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Design and Calibration Tests of a 5·5 in. Square Supersonic Wind Tunnel

By

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Summary.—The main design features of the wind tunnel are described and results are given of the investigations carried out to determine :—

(i) the minimum pressure ratio required to operate the wind tunnel at Mach numbers up to 3·5, and
(ii) the uniformity of the velocity distribution in the working section at Mach numbers of 1·57, 1·88, 2·48, 2·85, 3·25 and 3·5.

It was found that the tunnel pressure recovery can be appreciably increased by means of a contraction (' second throat ') located between the working section and subsonic diffuser.

All nozzles tested were designed with short throats and expansion profiles with the maximum angles of expansion for the given exit Mach number. The axial variation of Mach number over selected intervals of working section (not smaller than 5 in.) was found to be of the order of $\pm$ 1·0 per cent.

It was found that condensation in the wind tunnel nozzle (run with atmospheric air), has a detrimental effect on the velocity distribution in the working section, particularly at small Mach numbers.

1. *Introduction.*—This note describes some initial calibration tests of the 5·5 in. (No. 4) Royal Aircraft Establishment Supersonic Wind Tunnel, carried out at various times during the year ending October, 1948.

The design of the wind tunnel was started in January, 1946, as part of a larger project which also included the design of the 11 by 6 in. wind tunnel. Both tunnels were designed to suit the existing high altitude plant, which is briefly described in section 2.

The 5·5 in. square wind tunnel was manufactured at the R.A.E. during 1946 to 1947 and started operating on 27th October, 1947. During the ensuing year several modifications were made, mainly in order to facilitate the changing and aligning of the nozzle and diffuser liners. Tests were carried out to determine the minimum pressure ratio required for tunnel operation and the velocity distribution in the working section : the results are described in sections 3 and 4.

2. *Description of Wind Tunnel Installation.*—2.1. *Air Supply Plant.*—The air supply plant includes fourteen Nash Hyter exhauster pumps and two air drying units, each consisting of a cooler and an electric heater connected in series. The general layout of the plant is shown in Fig. 1 in which the air circuits are drawn diagrammatically. The air is sucked by the Hyter pumps and passes, prior to the wind tunnels, through coolers and heaters in which it is dried and subsequently heated to a normal stagnation temperature.

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The characteristics of the Hyter pumps, as determined by tests, are given in Fig. 2. The suction pressure was measured at the throttle valve downstream of the wind tunnel diffuser and this includes the losses in the pipes on the pump side. The volume flow corresponds to the suction pressure, and 16 deg C temperature. In order to obtain a maximum flow at any given pressure, the pumps operate in single stages at higher pressures, and are staged in two groups of 10 and 4 respectively at pressures below 6·4 in. of mercury absolute pressure.

There are two air-drying units connected in parallel and consisting of identical coolers and heaters.

The performance of the coolers is shown in Fig. 3 in terms of the temperature drop and air mass flow. The minimum temperature to which the air can be cooled equals about −85 deg C.

Connected in series with the coolers are two electric heaters of 95 kW each (≏ 50 C.H.U/sec each). The air can be heated to a maximum of 50 deg C.

2.2. *Wind Tunnel Size and Mach Number Range as Determined by Plant Performance ; Reynolds Number.*—The maximum wind tunnel size corresponding to the above suction and drying plant capacity can be determined as a function of Mach number provided the tunnel efficiency and the required dryness of the air are known. The results of such estimates are shown in Fig. 4 in terms of the wind tunnel working section size and Mach number.

For any given Mach number, the wind tunnel size is limited by the pumps' performance and at lower Mach numbers by the drying plant (coolers) capacity. The curves marked ' one cooler ' and ' two coolers ' show the maximum wind tunnel size permissible with one or two cold air units in operation, for air dried down to an absolute humidity of 0·0005 (at atmospheric stagnation pressure this corresponds to a dew point of −22·5 deg C). This criterion of air dryness, which was adopted in German supersonic wind tunnels, has been recently examined (R. & M. 2563[1]), and it was found that, even with this low air humidity, the condensation of water vapour would not be eliminated from the tunnel nozzle and working section except at Mach numbers below 1·6. The effect of the condensation shock on the pressure, density, *etc.*, is calculated by adding a term in the energy equation to allow for the release of latent heat when the moisture condenses. It can be shown that when the dew point is −22·5 deg C the effect on the static pressure is negligible, with current standards of uniformity of flow.

On the basis of Fig. 4 it was decided to design two wind tunnels of 5·5 × 5·5 in. and 11 × 6 in. cross sections respectively. The first of these wind tunnels, of interest here, should attain a Mach number of 4·8 and the existing drying facilities are sufficient for its size over the whole Mach number range. In Fig. 5 the air mass flow for the suction plant and the two wind tunnels is shown as a function of Mach number. In Fig. 6 the Reynolds number (per inch length), corresponding to atmospheric stagnation conditions, is shown as a function of Mach number. Over the range of supersonic Mach numbers it decreases from 0·4 million at $M = 1\cdot5$ to about 0·1 million at $M = 4$.

2.3. *Main Features of the Wind Tunnel Design.*—The two wind tunnels (5·5 in. square and 11 × 6 in.) were designed to be erected between the existing connections to the cold air and suction plants. The axes of the wind tunnels will be parallel so that for both tunnels, one schlieren apparatus, arranged on a movable trolley, can be used.

In the designing of the 5·5 in. supersonic wind tunnel the aim has been to produce a flexible design which, apart from the usual requirements, would also provide information for the design of supersonic wind tunnels and nozzles in general. Thus by fitting large windows provision has been made to observe visually the flow at, and downstream of the nozzle throat at all Mach numbers. Also two alternative types of traversing gear have been constructed. They can be used respectively for three or two-dimensional traverses of the tunnel nozzle and working section. Downstream of the working section provision was made for the fitting of alternative liners which can form a throat at the diffuser entry.

In Fig. 7 the general view of the wind tunnel, schlieren apparatus (camera end) and manometers are shown ; while the main components and tunnel internal dimensions are indicated diagrammatically in Fig. 8. The working section (Fig. 9) accommodates nozzle liners which are joined by flat, slightly divergent, working section liners. When these latter are omitted, the wind tunnel can be operated as a 'half-open' jet. (The jet is half-open because the sudden expansion occurs on two of the four sides only.)

In the next wind tunnel section, which has parallel side walls still 5·5 in. apart, traverse gear and liners are located.

The three-dimensional traverse gear shown in Fig. 10 consists of vertically sliding wall segments (z-movements) which carry a bridge spanning the wind tunnel. A combined pitot-static traversing tube is lowered between the top and bottom parts of the bridge in a block which can be moved across the bridge and tunnel (y-movement). The axial movement (x-direction) is obtained by a rack and pinion drive inside the block holding the pitot-static tube.

The flat working section liners (or half-open jet as the case may be) are followed, in the traverse-gear tunnel section, by interchangeable wooden liners, which join up with the three-dimensional subsonic diffuser.

An alternative type of traversing and model support gear is available, as shown in Figs. 11 and 12. It consists essentially of a hollow bar which enters the wind tunnel through one of the sliding sides and forms a right-angle, thus providing an axial support for a model or traversing tube. The z-movement is obtained as in the case of three-dimensional gear by means of sliding side wall segments; whereas the y-movement is provided by an external pinion and rack drive. An angle of incidence adjustment is also incorporated (worm drive).

The schlieren and shadowgraph equipment is mounted on a trolley serving both the 5·5 in. square and, when finished, the 11 × 6 in. wind tunnels. The arrangement as used is shown diagrammatically in Fig. 13. It consists of two 12 in. diameter, 96 in. focal length parabolic mirrors and two small flat mirrors. The mirror lying between the two wind tunnels is mounted complete with light source and with a flat mirror on a table. This table may be rotated so that it will only be necessary to move the second parabolic mirror to the other end of the trolley when the future second (11 × 6 in.) wind tunnel is in operation.

The camera end of the optical bench is clearly visible in Fig. 7 and the details of the mirror mounting are shown in Fig. 14. A coarse and fine adjustment of the mirror about the vertical and horizontal axes is provided.

3. *Minimum Pressure Ratio Required for Wind Tunnel Operation.*—Measurements were made of the minimum pressure ratio, p_0/p_0', at which supersonic flow could be obtained in the working section and the maximum Mach number which could be reached with the available plant. It was found that by using suitable liners downstream of the working section (traverse liners, Fig. 8) the pressure ratio was substantially reduced.

3.1. *Wind Tunnel Diffuser and Instrumentation.*—The wind tunnel was operated as a closed jet with alternative traverse liners and traversing gears fitted, but most of the tests were made with the three-dimensional (bridge) traverse (Fig. 10) in position. The dimensions of the main subsonic diffuser are shown in Fig. 8: the expansion is equivalent to that of a 10·6 deg total vertex angle cone.

The back pressure of the wind tunnel, p_0', was adjusted by means of a valve located downstream of the diffuser and was measured by a pitot tube as shown in Fig. 8. The wind tunnel stagnation pressure p_0 was obtained from a pitot tube upstream of the nozzle.

The critical condition corresponding to the maximum back pressure for supersonic flow in the working section was determined by schlieren observation of flow in the working section and from static pressure readings taken on the flat liner downstream of the nozzle exit (1, 2, 3 working section statics in Fig. 8). The results quoted correspond to the position of the wind tunnel shock such that at least two (1 and 2) or all three working section statics were not affected.

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3.2. *Traverse Liner.*—Seven pairs of traverse liners, six of which are shown in Fig. 15, were made and tried. They were designed to give different cross-sectional area variation between the working section liners and the subsonic diffuser, and various degrees of contraction. The characteristics of these liners are shown in Fig. 16 in terms of relative cross-sectional area, taking the cross-section area at the working section exit as unity. For each pair of liners four curves are drawn, corresponding to (i) empty wind tunnel without traversing gear (ii) three-dimensional (bridge) traverse in position and assuming full flow between the two halves of the bridge (iii) as (ii) with no flow through the bridge, and (iv) two-dimensional traverse fitted. Liners I and II do not cause contraction in most cases. Liners III, IV and V give constant area regions whereas liners VI and VII produce contraction with a short throat only.

3.3. *Experimental Results.*—The initial runs were made with liner I and the three-dimensional traverse in position. The minimum pressure ratios corresponding to this set-up are given in Table 1 and are compared with the design curve in Fig. 17. As is seen from Fig. 16, this traverse arrangement corresponds to an approximately linear area expansion. The recorded pressure ratios are much higher than the average ones as given by the design curve.

By suitable choice of liners it was possible to reduce appreciably the pressure ratios : the best results obtained so far are listed in Table 1 and indicated in Fig. 17. Not all of the possible combinations were tested so that still further improvements may be possible. For instance, no attempt was made to reduce the pressure ratio at Mach number of 1.57, and at Mach number 2·85 only No. IV traverse liners were tried. The design curve is closely approximated at lower Mach numbers but it appears that higher pressure ratios are required at Mach numbers larger than about 3. At the moment, only few results are available in this range from other wind tunnels. The pressure ratios of the Kochel and 1 in. square APL/JHU vacuum-tank-operated wind tunnels are shown in Fig. 17 : they fall approximately in line with the results here described. It should be remembered however, that both the Kochel and APL/JHU wind tunnels are intermittent ones and therefore their starting conditions are more favourable than in the case of the R.A.E. continuous operation wind tunnel, and that the results quoted correspond to the breakdown of supersonic flow in the working section as the vacuum tank pressure is increasing. Higher pressure ratios may be required to initiate supersonic flow when the pressure ratios is gradually increased.

Observations of the formation of wind tunnel shock during the starting process indicate that at small Mach numbers a nearly normal shock occurs with small regions of bifurcation at the nozzle walls. At high Mach numbers, in nozzles having necessarily a large angle of divergence, different flow patterns are formed. The flow starts as a free jet issuing from the nozzle throat and, as the pressure ratio is increased, the region of shock-free supersonic flow attached to the nozzle walls increases, but large separations persist further downstream. Due to unsteadiness of flow it is not possible to determine the resulting shock patterns from continuous light schlieren observations, but it appears that more than one shock system, followed by re-attachment of flow to the wind tunnel walls and re-expansion, may be formed ; or that alternatively, the effectively free-jet structure of the flow persists. It is presumably due to such shock boundary-layer effects that the pressure ratio required to start and run a wind tunnel increases rapidly at larger Mach numbers.

In Fig. 17, curves corresponding to a normal shock with and without subsonic pressure recovery are shown for comparison with the experimental results. It is known that at small Mach numbers (below about 1·8) better efficiencies than that given by normal shock-zero subsonic recovery curve can be realised. In the range $2 < M < 3$ the design curve represents, according to the data available at present, a fair average pressure ratio which is about 15 per cent in excess of that given by the normal shock-zero subsonic recovery curve. At Mach numbers higher than 3, however, the experimental pressure ratio increases more quickly ; at $M = 4 \cdot 5$ it attains a value some 50 per cent in excess of the normal shock-zero subsonic recovery curve.

So far a fully supersonic flow has not been obtained in the wind tunnel with the nozzle for a Mach number of 4·38 mounted. On the basis of Fig. 17, it appears that, taking into account the experimental variation of the pressure ratio and the limiting pumps performance, it may not be possible to reach Mach numbers higher than 4, instead of the originally estimated 4·8.

From the above tests of the minimum wind tunnel pressure ratio it is evident that the wind tunnel diffuser efficiency can be definitely improved by providing some contraction at the diffuser inlet. This is further illustrated in Table 2, in which minimum pressure ratios for various degrees of contraction are given for Mach numbers of 3·25. Although not all possible configurations of traverse liners and traverse types were tested, it seems that the form of contraction has not much effect on pressure recovery. It has sometimes been suggested that a wedge-shaped bridge spanning the wind tunnel, of the type used with the three-dimensional traverse, would increase the diffuser efficiency by facilitating the formation of oblique rather than normal shocks. The results here presented do not support this hypothesis : the pressure ratios corresponding to the bridge arrangement fall in line with the result for $M = 2 \cdot 48$ (empty tunnel, No. VII traverse liners) and with the data of the Kochel wind tunnel, which had a second throat and no bridge. The success of the bridge would appear to be due to the constriction it causes rather than to the oblique shock waves.

Throughout the test it was found that when the pressure ratio was being increased, the ratio required to initiate supersonic flow was about 5 per cent higher than when the pressure ratio was being decreased from a high value. Hysteresis effects of this type are often encountered in supersonic flow but in the cases investigated were not appreciable.

An attempt was made to determine the maximum 'second throat' contraction for which supersonic flow can be obtained in the working section. On the basis of one-dimensional theory, this limiting contraction is reached when velocity in the second throat becomes sonic with the normal shock occurring in the working section at the maximum Mach number. This theory has been largely confirmed by tests carried out in Germany. In the cases described here the maximum contraction could not be determined accurately owing to the limited number of the interchangeable traverse liners available, but the results obtained are consistent with the one-dimensional theory.

During a subsequent series of conical-diffuser model tests it was noticed that wind tunnel pressure ratio was reduced with a model mounted in the working section. At a Mach number of 1·88 a fully supersonic flow was obtained with a pressure ratio of 1·5, as compared with 1·65, the lowest recorded pressure ratio without a model, Table 1. The flow in the working section in this condition is shown by the first schlieren photograph in Fig. 18 ; the wind tunnel shock is clearly visible. In order to maintain supersonic flow at the entry of the diffuser model alone, a pressure ratio of 1·375 was sufficient, Fig. 18 (ii). When the flow through the diffuser was reduced (iii), the transonic shock moved further downstream with the same wind tunnel pressure ratio, thus indicating an increase in the tunnel efficiency ; this was presumably due to an increase of the effective flow contraction.

A reduction in the wind tunnel pressure ratio with the diffuser model in position was also observed at higher Mach numbers (Table 1, and Fig. 17). At $M = 2 \cdot 85$ a pressure ratio of 3·44 to 3·66 was sufficient to maintain fully supersonic flow on decreasing and increasing pressure ratio respectively, as compared with 4·14 with the empty wind tunnel. At $M = 3 \cdot 5$ the pressure ratio was reduced from 8·67 to 7·18 with fully supersonic flow, and a ratio of 5·87 was sufficient to maintain supersonic flow at the model entry only. However, even with the model in position, fully supersonic flow was not obtained in the 4·4 Mach number nozzle.

4. *Velocity Distribution in the Working Section.*—4.1. *Design of Tested Nozzles.*—Seven different pairs of nozzle liners were tested. Five of them, manufactured in brass, are scaled down versions of nozzles used in the Kochel wind tunnel. These five Kochel nozzles are designated as 1·57, 1·88, 2·48, 3·25, and 4·38 Mach number nozzles, according to the mean Mach number in the working section determined from the tests with the normal design setting of the liners.

They are designed with circular throats up to the point of inflection, the throat radius being equal to the total throat width. The corresponding angle of expansion is equal to one half of the Prandtl-Meyer angle of deflection for the final Mach number, *i.e.*, it has the maximum value. In this manner profiles of minimum length for a given throat radius are obtained.

The above type of nozzle design was widely used in Germany but, in the light of more recent American and British investigations, more uniform velocity distribution is obtained with profiles having a longer throat and smaller angle of expansion. With circular throat nozzles very large velocity and pressure gradients are present down to the inflection point, at which they change abruptly to much smaller values, causing the boundary layer to thicken and a compression wave to form at the beginning of the working section.

In the design of two other nozzles, manufactured in wood and designated as 2·85 and 3·5 Mach number nozzles, an attempt was made to reduce the sudden change in the velocity gradient at the inflection point by using a cosine curve at the throat. The maximum expansion angle, equal to one half of the Prandtl-Meyer angle was used again. This design resulted in nozzles relatively longer than the Kochel ones, but no definite improvement in the velocity distribution was obtained.

The main dimensions and characteristics of the seven pairs of nozzle liners are given in Table 3. The 2·85 Mach number nozzle liners are seen mounted in the wind tunnel in Fig. 9; the other liners are shown in Fig. 19.

In all cases except the 1·57 Mach number liners a straight subsonic contraction was used, as seen in Figs. 9 and 19; with the 1·57 Mach number liners, curved contraction profiles were fitted.

4.2. *Determination of Mach Number*.—Mach number can be determined from either pitot or static traverses when the total pressure upstream of the nozzle is known.

For low supersonic Mach numbers the pitot traverse becomes inaccurate, since the pitot pressure ratio is very near unity, while at higher Mach numbers the absolute static pressure becomes very small, and unless very great care is taken, small manometer errors are present and cause large errors in Mach number.

In all the present tests it was found more convenient to use the pitot traverse; but check readings using a static traverse were made at $M = 2 \cdot 48$. Some trouble was experienced in reading static pressures of the order of 2 in. of mercury to an accuracy of 1 per cent or better; but when these troubles were overcome, satisfactory agreement between the two methods of calibration was obtained. An example of these check traverses is shown in Fig. 20, and there is no systemmatic difference between the Mach numbers determined by either method, the very small differences being within the estimated experimental error.

Stagnation pressure was measured, relative to atmospheric pressure, from a water manometer; pitot pressure was read directly on a normal mercury barometer; and static pressure (in the check traverses) was read, relative to the atmosphere, on a mercury U-tube using a vernier-scale. The standard barometer could not be used for absolute pressures less than 3 in. of mercury and could not therefore be used for the static pressure measurements, except at low Mach numbers.

The only appreciable errors were an uncertainty in reading the static pressure manometer which could amount to $\pm$ 0·02 in. of mercury, and an uncertainty of $\pm$ 0·02 in. of mercury in the pitot pressure reading due to unsteadiness of the pressure reading. This latter error is equivalent to an error in Mach number of less than 0·15 per cent.

The stagnation pressure was normally subject to no appreciable errors, but at the lower Mach numbers (higher mass flow) it was observed to fluctuate occasionally by about 2 or 3 in. of water and it is possible that on some occasions such a fluctuation may have occurred unnoticed during the reading of pitot and static pressures, although this would not normally have been the case. This error would be equivalent to an error in Mach number of 1 per cent.

Throughout the tests the pressure lines were repeatedly tested for leaks by pumping to a pressure of about two atmospheres.

In a number of cases the reliability of the results was checked by repeating traverses on different days. The agreement found was good : examples of repeated traverses in 3·5 and 3·25 Mach number nozzles are shown in Figs. 32 and 31 (bottom).

4.3. *Experimental Results.*—4.3.1. *Schlieren photographs of flow.*—Schlieren photographs of dry air flow in all the nozzles are shown in Figs. 21 and 22. As already stated, fully supersonic flow was not obtained in the 4·38 Mach number nozzle and only a photograph of supersonic flow a short distance downstream of the nozzle throat is shown. All photographs were taken with the knife edge in the horizontal position. In two cases wires were fixed to the bottom liner.

The most noticeable characteristic of the flow in all (except the $M = 1\cdot57$) nozzles, apparent from the schlieren photographs, is a sudden change in the density gradient originating near the point of inflection of the profiles. This is particularly well defined in the 1·88 and 2·48 Mach number nozzles.

In a number of cases flow irregularities due to the nozzle profiles can be detected (*e.g.*, the 1·57 and 1·88 Mach number nozzles). The sensitivity of the schlieren decreases with the increasing Mach number, but disturbances can still be seen at the beginning of expansion in the 3·5 and 4·38 Mach number nozzles ; they are particularly marked in the latter one. The nozzle liners were not checked for waviness and accuracy of manufacture, so that it was not possible to correlate the observed disturbances with the actual profiles. It is suspected that the wooden nozzle liners (2·85 and 3·5 Mach number nozzles) were not free from waviness.

On the bottom liners of the 2·48 and 3·25 Mach number nozzles thin wires (0·006 in. diameter) were affixed. As seen from the schlieren photographs much thinner wires must be used in order to produce disturbances which would approximate Mach waves ; in the case illustrated each disturbance consists of two successive compression-expansion systems of appreciable intensity.

4.3.2. *Mach number distribution.*—The results of pitot pressure traverses are plotted in terms of Mach number in Figs. 24 to 32 ; the space co-ordinates as used are shown in Fig. 23. The majority of traverses were taken along the x-axis, but some distributions along y and z-axes are also shown.

The degree of flow uniformity obtained with the different nozzles can be judged from axial traverses, Figs. 24, 27, 29, 30, 31 and 32. The variations in Mach number, expressed as a percentage, based on pitot/stagnation-pressure ratio over specified intervals of x-axis are given in Table 4, and general characteristics of distribution are indicated. The uniformity of flow over the chosen intervals (not smaller than 5 in.) is of the order of ± 1 per cent variation in Mach number. In most cases a monotonic gradient seems to be superimposed on irregular oscillations of Mach number ; this is particularly noticeable at high Mach numbers, Figs. 30, 31 and 32. Whereas the random waviness in the distribution may be attributed to the waviness of the liners' surfaces, the definite gradients are presumably due to the growth of the boundary layer being different from that estimated in the liner design.

It was mentioned earlier in this report that by the use of packing pieces, the liners could be tilted in the longitudinal direction. The ratio of the area of the working section to that of the throat (and therefore the mean Mach number) were thereby altered.

In Fig. 28, results are given for z-traverses (traverse across the stream in a vertical direction) made with two settings of the liners. In one, the liners were set to give the Mach number for which they were designed (about $M = 1\cdot88$), in the other, the liners were tiled so as to give a Mach number about 1·97. From the figure it can be seen that the resulting curves are of the same form ; the maximum and the minimum being in approximately the same positions. The departure from uniformity when the liners are moved from their design position is only slightly greater than when used at their design setting.

This result can be regarded as giving support for the theory that irregularities in the Mach number distribution in the x-direction are due to waviness of the nozzle profiles, rather than to bad design. For the experiment considered the waviness is the same in the two cases giving the same irregularities of distrubition.

A similar result was obtained at a higher speed ($M = 3 \cdot 30$), as shown by the results in Fig. 31. At a lower speed, $M = 1 \cdot 5$ (approximately) (Fig. 26), however, there is a considerable change of distribution in passing from one liner setting to the other.

Certain arbitrary allowances were made for the boundary layer in the design of Kochel nozzle profiles. In the 2·85 and 3·5 Mach number nozzles having ' cosine-shaped ' throats no allowance for the boundary layer was made. In these two nozzles and in the 3·25 Mach number nozzle the velocity corresponding to the geometrical area expansion, indicated on the right hand side of the diagrams (Figs. 30, 31 and 32), is reached at the beginning of the working section and then shows a tendency to decrease with x. It may be possible to compensate for the boundary layer growth and to eliminate the velocity gradient by setting the nozzle liners with an increased exit dimension.

Results for y and z-traverses are shown in Figs. 26, 28, 29 and 31. The near-constancy of the y-traverses shows that the flow is nearly two-dimensional. This is to be expected as the method of manufacture tends to produce uniformity across the profile.

With regard to variation in the z-direction, in nearly all cases where the tilt of the liner is altered the shape of the curve is not appreciably altered but is merely displaced. Here again the results lend support to the theory that random variations in the static distribution are due to ripples in the surface rather than to defect in general shape.

As seen from the schlieren photographs of flow, the disturbances originating from the junction of the shaped and flat liners are of appreciable intensity. This is confirmed by the axial traverses, Figs. 24, 27 and 29.

In a number of cases the Mach number was determined from the angle of shocks formed around 60 deg, 40 deg and 20 deg cones, and measured off the schlieren photographs, a set of which is shown in Fig. 33. The results plotted in Figs. 27, 29, 30 and 32 are in general agreement with the axial traverses, but the method is not sufficiently accurate to provide an independent check of the local Mach number.

4.3.3. *Effect of condensation on Mach number distribution.*—Typical schlieren photographs of condensation shocks in nozzles for low and high Mach numbers are shown in Fig. 34. Oblique condensation shocks appear a short distance downstream of the throat and their reflections are propagated towards the working section. In the low Mach number nozzles, several reflections occur before the working section.

The detrimental effect of condensation shocks on the velocity distribution, particularly at lower Mach numbers, is clearly seen from axial traverses made with the 1·57, 1·88, 2·48 and 3·25 Mach number nozzles in position, run with atmospheric air. In the 1·57 Mach number nozzle the condensation shocks form a Mach type reflection, Fig. 34, the shock intensity approaching in the central part that of a normal adiabatic shock as indicated in Fig. 25.

5. *Summary of Results.*—(i) Tests with interchangeable diffuser liners have shown that the wind tunnel pressure recovery can be appreciably increased by means of a contraction (second throat) located between the working section and the subsonic diffuser.

(ii) The minimum pressure ratio (*i.e.*, ratio of stagnation pressure before the nozzle to the stagnation pressure downstream of the diffuser) required to run a wind tunnel is known to be smaller at low Mach numbers ($< 1 \cdot 8$) than that corresponding to the normal shock and zero-subsonic recovery ; in the range $2 < M < 3$ the required pressure ratio is some 15 per cent in excess of the latter value and increases more quickly at higher Mach numbers, attaining a value some 50 per cent larger (than the normal shock-zero subsonic recovery value) at $M = 4 \cdot 5$.

(iii) Mach number distributions in the working sections of six nozzles (for Mach numbers of 1·57, 1·88, 2·48, 2·85, 3·25 and 3·5) were determined by pitot pressure traverses. All nozzles were designed with short, circular or 'cosine-shaped' throats and with maximum angle of expansion (equal to half of the Prandtl-Meyer angle of deflection for the working section Mach number), giving shortest nozzles for given throat profiles. The axial variation of Mach number over the selected intervals of working section (not smaller than 5 in.) was found to be of the order $\pm$ 1 per cent.

(iv) The condensation in the wind tunnel nozzle (when run with atmospheric air) has a detrimental effect on the velocity distribution in the working section, particularly at lower Mach numbers.

6. *List of Symbols.*

A	Nozzle outlet height ($\propto$ cross-sectional area at outlet)
A^*	Nozzle throat height ($\propto$ throat cross-sectional area)
A/A^*	Nozzle expansion ratio
M	Mach number
p	Static pressure
p_0	Stagnation pressure
p_0'	Pitot pressure or stagnation pressure downstream of the wind tunnel diffuser
T_0	Stagnation temperature
x, y, z	Flow co-ordinates, defined in Fig. 23
γ	Ratio of specific heats, taken in all computations as 1·4 (for air)
ϕ_0, Ω_0	Relative and absolute humidity in stagnation conditions upstream of the wind tunnel nozzle

REFERENCES

No.	*Author*	*Title, etc.*
1	J. Lukasiewicz	Humidity Effects in Supersonic Flow of Air. R. & M. 2563. June, 1948.

TABLE 1

Minimum Tunnel Pressure Ratio

Mach number (Based on mean pitot/stagn. pressure ratio in working section)	Min. p_0/p_0' with No. I traverse liners and three-dimensional (Bridge) traverse. No model	Best arrangement tested (No model)			Min. p_0/p_0' with model in position	
		Traverse liners No.	Traverse type	$\frac{p_0}{p_0'}$	Traverse liners No.	$\frac{p_0}{p_0'}$
1·57	1·52	I	3-dim. (Bridge)	1·52	—	—
1·88	2·03	II	3-dim. (Bridge)	1·65	I	1·5
2·48	3·95	VII	None (Empty Tunnel)	2·80	—	—
2·85	—	IV	2-dim.	4·14	IV	3·44 to 3·66
3·25	8·9	V	3-dim. (Bridge)	6·46	—	—
3·50	—	IV	3-dim. (Bridge)	8·67	IV	7·18

TABLE 2

Effect of Contraction at the Diffuser Entry on Minimum Wind Tunnel Pressure Ratio p_0/p_0' at $M = 3 \cdot 25$

Traverse liners No.	$\frac{p_0}{p_0'}$
I	8·9
III	8·0
IV	7·1
V	6·46

$M = 3 \cdot 25$, 3-dimensional (Bridge) type traverse
All (1, 2, 3) working section static pressures unaffected.

TABLE 3

Design Dimensions of Nozzles

(exit width = 5·500 in.)

Nozzle Mach number	Nozzle length from throat in.	Throat width in.	Radius of curvature at throat in.	Mach No. based on A^*/A = throat/exit area ratio	
1·57	6·75	4·438	4·438	1·587	Kochel profiles
1·88	8·12	3·548	3·548	1·896	
2·48	10·44	2·063	2·063	2·513	
3·25	12·38	0·963	0·963	3·313	
4·38	14·85	0·357	0·357	4·415	
2·85	12·0	1·448	1·150	2·888	Cosine curve at throat
3·5	14·0	0·764	0·515	3·563	

TABLE 4

Axial Distribution of Mach Numbers

(Design nozzle setting)

Nozzle Mach number	x co-ordinate from (in.)	to (in.)	$\pm$ % M	Remarks
1·57	−3	2	1·5	M tends to increase with x
1·88	−3	2	0·75	M tends to increase with x
2·48	−1	4	0·78	Expansions to $M = 2{\cdot}518$ at $x = -4{\cdot}2$ followed by compression to $M = 2{\cdot}45$ at $x = -2$ and again a steady increase of M with x
2·85	−4	4	1·1	M tends to decrease with x (from $x \simeq -6$)
3·25	−3	6	0·80	M tends to decrease with x (from $x \simeq -4$)
3·5	−2	4	0·70	Good distribution within the interval indicated, with a general tendency of M to decrease with x; an intense compression at $x = -4$

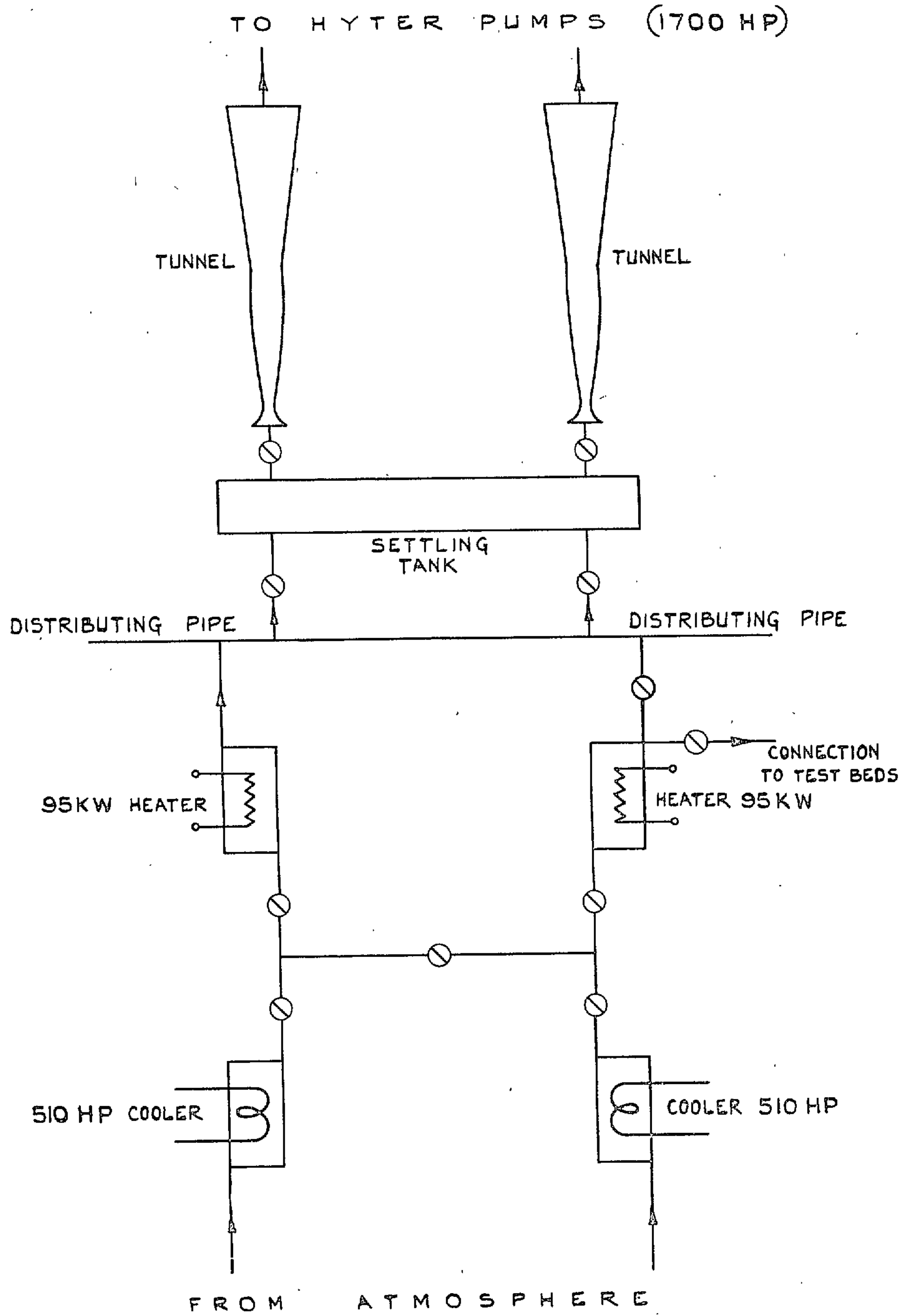


FIG. 1. Diagram of air circuits.

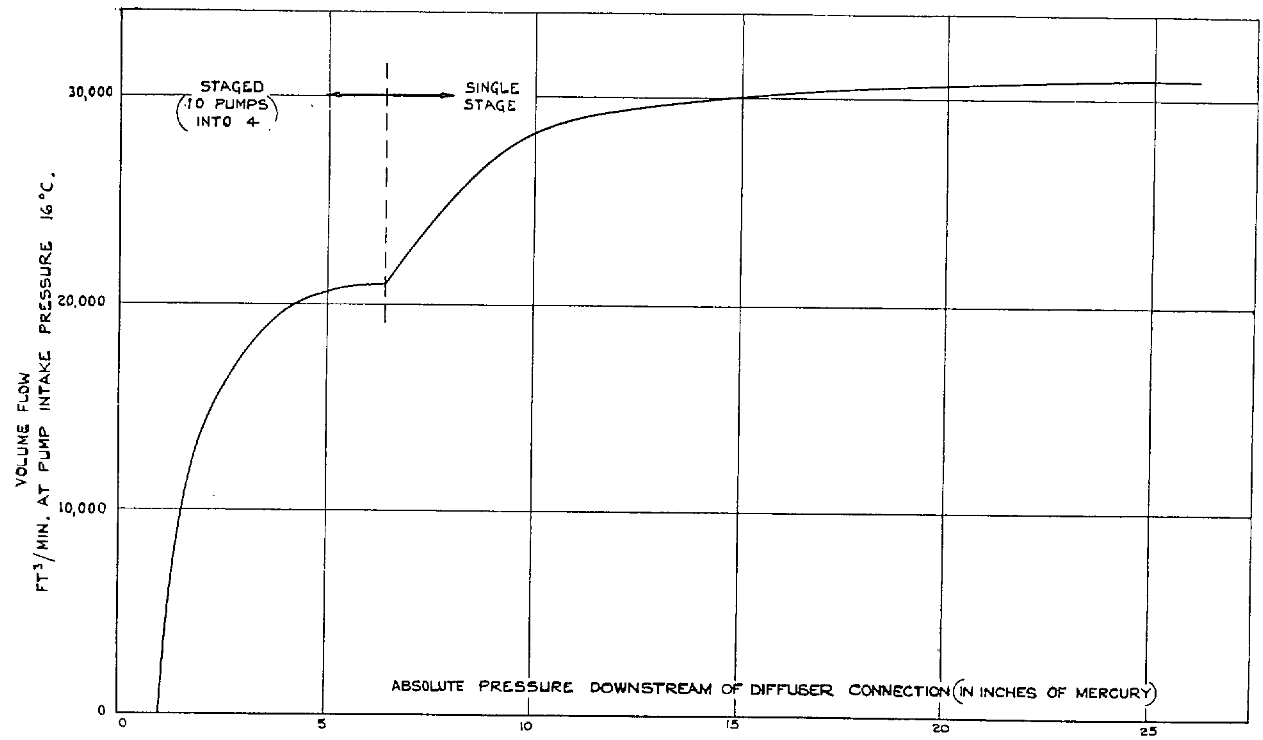


FIG. 2. Performance of fourteen Nash Hyter pumps.

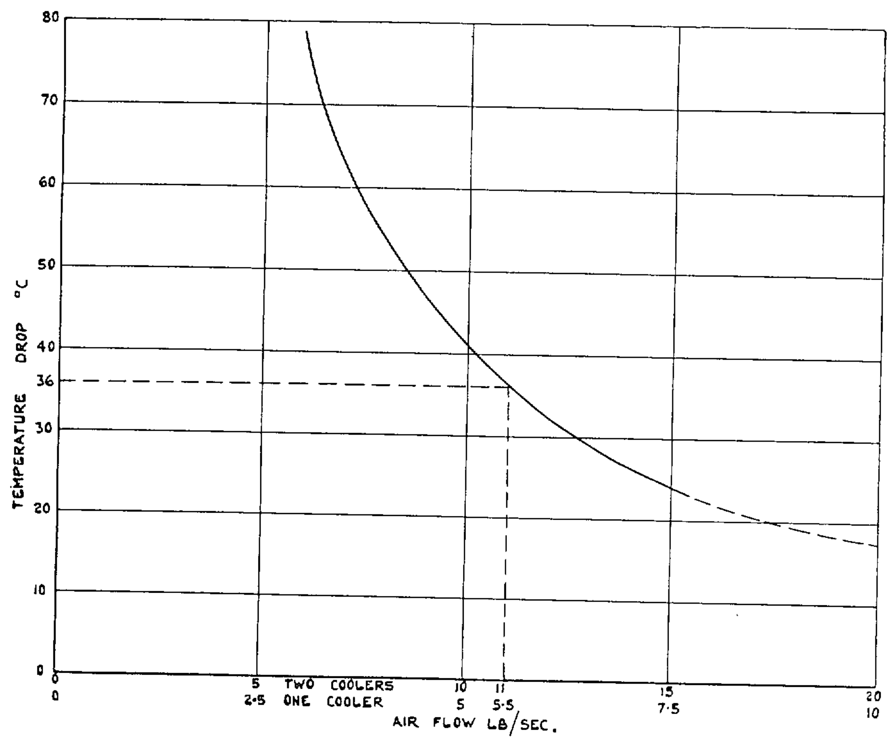


FIG. 3. Cooler performance.

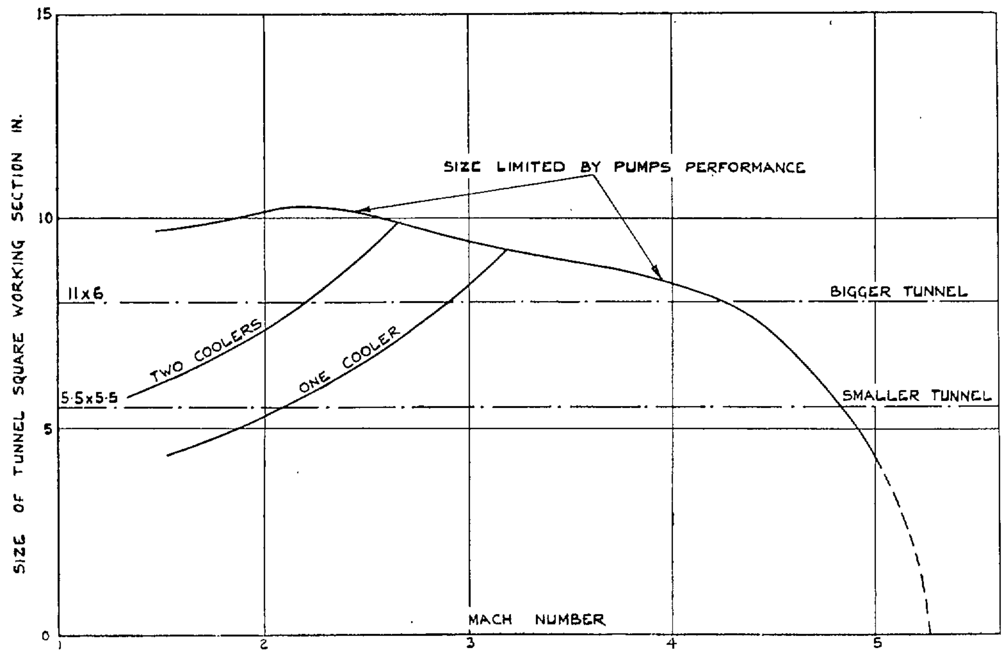


FIG. 4. Determination of wind tunnel size.

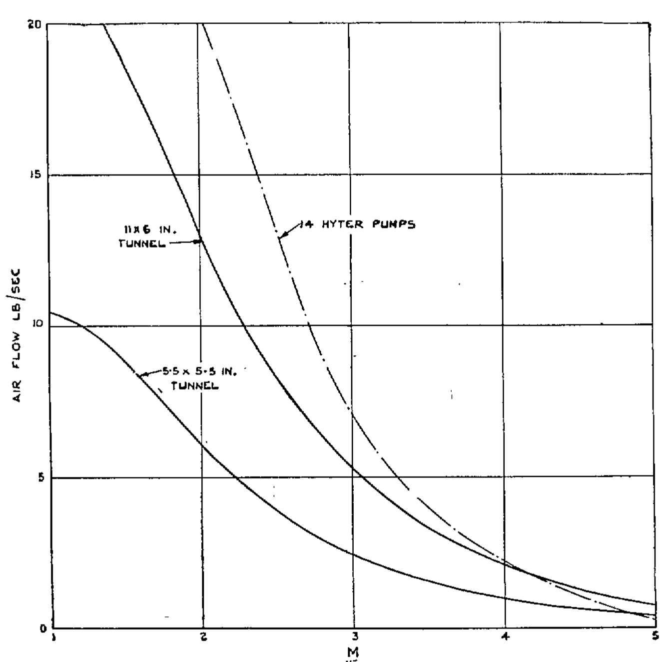


FIG. 5. Air mass flow as a function of the wind tunnel Mach number M. Stagnation conditions : temperature 10 deg C, pressure 760 mm Hg.

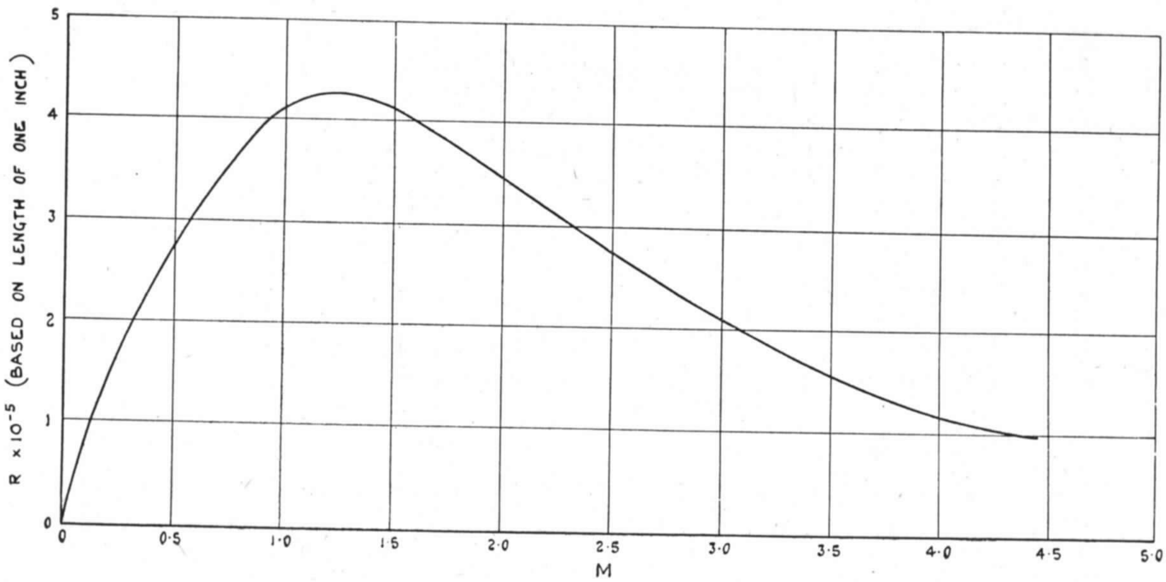


FIG. 6. Reynold's number as a function of Mach number.

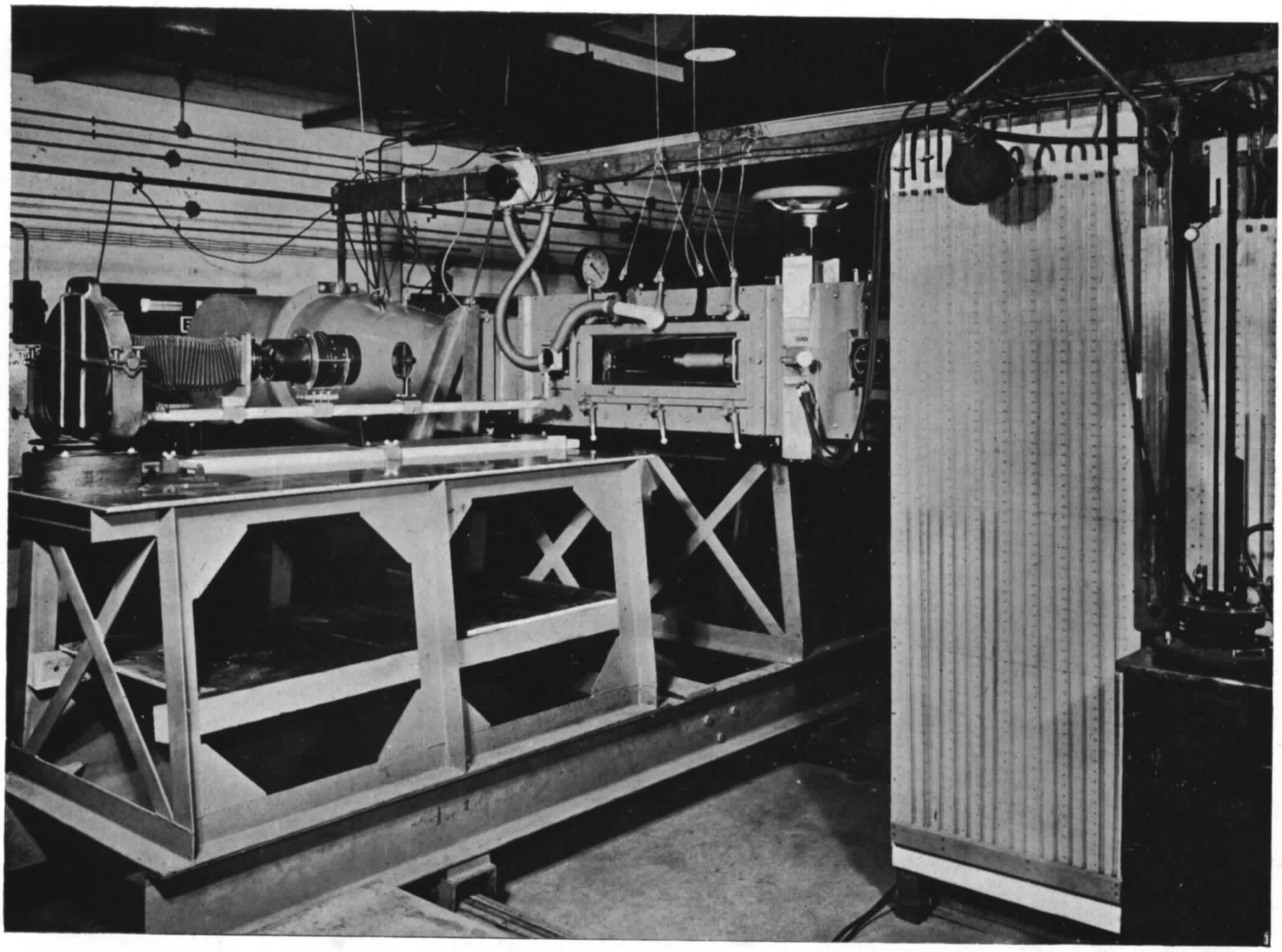


FIG. 7. General view of 5·5 × 5·5 in. wind tunnel. Schlieren apparatus and manometers.

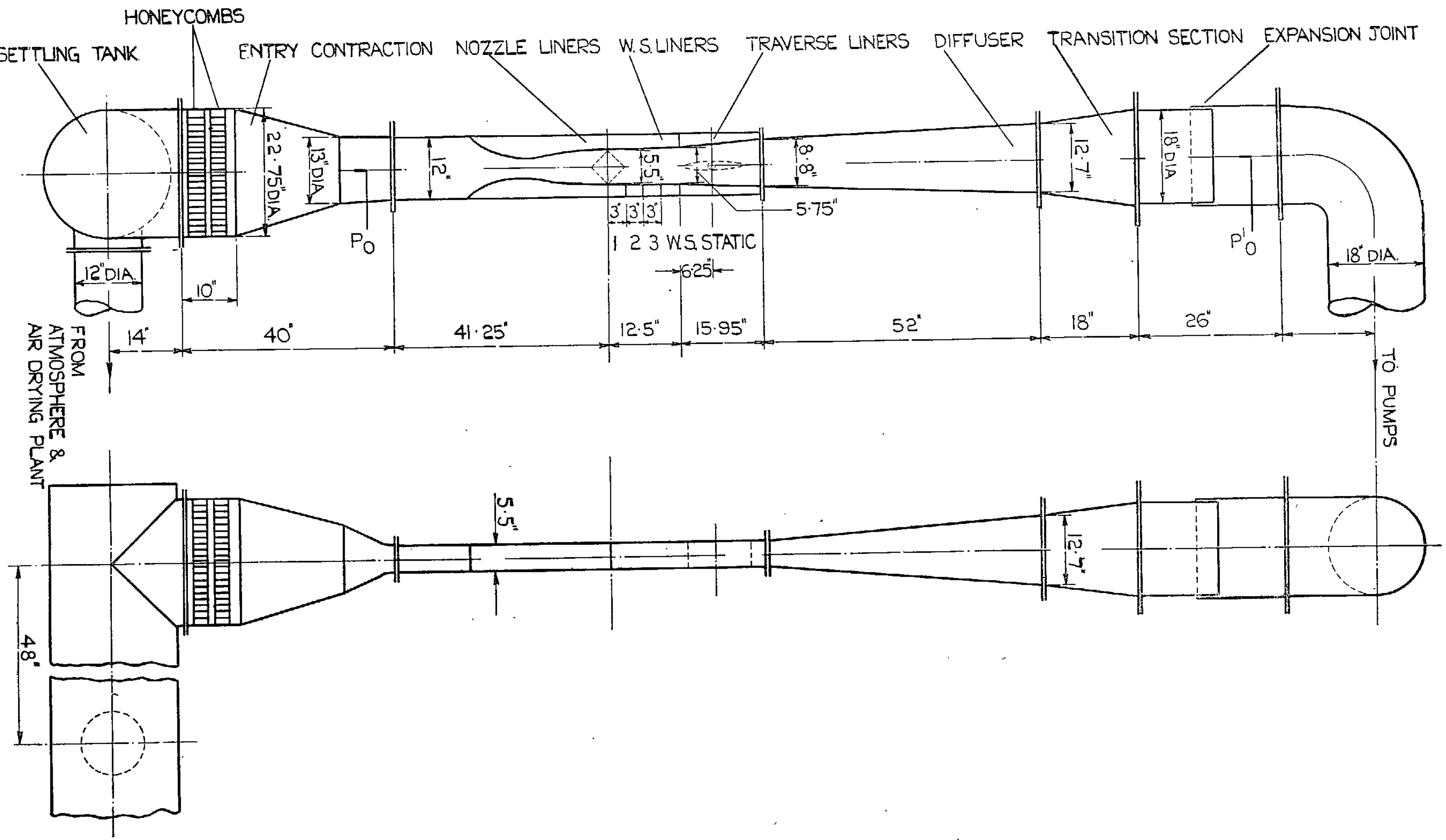


FIG. 8. 5·5 × 5·5 in. (No. 4) supersonic wind tunnel. Main components and internal dimensions.

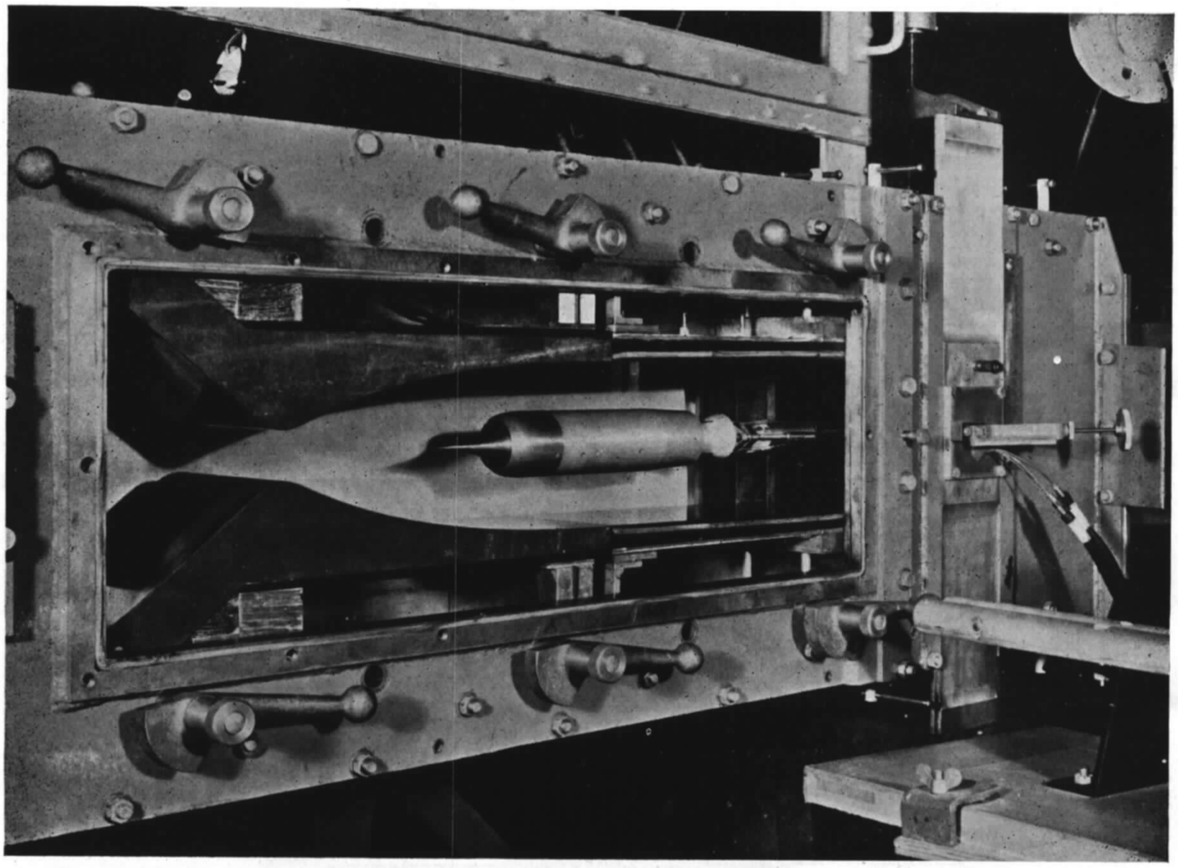


FIG. 9. Tunnel working section with 2·85 Mach number nozzle and diffuser model in position.

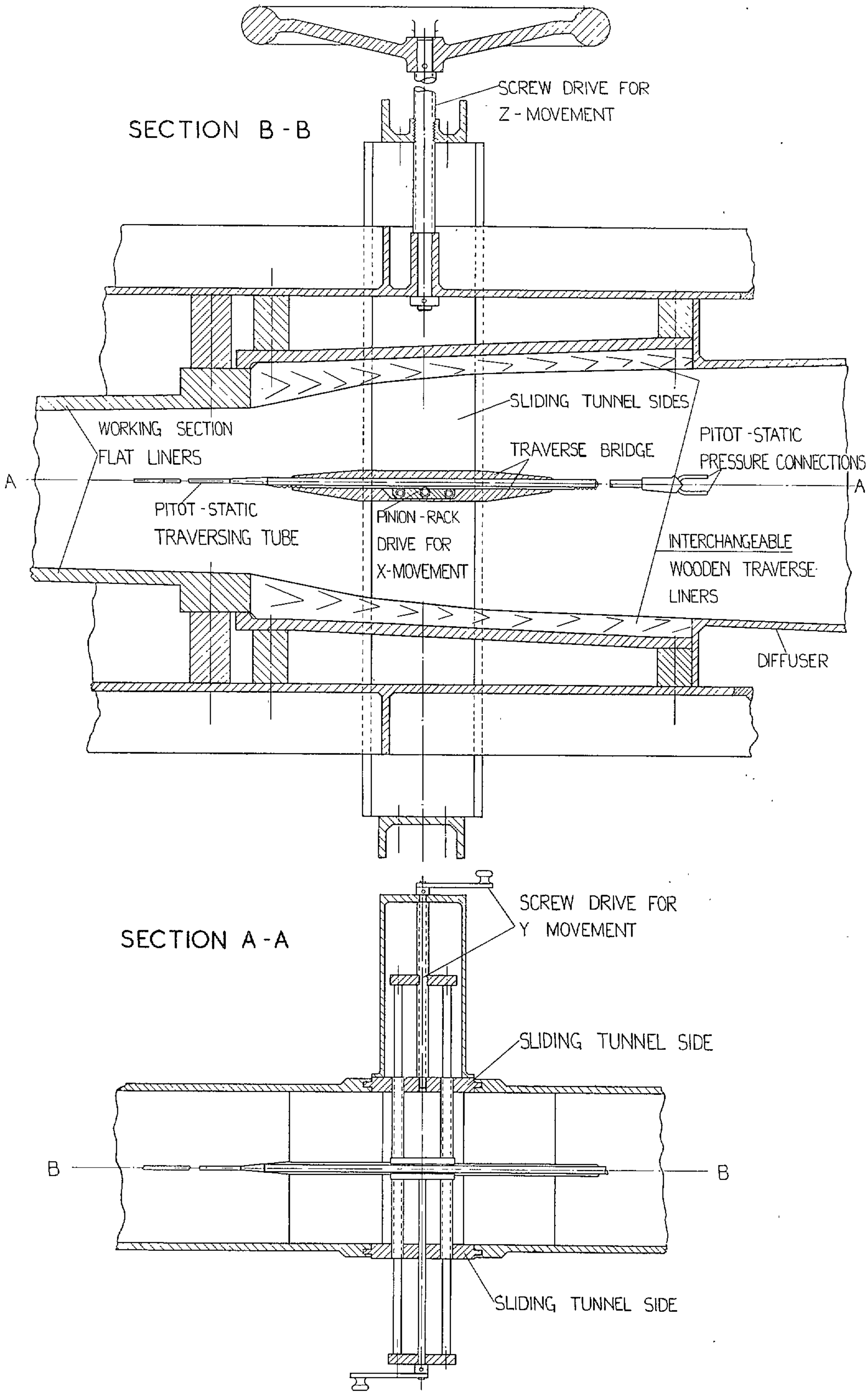


FIG. 10. Three-dimensional traverse and traverse liners.

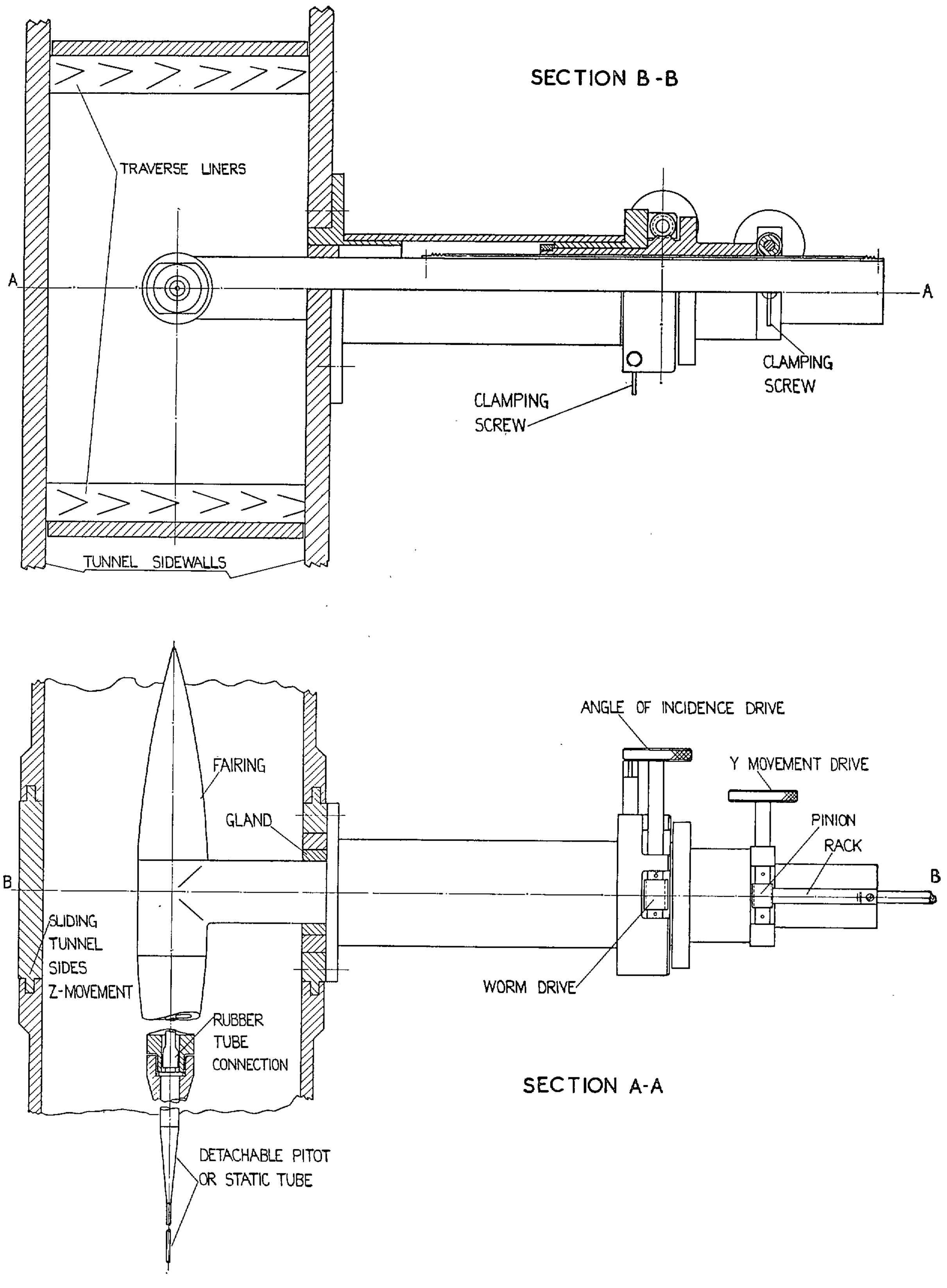


FIG. 11. Two-dimensional traverse.

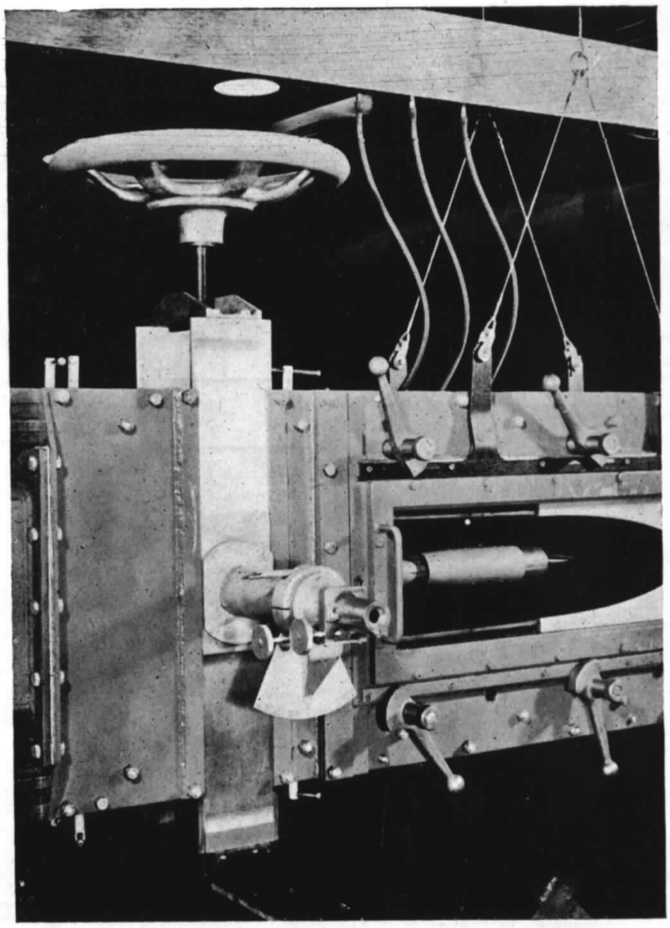


FIG. 12. Two-dimensional traverse.

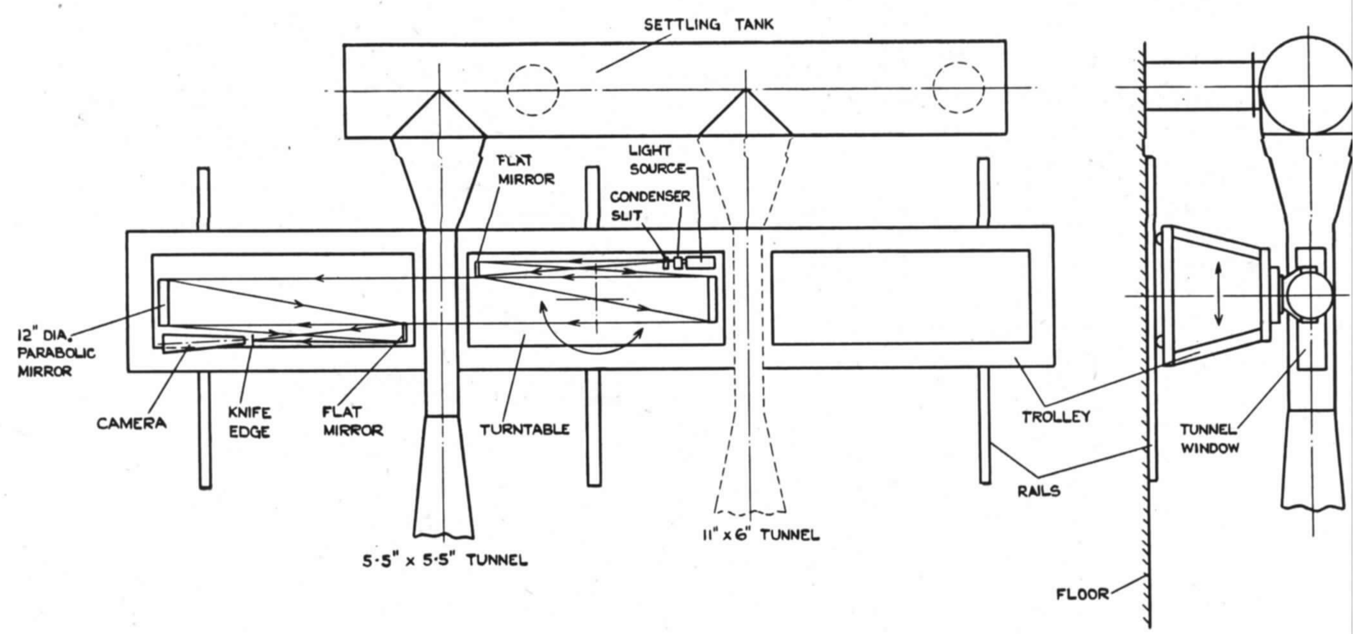


FIG. 13. Diagrammatic arrangement of optical bench.

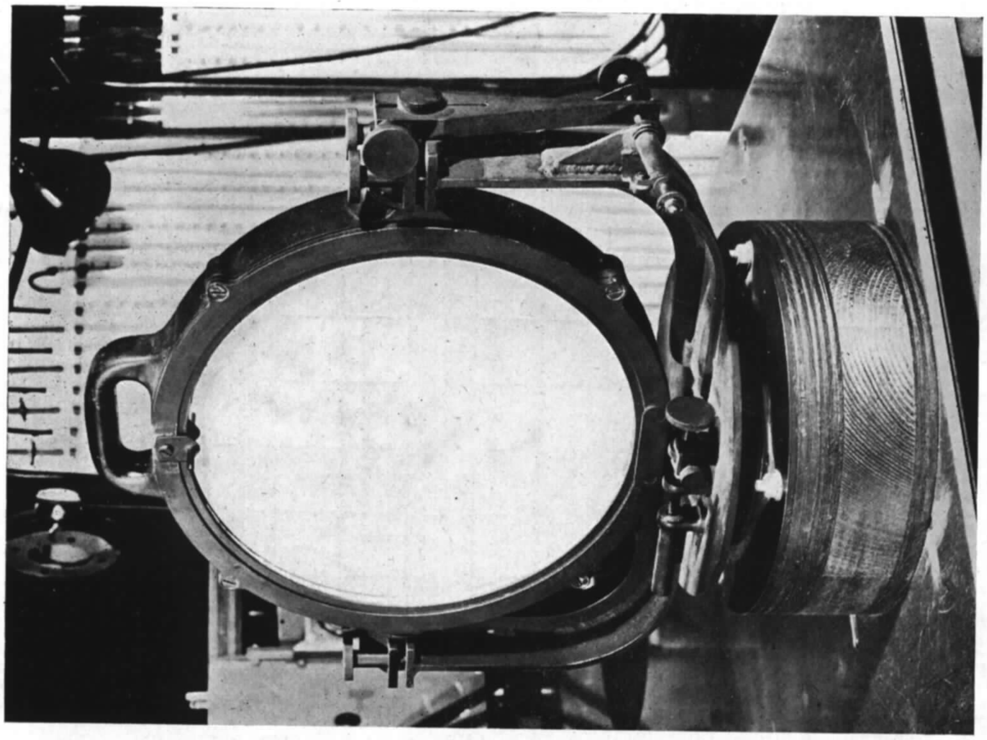


Fig. 14. 12 in. parabolic mirror and mounting.

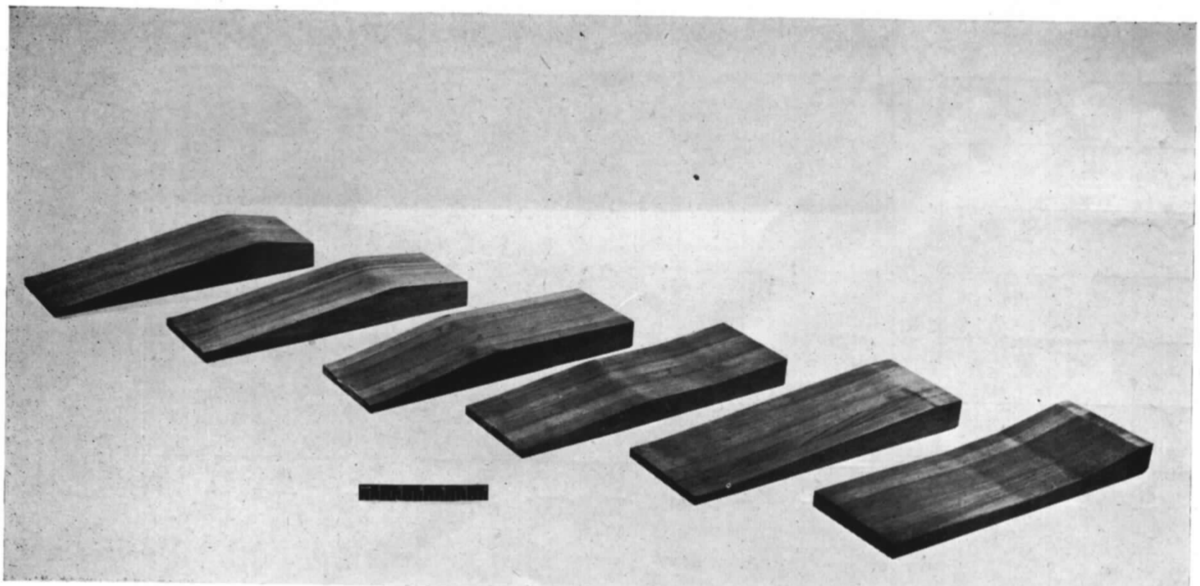


Fig. 15. Traverse liners. Left to right—Nos. VII, VI, V, III, II, I.

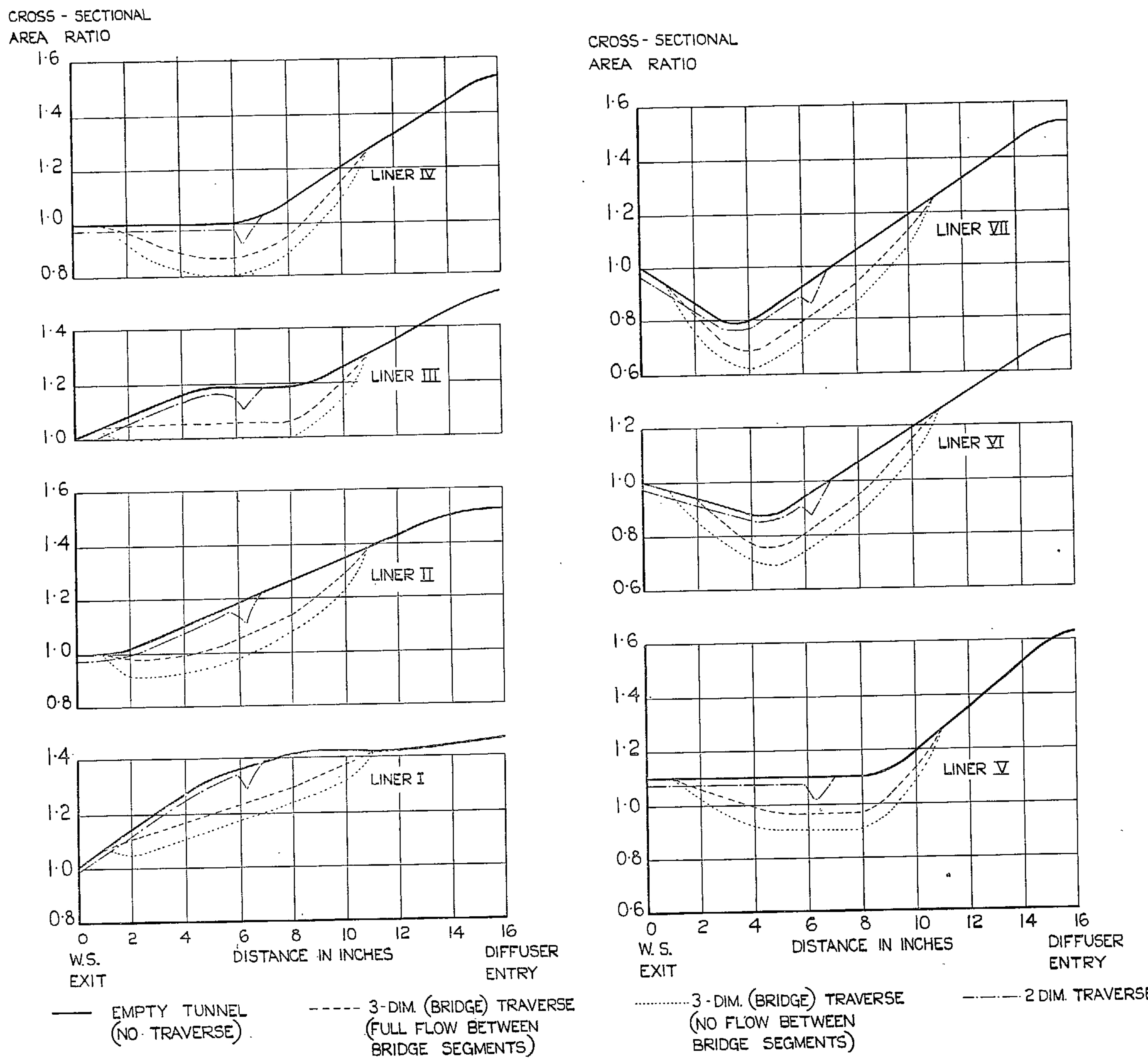


FIG. 16. Flow cross-sectional area for interchangeable traverse liners.

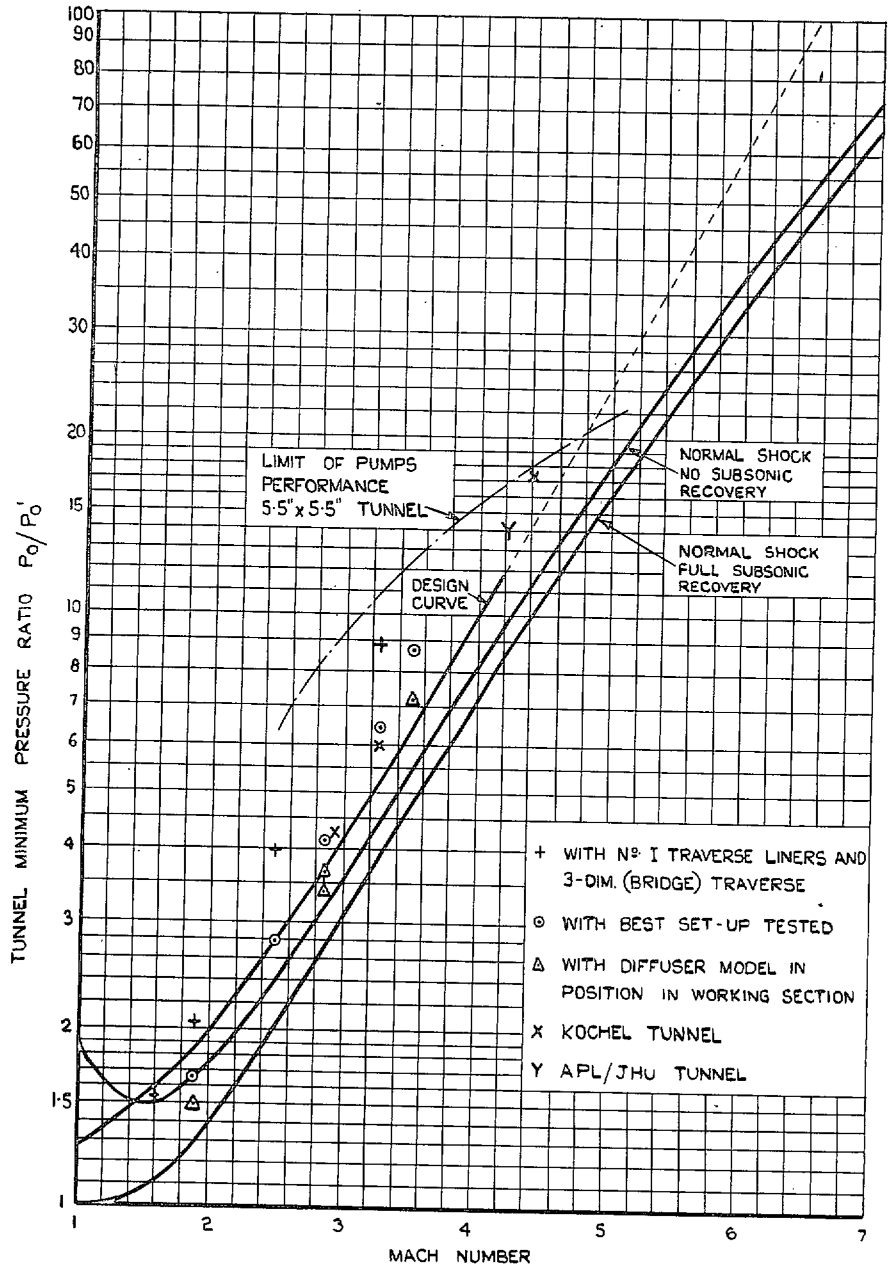
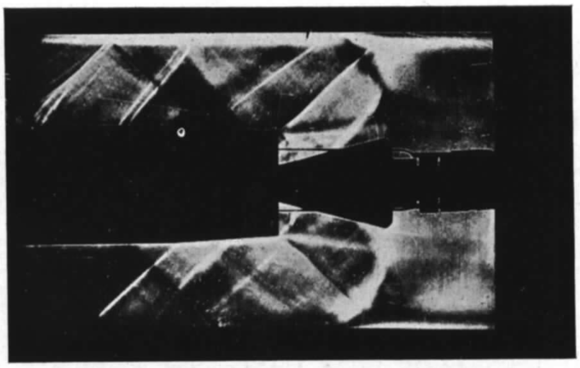
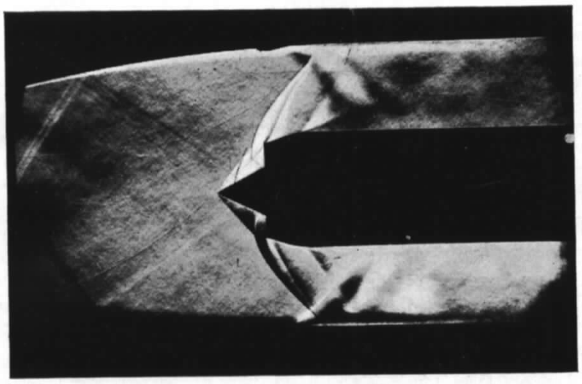


FIG. 17. Minimum wind tunnel pressure ratio.



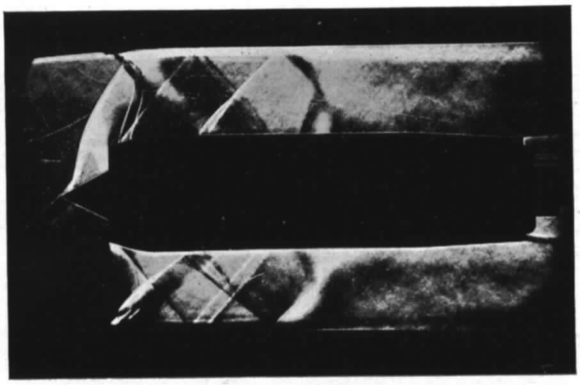
I. $p_0/p_0' = 1 \cdot 5$

(Maximum flow through diffuser model ; fully supersonic flow in working section).



II. $p_0/p_0' = 1 \cdot 375$

(Maximum flow through diffuser model; supersonic flow at entry of the model only).



III. $p_0/p_0' = 1 \cdot 375$

(As II, with flow through diffuser model reduced).

FIG. 18. Tunnel shock with diffuser model in the working section. $M = 1 \cdot 88$.

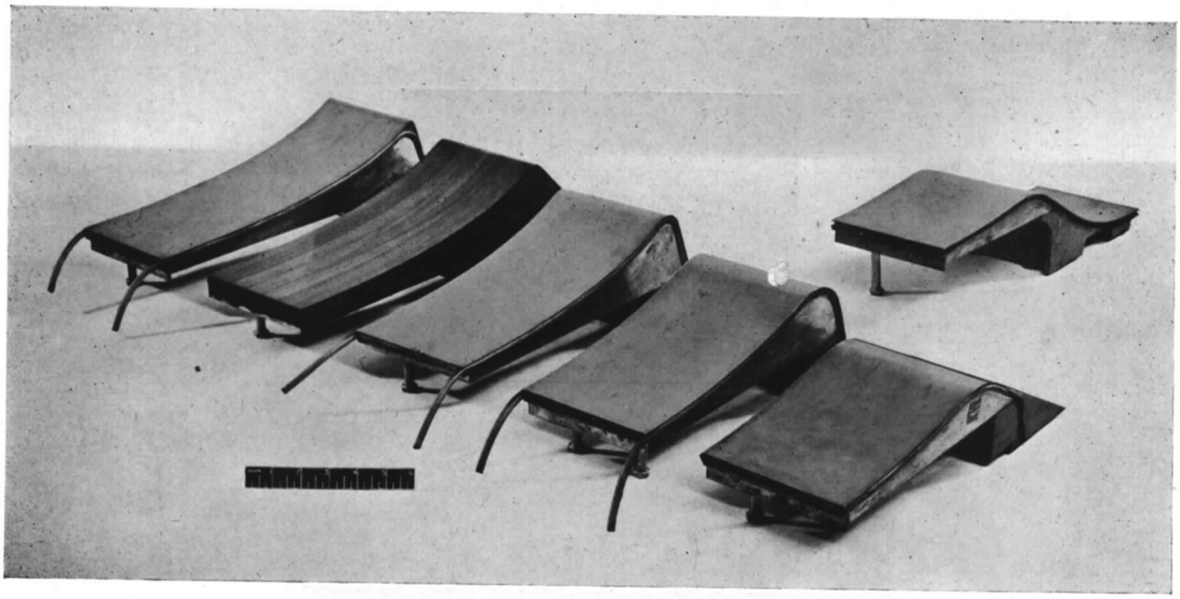


Fig. 19. Supersonic nozzles.

Left to right—liners for $M = 4{\cdot}38$, $3{\cdot}5$, $3{\cdot}25$, $2{\cdot}48$ and $1{\cdot}88$, with straight contraction profiles ; in the background $M = 1{\cdot}57$ liner with a shaped contraction.

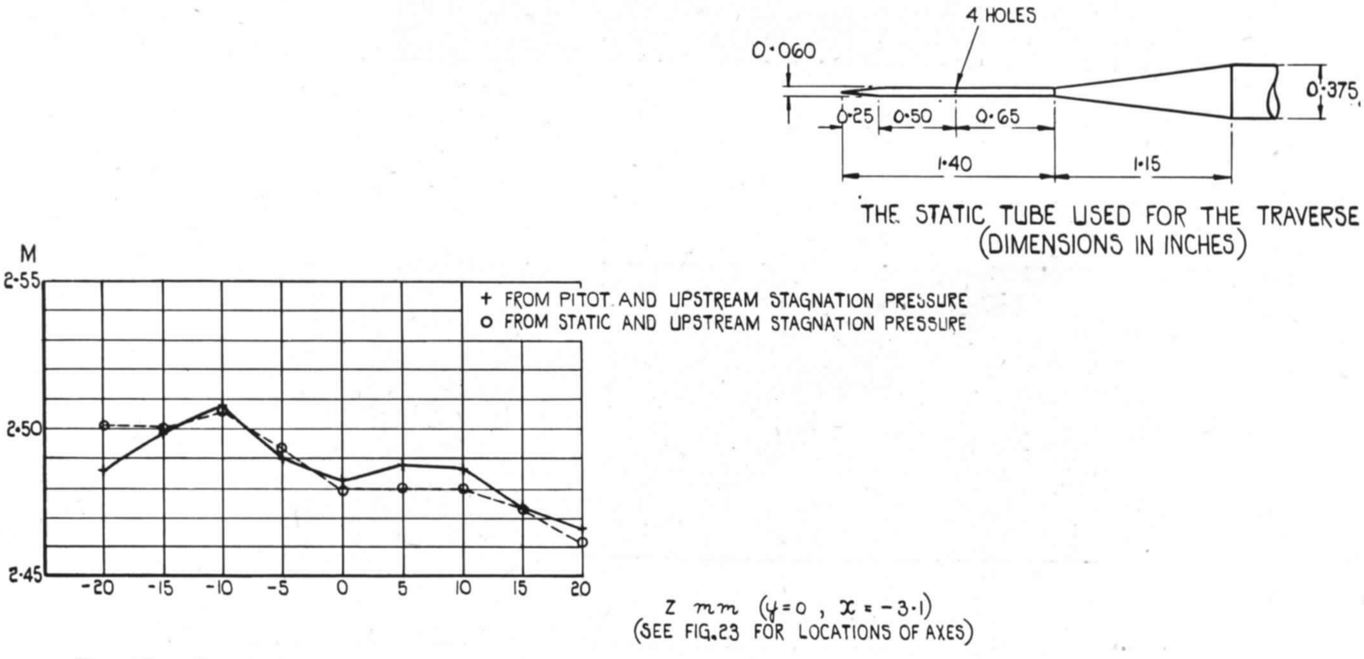


Fig. 20. Comparison of Mach number distributions given by a pitot and by a static tube at $M = 2{\cdot}48$.

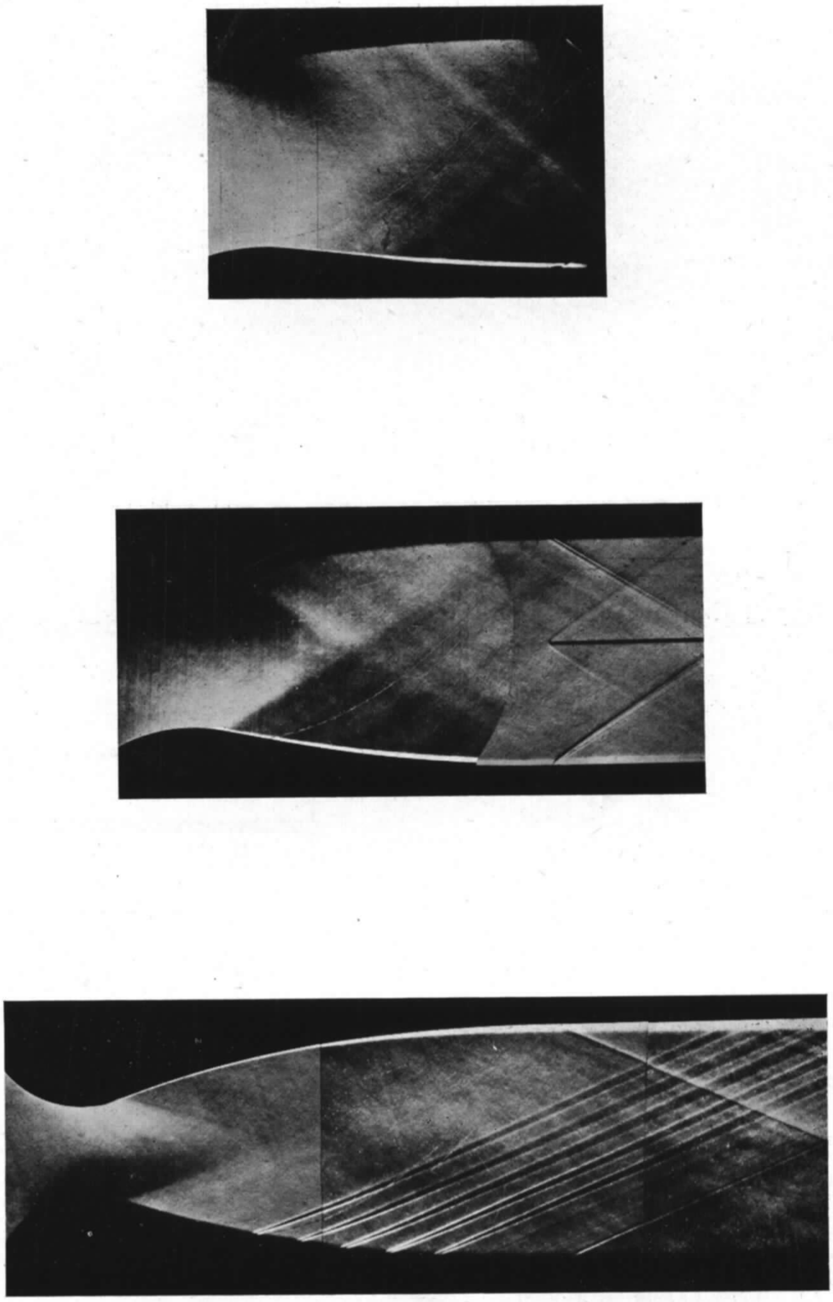


FIG. 21. Schlieren photographs of flow in the $M = 1{\cdot}57$, $1{\cdot}88$ and $2{\cdot}48$ nozzles. Dry air.

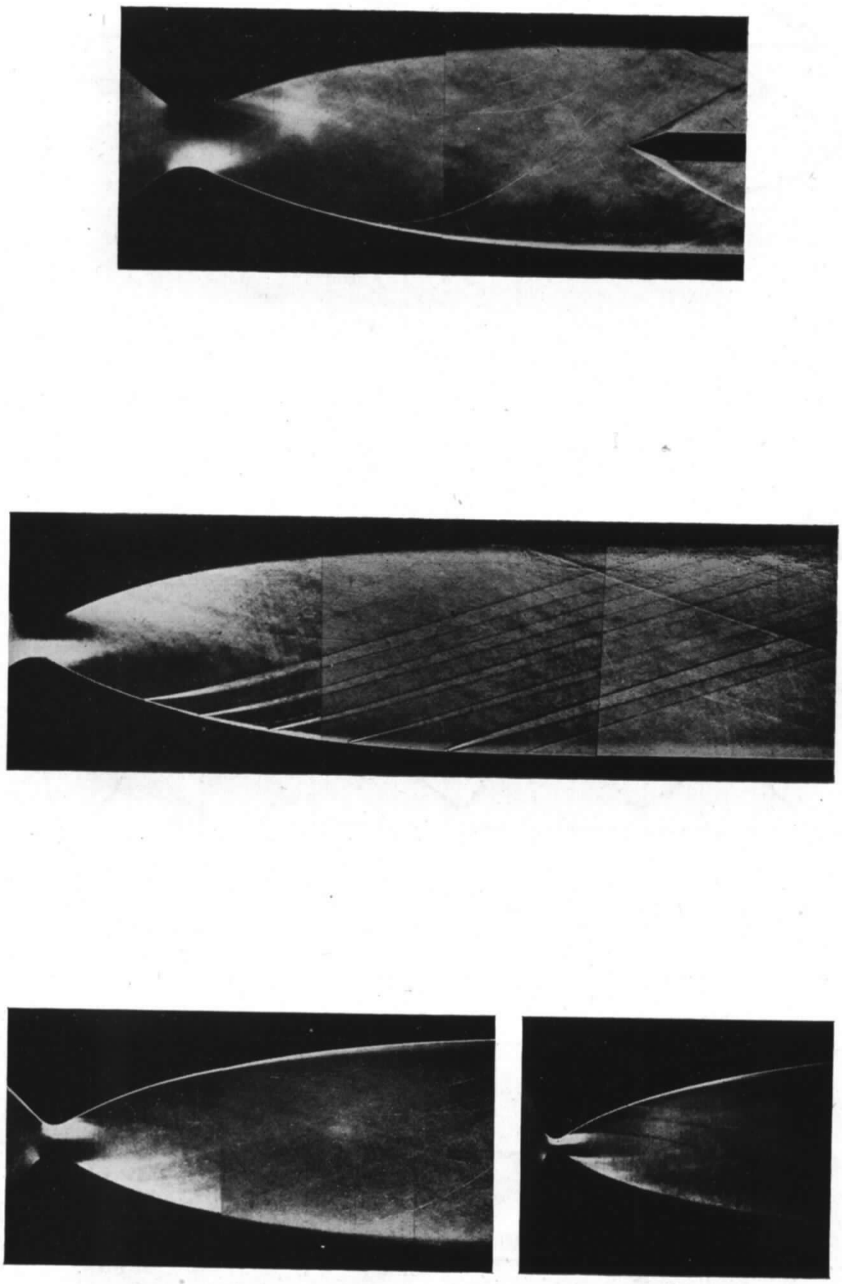


FIG. 22. Schlieren photographs of flow in $M = 2\cdot85$, $3\cdot25$, $3\cdot5$ and $4\cdot38$ (nominal) nozzles. Dry air.

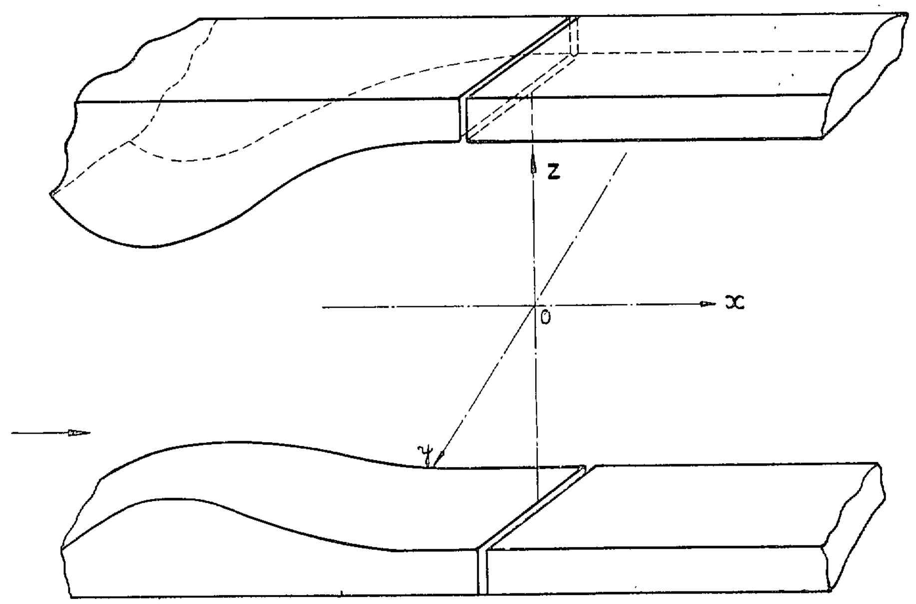


FIG. 23. Wind tunnel working section co-ordinates.

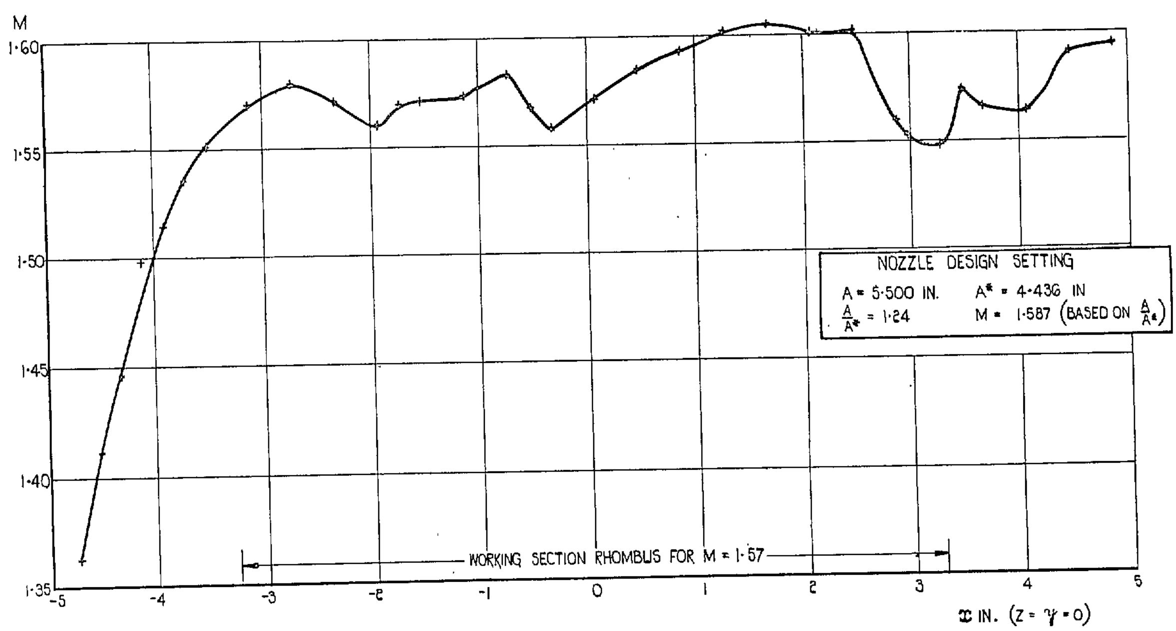


FIG. 24. Axial Mach number distribution of $M = 1\cdot57$ nozzle.

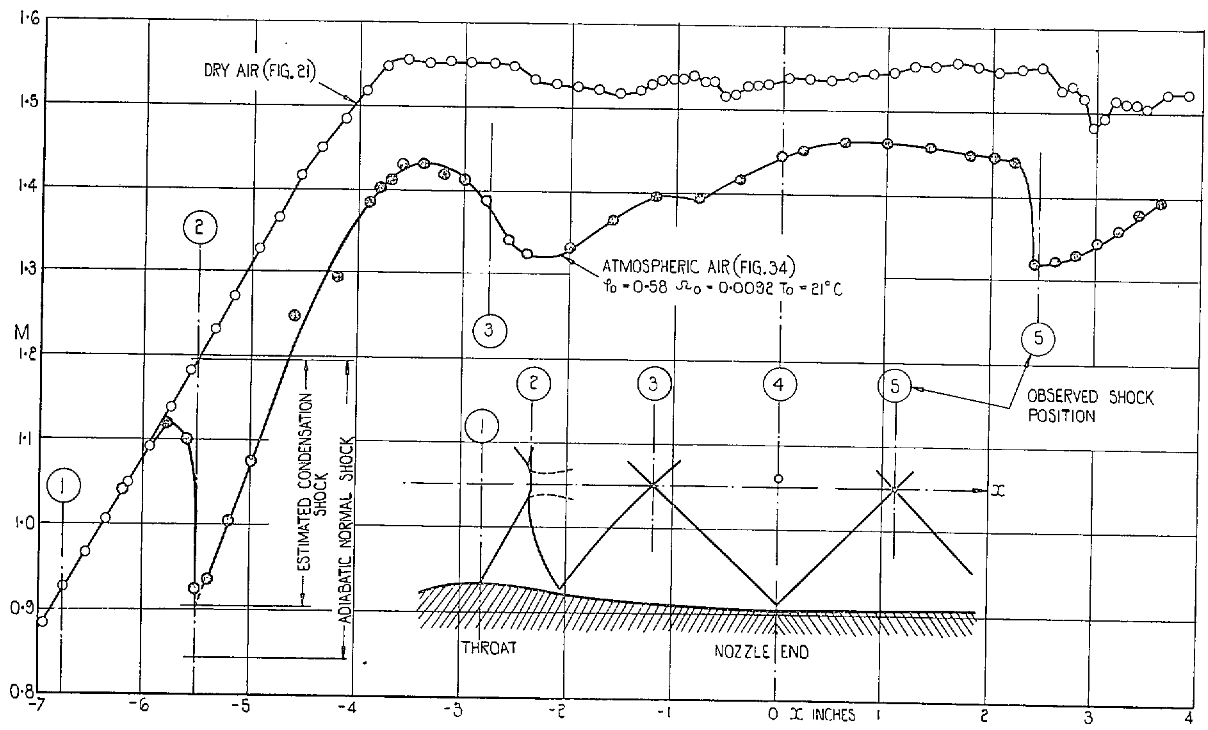


FIG. 25. Mach number distribution in 1·57 Mach number nozzle : atmospheric and dry air.

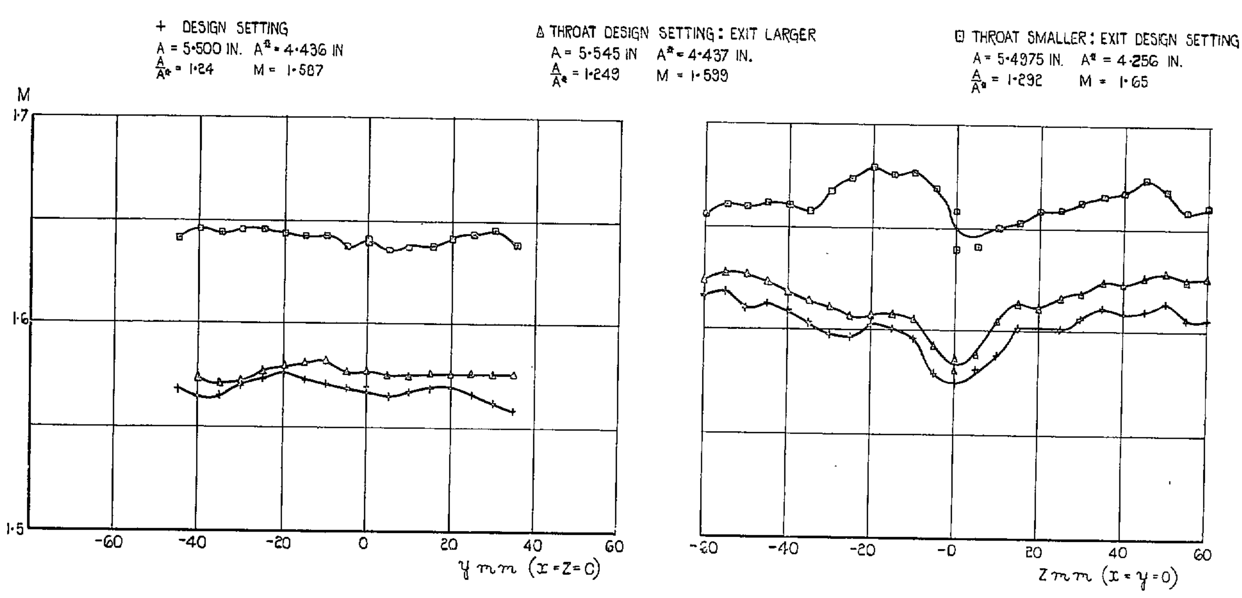


FIG. 26. Effect of nozzle setting on final Mach number distribution of $M = 1 \cdot 57$ nozzle.

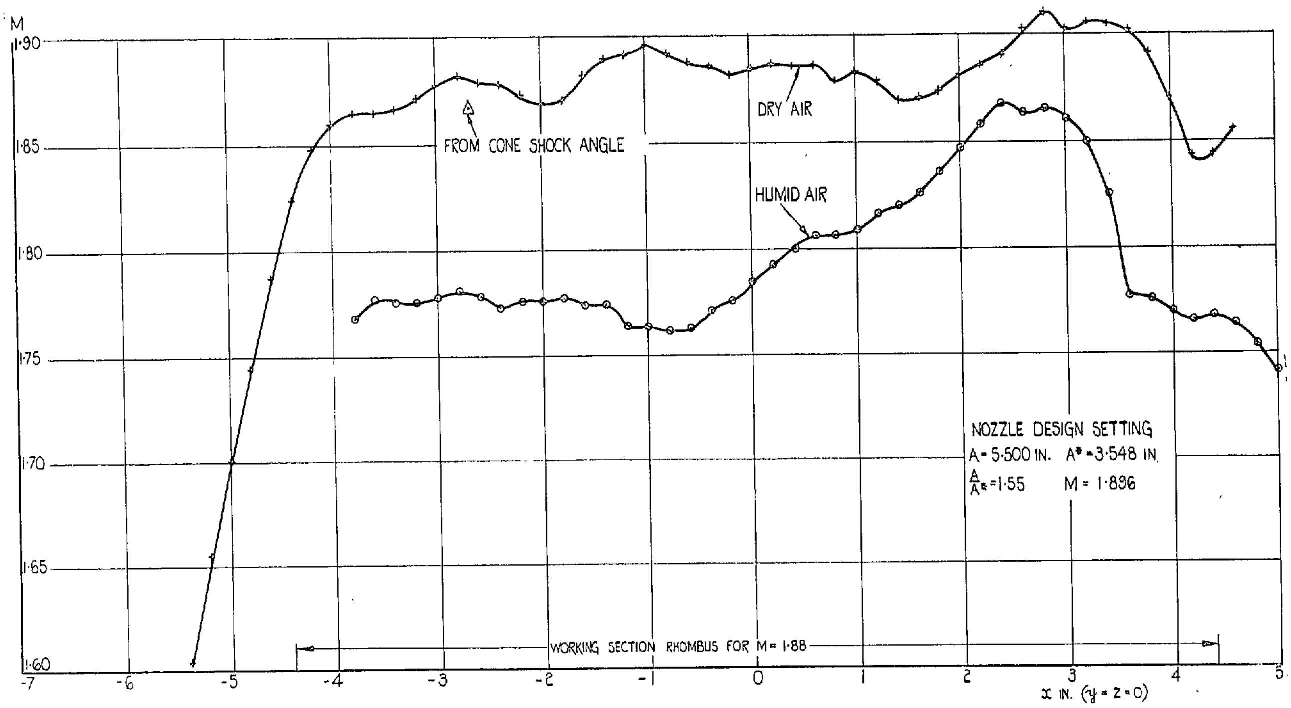


FIG. 27. Axial Mach number distribution of $M = 1 \cdot 88$ nozzle.

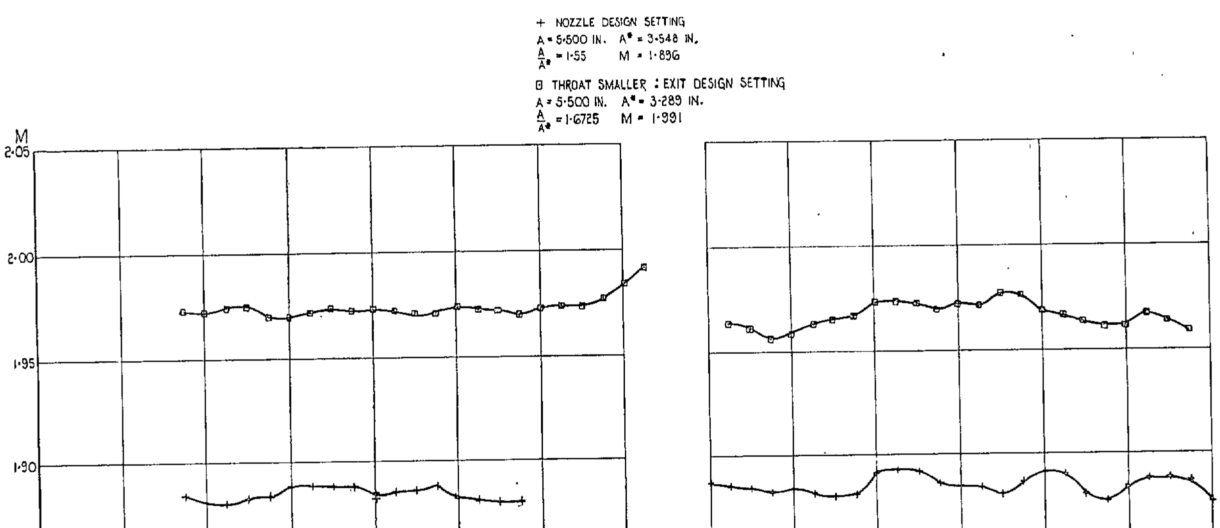


FIG. 28. Effect of nozzle setting on final Mach number distribution of $M = 1 \cdot 88$ nozzle.

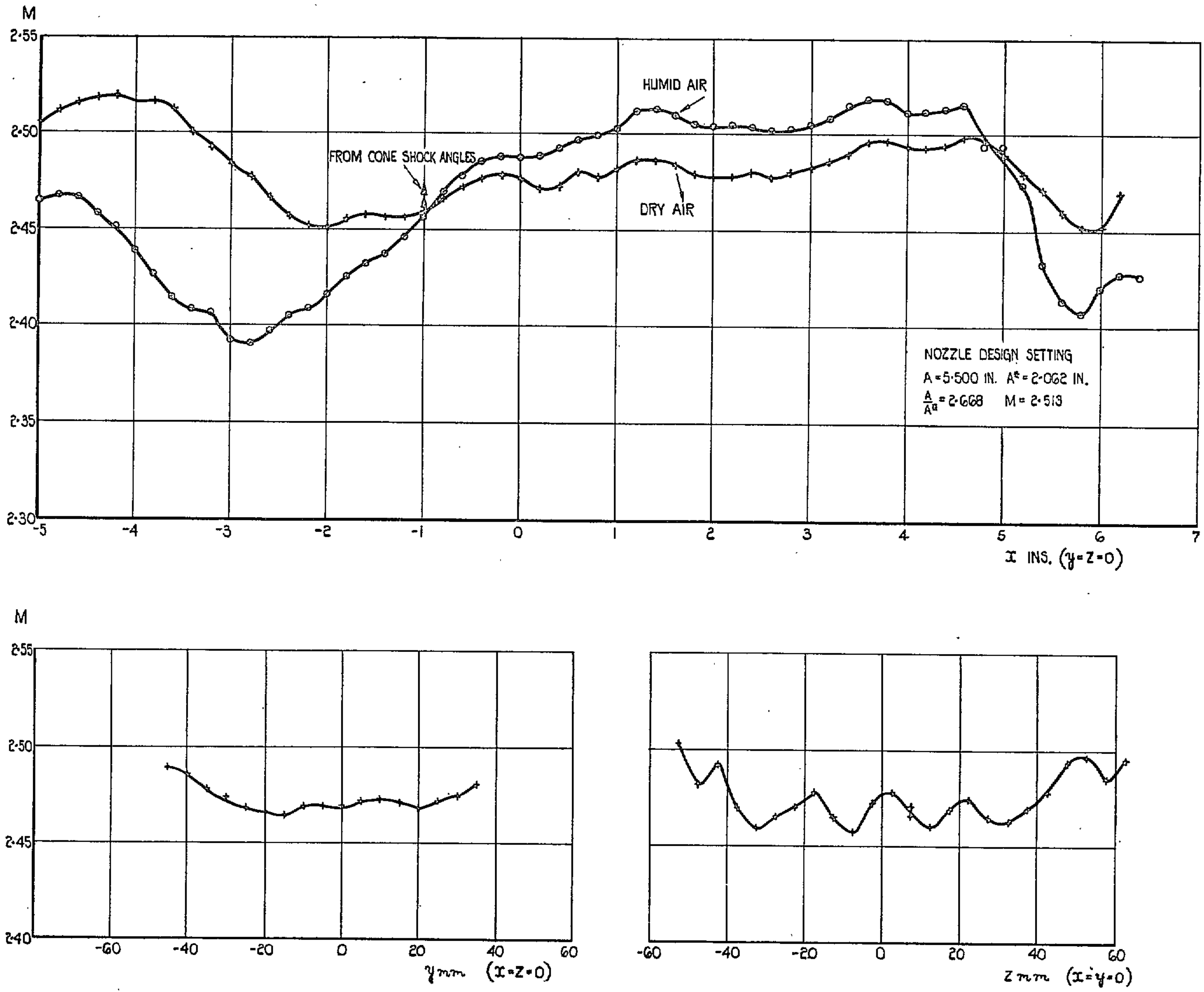


FIG. 29(a) and (b). Axial and final Mach number distributions of $M = 2 \cdot 48$ nozzle.

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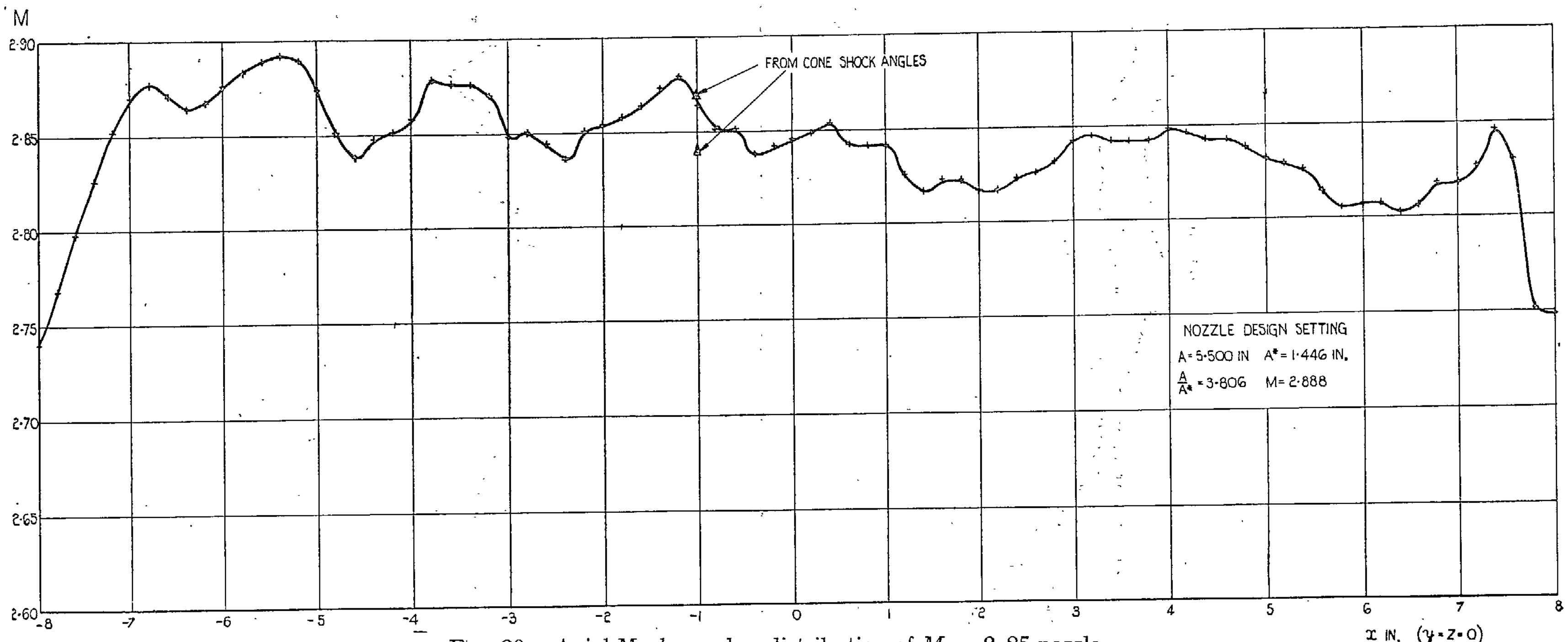

FIG. 30. Axial Mach number distribution of $M = 2{\cdot}85$ nozzle.

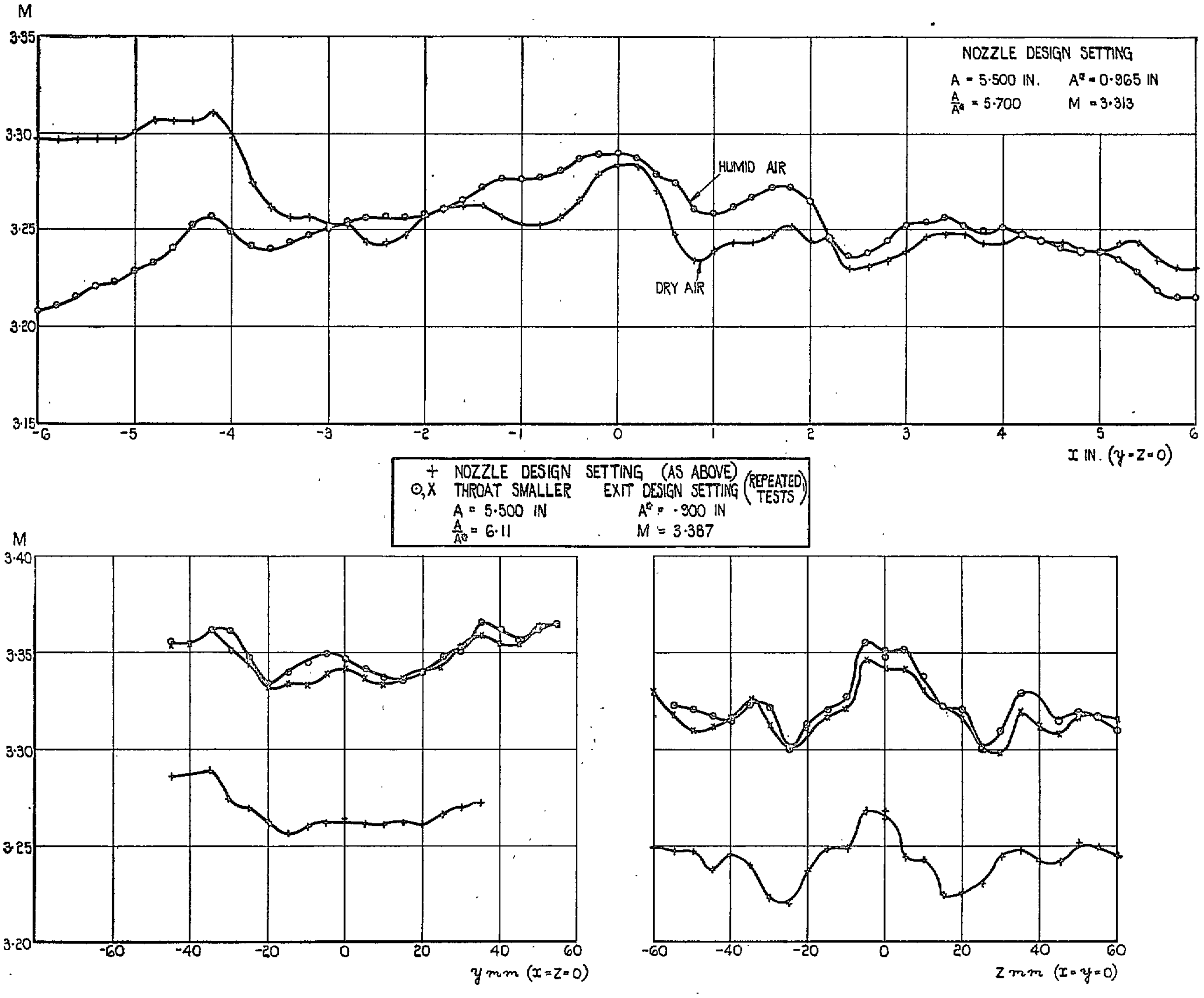

FIG. 31(a) and (b). Axial and final Mach number distribution and effect of nozzle setting for $M = 3{\cdot}25$ nozzle.

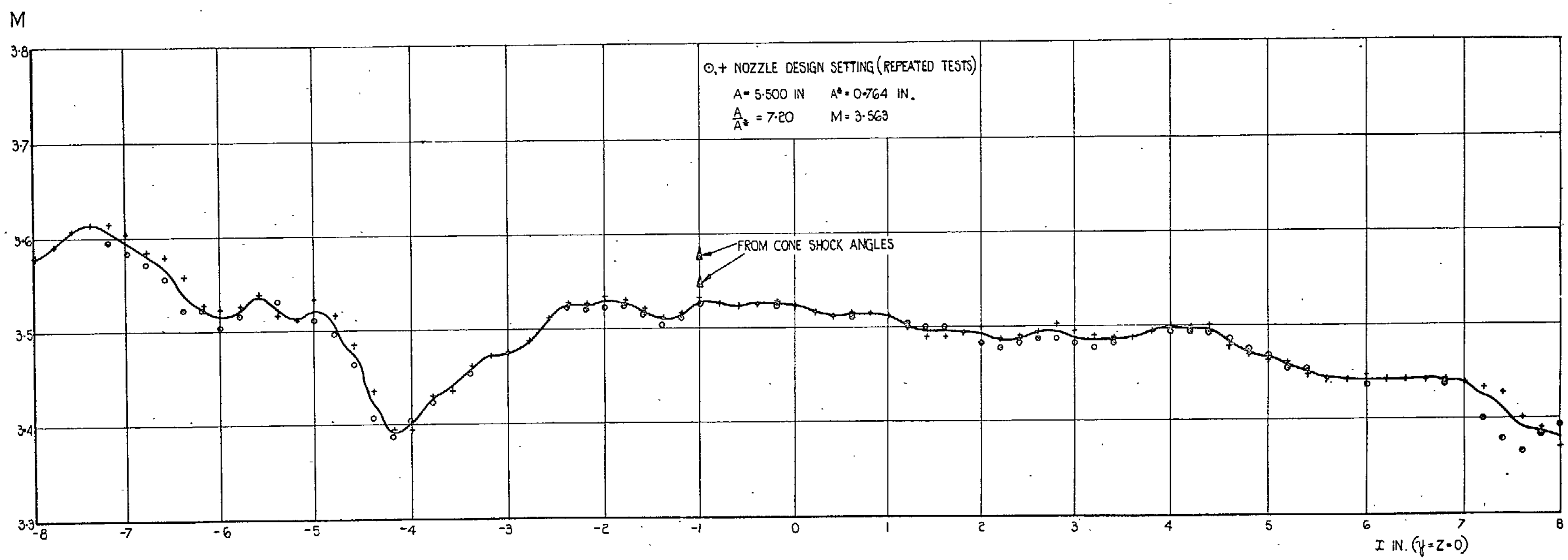

FIG. 32. Axial Mach number distribution of $M = 3\cdot5$ nozzle.

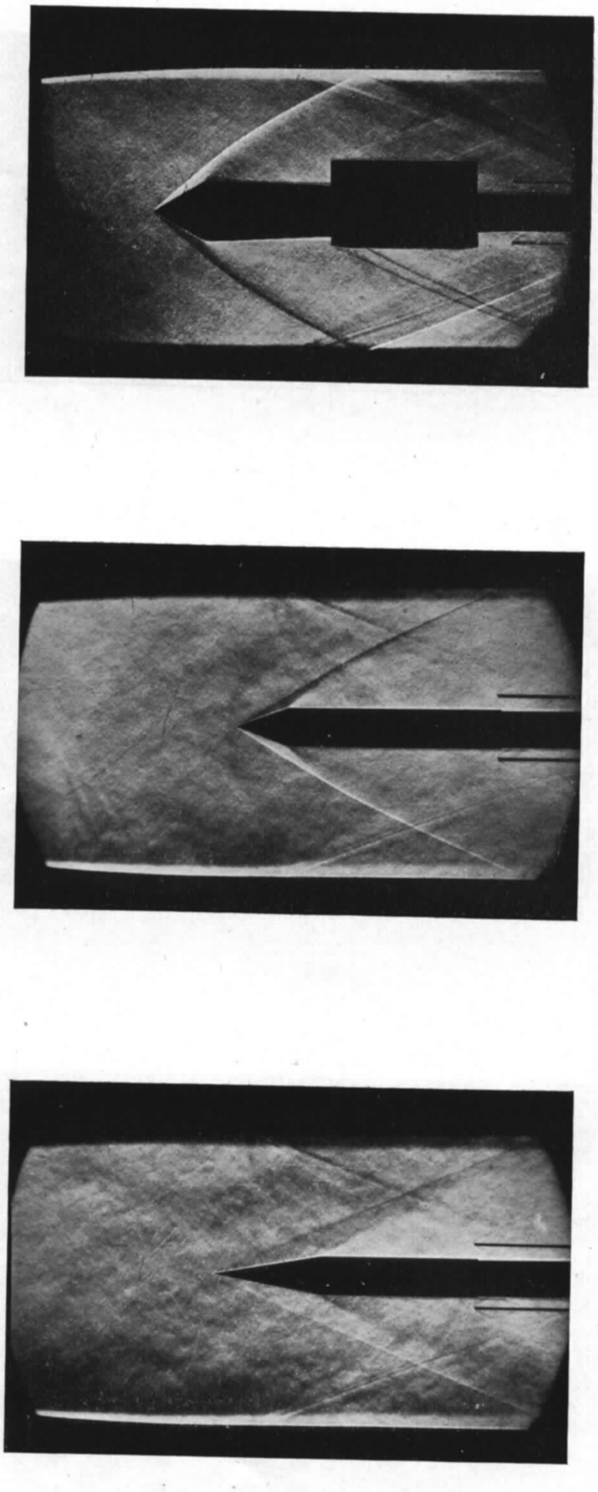

FIG. 33. Conical shocks obtained with 60 deg, 40 deg and 20 deg cones. $M = 2 \cdot 85$ nozzle.

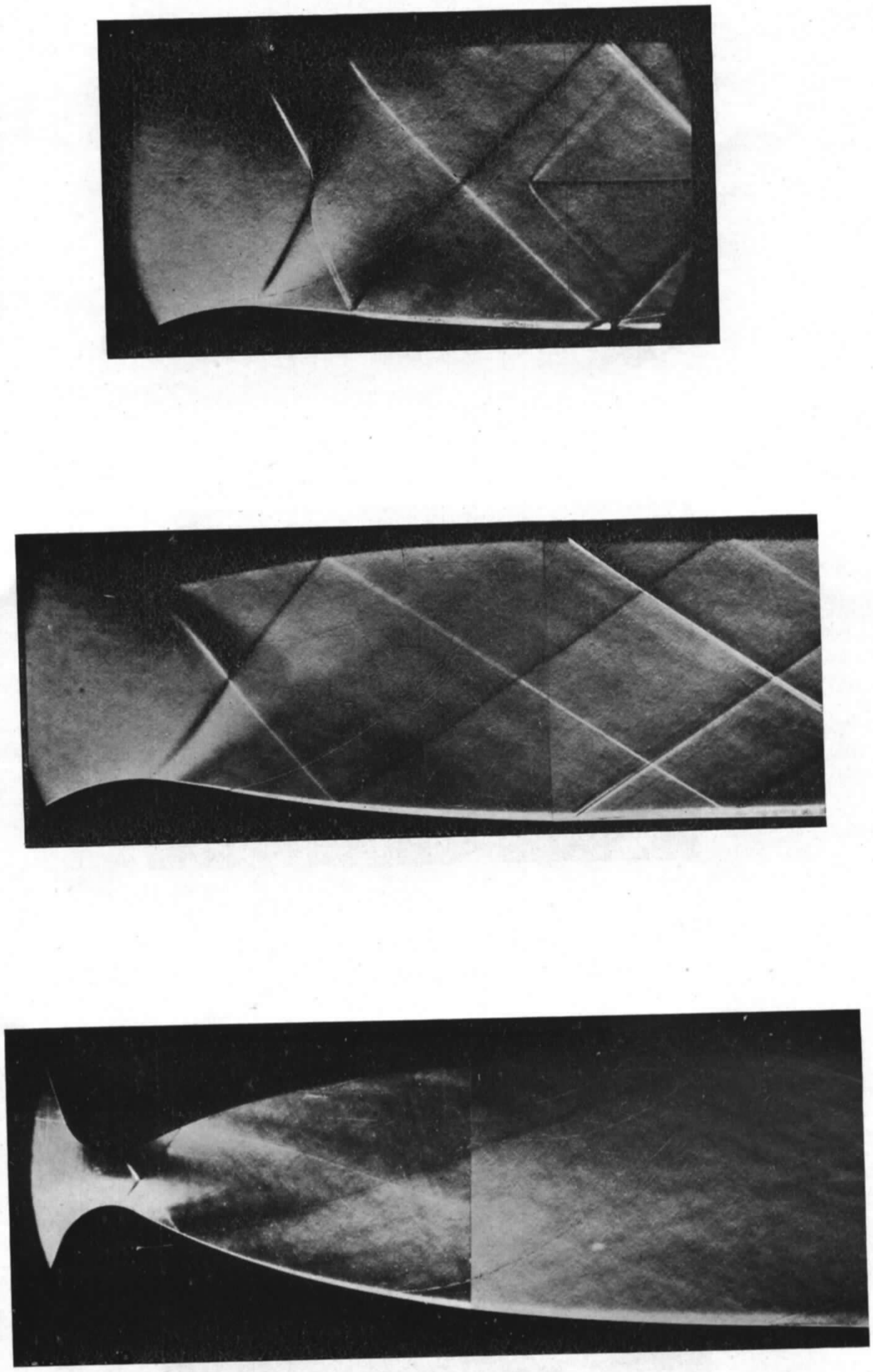

FIG. 34. Condensation shocks in the $M = 1 \cdot 57$, $1 \cdot 88$ and $3 \cdot 25$ nozzles.

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