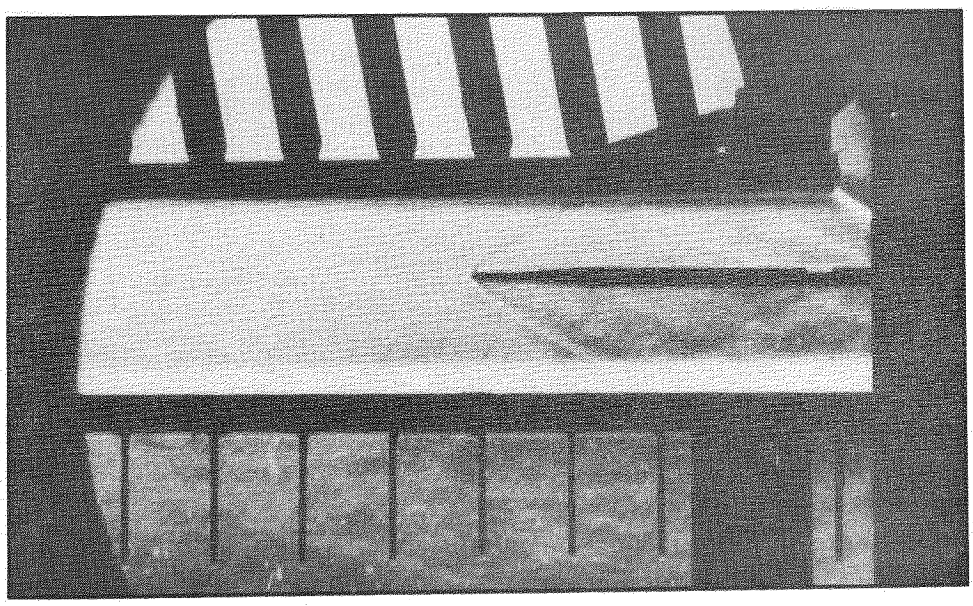
M = 1.53



M = 1.97



Showing shock from deformation of plate



M = 2.27

Fig.10. Schlieren pictures of flow in working section

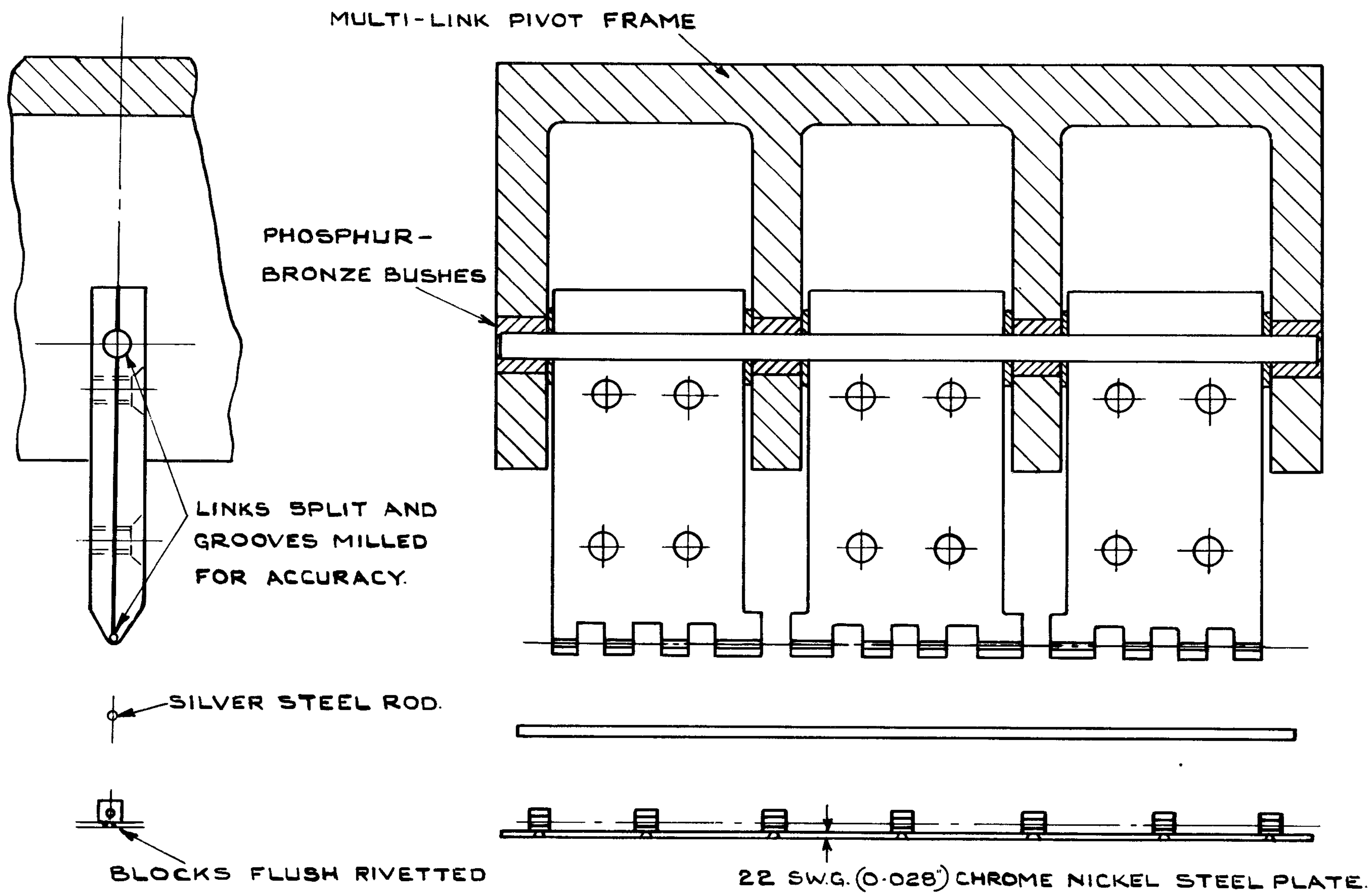


FIG.11 EXPLODED DETAILS OF LINKS AND FLEXIBLE PLATE BEARINGS.

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