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Calibration of the Flow in the Working Section of the 3ft x 3ft Tunnel, National Aeronautical Establishment

By

D. E. Morris

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Calibration of the flow in the working section of the 3 ft × 3 ft tunnel, National Aeronautical Establishment

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D. E. Morris
N.A.E.

SUMMARY

A number of calibrations, consisting of both pitot and static pressure measurements and also flow direction measurements, have been made of the flow in the working section of the 3 ft × 3 ft supersonic tunnel. In this report some selected examples are given to show the general nature of the flow distribution with the M = 1.4, 1.6, 1.8 and 2.0 nozzles and to demonstrate a number of interesting points in the measurements and in the characteristics of the flow.

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1 Introduction

All too often a wind tunnel has to be put into operation on model testing before it has been possible to do more than obtain a brief calibration of the flow in the working section. From then on the tunnel is too heavily engaged on its testing programme to allow interruption for calibration. The result is that very little is known of the details of flow distributions in supersonic tunnels.

The 3 ft. tunnel has an easily removable and duplicated section immediately downstream of the working section into which have been built the supports and traversing gear for the calibrating heads. These consist of a comb of static heads, another of pitot heads and a tilting arrangement for a wedge which can be used to measure flow direction in the pitching plane. When not required the heads can be easily dismantled, and suitable fairing pieces fixed to the supports enable the section to be used for other purposes but leaving the calibrating gear easily available for use when required. The equipment allows a comprehensive calibration of a nozzle to be done in a few hours tunnel running so that interruptions in the normal tunnel programme can be used for a check calibration. On occasions, as a preliminary to an accurate pressure plotting experiment it has been found desirable to measure local free stream pressure distributions in detail.

This report, which gives the results of a number of calibrations done at different times with the M = 1.4, 1.6, 1.8 and 2.0 nozzles, includes some comparative measurements made with a pitot and a static comb at M = 1.6 and also some measurements of flow direction together with an attempt to correlate these with the pressure measurements.

2 Brief description of the tunnel

Fig. 1 shows the general arrangement of the tunnel, the driving plant and the auxiliary machinery. The working section is 3 ft. square and the nominal Mach number range is up to 2.0. It is a closed circuit variable pressure tunnel, the pressure range being from about 1/20 atm. up to 2.0 atm. absolute. The rated power of the driving plant is 12,000 H.P. and the maximum overload is 16,000 H.P. The air is driven by means of two large double entry centrifugal compressors which are set in series with an intercooler. An aftercooler is located in the settling chamber from which the contraction ratio into the working section is nearly 40 : 1. There are three gauze screens of 0.010 in. diameter wire with 30 mesh per inch in the entry into the contraction.

The auxiliary plant consists of two 300 H.P. reciprocating type compressor evacuators and a large capacity silica gel air drying plant with its auxiliary equipment.

Single-sided fixed block nozzles are used to generate the flow. A sketch showing the arrangement of the nozzles in the working section is given in Fig. 2. Each nozzle is made complete with its own steel top cover to the working section, for ease of changing by means of an overhead crane. The nozzle shape is formed of laminated teak about 4 inches thick which is carried on a suitable steel framework welded to the top cover. The flat bottom wall is also made of laminated teak and has a series of static pressure holes along its centreline. Its supporting framework is bolted to the steel outside wall. The side walls of the working section are not lined but the steel surfaces, which are parallel, are coated with a thin layer of Marco resin which has been carefully rubbed down to give a flat smooth finish. Inflatable rubber seals are used to seal the 1/8 in. wide gap between the sides of the wooden top and bottom liners and the side walls.

A wire 0.025 in. diameter is fixed round the perimeter of the contraction about 70 in. upstream of the throat. This was done in order to ensure transition to a turbulent boundary layer at this point thus reducing considerably the variation in working section Mach number with stagnation pressure. That transition occurs at this point has been checked.

3 Calibration equipment

The arrangement of the calibration equipment is shown in Fig. 3 and details of the pitot and static heads and the yawmeter wedge in Fig. 4. The main support body spans the tunnel from top to bottom, being carried on a steel shaft which slides in bushes set into the wall of the tunnel. Two lead screws, one at the top and the other at the bottom, connected together by shafts outside the tunnel section drive the main support across the tunnel; this operation is manually operated. Two shafts which carry the calibrating heads slide in bushes set into the main support. These shafts have racks on them by means of which they are driven along the tunnel by pinions, coupled together by shafts external to the tunnel shell and driven by an electric motor. Thus longitudinal motion of the calibrating heads is controlled remotely from the Observation Room. A calibrated indicator operated from the motor shaft shows its position.

The pitot and static combs each have 9 heads spaced 3 inches apart symmetrically relative to the tunnel centreline. Care was taken in locating the holes in the static heads to ensure no interference between the heads. At M = 1.4 the shock wave from the nose of the static tube strikes the adjacent tube 1.9 in. downstream of the static holes. The static heads are made of 2 mm hypodermic steel tubing fitted with conical heads. The pitot heads are also 2 mm hypodermic tube. The heads could be connected to a bank of mercury filled or alcohol filled manometers.

The yawmeter wedge is arranged to measure flow direction only in pitch and its movement is limited to the horizontal plane through the centreline of the tunnel. These limitations in the design were accepted because an extremely high standard of flatness had been achieved on the Marco surface of the side walls and therefore no appreciable disturbances would be expected to originate from them, apart from the window joints. Most disturbances were expected to arise from errors in the nozzle shape or from distortions of the wooden nozzle or of the wooden bottom wall liner. A yawmeter traverse in a fixed horizontal plane together with the extensive pressure measurements possible is adequate to trace disturbances of importance.

The wedge, shown in Fig. 4, has an angle of 10^{o} and has accurately ground surfaces with a small static pressure hole in each surface. The differential pressure is measured by means of a water-filled U-tube. In the design of the wedge its area was kept to a minimum in order to minimise deflections due to the lift loads on it. This explains the sweep of the edges. The holes were located as near the front of the wedge as possible consistent with getting square-shouldered holes normal to the surface. At M = 1.4, when the Mach number at the surface of the wedge is about 1.2 the Mach lines from the corners meet in front of the holes, but this does not seem to affect the linearity of the calibration (Fig. 5). For calibration purposes the wedge can be rotated through 180^{o} in its holder which is mounted on two struts. The wedge holder and the two struts which are swept forward from the holder form a rigid structure. The other ends of the struts are attached through pivots to electrically driven linear actuators which are rigidly fixed to the ends of the longitudinal traverse shafts (see Fig.3). The actuators can be operated differentially or singly to produce a maximum angular movement of the wedge of about $\pm 2.5^{\circ}$. The reason for sweeping the struts forward from the wedge was to locate the leading edge of the wedge in line with the support pivots thus ensuring rotation of the wedge about its leading edge when the actuators are moved differentially. A slight and negligible distortion of the support shafts takes place when the wedge is rotated.

The angular setting of the wedge was measured by means of a telescope.

4 Accuracies

Readings accurate to ± 0.02 in. can be taken on the mercury manometers and to about ± 0.03 in. on the alcohol manometers. The following table gives the equivalent error in terms of M for the mercury manometer used with static heads; the corresponding errors with the alcohol manometer are approximately a tenth of these values and therefore negligibly small.

TABLE I

Error in M due to an error of 0.02 in. Hg. in static pressure measurement

Stagnation Pressure / M	30 in. Hg	20 in. Hg	10 in. Hg
1.4	0.0015	0.0020	0.0045
1.6	0.0020	0.0030	0.0055
1.8	0.0025	0.0035	0.0075
2.0	0.0035	0.0050	0.0100

When the alcohol manometer was used, a mercury manometer was used as a reference, hence though this ensured a highly accurate comparison between the different static heads the absolute value in any position was dependent on the accuracy of reading the mercury reference tube.

A water U-tube was used to measure the pressure difference between the two faces of the yawmeter wedge which could be obtained to an accuracy of ± 0.1 in. water, which is equivalent to an accuracy of about 0.01° in flow direction at atmospheric stagnation pressure. However the incidence of the wedge could not be measured more accurately than $\pm 0.05^{\circ}$ using the telescope. The technique employed with the yawmeter was to bring the wedge up to the desired longitudinal position, set and measure its incidence and then traverse across the working section without altering the setting of the wedge, measuring the differential pressure at each position. This method gives extremely accurate comparisons of flow direction in various positions across the tunnel, but the absolute value might be in error by $\pm 0.05^{\circ}$. Small variations in the rack and pinion drive of the main support shafts resulting in alterations to the wedge incidence with setting along the tunnel forced the use of the technique described.

The calibration curves for the wedge in its normal position and inverted are given for M = 1.4 and 1.6 in Fig. 5. These were obtained by rotating the wedge about its leading edge which was kept at a fixed position in the tunnel.

5 Range of Tests

Calibrations have been done as follows, May and July 1952, June 1953 and December 1953. Static and pitot comb measurements were made with the M = 1.4, 1.6 and 2.0 nozzles in May 1952 when the tunnel was first commissioned and these were followed with some measurements of flow direction in July 1952 with the M = 1.4 and 1.6 nozzles. A calibration of the flow with the M = 1.8 nozzle was made with the pitot comb in June 1953. Repeat calibrations of the M = 1.4, 1.6 and 1.8 nozzles using the static comb were made in December 1953 in conjunction with a pressure plotting experiment. During this last calibration it was found that there was a marked disturbance arising from the upstream end of the window.

The calibrations have covered a range of stagnation pressures from 10 in. Hg. up to 30 in. Hg. Comparisons are available between calibrations using a static comb and a pitot comb.

As wooden nozzle blocks are used the variation in the calibration of a nozzle with time, over a period of 18 months, is of interest. During this period some maintenance work was done on the surfaces of the nozzles to repair damage arising from the splitting of some of the lamination joints as the wood dried.

During all the calibration runs described the humidity of the air in the tunnel corresponded to a frost point of -40°C or less. The stagnation temperature was maintained within the range 25°- 30°C.

6 Results

6.1 Bottom wall pressures

Fig. 6 - 9 give the results of measurements of bottom wall pressures for the M = 1.4, 1.6, 1.8 and 2.0 nozzles. These are included to illustrate the development of the flow. Also given are the postulated variation in M along the bottom wall from which the nozzles were designed. The agreement between the experimental points and the theoretical curves in the accelerated flow region is excellent for the M = 1.4 and 1.6 nozzles, but is not as satisfactory for the M = 1.8 and 2.0 nozzles.

The variations in M as measured along the bottom wall must not be taken as indicative of the distribution in the working section. The static holes are drilled straight into the wood and though the quality of the hole was initially very good it has been found impossible to maintain this standard. This explains the considerably smaller irregularities in the pressures measured with the M = 1.4 and 1.6 nozzles compared with those taken at a later date, the M = 1.8 and 2.0 nozzles. Fig.10 demonstrates clearly to what extent imperfections in the static holes affect the pressure measurements. It gives bottom wall pressures with the M = 1.4, 1.6 and 1.8 nozzles, the similarity in irregularities of the measurements is remarkable and this can only be due to the quality of the static holes, or, of course, leaks in the pressure leads.

6.2 Static and pitot comb measurements

The results given in this report have been selected from the large number of results available with the threefold object of showing the quality of the flow with each nozzle and of illustrating interesting points in measurement or in the characteristics of the flow.

The method of plotting the results has been to make the line along which any given tube of the comb travels the datum of the Mach number scale for that tube. In order to obtain a reasonable spacing the vertical scale indicating the vertical positions of the tube relative to the centre line, differs from the horizontal scale representing distance along or across the tunnel. This should be noted when attempting to trace the propagation of a disturbance.

It has been assumed that H, the total head, is constant along the working section and equal to the settling chamber pressure. This is justified by the bottom wall Mach number distribution (Fig. 6 - 9 which show no strong shocks upstream.

6.21 M = 1.4 nozzle

Results of calibrations of this nozzle are given in Fig. 11 - 15.

Fig. 11 shows the last calibration done, the disturbance arising from the window joint shows up very clearly on all the tubes at a position just downstream of the centre of the window. A mean Mach number for the actual test region for a model was obtained by taking the average of the readings for the 5 middle tubes of the comb. At atmospheric stagnation pressure the mean Mach number is 1.416. The maximum observed variation from this value is ±0.005, ignoring the disturbance due to the window.

At a stagnation pressure of 16 in.Hg the mean Mach number in the test section is 1.415 which is very little lower than at atmospheric pressure (cf. para 6.23).

There is a gradient in Mach number vertically across the tunnel, especially at positions between 10 and 20 inches upstream of the centre of the window. There is also a slight gradient along the test section more especially for the centre line and above. This gradient is equal to about +0.005 in M over about 20 inches.

Fig. 12 shows a calibration done 18 months earlier at a lower stagnation pressure using an alcohol manometer and also a mercury manometer. There is good agreement between the general shape of these curves and those of Fig. 11 showing no marked effects of any changes in the nozzle block.

In general the agreement between the points for the mercury and the alcohol manometers are very good, almost as good as between repeat measurements with the alcohol manometer. The differences between repeat readings are the same for all the tubes in one position of the comb illustrating the point made in para. 4 that extremely accurate comparisons from tube to tube can be made using the alcohol manometer but that the absolute value depends on the accuracy of the mercury reference tube.

Fig. 13, 14 and 15 give the results of traverses across the tunnel from 12 in. one side to 11 in. the other side of the centre line. (For convenience the one side is called the "Observation Room Side" and the other the "Schlieren Room Side"). The variation shown by any one head is much smaller than in the longitudinal traverses of Fig. 11 and 12, showing that the larger disturbances present are two dimensional arising from the nozzle shape or the wooden bottom wall.

6.22 The M = 1.6 nozzle

Some results of calibrations of the M = 1.6 nozzle are given in Fig. 16 - 21. Fig. 16 - 19 are taken from the latest calibration done in December 1953. As for the M = 1.4 nozzle the disturbance due to the window joint is very obvious at stations about 5 in. downstream of the centre of the window in the centre plane traverse. The distributions taken in parallel planes 3 in. and 6 in. away from the centre plane on the Schlieren Room side (Fig.18) also show a disturbance of this nature; similarly positioned planes on the Observation Room side are affected to a lesser extent, all at positions upstream of the disturbances in the centre plane. This shows that both window joints are causing disturbances but that due to the Schlieren Room side window is the larger of the two.

The mean Mach number in the model test section is 1.612 at atmospheric pressure as obtained from this calibration. Neglecting the disturbance arising from the window joint the maximum observed variation from this mean is ± 0.006.

As in the case of the M = 1.4 nozzle, a noticeable feature of the distribution is the increase in Mach number from top to bottom of the test section. At the 6 in. station above the centre line the mean M is 1.610 compared with 1.612 along the centre line and 1.616 at 6 in. below the centre line. There is also a small gradient in Mach number along the test section.

Fig. 19 giving the distribution in the transverse plane through the centre of the window is obtained by cross-plotting from Fig. 16, 17 and 18. The variation shown by any one head is generally small.

The results given in Fig. 16 - 19 were obtained using the static comb at atmospheric stagnation pressure. Fig. 20 gives some earlier results at 16 in.Hg. stagnation pressure and compares measurements made with the static and the pitot combs. The agreement is very good except where the readings of the static heads have been affected by leaks in the lead tubes.

It is noticeable that the mean Mach number at this stagnation pressure (16 in.Hg.) is considerably lower than at atmospheric stagnation pressure as shown in Fig. 16. In this case the mean M in the test section is 1.605. This difference is attributed to the different rate of boundary layer growth.

In Fig. 21 the calibrations along the centre plane of Fig. 16 and 20 have been expressed as variations of M from their respective means along the centre line in order to demonstrate more clearly the differences between pitot and static comb measurements and also the change in calibration with time. The variation in M shown by any one head is generally the same for the three sets of points. This proves that again in the case of the M = 1.6 nozzle, as for the M = 1.4 nozzle, the change in nozzle shape with age and maintenance has been negligibly small. Several of the early static head measurements are low suggesting small leaks in the pressure leads.

6.23 The M = 1.8 nozzle

The latest calibration done in December 1953 was at atmospheric stagnation pressure and the static head comb was used. Results of traverses in the longitudinal vertical centre plane are given in Fig. 22 and of traverses in parallel planes displaced 3 in. and 6 in. to both sides in Fig. 23 and 24.

The disturbance due to the window joint which showed clearly in the corresponding calibration of the M = 1.4 and 1.6 nozzles, now passes downstream of the centre plane traverse but similar disturbances show in the traverses at the 6 in. stations on either side in positions just downstream of the centre of the window. The disturbances shown at 6 in. on the Schlieren Room side are the greater confirming the results obtained with the M = 1.6 nozzle.

The mean Mach number in the test section is 1.816 and the maximum deviation from this value is ±0.005, apart from the obvious effects due to the window joints.

There is an appreciable gradient of mean Mach number from top to bottom of the test section. In Fig. 22 the mean of readings at the station 6 in. above the centre line is 1.813, at the centre line it is 1.816 and at 6 in. below the centre line it is 1.818.

Fig. 25 is a typical traverse across the test section. As in the case of the other nozzles the variation shown by any one head is small.

Fig. 26 and 27 give the results of earlier calibrations of the flow in the centre plane at 20 in.Hg. and 10 in. Hg. stagnation pressure respectively, the pitot head comb was used in these traverses. The very large change in Mach number with stagnation pressure is obvious and in the following table the mean Mach numbers in the model test section are compared.

Stagnation Pressure H. in. Hg	10	20	30
Mean M in test section	1.798	1.802	1.816

6.24 The M = 2.0 nozzle

Only a very brief calibration of the working section with this nozzle has been attempted because with the existing diffuser arrangement the normal maximum rpm of the main drive motors has to be exceeded by a small amount in order to locate the main tunnel shock downstream of the test section. An improved diffuser will be available shortly which will be much more efficient.

Fig. 28 gives the results of measurements made with the pitot head comb in the centre plane at a stagnation pressure of 15 in. Hg. The mean Mach number is 2.003 and the maximum variation from this value is from -0.005 to +0.007. The error in measurement in this case is about ±0.0025.

As for the M = 1.6 and 1.8 nozzles there is a gradient in M from top to bottom of the test section though it is not so marked in this case. At 6 in. above the centre line the mean M is 2.000 and at the centre line and 6 in. below it is 2.004.

6.3 Yawmeter measurements

Results of traverses along the centre line and along lines 3 in. and 6 in. away on either side of the centre line with the M = 1.4 and M = 1.6 nozzles are given in Fig. 29 and 30 respectively. It must be noted that the values apply to the flow at stations in the horizontal central plane only, the flow directions along lines displaced up or down from the central plane may be very different. In fact the same order of flow direction variation would be expected in a vertical traverse as in a horizontal longitudinal traverse.

Fig. 29 shows that for the M = 1.4 nozzle the direction of flow in the horizontal central plane at distances between 15 and 5 inches upstream of the window centre is inclined downwards at an angle of about 0.2° to the centre line. Downstream of this region it pitches upwards and the flow is along the centre line at about 2 inches downstream of the window centre and it then becomes inclined slightly towards the top wall. By comparison the angle of flow varies little in cross traverses. This emphasises the evidence of the pressure measurements that most of the disturbances to the flow are two dimensional.

In the case of the M = 1.6 nozzle (Fig. 30), the flow is along the centre line at 15 inches downstream of the window centre but then pitches downwards through about 0.2° by the centre of the window. Downstream of this point the downward tilt is reduced until at 10 in. downstream of the window it is along the centre line again. As for the M = 1.4 nozzle the differences between points at corresponding longitudinal position in a cross traverse are small, confirming again that for the M = 1.6 nozzle the disturbances arise mainly from the top and bottom walls.

7 Discussion

Attention has already been drawn to the disturbance due to the window joint which shows in all the calibrations done in December 1953 but not in ealier calibrations. The source of the disturbance was found to be a small step, no more than 0.003 in. from the steel frame of the window to the glass due to a movement of the glass in the frame. In order to obtain a measure of the effect of a step of this size adhesive tape 1 in. wide, 10 in. long and 0.0025 in. thick was stuck on to the bottom wall normal to the line of flow and symmetrically placed relative to the centre line; the displacement thickness of the boundary layer in the neighbourhood of the tape was 0.24 in. The static head comb was traversed along the centre line through the disturbance which showed up very clearly on the Schlieren. Fig. 31 shows the results of traverses through the disturbance 18 in. above the bottom wall and at 6 in. above the bottom wall at M = 1.4 The traverse at the centre line was done at close enough intervals to enable the exact magnitude of the disturbance to be determined but this was not done at the 6 in. station so that the strength can be deduced only from the former. The strength of the initial shock wave at the centre line ($\Delta M = 0.010$) is a little less than the value of 0.015 calculated from a theoretical formula for the decay of weak oblique shockwaves given by Hermann in Ref. 1. The formula is

$$\frac{\Delta p}{p} = \frac{2\gamma}{\sqrt{\gamma+1}} \cdot \sqrt{\frac{h}{y}}$$

Where p is the static pressure, h is the height of the step and y is the distance out from the step.

The formula does not allow for any effects of wall boundary layer and it is therefore not surprising that the theoretical value is greater than the measured value.

This is a good example and a guide to the care that must be taken in fitting windows etc., even in large supersonic tunnels.

The order of the changes in flow direction along the centre line of the test section would not necessarily have been deduced from the pressure distributions. This emphasises the need for both yawmeter and pressure calibrations. Fig. 32 shows an attempt to deduce the flow direction along the centre line for the M = 1.4 nozzle from the pressure measurements. In view of the random nature of the disturbances this is a difficult task and a number of equally possible interpretations are possible. For this reason the result obtained should not be treated too seriously. It is, however, considered to be worth while as it helps to give a clearer picture of the nature of the flow. Traverses in the centre plane by 5 tubes spaced 6 inches apart have been used. Expansions and compressions, i.e. positive and negative slopes in Mach number, are indicated and the exercise was to correlate these into a series of waves. Fig.32 shows the results. From these waves the changes in flow direction have been deduced and are plotted from an assumed datum in Fig.29; the agreement happens to be excellent.

Fig.32 serves the purpose of showing up very clearly what a complex system of disturbances is present in the flow. The difficulties of determining the sources of these disturbances are obvious.

A question that arises is whether the standard of flow as shown by the calibrations is considered satisfactory. The most disturbing feature shown up is the variation in flow direction especially with the M = 1.4 nozzle. However, a closer analysis suggests that this is by no means disastrous; it may introduce an error in pitching moment equivalent to twice the probable error in tail setting on a model (about 0.1°) but, if necessary, a correction can be applied. The same gradient in flow direction may be assumed to be possible in a vertical traverse i.e. a maximum of 0.2° in 5 inches. If the tail of the model were in such a region the order of the error in the pitching moment due to the tail as the tail moved up and down with change of incidence would be equivalent to about 0.05°, for 10° incidence equivalent to a shift in neutral point of 0.5% which can normally be accepted for the usual order of longitudinal stability existing at supersonic speeds.

The variations in pressure, apart from those due to the window joint which has now be remedied, are acceptable for general model tests but a slightly higher standard is desirable for pressure plotting experiments, especially for work on bodies without wings.

8 Conclusions

Calibration of the 3 ft × 3 ft tunnel which is fitted with wooden fixed block nozzles has shown a small random distribution of the flow superimposed on some general gradients in both Mach number and flow direction. The quality of the flow is satisfactory for general model testing but a slightly higher standard is desirable for research investigations.

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No.	Author	Title, etc.
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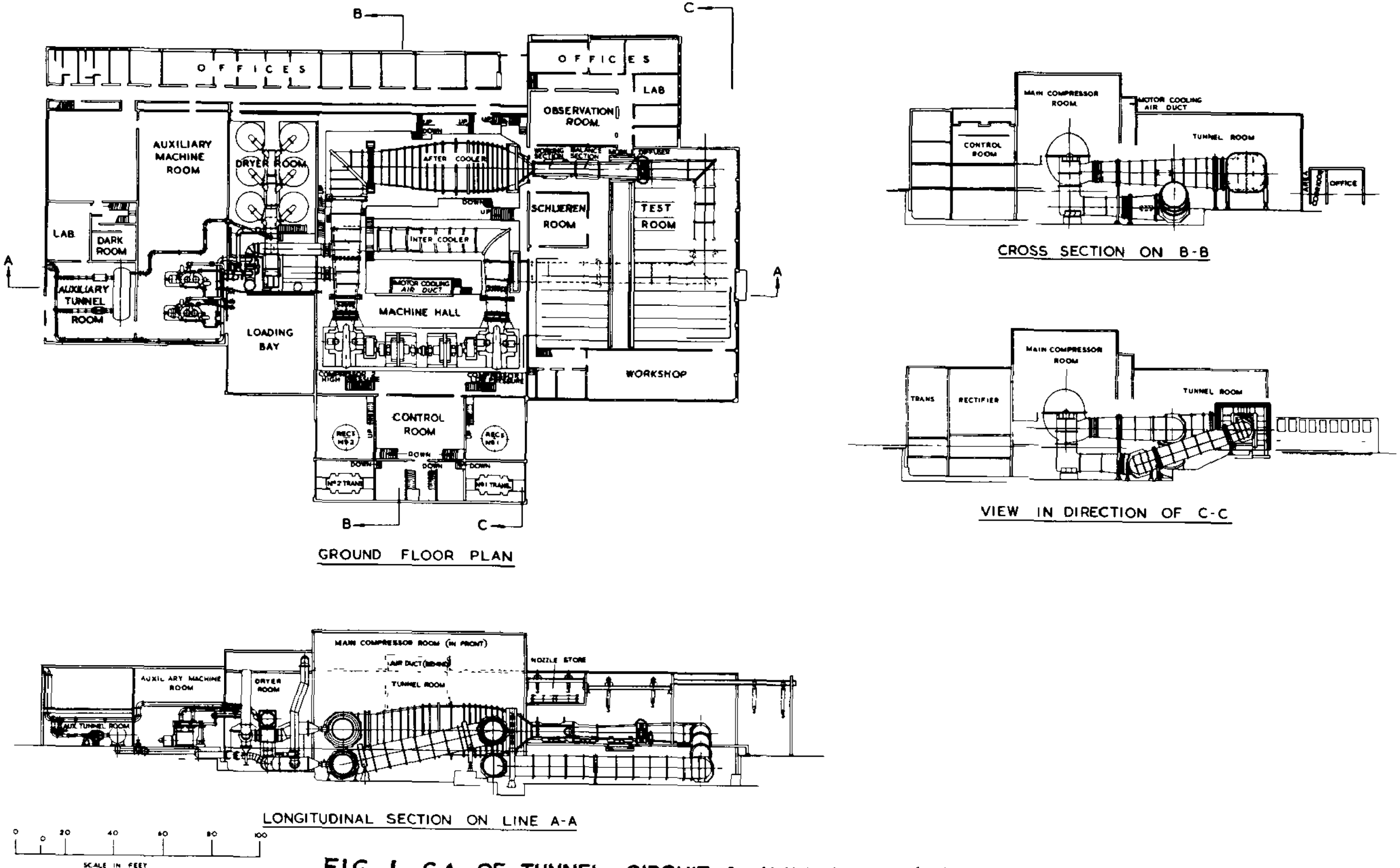


FIG. 1. GA OF TUNNEL CIRCUIT & AUXILIARIES - 3'x3' SUPERSONIC WIND TUNNEL

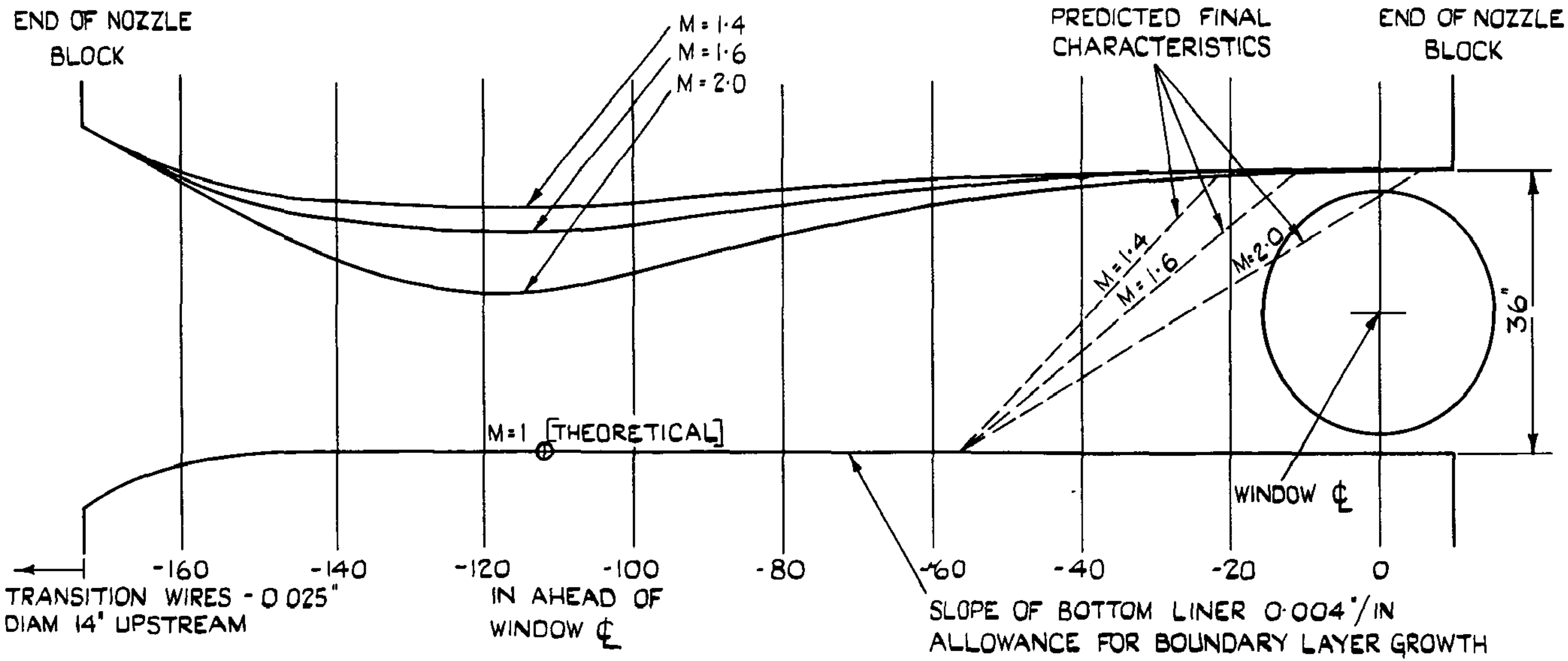


FIG. 2. ARRANGEMENT OF NOZZLE BLOCKS IN WORKING SECTION.

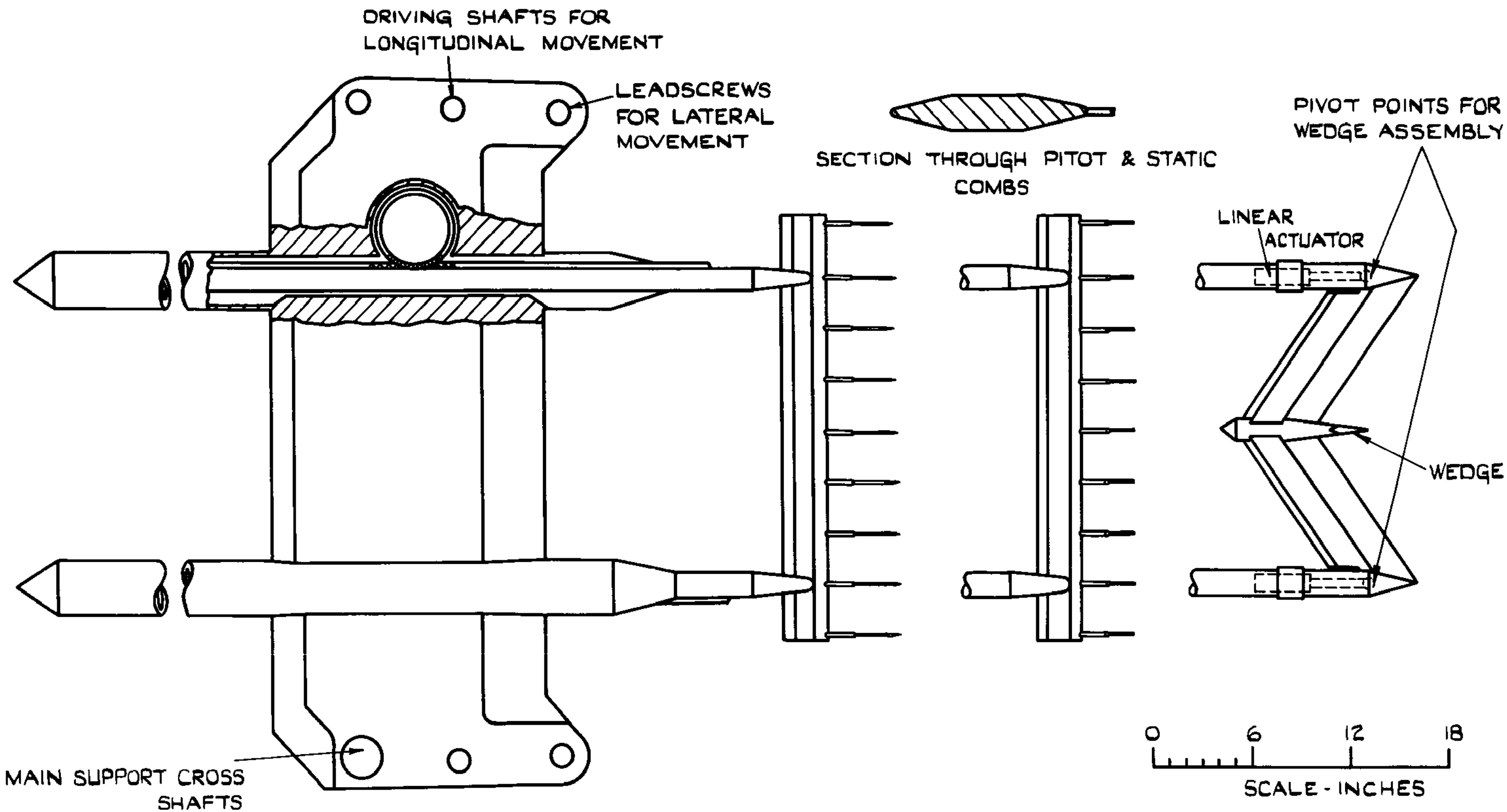


FIG. 3. CALIBRATING GEAR 3' x 3' TUNNEL. STATIC AND PITOT COMBS, AND YAWMETER.

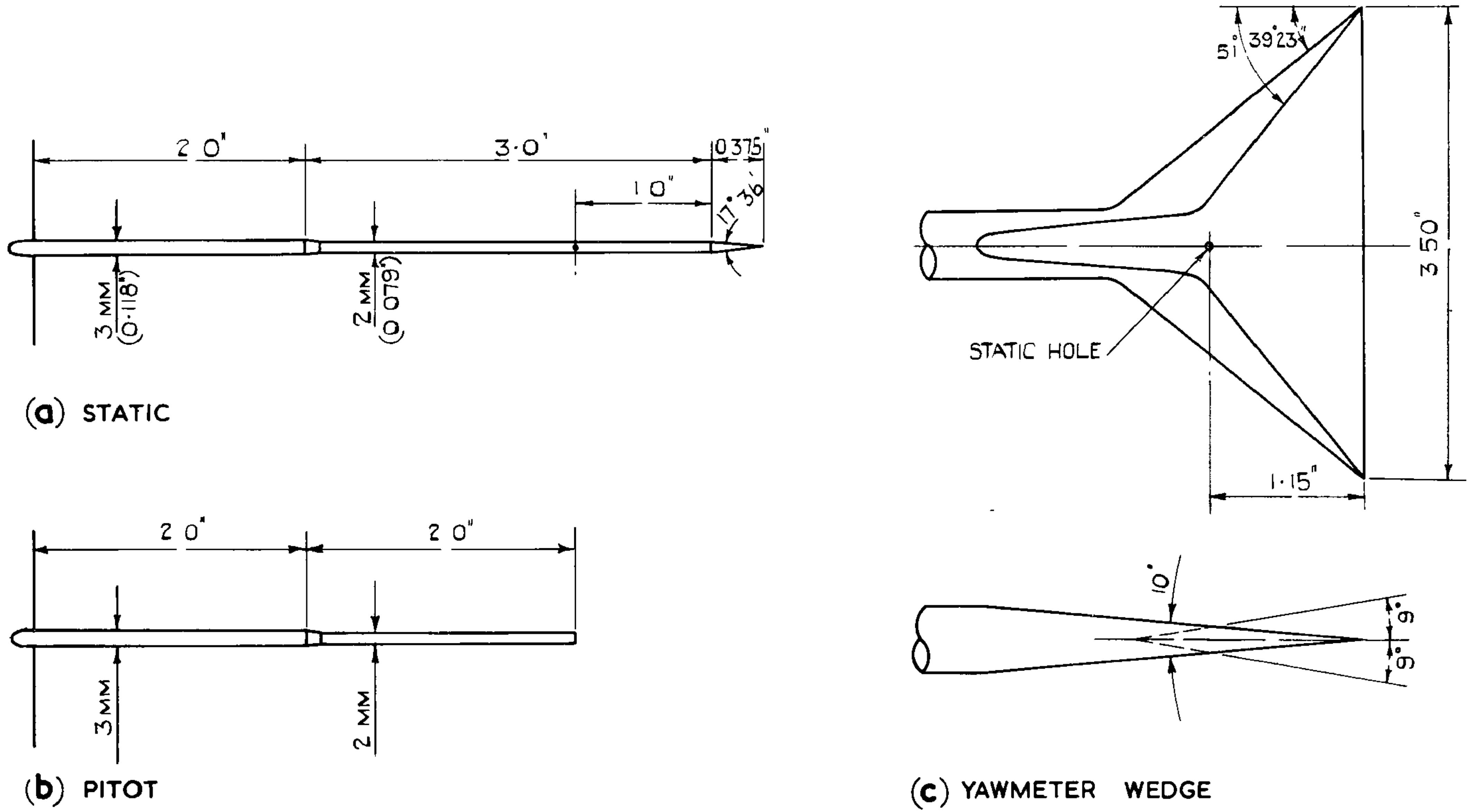
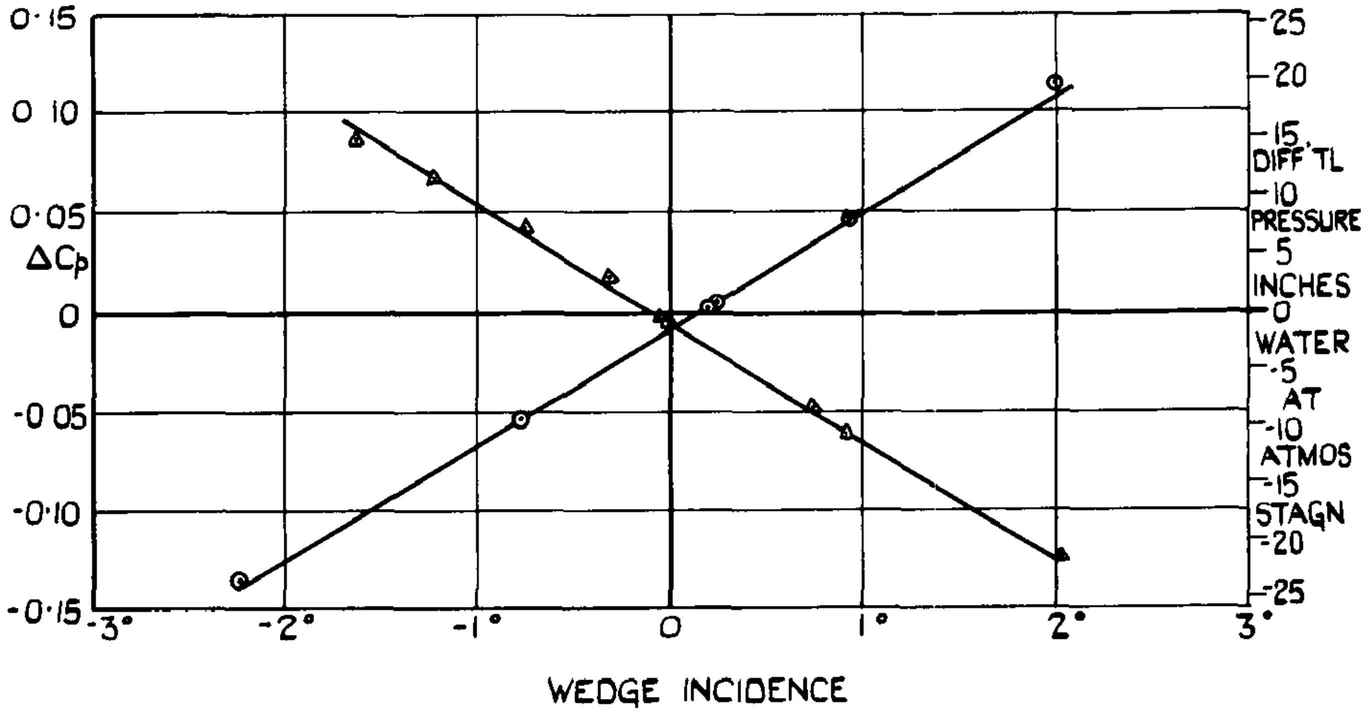
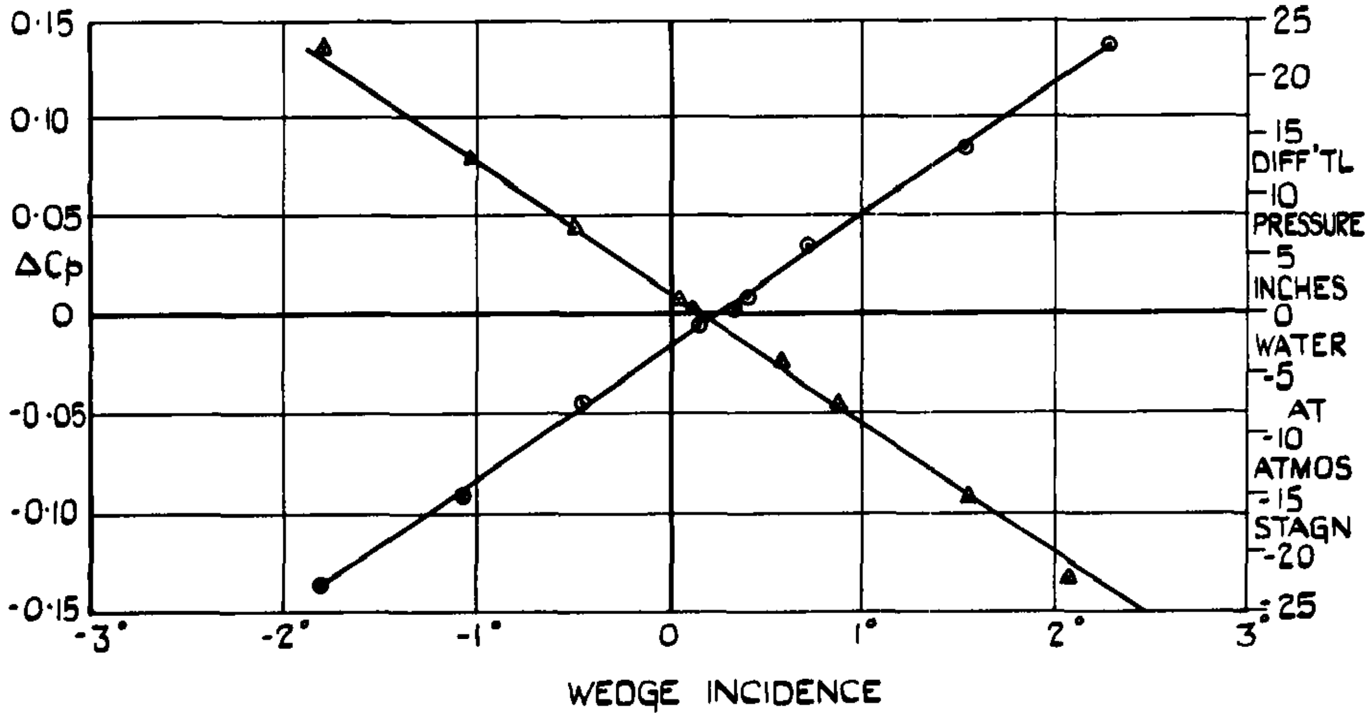


FIG.4. (a – c) DETAILS OF PITOT AND STATIC HEADS, AND YAWMETER WEDGE.



M = 1·4.



M = 1·6.

FIG. 5. CALIBRATION CURVES FOR THE YAWMETER WEDGE.

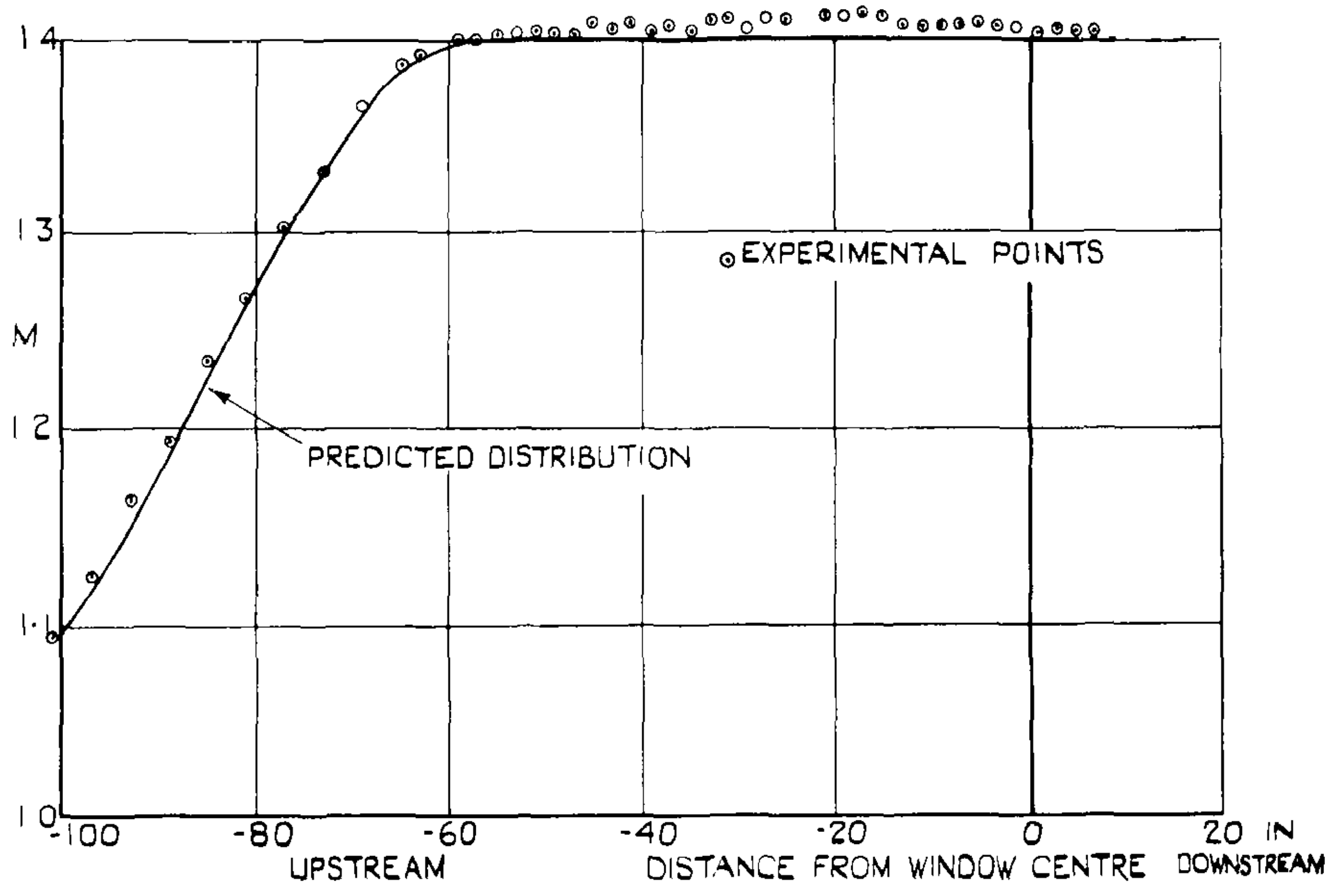


FIG. 6. M = 1·4 NOZZLE (H=16 IN. Hg.)
DISTRIBUTION ALONG BOTTOM WALL.

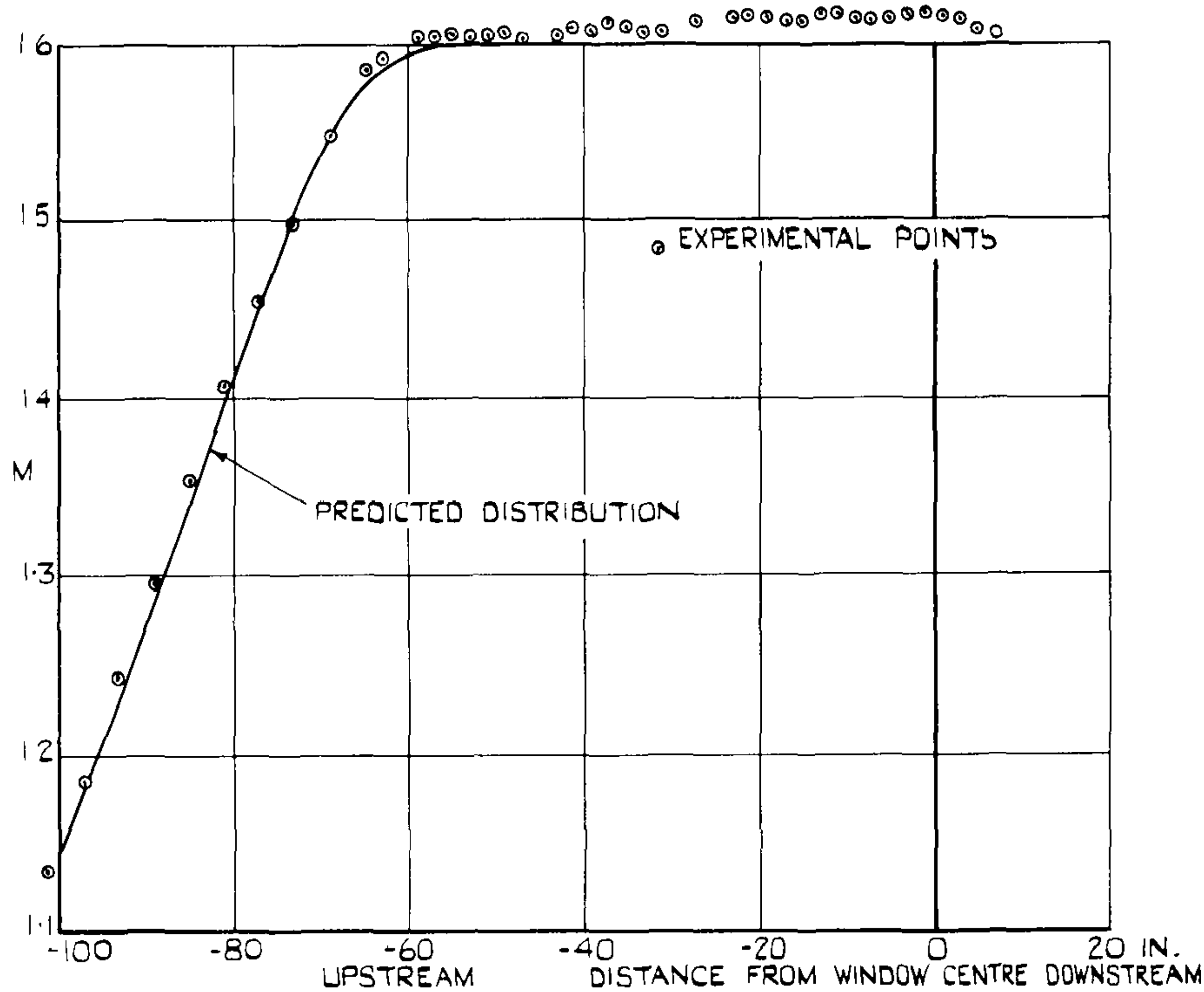


FIG. 7. M = 1·6 NOZZLE (H=16 IN. Hg.)
DISTRIBUTION ALONG BOTTOM WALL.

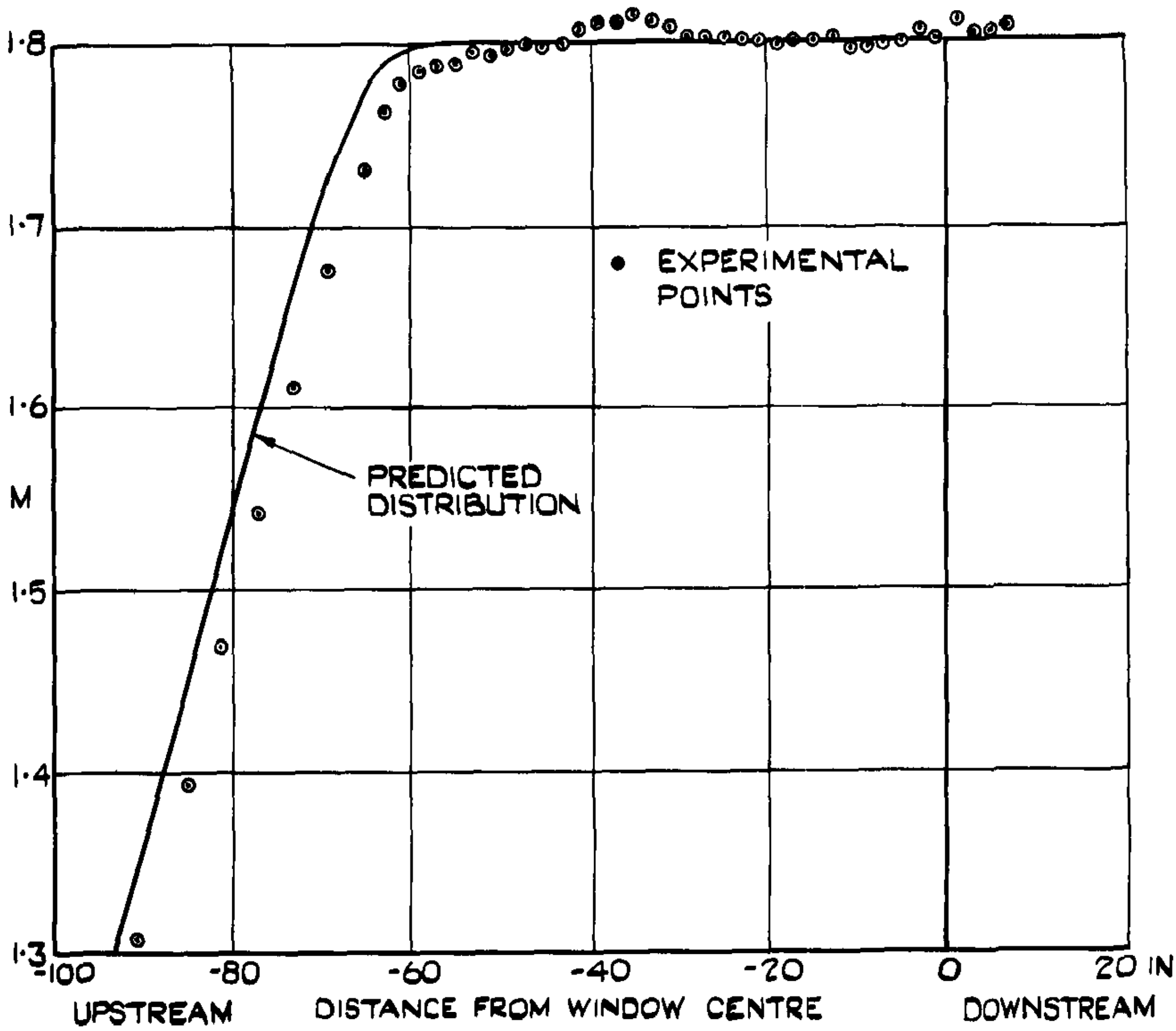


FIG. 8. M = 1·8 NOZZLE (H = 20 IN. Hg) DISTRIBUTION ALONG BOTTOM WALL.

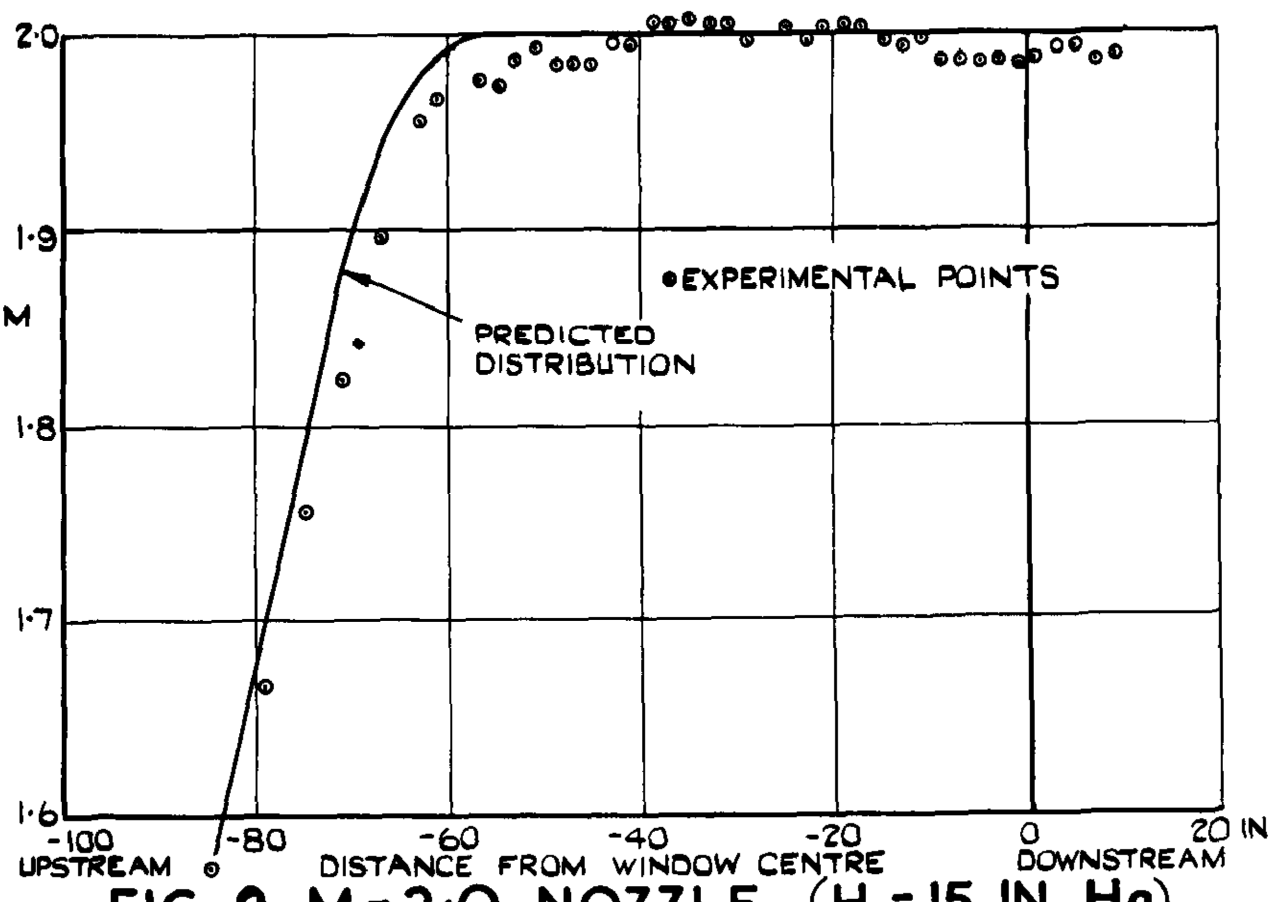


FIG. 9. M = 2·0 NOZZLE (H = 15 IN. Hg) DISTRIBUTION ALONG BOTTOM WALL.

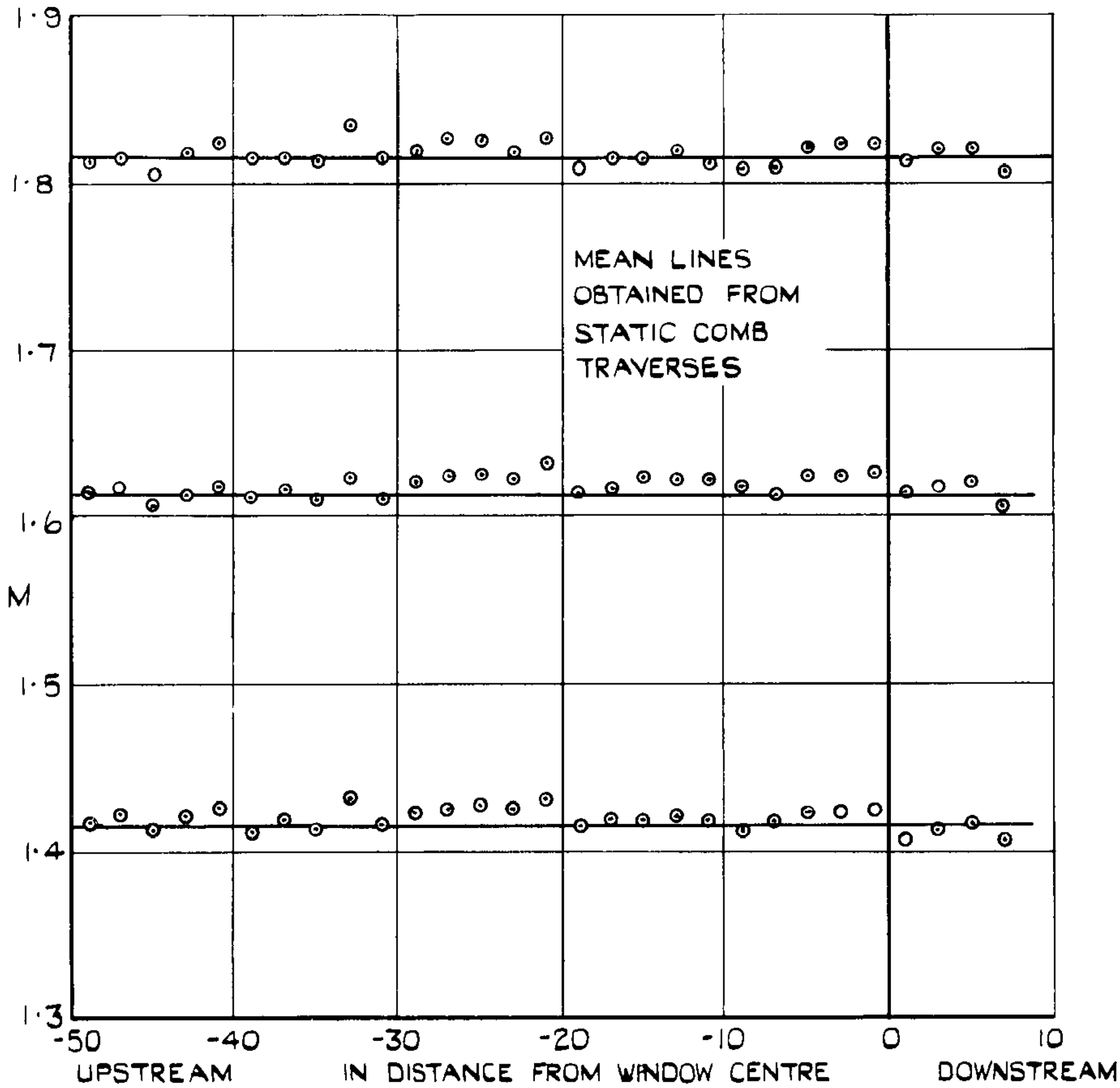


FIG. 10. M = 1·4, 1·6 & 1·8 NOZZLES.

(H = 30 IN. Hg. DEC. 1953.)

DISTRIBUTIONS ALONG BOTTOM WALL.

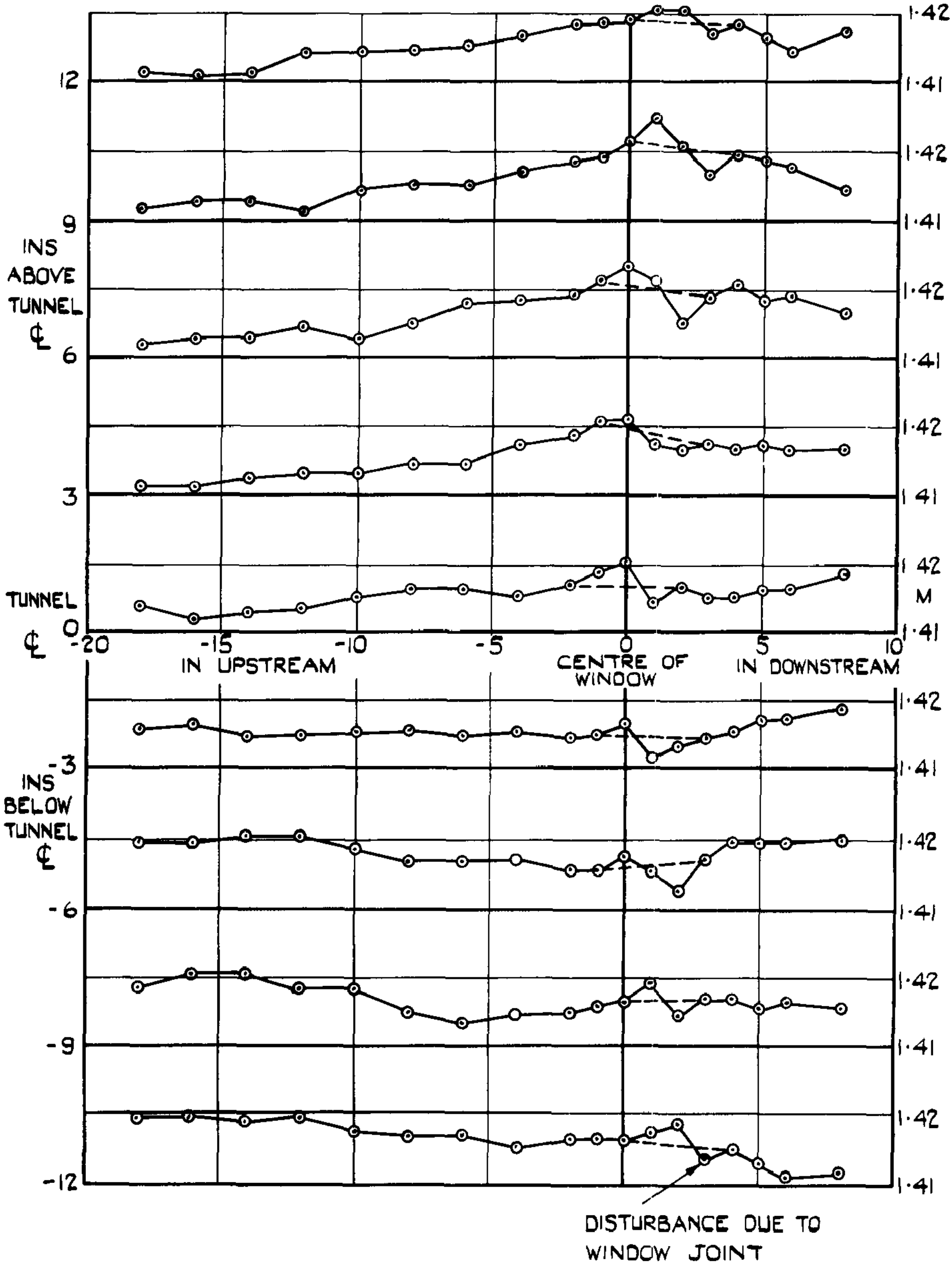


FIG. 11. M = 1·4 NOZZLE.

(H = 30 IN. Hg. DEC. 1953. ALCOHOL MANOMETER. STATIC HEADS.)

DISTRIBUTION ALONG THE VERTICAL CENTRAL PLANE.

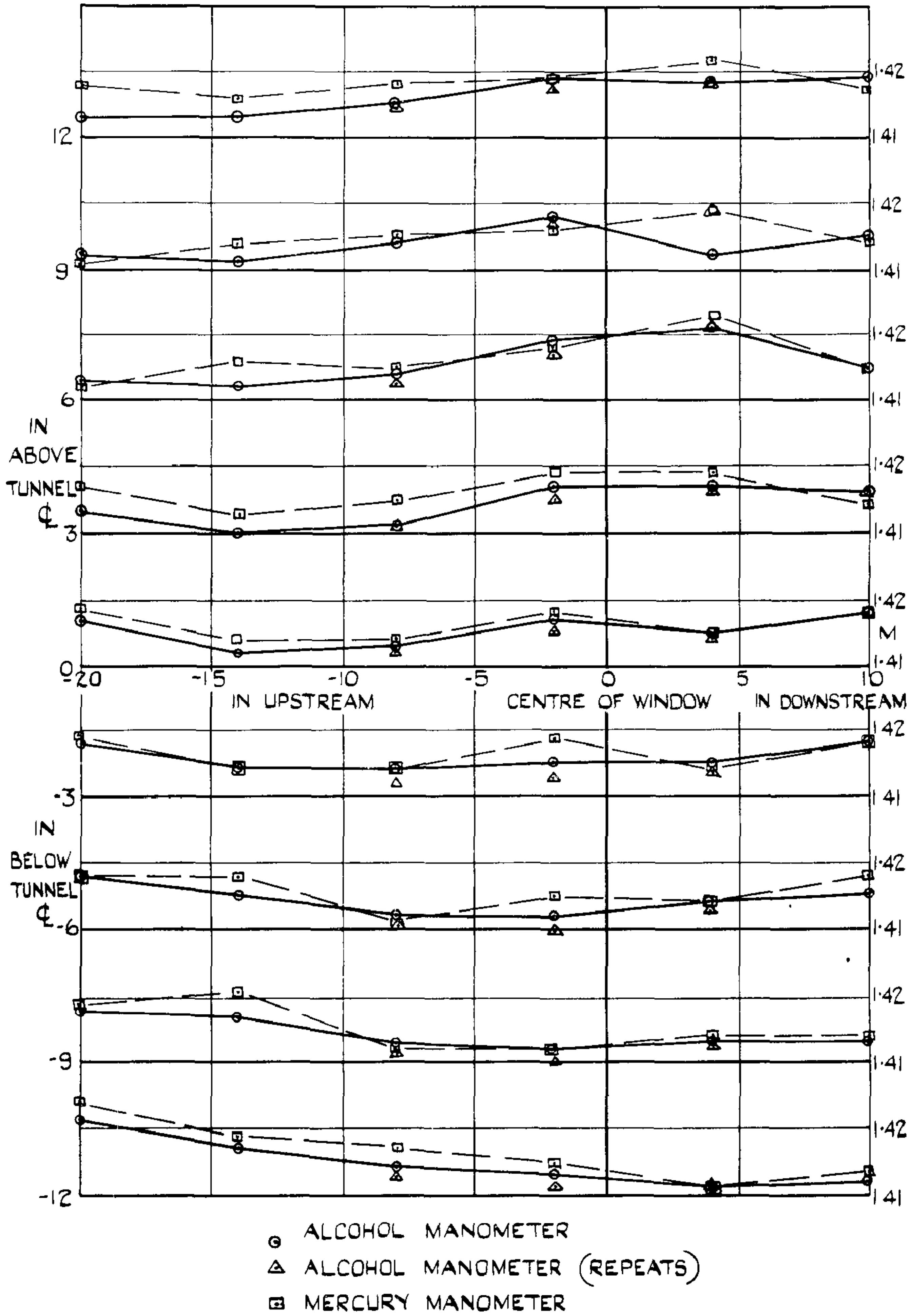


FIG. 12. M=1·4 NOZZLE.

(H=16 IN. Hg. APRIL 1952 STATIC HEADS.)

DISTRIBUTION ALONG THE VERTICAL CENTRAL PLANE.

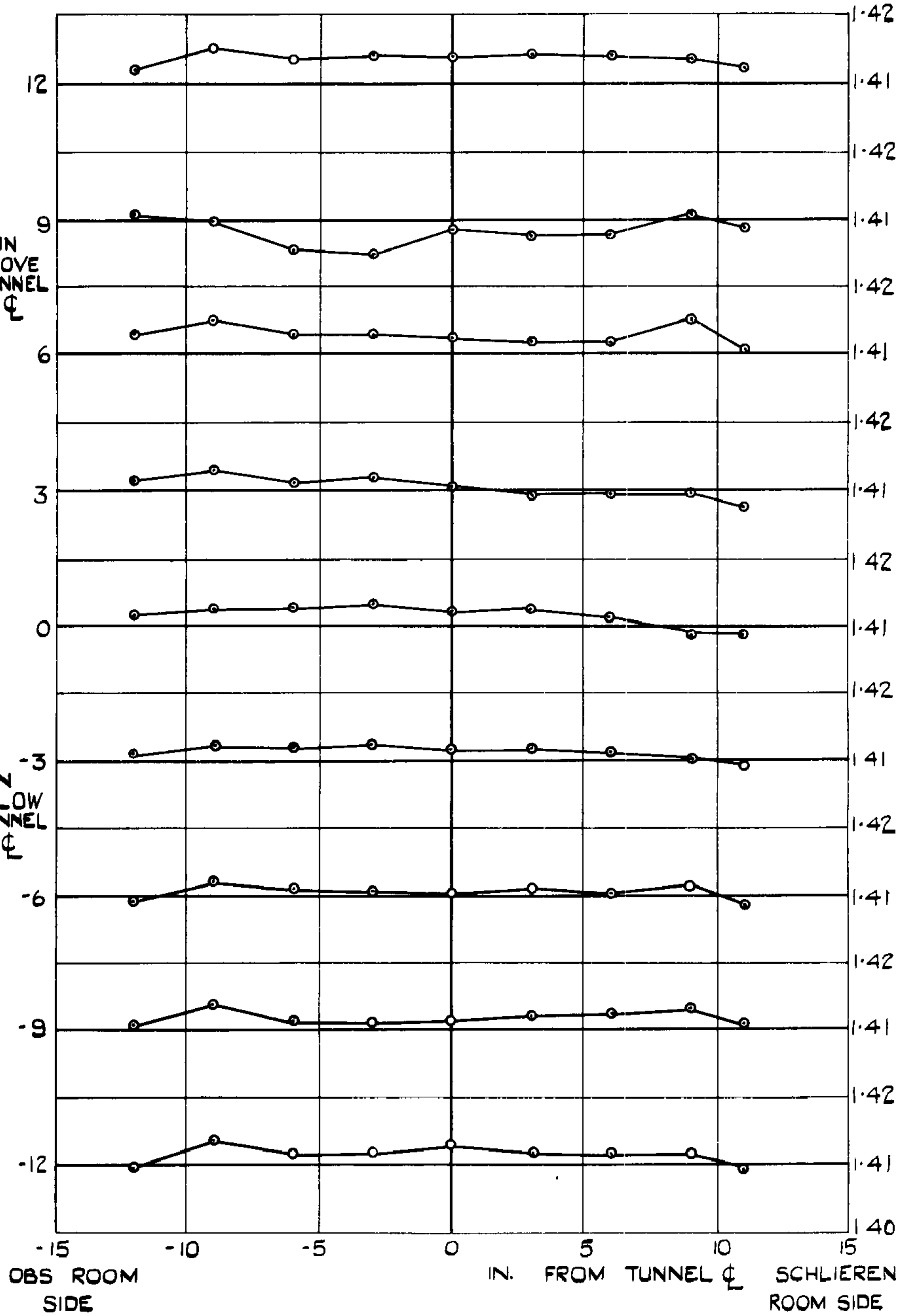


FIG. 13. M = 1·4 NOZZLE.

(H = 16 IN. Hg APRIL 1952 ALCOHOL MANOMETER)

TRANSVERSE DISTRIBUTION AT 8 IN. UPSTREAM OF WINDOW CENTRE.

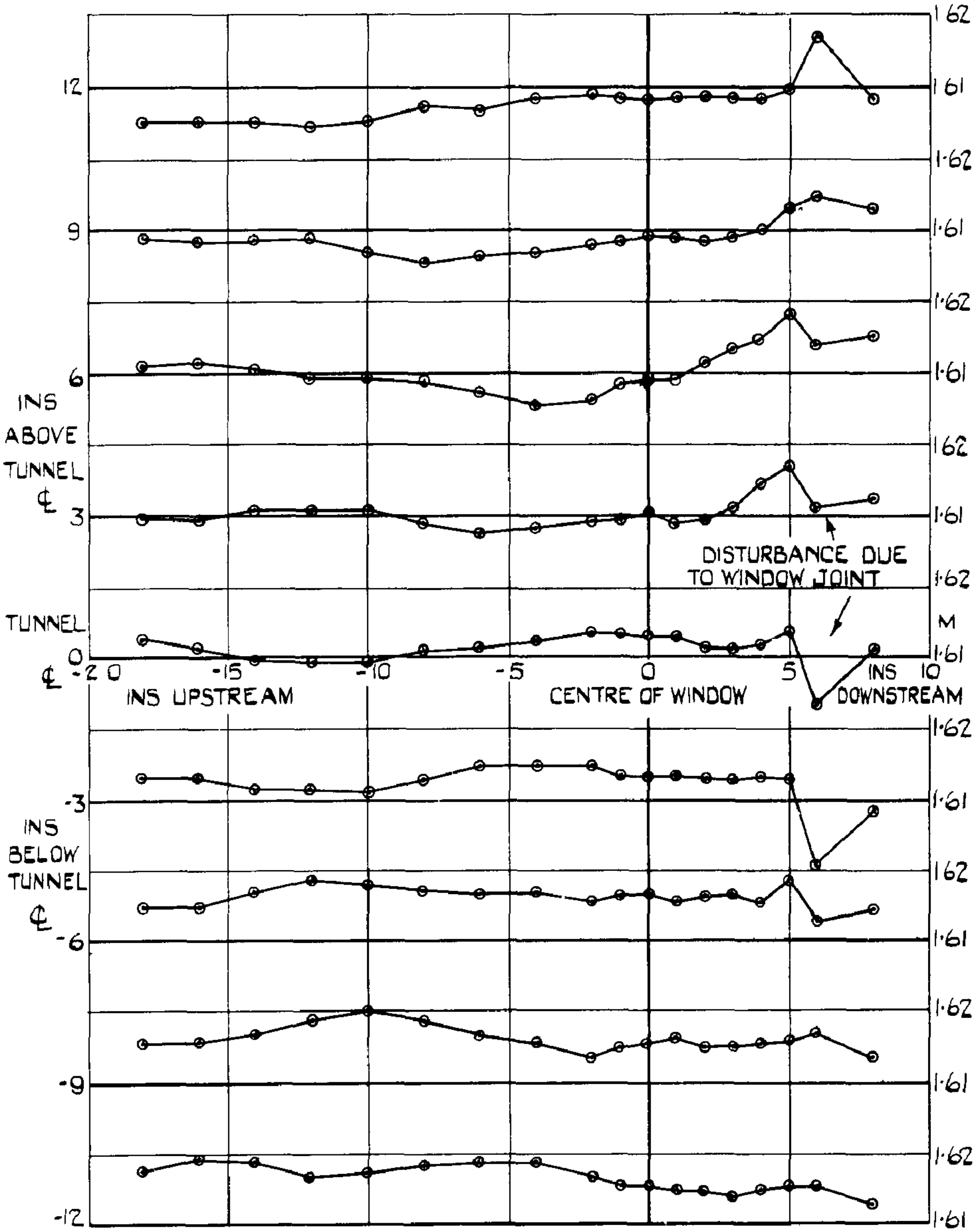


FIG. 16. M=1·6 NOZZLE.

(H=30 IN Hg DECEMBER 1953 ALCOHOL MANOMETER STATIC HEADS.)

DISTRIBUTION ALONG THE VERTICAL CENTRAL PLANE.

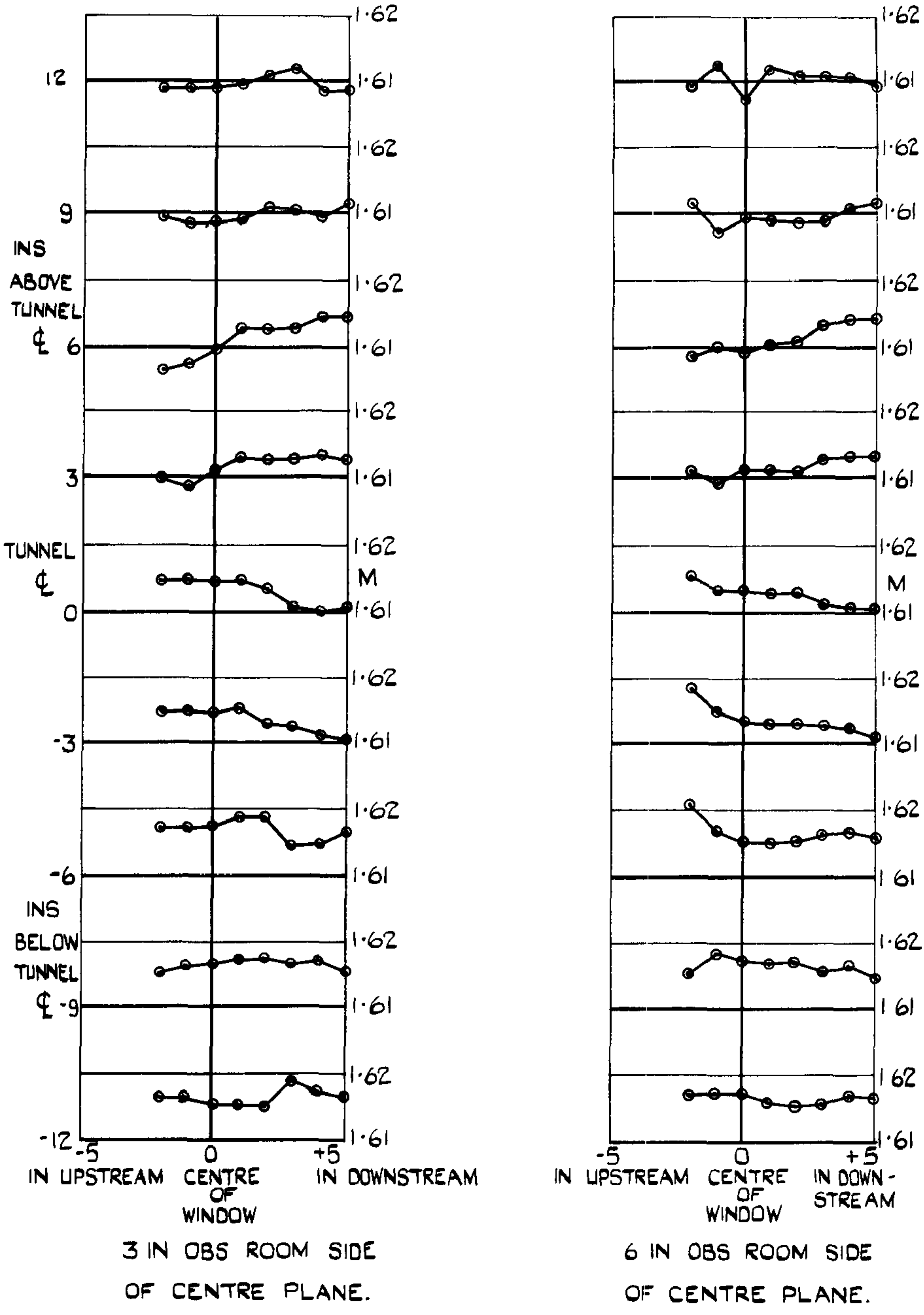


FIG. 17. M = 1·6 NOZZLE.

(H=30 IN. Hg. DECEMBER 1953 ALCOHOL MANOMETER.)

DISTRIBUTIONS IN PLANES PARALLEL TO LONGITUDINAL CENTRAL PLANE.

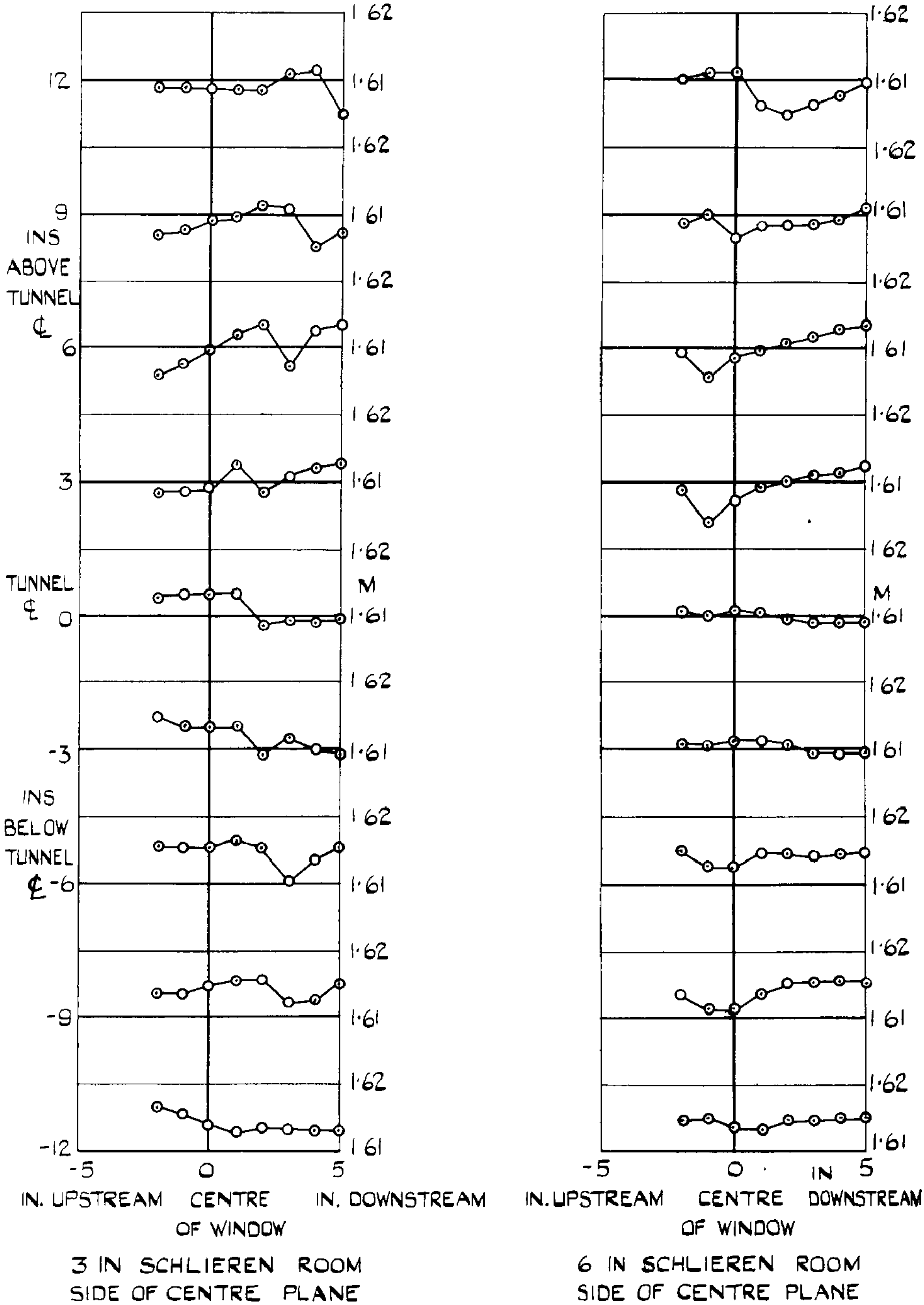


FIG. 18. M = 1·6 NOZZLE.

(H = 30 IN. Hg. DECEMBER 1953 ALCOHOL MANOMETER)

DISTRIBUTIONS IN PLANES PARALLEL TO LONGITUDINAL CENTRAL PLANE.

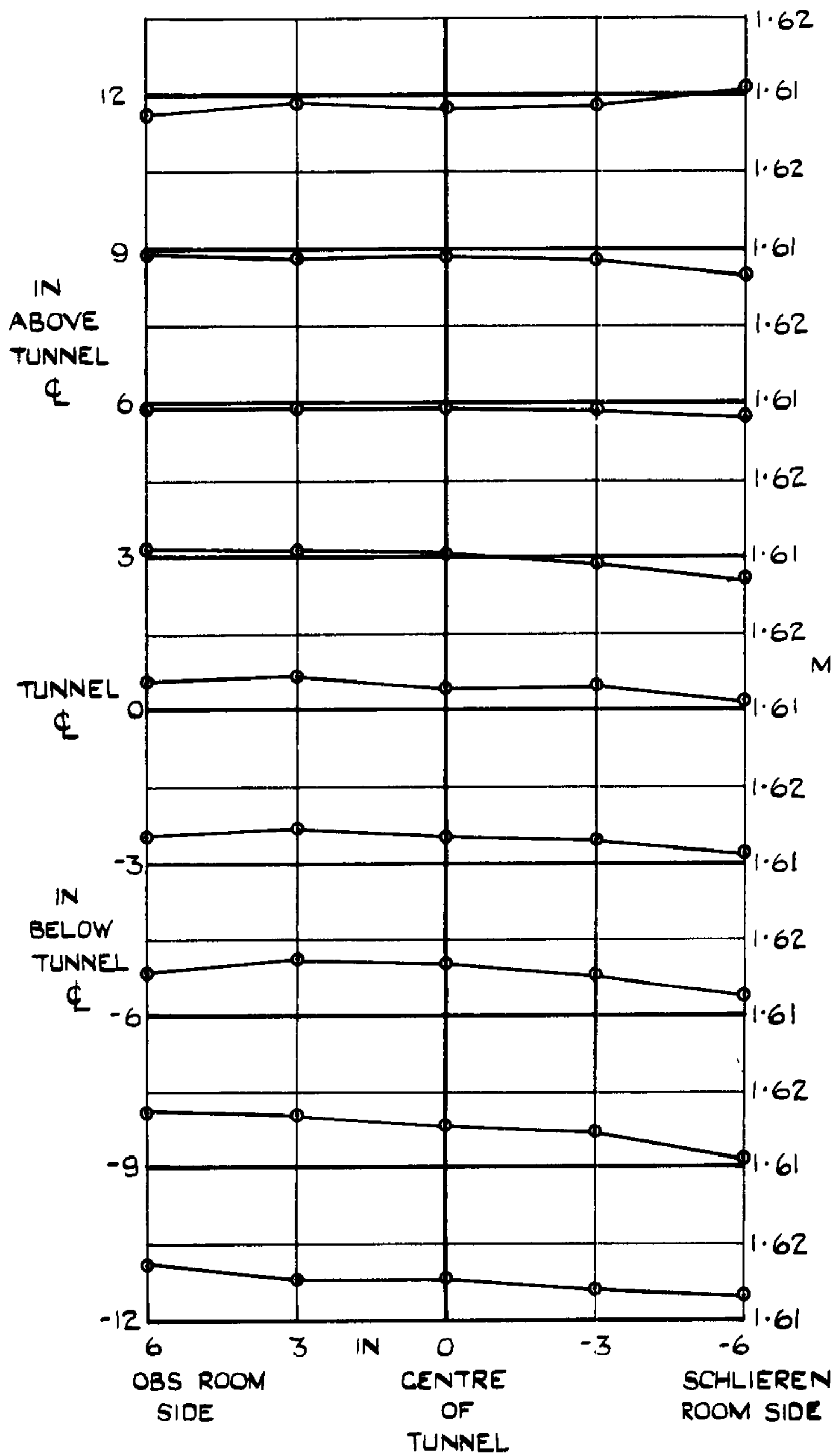


FIG. 19. M = 1·6 NOZZLE.

(H = 30 IN. Hg. DECEMBER 1953. ALCOHOL MANOMETER.)

DISTRIBUTION IN THE TRANSVERSE PLANE THROUGH THE CENTRES OF WINDOWS.

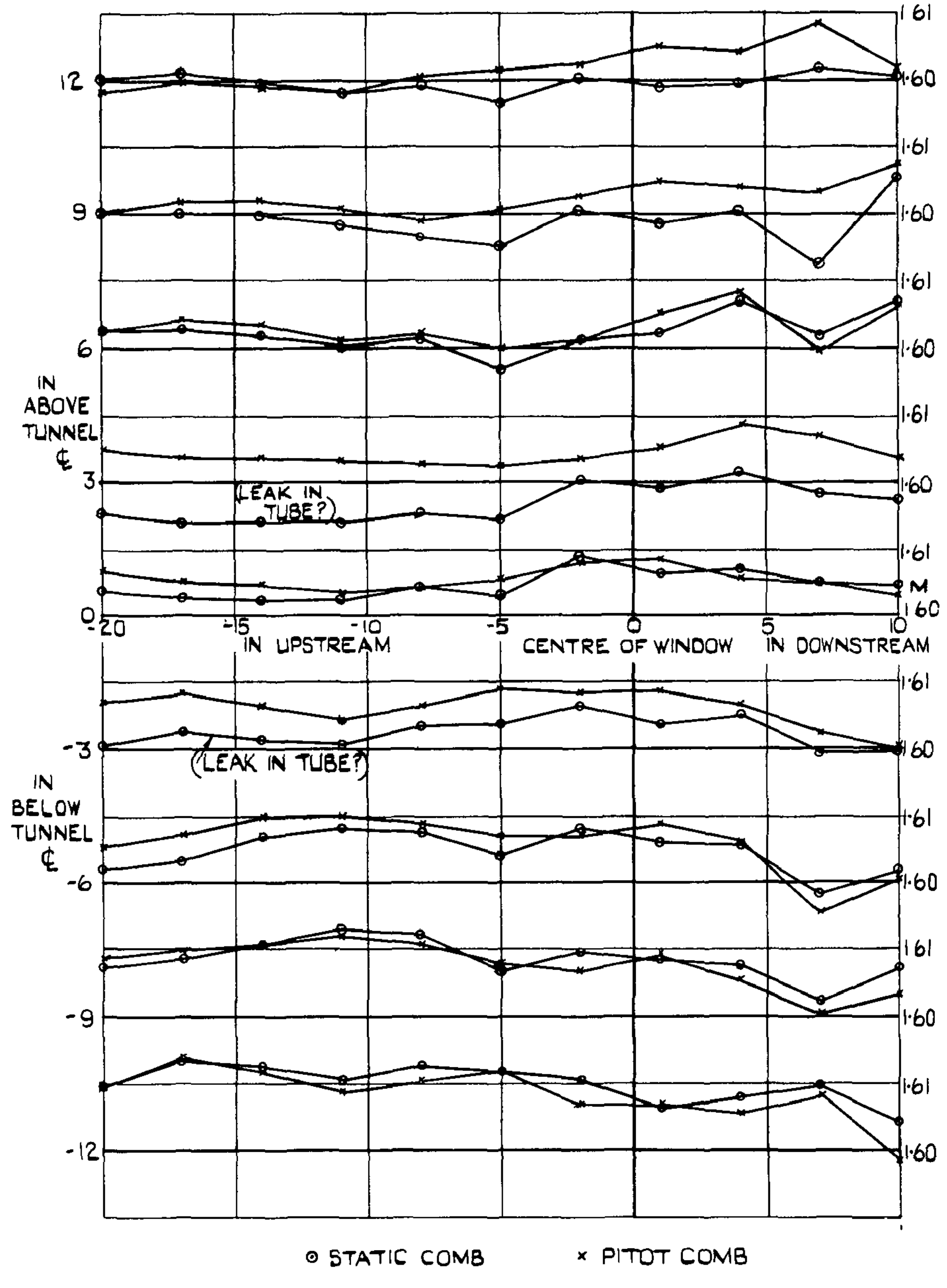


FIG. 20. M=1·6 NOZZLE.

(H=16 IN. Hg. MAY 1952 ALCOHOL MANOMETER.)

DISTRIBUTION ALONG VERTICAL CENTRAL PLANE.

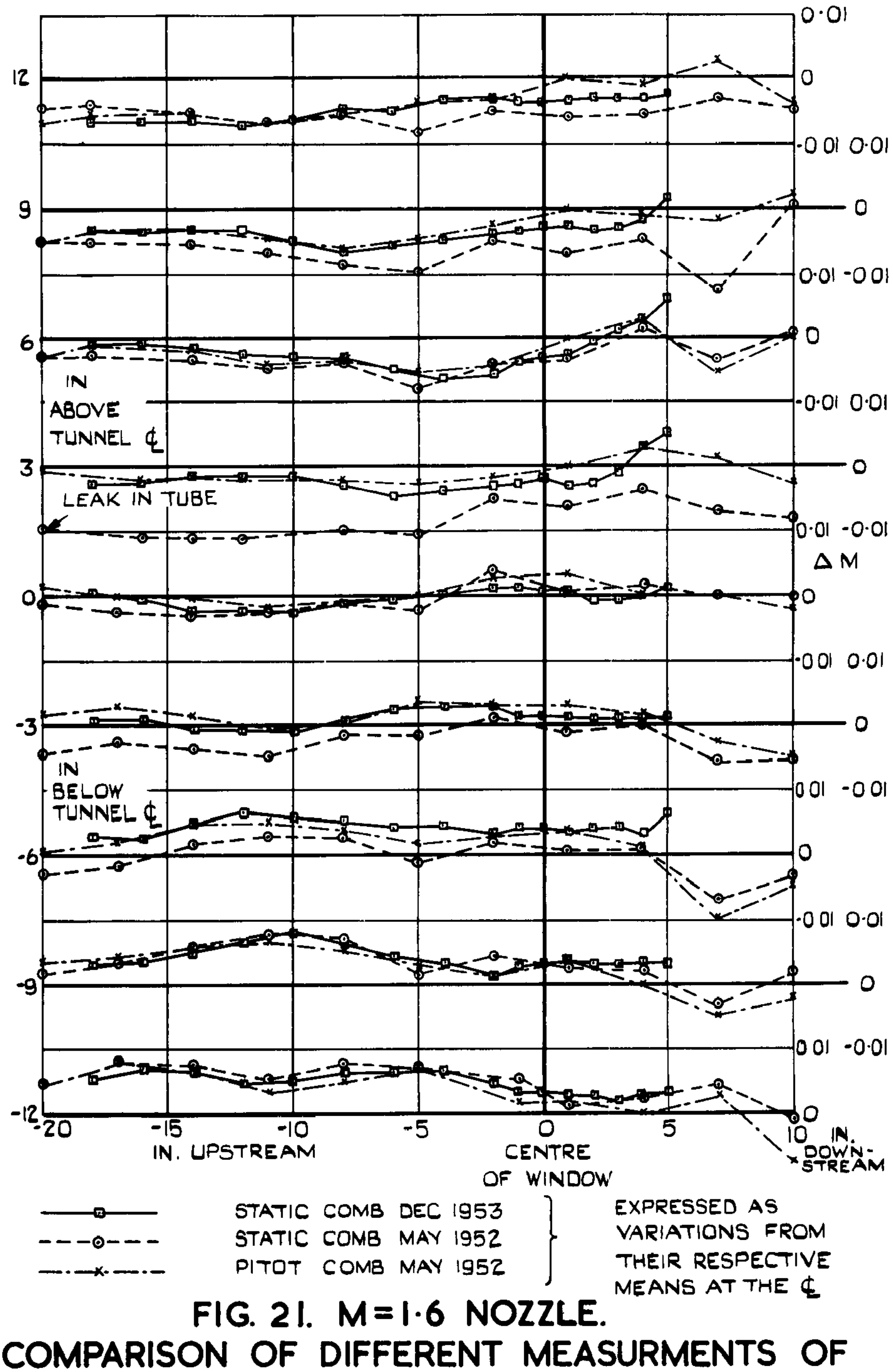


FIG. 21. M=1·6 NOZZLE.

COMPARISON OF DIFFERENT MEASURMENTS OF DISTRIBUTIONS ALONG THE VERTICAL CENTRAL PLANE.

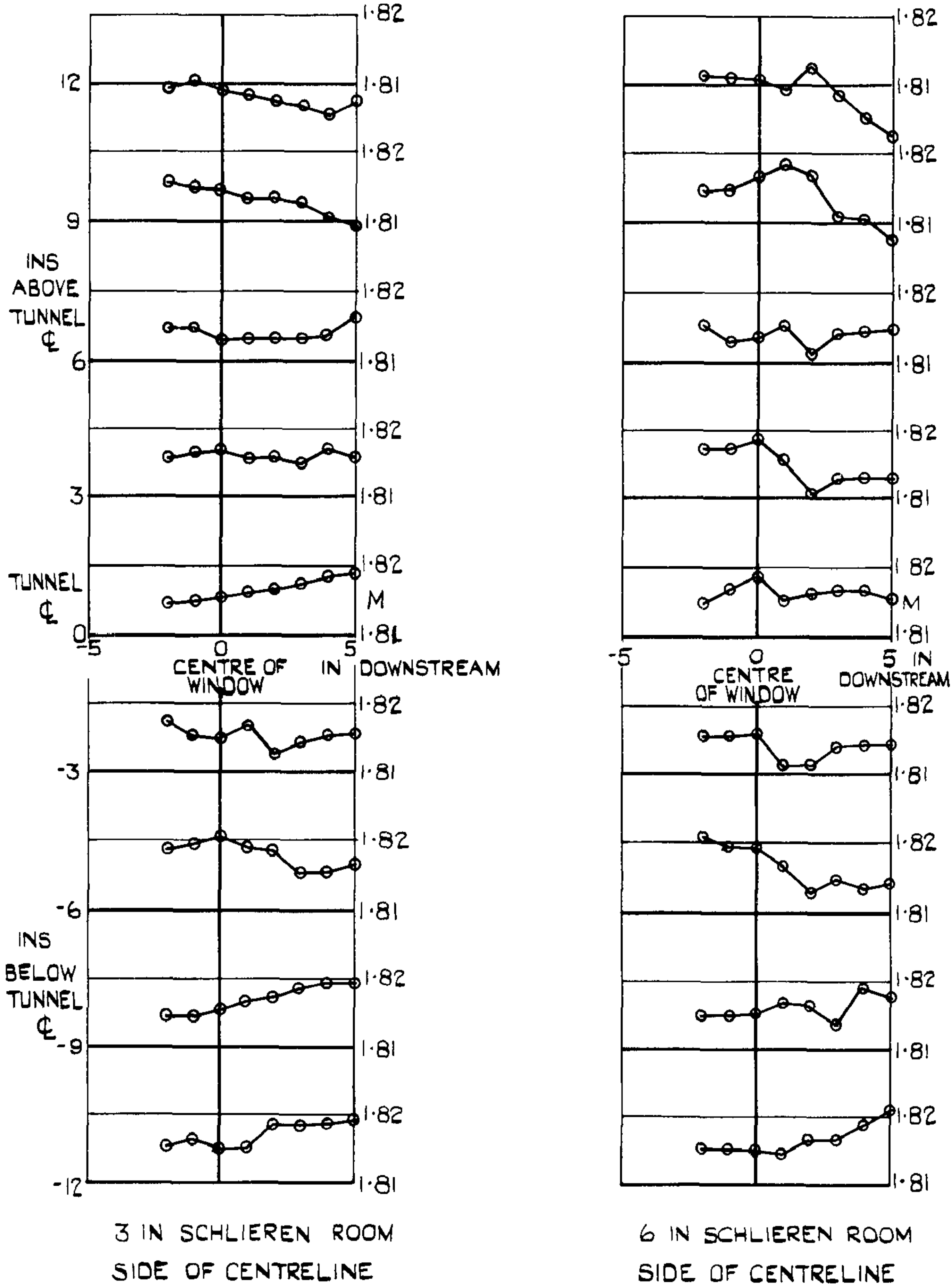


FIG. 24. M = 1·8 NOZZLE.

(H 30 IN. Hg. DECEMBER 1953 ALCOHOL MANOMETER STATIC, HEADS)

DISTRIBUTIONS IN PLANES PARALLEL TO LONGITUDINAL CENTRAL PLANE.

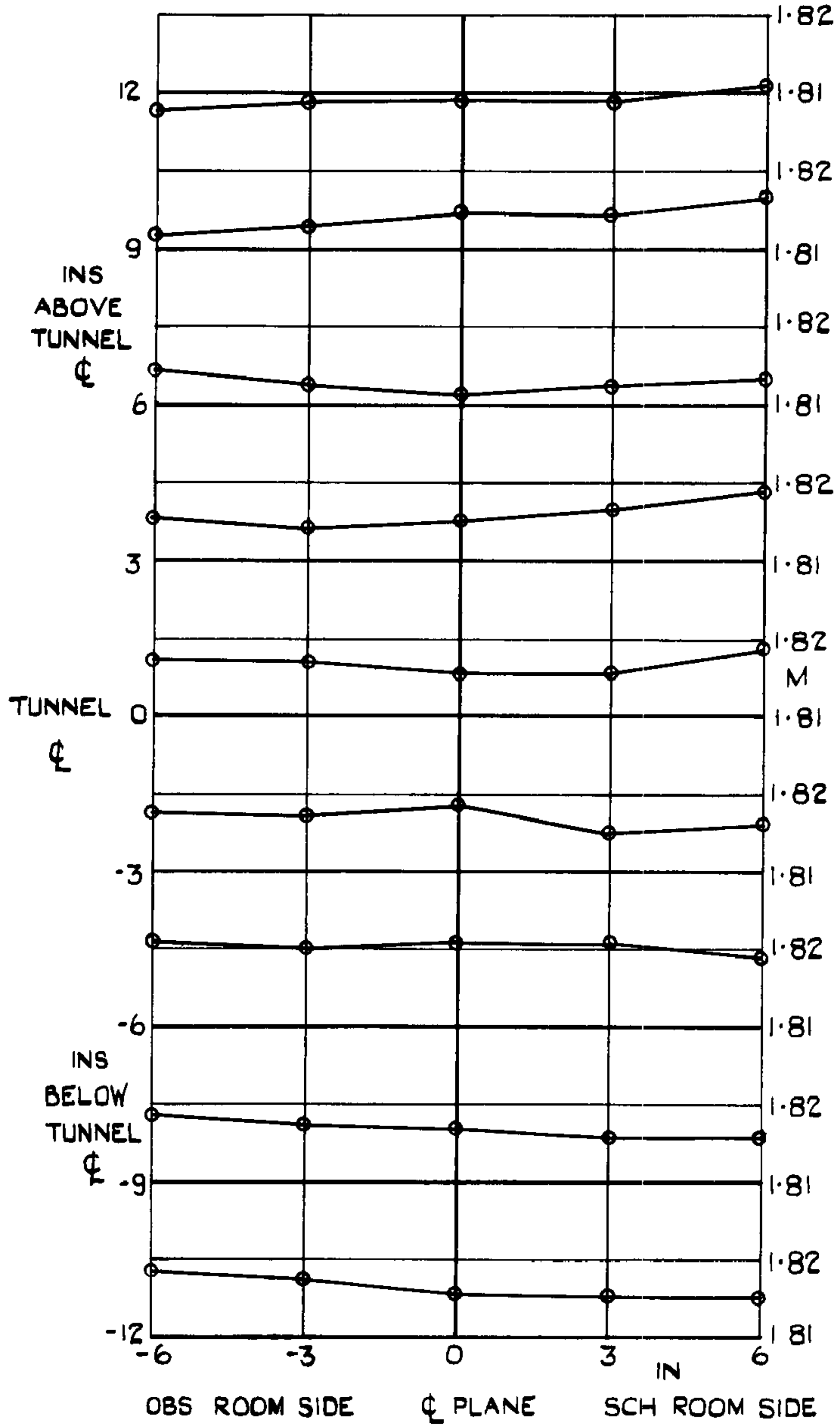


FIG. 25. M = 1·8 NOZZLE.

(H=30 IN. DECEMBER 1953 ALCOHOL MANOMETER STATIC, HEADS)

DISTRIBUTION IN THE TRANSVERSE PLANE THROUGH THE CENTRES OF WINDOWS.

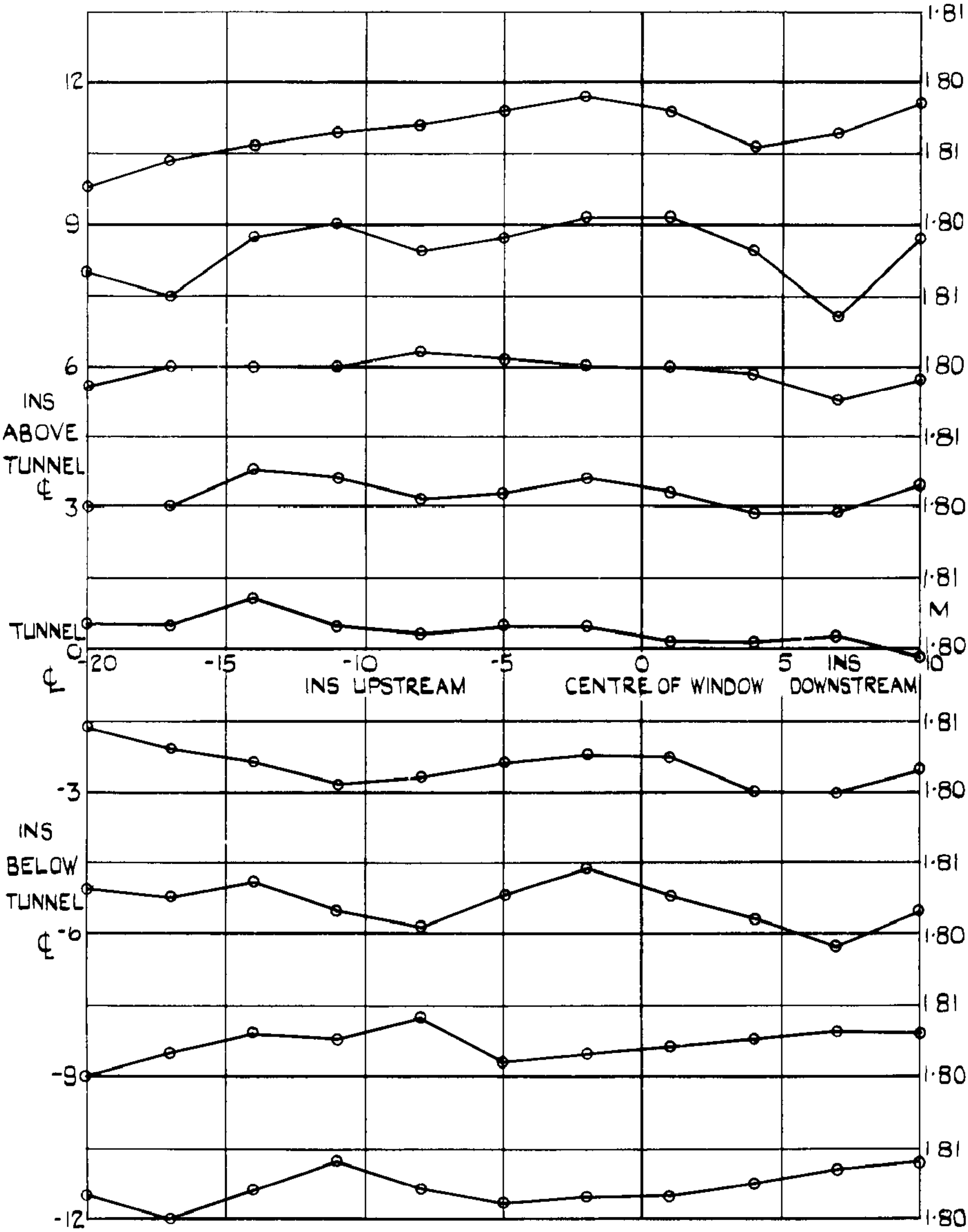


FIG. 26. M=1·8 NOZZLE.

(H=20 IN. Hg. JUNE 1953 ALCOHOL MANOMETER, PITOT HEADS.)

DISTRIBUTION ALONG THE VERTICAL CENTRAL PLANE.

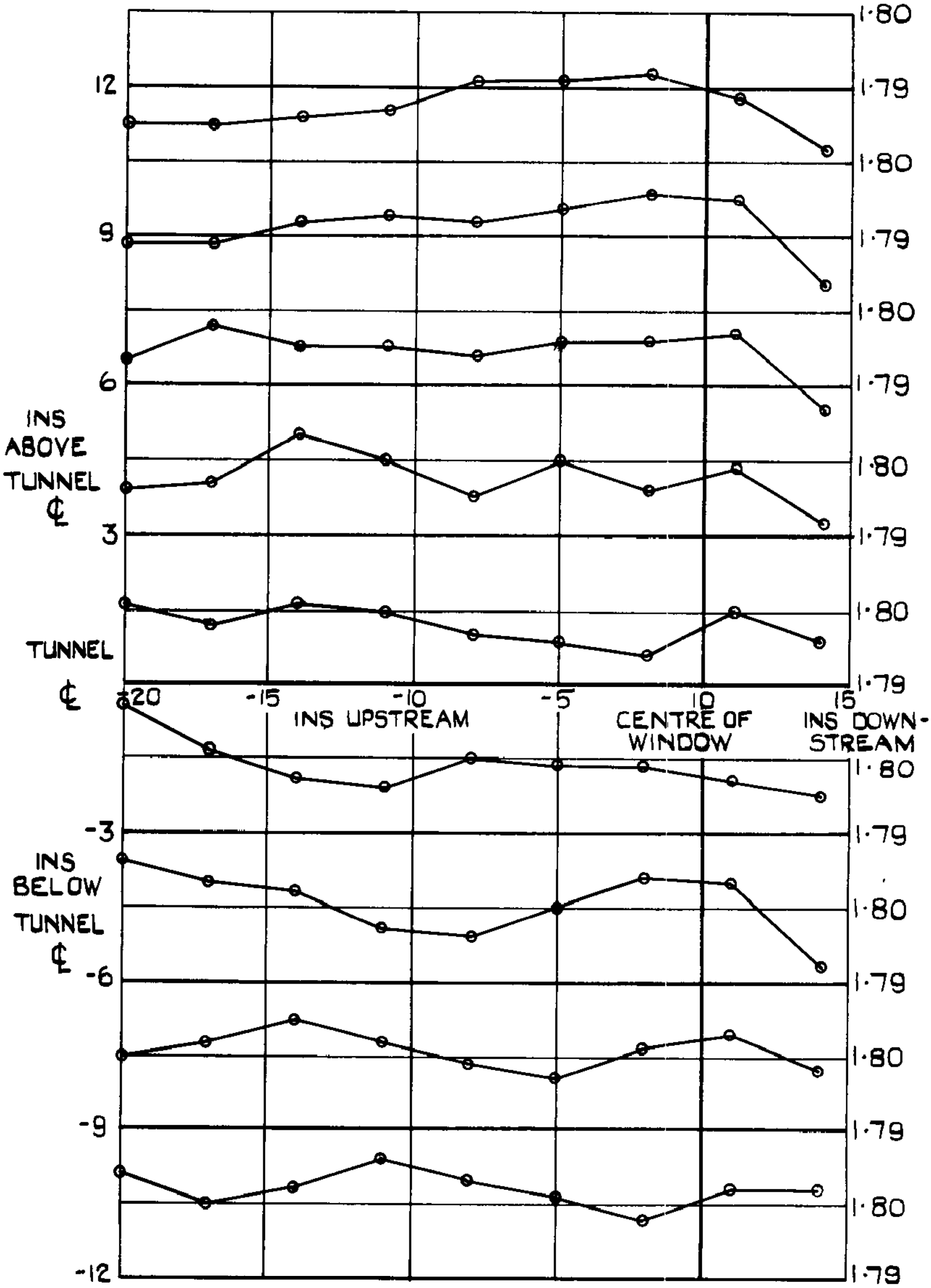


FIG. 27. M=1·8 NOZZLE.

(H=10 IN. Hg. JUNE 1953 ALCOHOL MANOMETER, PITOT HEADS)

DISTRIBUTION ALONG THE VERTICAL CENTRAL PLANE.

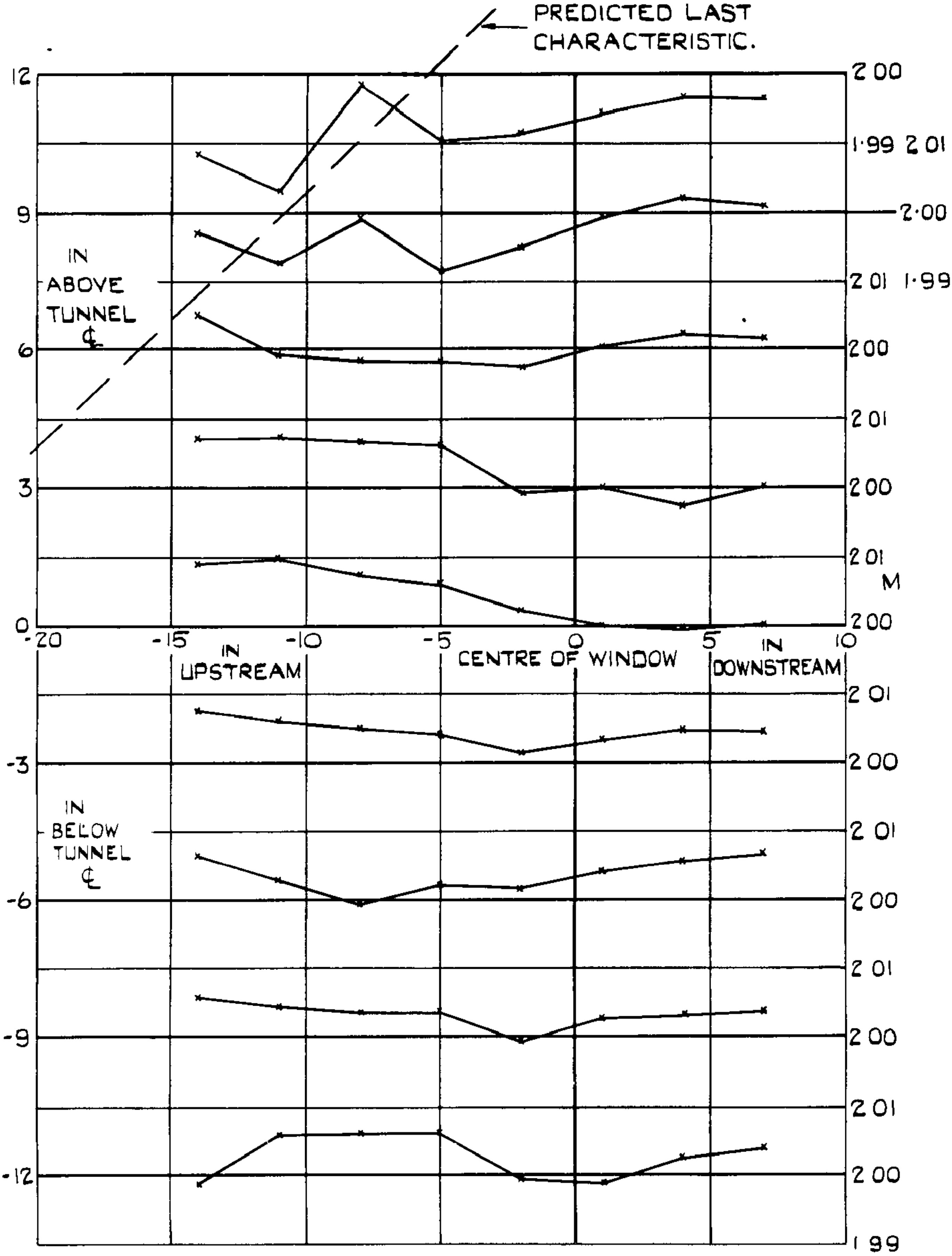


FIG. 28. M = 2·0 NOZZLE.

(H=15 IN Hg. MAY 1952 ALCOHOL MANOMETER PITOT, HEADS.)

DISTRIBUTION IN LONGITUDINAL VERTICAL CENRAL PLANE.

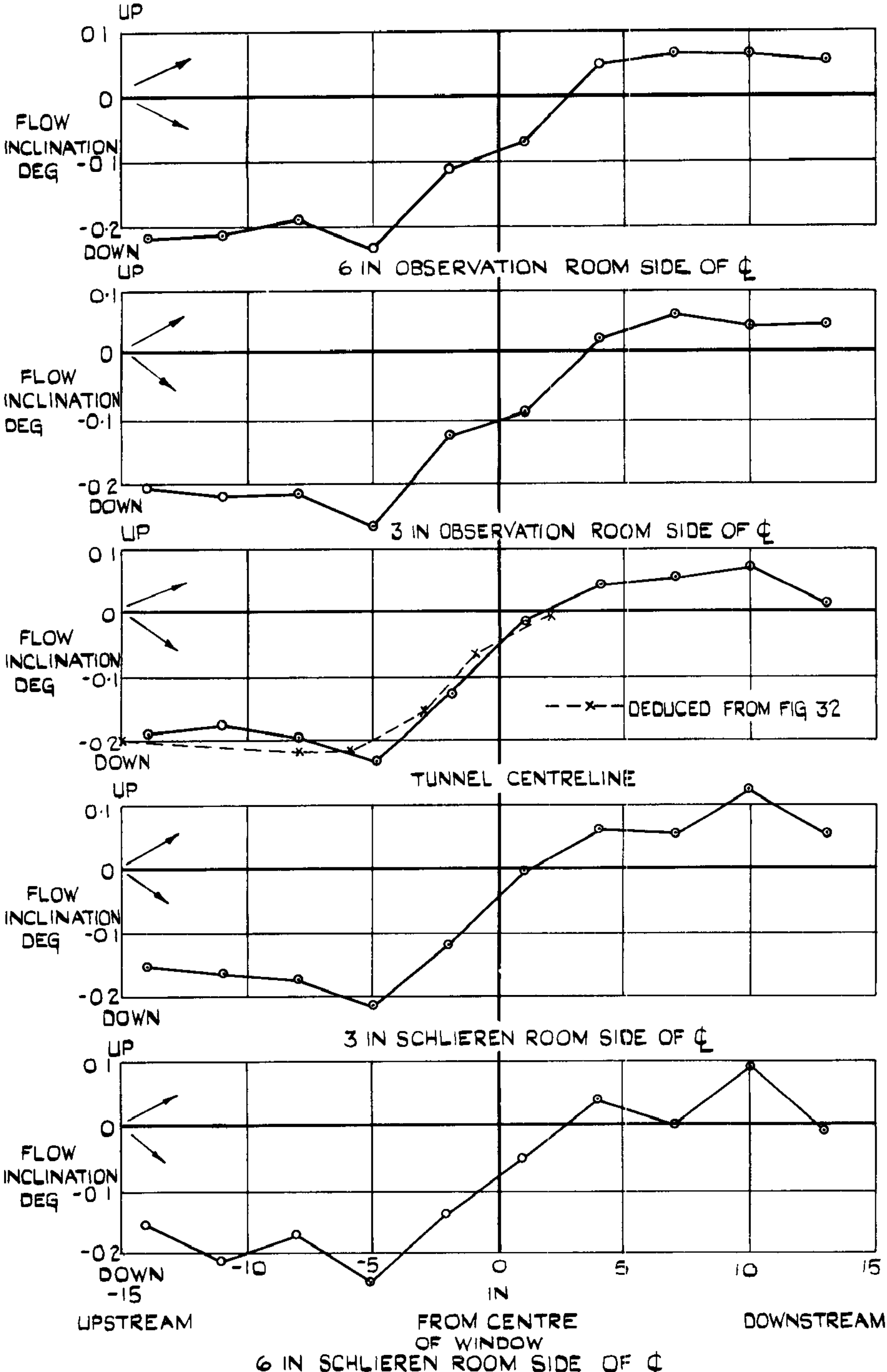


FIG. 29. M = 1·4 NOZZLE.
FLOW DIRECTION IN THE HORIZONTAL CENTRAL PLANE.

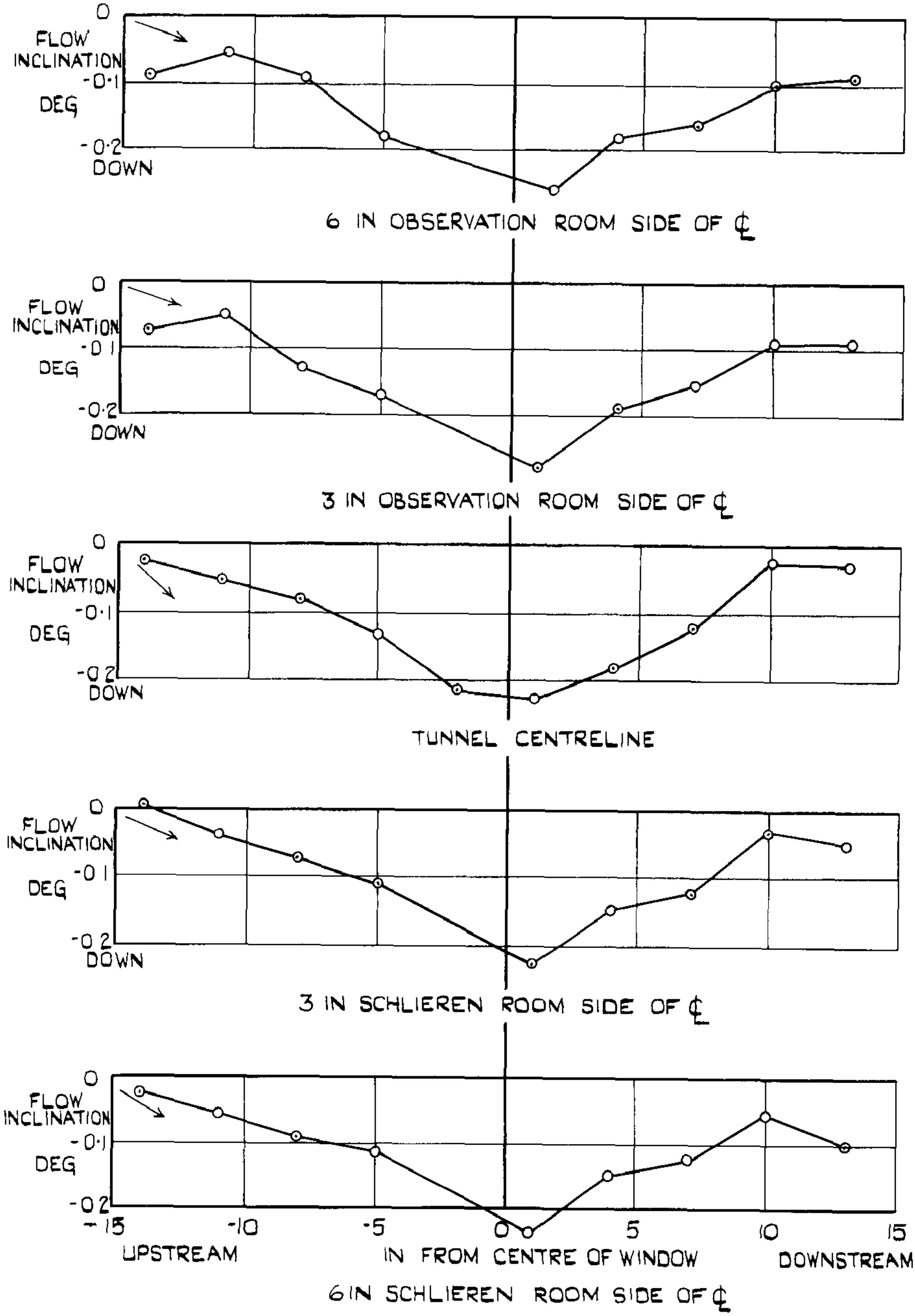
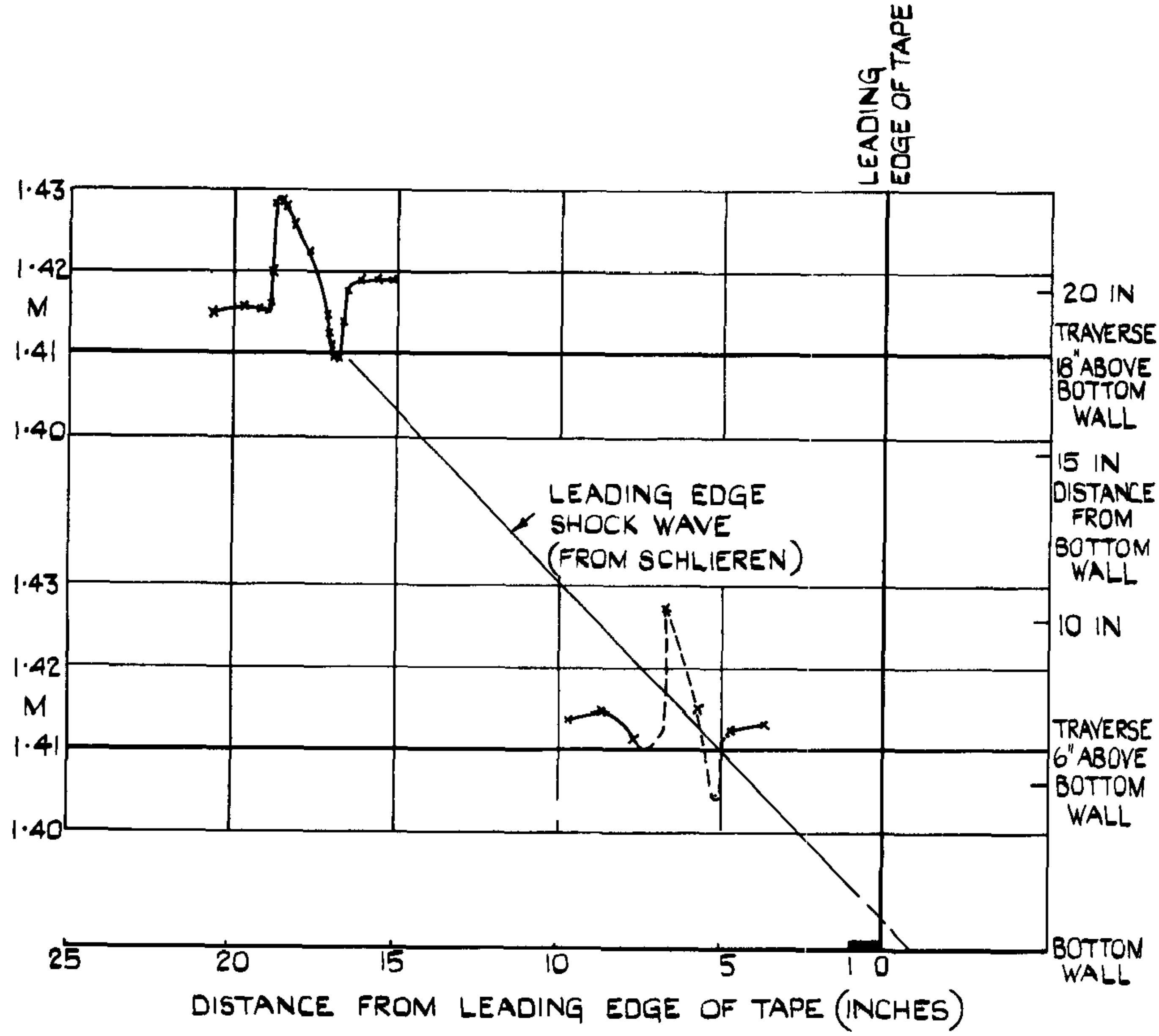


FIG. 30. M=1·6 NOZZLE.
FLOW DIRECTION IN THE HORIZONTAL CENTRAL PLANE.



THICKNESS OF TAPE = 0·0025 IN
DISPLACEMENT THICKNESS OF
LOCAL BOUNDARY LAYER = 0·24 IN
THICKNESS OF LOCAL
BOUNDARY LAYER = 1·4 IN

FIG. 31. DISTURBANCE DUE TO A SMALL STEP (TAPE) ON THE TUNNEL WALL — M = 1·4.

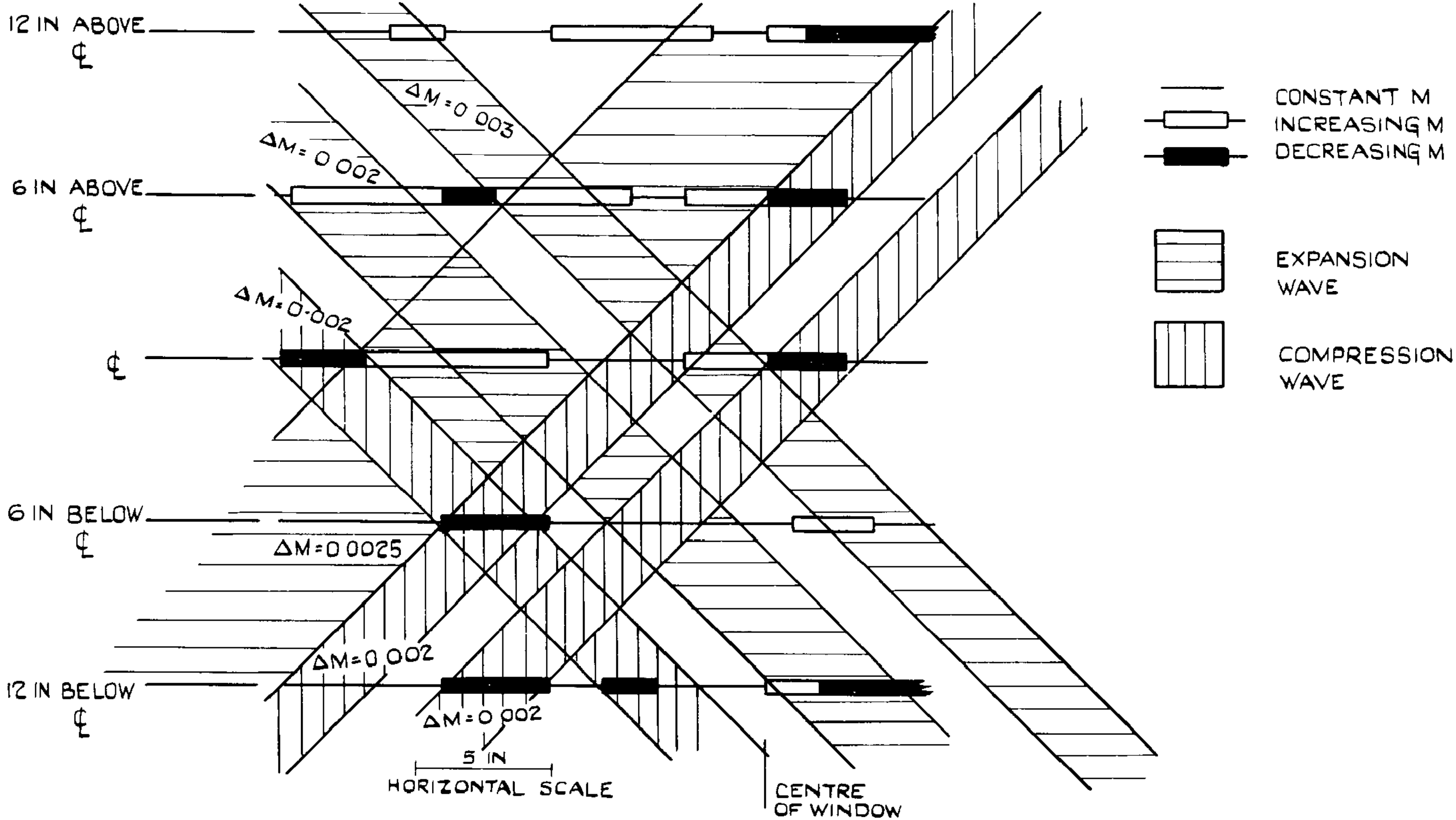


FIG. 32. COMPRESSION & EXPANSION WAVES AS INDICATED BY THE PRESSURE DISTRIBUTION IN THE VERTICAL CENTRAL PLANE. M = 1·4 NOZZLE.

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