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Calibration of the R.A.E. No. 18 (9 in. x 9 in.) Supersonic Wind Tunnel

Part II. Tests at Atmospheric Stagnation Pressure

By

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R. J. Pallant and J. Turner

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Calibration of the R.A.E. No.18 (9" × 9") Supersonic Wind Tunnel

Part II:- Tests at Atmospheric Stagnation Pressure

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SUMMARY

This report presents distributions of Mach number in the empty working section of the R.A.E. No.18 (9" × 9") Supersonic Wind Tunnel at nominal Mach numbers of 1.4, 1.5, 1.6, 1.8 and 1.9, for condensation-free flow at atmospheric stagnation pressure and at a stagnation temperature of 35°C. The results confirm that the accuracy of the tests is of the order predicted in Part I. The mean measured Mach numbers are 1.41, 1.51, 1.61, 1.81 and 1.91 when calculated from values of pitot and stagnation pressures. The major contributions to the non-uniformity of the flow are from the disturbances which arise from the junctions of the windows with the side walls of the tunnel; these disturbances are of the order of ±0.015 in Mach number, whilst the maximum gradual variations in the flow caused by other sources are of the order of ±0.010. An indication of the boundaries of the working section for each Mach number is given.

Note (August, 1953)

Since the accounts of the calibration contained in Parts I and II were written (Part I: December, 1951; Part II: March, 1952), the tunnel equipment has been greatly improved and its limitations are no longer as severe as those described here; the improvements do not invalidate the present results, but no further detailed calibration measurements have been made.

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1 Introduction

The aims and programme of the calibration of the R.A.E. No.18 (9" × 9") Supersonic Wind Tunnel were set out in Part I[1], in the discussion of the preliminary investigations which were necessary before results of sufficient accuracy could be obtained. Part II describes the tests which have been made (during November and December 1951) in the most straightforward case when the stagnation pressure is atmospheric. The tests were performed with air free from condensation shocks, at nominal Mach numbers $\bar{M}$ of 1.4, 1.5, 1.6, 1.8, 1.9 which represent the full working range of the tunnel, and at a stagnation temperature of 35°C.

We present the distributions of measured Mach number along representative lines throughout the empty working section, together with distributions of the measured differences between the Mach numbers at corresponding points away from and on the tunnel centre-line. The Mach number at each point is calculated from the pitot pressure there and the stagnation pressure in the reservoir.

The pressure traversing instrument, the pitot shower, has been modified from the design described in Part I, but the modifications do not make the tests less comprehensive. By means of the shower, the pitot pressure was measured simultaneously at nine points arranged in a pattern 5" square in planes perpendicular to the tunnel centre-line at intervals of $\frac{1}{4}$" over a total length of 18".

The modified shower and the scheme of the traverses are illustrated in Figs.1, 2, 3.

2 Description of modified pitot shower

The tests described in this report were carried out using a new pitot shower which was constructed from a modified design of the original shower (see Figs.1, 2). The modifications were made to facilitate the rigging of the shower in the tunnel, to reduce the possibility of leaks and to stabilise the shower against vibrations particularly at $\bar{M}$ = 1.8 and 1.9. The size of the shower was reduced to 5" square, and the tube supports were sweptback to allow the centre-line pitot tube to be in the same plane as the others without its reading being affected by the conical shield.

The arrangements for measuring the pressure were precisely the same as described in Part I for the original shower.

3 Discussion of test procedure

The procedure followed in performing the calibration was outlined in Part I, but it may be well to reiterate briefly the chief points.

For a test at a given $\bar{M}$ and at atmospheric stagnation pressure ($\bar{p}_0$ = 30), the $\bar{M}$ liner was fixed in the tunnel so that the positions of its throat and end were coincident, as nearly as could be seen with the naked eye, with the appropriate lines scribed on the tunnel walls. The tunnel was evacuated of wet air and flow at $\bar{M}$ established at low pressure to reduce buffetting of the shower by the tunnel shock. Fresh air was then introduced through the driers and the stagnation pressure maintained at atmospheric throughout the test. The nominal stagnation temperature T_0 was adjusted to be 35°C, and the humidity $\bar{\Omega}$ checked to be below the corresponding critical value for condensation-free flow. The automatic speed control was used to keep the compressor speed to within ±50 r.p.m. of its nominal value. The pressure traverse was started at its upstream point, to reduce the position error due to slackness in the flexible drive, and pressure measurements made, every $\frac{1}{4}$", when the readings of the water manometers were steady. To prevent the pressures being disturbed by unexpected fluctuations in the compressor speed, they were clamped before reading and then checked when later unclamped. Occasional measurements of humidity were made during each run.

Each full traverse was checked by a repeat run under the same basic conditions, in some cases with, and in others without, the liner being moved. In the check traverses the pressures were not always read every $\frac{1}{4}$". The various quantities which were changed between similar traverses are listed in Table I for comparison with the distributions of Mach number given in Figs.4,-8.

It was predicted in Part I that, with the existing tunnel equipment and by following the established procedure it should be possible to measure

(i) the difference between the Mach number at any point in the empty working section and the Mach number at the corresponding point on the tunnel centre-line correct to within ± 0.002 at all $\bar{M}$,

(ii) the absolute Mach number at any point correct to within limits varying from ± 0.006 at $\bar{M} = 1.4$ to ± 0.004 at $\bar{M} = 1.9$,

except in the immediate vicinity of large disturbances of the order of ± 0.010, say, where the position error may be large. These predictions are here confirmed.

4 Presentation and interpretation of Mach number distributions

The distributions of Mach number along the lines of traverse for each value of $\bar{M}$ are presented in two figures:

(a) showing the distributions of the measured difference m_n between the Mach number M_n at a point on the n^{th} line and the simultaneous Mach number M_5 at the corresponding point on the centre-(No.5) line

(b) showing the distributions of the measured absolute Mach number M_n at a point on the n^{th} line

Each figure gives the results of two traverses in each of the Positions I and II; the results of a full traverse are presented as a "jointed curve", obtained by joining consecutive points by straight lines, whilst the check results are plotted as crosses in the vicinity of that curve.

The agreement between two corresponding traverses is best illustrated by the distributions of m_n, which should not disagree by more than 0.004 in the cases when the liner was moved or by more than 0.002 with the liner unchanged, except near large disturbances.

The distributions of M_n, which are subject to larger errors than those of m_n, give an idea of the trends of the local Mach number and indicate the positions of the large disturbances. Also, in conjunction with the values of the estimated experimental error $\Delta\tilde{M}$ (see Table 2) they may be used to give an idea of the distributions of the mean Mach number $\tilde{M}_n$ from the relation $|\tilde{M}_n - M_n| \leq \Delta\tilde{M}$. No attempt has been made to draw these $\tilde{M}_n$ distributions from just two examples of M_n distributions, since this would be largely guesswork. However, the maximum discrepancy which may be allowed between any two corresponding values of M_n is clearly $2\Delta\tilde{M}$, and it may be seen from Table 2 and Figs.4(b),-8(b) that the results of all check runs lie well within this error of the results of the corresponding full traverses.

Simply joining experimental points by straight lines to produce M_n distributions may defeat the object of the calibration to discover the positions and magnitudes of "comparatively large" disturbances, since large changes in M_n may occur in distances much smaller than the $\frac{1}{4}$" intervals of the traverses. However, in many such cases the positions of the disturbances are well established by the disagreement of the check results there. It is found that the disturbances which are easily identified lie close to the theoretical envelopes of the disturbances from the two window junctions. Consequently the intersections of these envelopes with the lines of traverse are indicated in Figs.4(b),-8(b) to facilitate the tracing of disturbances which are not apparent from the rather coarse traverses. We may point out, however, that there is not necessarily a measurable disturbance at every point on the envelopes since the disturbance fronts caused by the window junctions are by no means uniform: Table 3 gives typical measurements of the differences in level between the tunnel side walls and the windows at several points on the circumference of the windows. The window A (see Fig.3) was unchanged for all the runs, but a window B_1 was used for runs at $\bar{M} = 1.4$, 1.5 and 1.6 and a new window B_2 for runs at $\bar{M} = 1.8$ and 1.9. Discrepancies between the theoretical and experimental positions of the disturbance envelopes are due to an unavoidable constant small roll in the pitot shower during all traverses.

The essential points of an interpretation of the Mach number distributions for a given $\bar{M}$ therefore seem to be:

(1) to note the agreement between corresponding traverses by comparing their m_n distributions,

(2) to compare the trends of corresponding M_n distributions and, if possible, deduce the form of the $\tilde{M}_n$ distribution,

(3) to note the positions and, if possible, the magnitude of the disturbances from the window junctions,

(4) to estimate the measured overall mean Mach number M^* throughout the working section - M^* is thus an experimental value of the theoretical nominal Mach number $\bar{M}$ - and the likely maximum variations from it,

(5) to estimate the approximate upstream limit of the working section at this given $\bar{M}$, and to note any regions of fairly uniform or violently non-uniform flow downstream of it,

(6) to list any peculiarities of the distributions.

5 Conclusions

This report presents the distributions of Mach number along specified representative lines throughout the empty working section for the full working range of nominal Mach number $\bar{M}$ = 1.4, 1.5, 1.6, 1.8, 1.9, for condensation-free flow at atmospheric stagnation pressure and at a stagnation temperature of 35°C.

The results confirm that the accuracy of the tests is of the order predicted in Part I. Thus, comparable distributions of m_n, the measured difference between the Mach number M_n at a point on the n^{th} line of traverse and the simultaneous Mach number M_5 at the corresponding point on the centre (No.5) line, agree to within ± 0.002 at all $\bar{M}$, except near large disturbances of order greater than ± 0.01. The agreement is even closer when the liner is not moved between performing the traverses. Further, the distributions of $\tilde{M}_n$ for comparable traverses agree to within $\pm \Delta\bar{M}$, where $\Delta\bar{M}$ varies with $\bar{M}$ and is given in Table 2, except near large disturbances. The steadiness of the readings in all tests, and the very satisfactory agreement between results of comparable tests, confirm the belief that all tests were performed with air sufficiently dry to prevent the occurrence of condensation shocks.

Comparable traverses show the same trends of Mach number gradient, except near steep disturbances where the intervals of the traverses are too coarse to permit a proper comparison.

The largest disturbances in the working section arise from the window junctions with the side walls and from the joint between the recess block and the top liner (see Fig.3). In fact, the latter disturbance is so large, about ± 0.050, that, with the expansion from the ends of a shaped liner, it forms the downstream boundary of the effective working section. The disturbances arising from the window junctions are of the order of ± 0.015 and are serious, since they affect the flow in more than half of the working section. In view of the relatively smooth flow upstream of the region influenced by the window junctions, which tends to eliminate the liners themselves as sources of any large non-uniformities of flow, it is clear that particular attention should be paid to ensure smooth joints between the side walls and windows or mounting plates.

The values of the overall mean Mach number M^* are +0.01 higher than the corresponding values of nominal Mach number $\bar{M}$. The maximum variations due to the window junction disturbances are about ± 0.015. Neglecting these "artificial" disturbances, the gradual variations due to other causes are of the order of ± 0.010, which should represent the limit of variation with perfectly smooth window joints.

By measuring the positions in the three horizontal planes of traverse where the Mach number begins to decrease steadily in an upstream direction, and drawing a mean plane through them at the appropriate Mach angle to the flow direction, it is possible to estimate roughly the beginning of the working section for each $\bar{M}$. Fig.9 indicates the estimated boundaries of the effective working sections, and shows that the tests described here adequately cover the effective working sections.

The close agreement which is obtained even when the liner has been removed and replaced between comparable traverses is a justification of the simple method of liner installation which is used in the calibration.

It is possible that a more detailed analysis of particular distributions may reveal characteristics peculiar to individual liners. One such peculiarity is noticed in the M_n distributions for the $\bar{M} = 1.6$ liner (see Fig. 6(b)). There is a relatively steep negative Mach number gradient in the central horizontal plane (see M_4, M_5, M_6) between points 10 and $8\frac{1}{2}$ where the Mach number falls about 0.01; this gradient, which seems to be perpetuated in the other planes (see M_1, M_2, M_3 near point 13, and M_7, M_8, M_9 near point 8), is well upstream of any artificial disturbances and is presumably due to the shape of the liner.

Although it is not easy to assess the relative merits of the M_n distributions of the different liners, we note that the largest "non-artificial" variations are observed with the $\bar{M} = 1.9$ liner, whilst the one which gives closest repeatability of results and for which the artificial disturbances may be most easily isolated is the $\bar{M} = 1.6$ liner Ironically, the design of this liner included an eroneous boundary-layer correction.

6 Remarks on recent modifications

The tests described here were performed during November and December, 1951. Now, in March, 1952, we must mention two modifications which have become permanent features of the tunnel.

The window B_2 which was used during Runs 13, 20 has superseded the window B_1 used for Runs 1, 12, and is now in constant use in the tunnel. Typical measurements of the discontinuities between the side wall and these windows are given in Table 3. There is no improvement in B_2, though in this case the cement junction between glass and steel is intact whilst in B_1 it had crumbled in several places. It is possible that inaccuracies in the side walls make a substantial contribution to the total discontinuities.

The shims which were placed between the bottom wall of the tunnel and the shaped liners to fix them in their correct positions (see Part I) have been incorporated into the liners. It was found that during the few months of the preliminary investigation and accurate tests the liners for $\bar{M}$ = 1.4, 1.5, 1.8, 1.9, which are made of teak, had shrunk somewhat, whilst the $\bar{M}$ = 1.6 liner, which is made of permali, was apparently unchanged. Thus, future distributions may be expected to differ from those given here by a liner basic error, which, however, should be small, say of order ± 0.002, and may in fact be allowed for by the generous errors estimated for the present results. We suggest that the liners should be inspected periodically, say once a month, to test for shrinkage, and when the shrinkage is appreciable, about 0.010", extra shims should be incorporated into the liners to bring them back to their design positions as scribed on the tunnel wall. The liners for $\bar{M}$ = 1.4, 1.5, 1.6, 1.8, 1.9 were checked as conforming to their design positions on March 5th, 1952.

List of Symbols

m_n Mach number difference (see below)

p_o stagnation pressure

M Mach number

$\frac{Re}{d}$ Reynolds number per inch

T_o stagnation temperature

Δ denotes "absolute error in ....."

Ω absolute humidity

Superscripts:

-	denotes nominal value	
~	denotes mean value at a point over any number of tests	applied to Mach number only
*	denotes overall mean value throughout working section over any number of tests	applied to Mach number only

Subscripts:

n number of tube in pitot shower

$(1 \leqslant n \leqslant 9)$

For example:

M_n measured Mach number at a given position of the n^{th} tube

M_5 " " " " " " " central (No.5) tube

$m_n = M_n - M_5$ Mach number difference between positions of n^{th} and central tubes with shower in a given position

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REFERENCE

No.	Author	Title, etc.
1	Lord, W.T. and Beastall, D.	"Calibration of the R.A.E. No.18 (9" x 9") Supersonic Wind Tunnel: Part I: Preliminary Investigations". ARC 16,554. C.P. 162. September, 1953.

Wt.2078.CP163.K3 - Printed in Great Britain.

Table 1

Guide to traverses

$\bar{M}$	$\frac{Re}{d} \times 10^{-6}$	Figure	Position	Run	$\bar{\Omega}$	Windows	Type of Traverse
1.4	0.38	4	I	1	0.0002	A, B_1	Full
				2	0.0002	A, B_1	Check (Liner Moved)
			II	3	0.0003	A	Full
				4	0.0003	A	Check (Liner Unmoved)
1.5	0.37	5	I	5	0.0003	A, B_1	Full
				6	0.0004	A, B_1	Check (Liner Moved)
			II	7	0.0004	A	Full
				8	0.0003	A	Check (Liner Unmoved)
1.6	0.36	6	I	9	0.0003	A, B_1	Full
				10	0.0003	A, B_1	Check (Liner Moved)
			II	11	0.0003	A	Full
				12	0.0002	A	Check (Liner Unmoved)
1.8	0.34	7	I	13	0.0001	A, B_2	Full
				14	0.0001	A, B_2	Check (Liner Unmoved)
			II	15	0.0002	A	Full
				16	0.0001	A	Check (Line Moved)
1.9	0.33	8	I	17	0.0001	A, B_2	Full
				18	0.0001	A, B_2	Check (Liner Moved)
			II	19	0.0001	A	Full
				20	0.0001	A	Check (Liner Moved)

Table 2

Estimated total experimental errors

$\bar{M}$	$\Delta\tilde{M}$
1.4	0.006
1.5	0.005
1.6	0.004
1.8	0.004
1.9	0.004

Table 3

Typical values of discontinuities at window junctions

Position		Difference in Level Between Side Wall and Steel Rim			Difference in Level Between Steel Rim and Glass Pane		
		Window A	Window B_1	Window B_2	Window A	Window B_1	Window B_2
Upstream Junction	Top	0	-0.004"	-0.004"	+0.001"	0	+0.001"
	Centre	-0.002"	-0.001"	-0.003"	+0.002"	-0.002"	-0.002"
	Bottom	-0.002"	-0.002"	-0.002"	+0.002"	0	0
Downstream Junction	Top	0	0	0	+0.002"	-0.001"	-0.001"
	Centre	-0.002"	+0.003"	+0.005"	0	0	+0.001"
	Bottom	-0.005"	0	0	+0.003"	0	-0.001"

These values indicate the orders and trends of the discontinuities. The measurements are accurate only to within $\pm 0.001"$, and removal and replacement of a window involves changes of similar order.

In window B_1, the cement joint between the steel rim and the glass panel contains cracks of depth > 0.010".

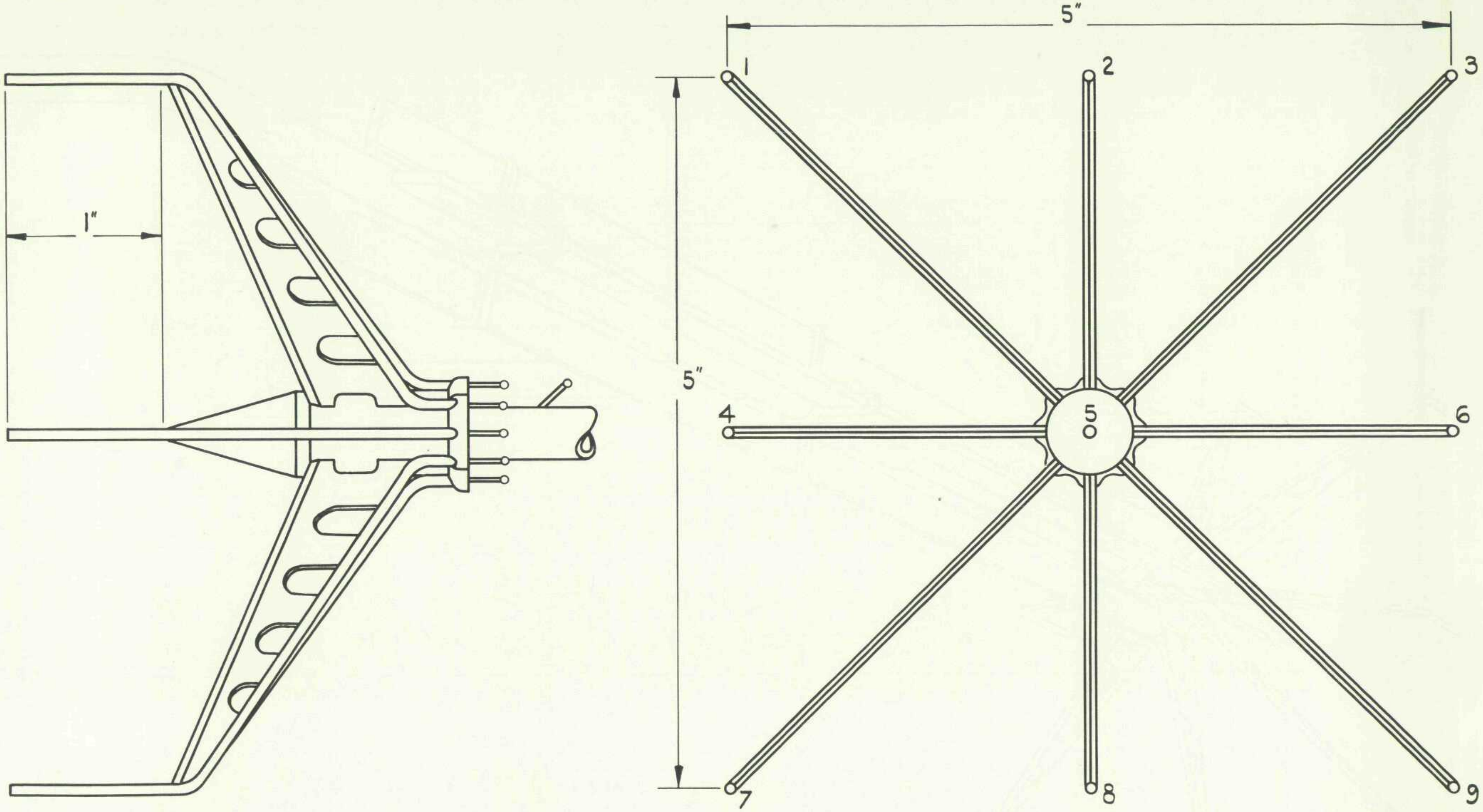

FIG. 1 MODIFIED PITOT SHOWER.
FULL SIZE

FIG. 1

FIG. 2

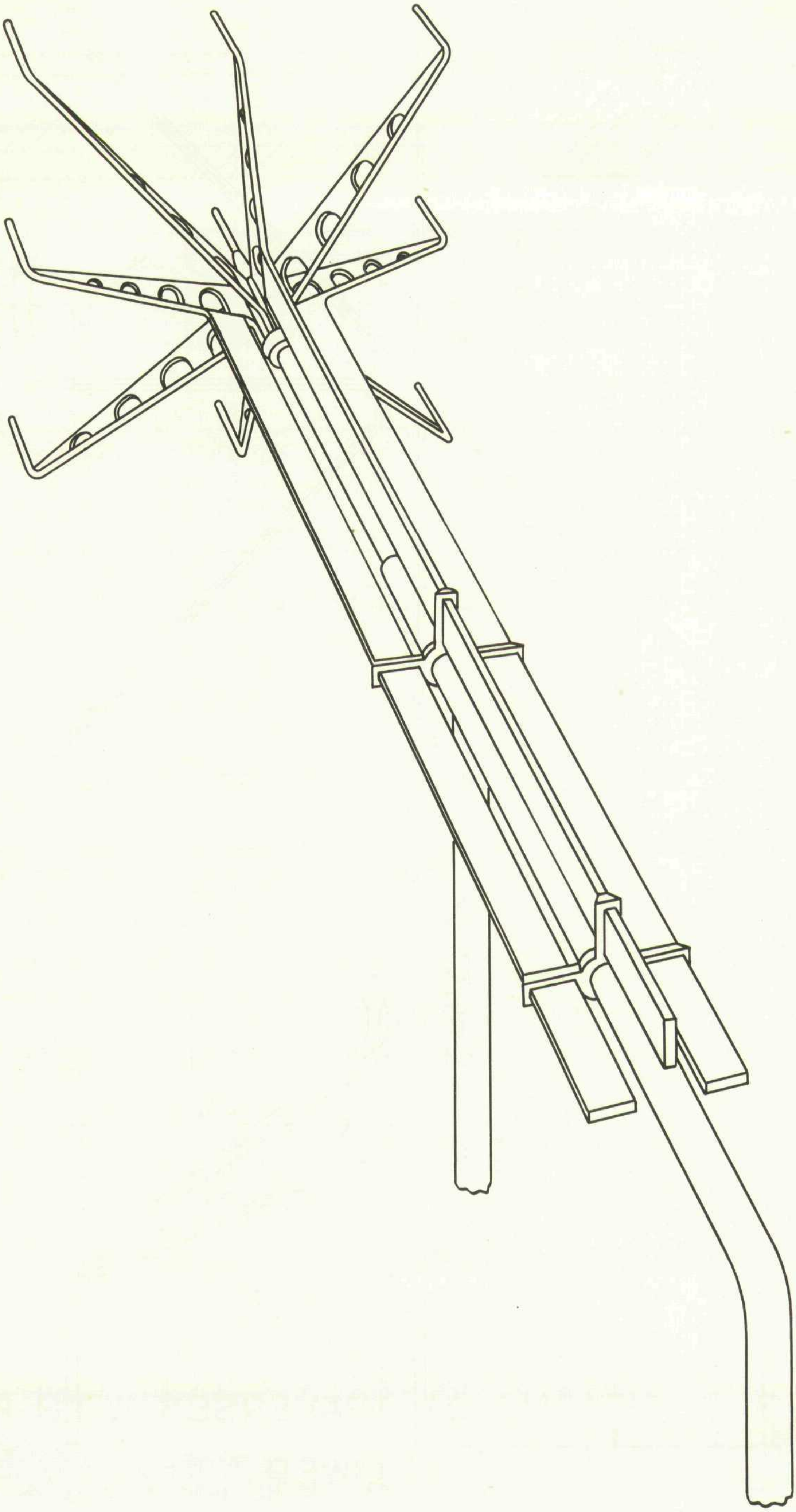

FIG. 2 METHOD OF STIFFENING TRAVERSING GEAR FOR PITOT SHOWER.

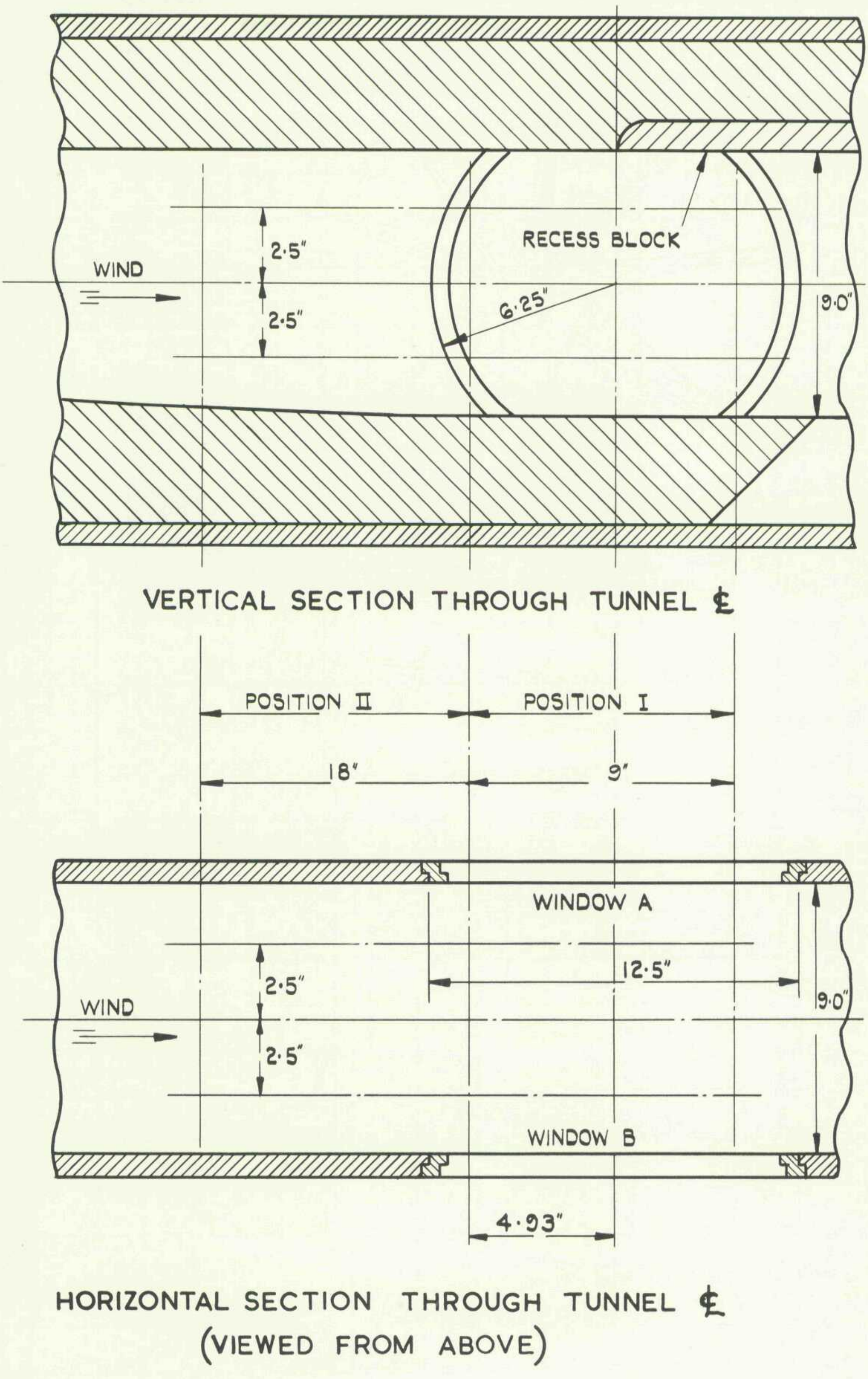

FIG. 3 POSITIONS OF TRAVERSES WITH PITOT SHOWER.

FIG 4 (a)

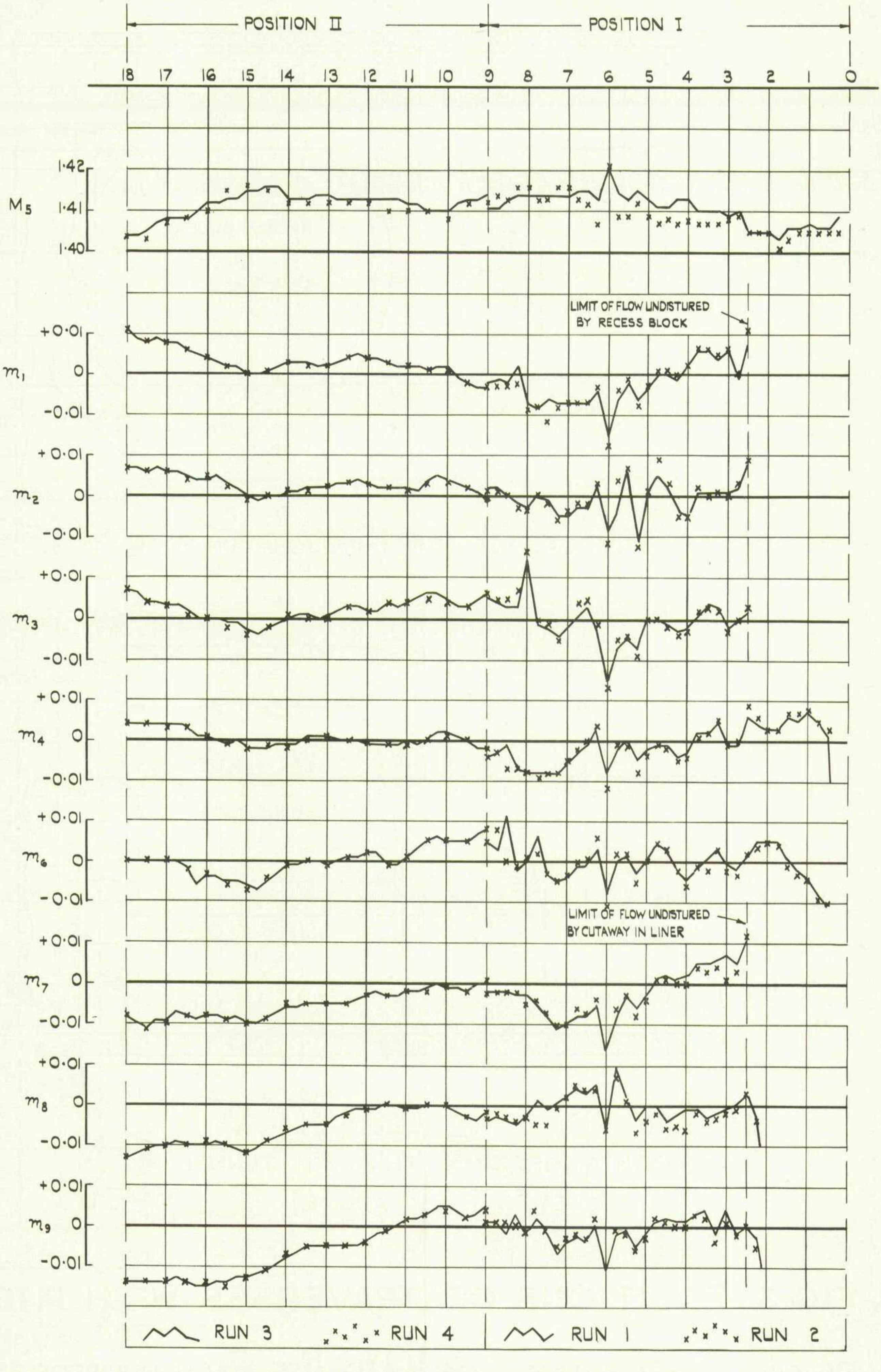

FIG 4 (a) DISTRIBUTIONS OF MACH NUMBER DIFFERENCES m_n

$\overline{M} = 1{\cdot}4 \quad \overline{p_o} = 30 \quad \overline{T_o} = 35 \quad \overline{\Omega} = {\cdot}0003$

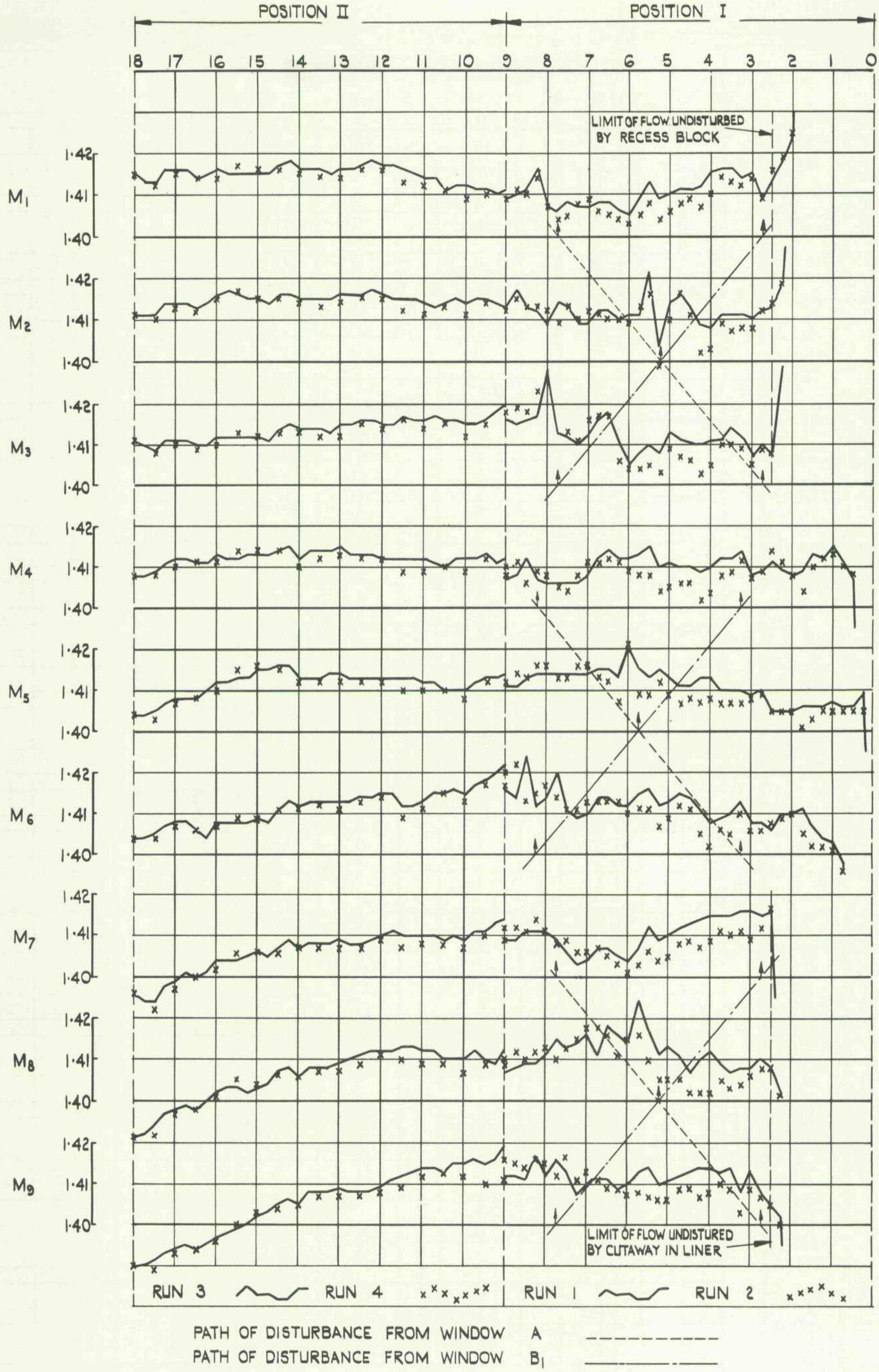

FIG. 4(b) DISTRIBUTIONS OF ABSOLUTE MACH NUMBERS M_n

$\overline{M} = 1{\cdot}4 \quad \overline{P}_o = 30'' \quad \overline{T}_o = 35°C \quad \overline{\Omega} = {\cdot}0003$

FIG.5(a)

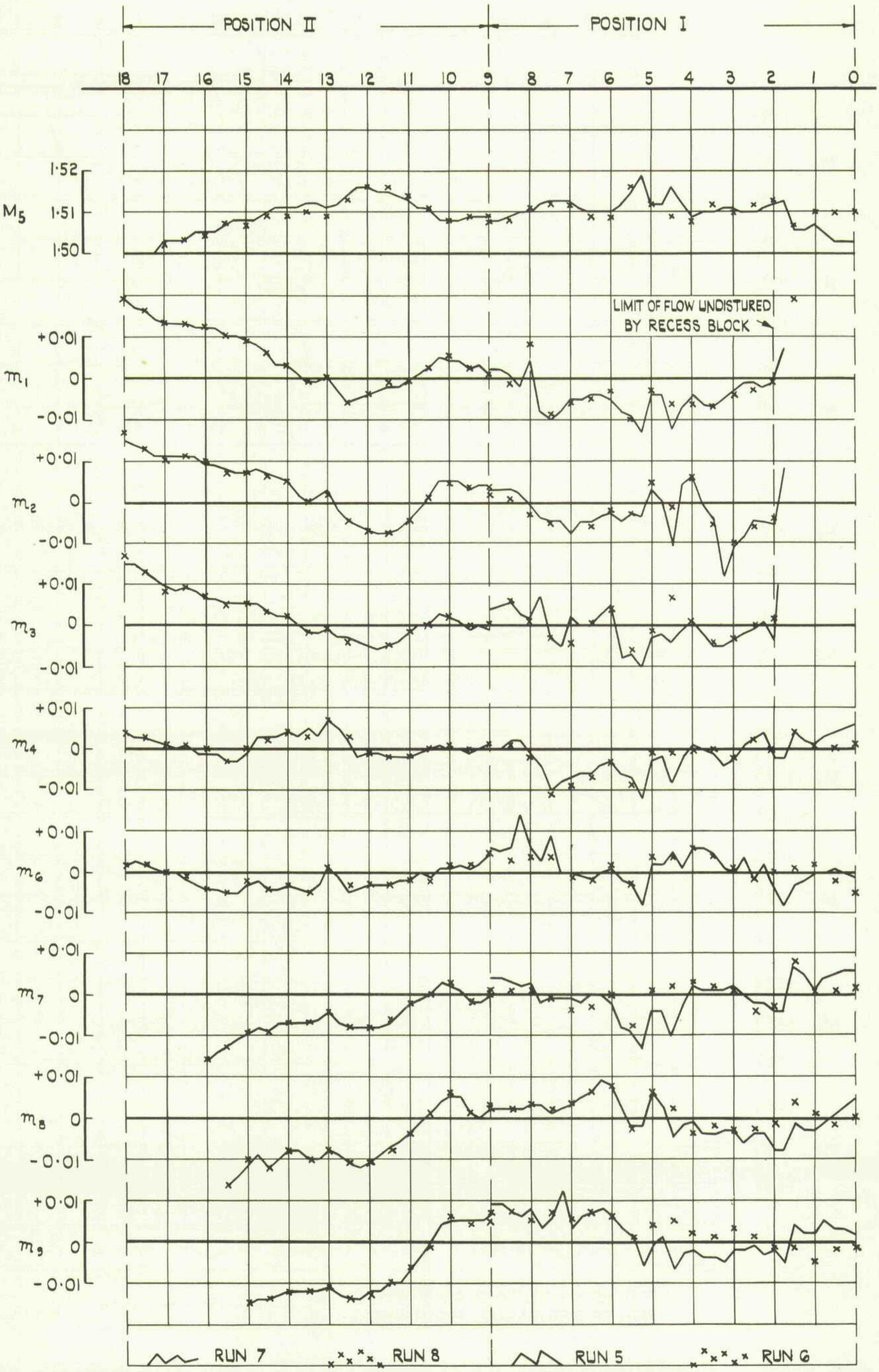

FIG.5(a). DISTRIBUTION OF MACH NUMBER DIFFERENCES m_n

$\overline{M} = 1{\cdot}5 \quad \overline{P}_o = 30 \quad \overline{T}_o = 35 \quad \overline{\Omega} = {\cdot}0004$

FIG.5(b)

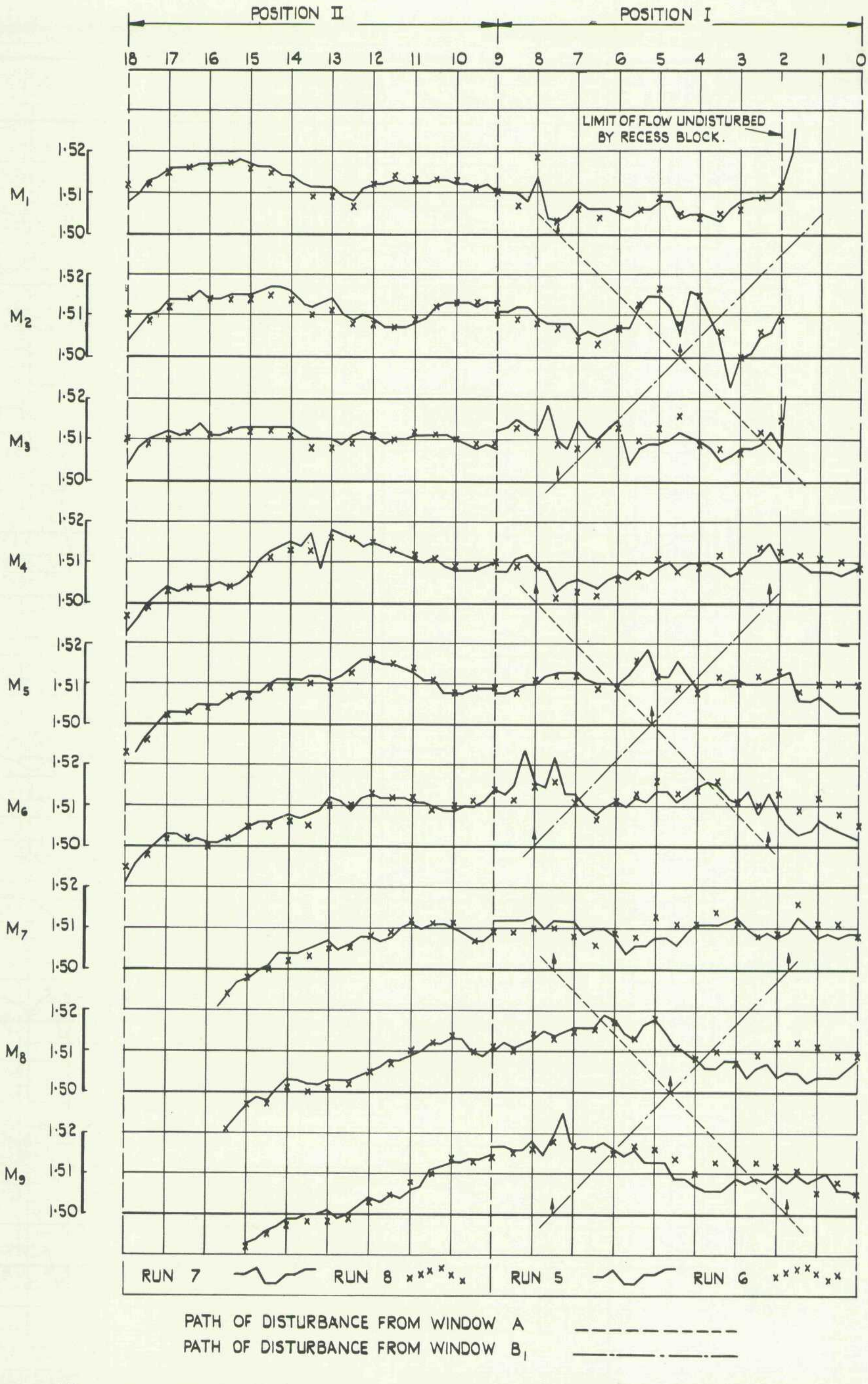

FIG. 5 (b) DISTRIBUTION OF ABSOLUTE MACH NUMBERS M_n

$\overline{M} = 1{\cdot}5$ $\overline{P}_o = 30''$ $\overline{T}_o = 35°C$ $\overline{\Omega} = {\cdot}0004$

FIG. 6 (a)

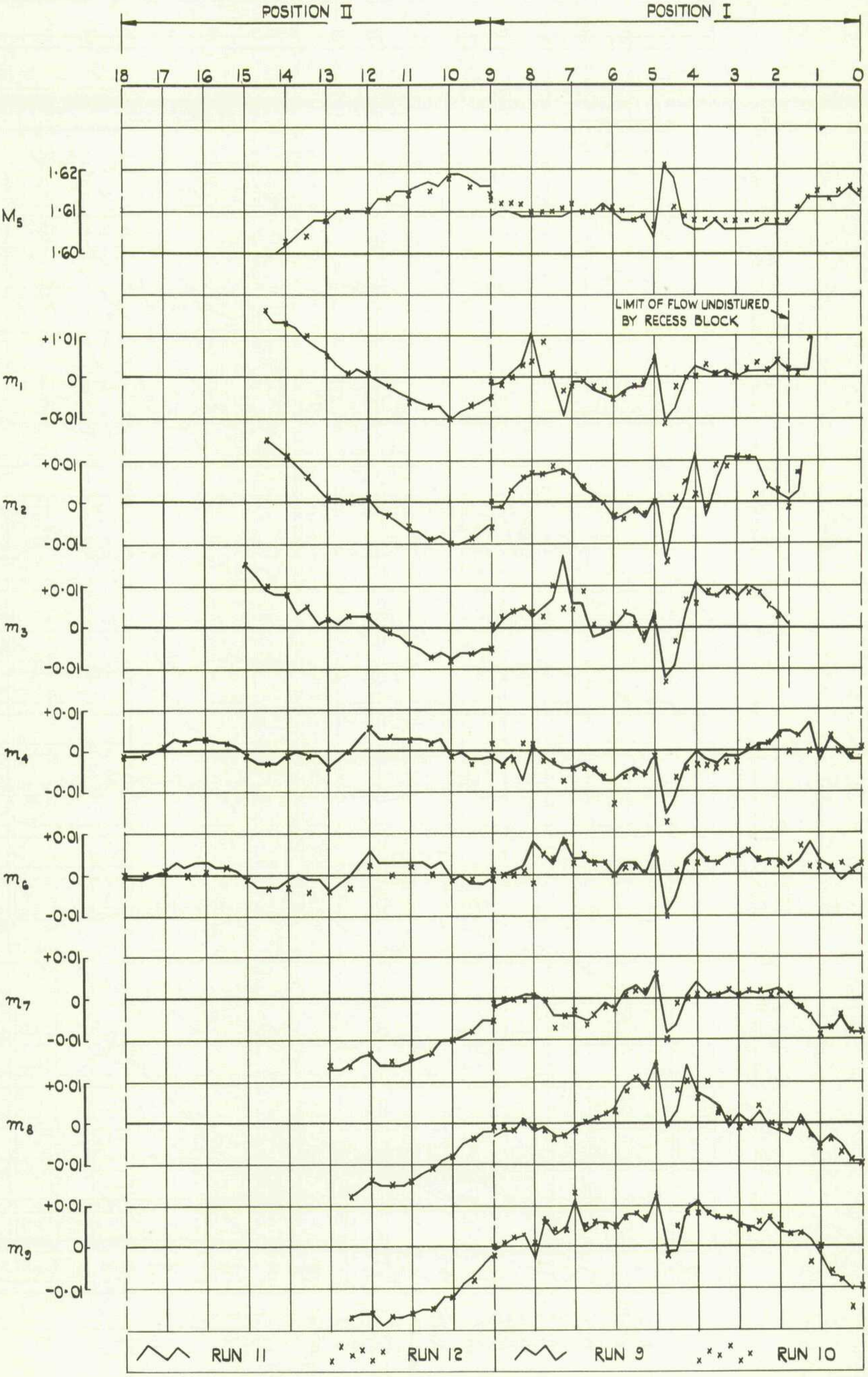

FIG. 6(a) DISTRIBUTIONS OF MACH NUMBER DIFFERENCES m_n

$\overline{M} = 1{\cdot}6 \quad \overline{p}_o = 30 \quad \overline{T}_o = 35 \quad \overline{\Omega} = {\cdot}0003$

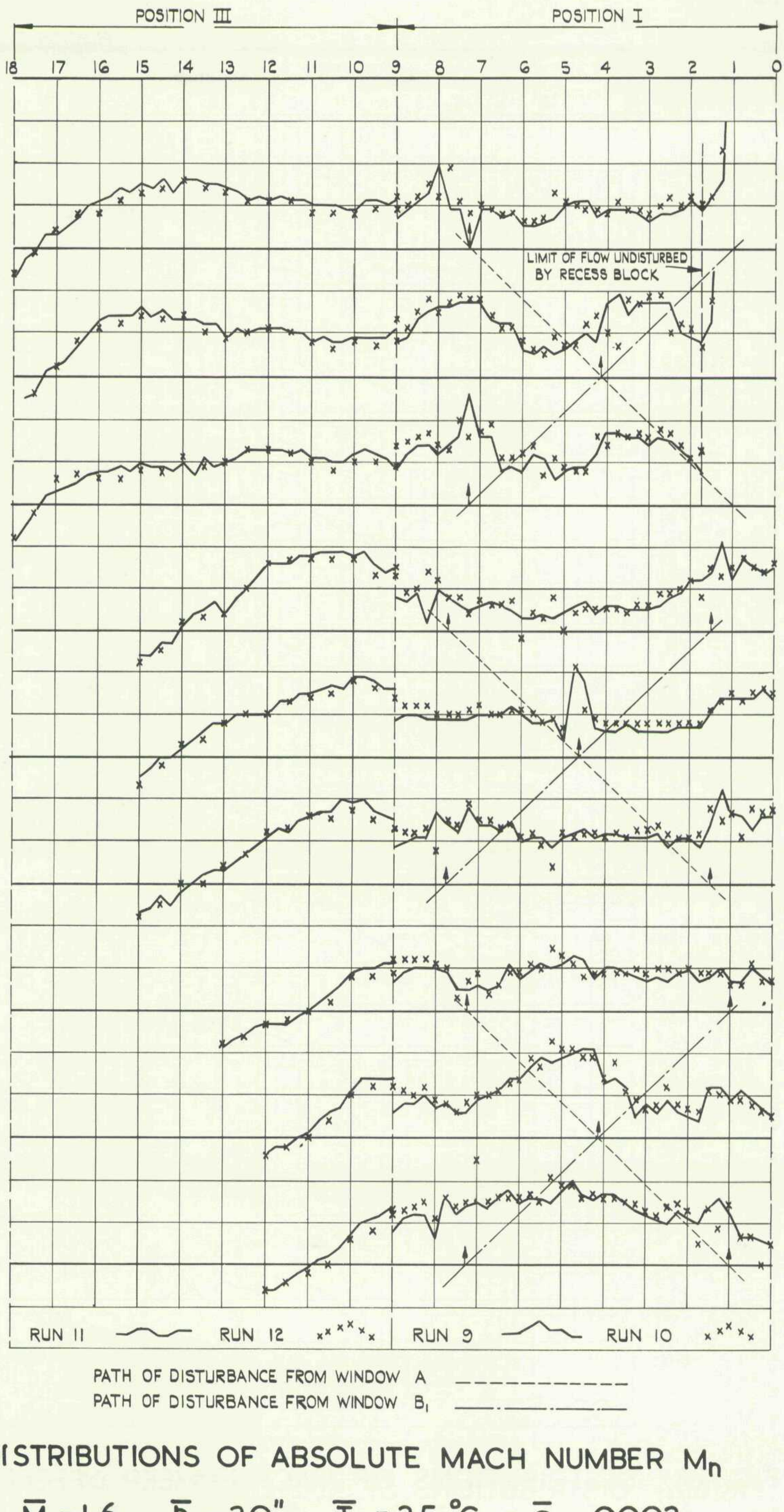

FIG. 6(b) DISTRIBUTIONS OF ABSOLUTE MACH NUMBER M_n

$\overline{M} = 1{\cdot}6 \quad \overline{P}_o = 30'' \quad \overline{T}_o = 35\ ^\circ C \quad \overline{\Omega} = {\cdot}0003$

FIG. 7(a)

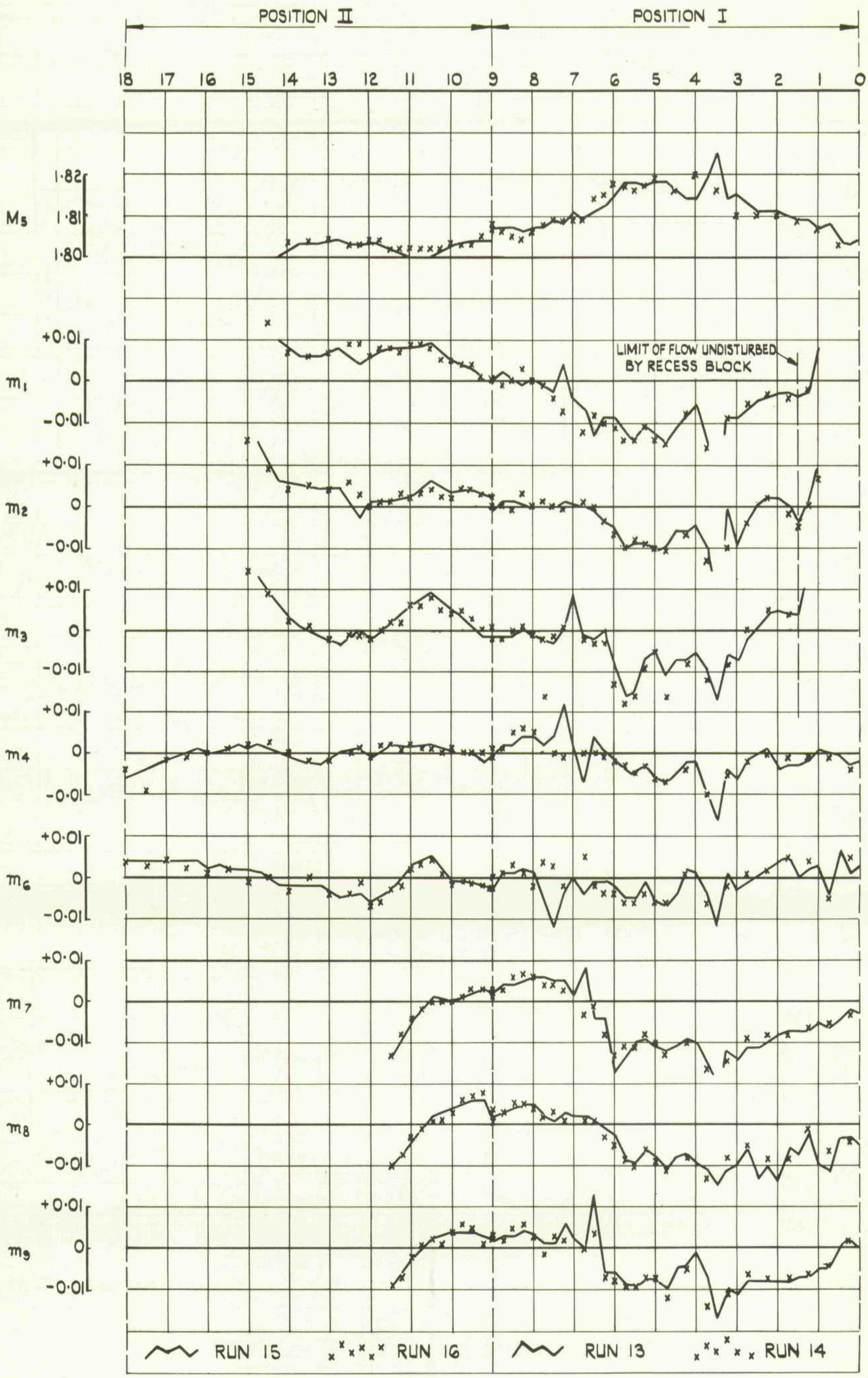

FIG. 7(a) DISTRIBUTIONS OF MACH NUMBER DIFFERENCES m_n

$\bar{M} = 1{\cdot}8$ $\bar{P}_0 = 30$ $\bar{T}_0 = 35$ $\bar{\Omega} = {\cdot}0002$

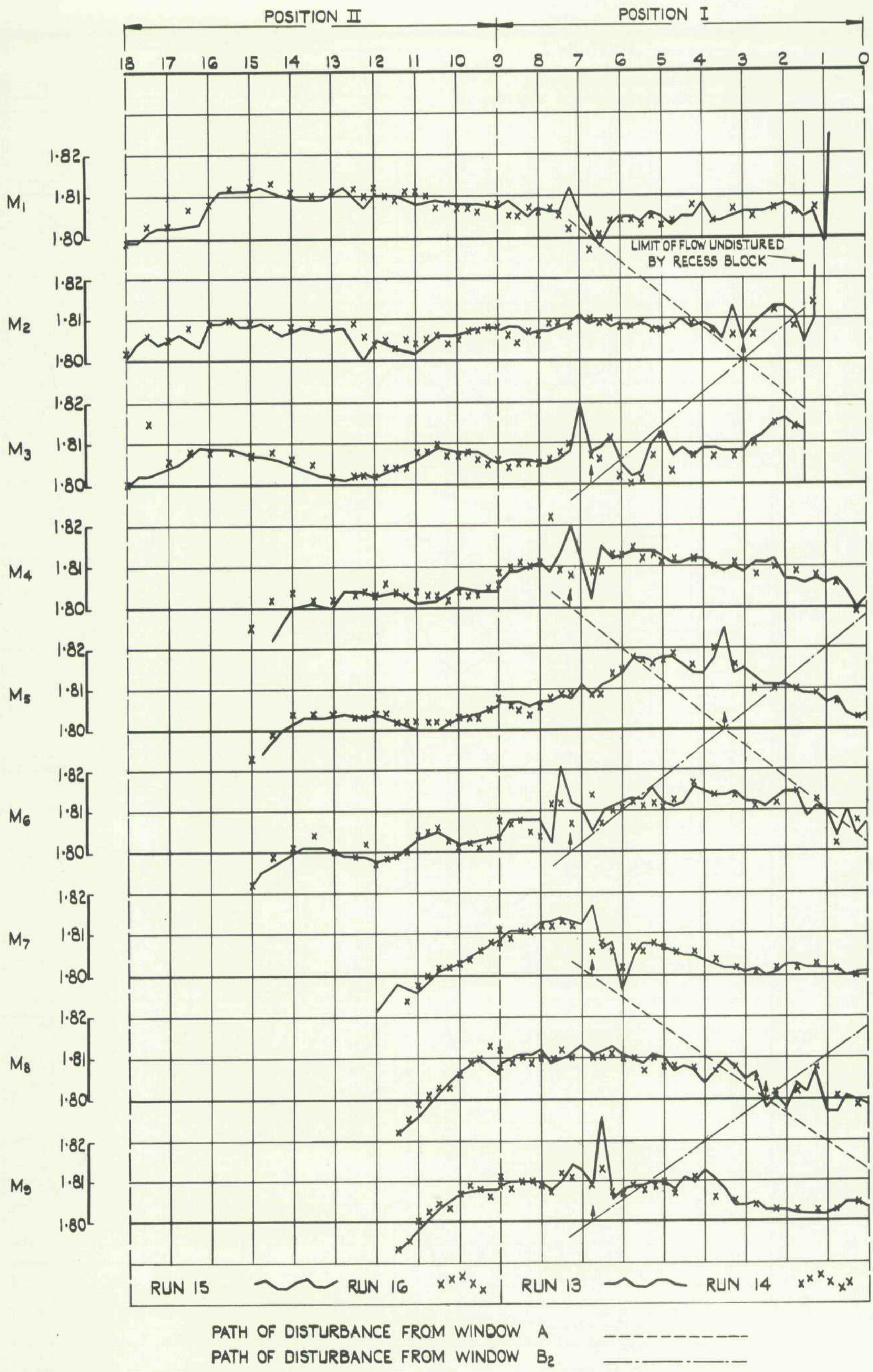

FIG. 7(b) DISTRIBUTIONS OF ABSOLUTE MACH NUMBERS M_n

$\overline{M} = 1{\cdot}8 \quad \overline{P}_o = 30'' \quad \overline{T}_o = 35°C \quad \overline{\Omega} = {\cdot}0002$

FIG. 8 (a).

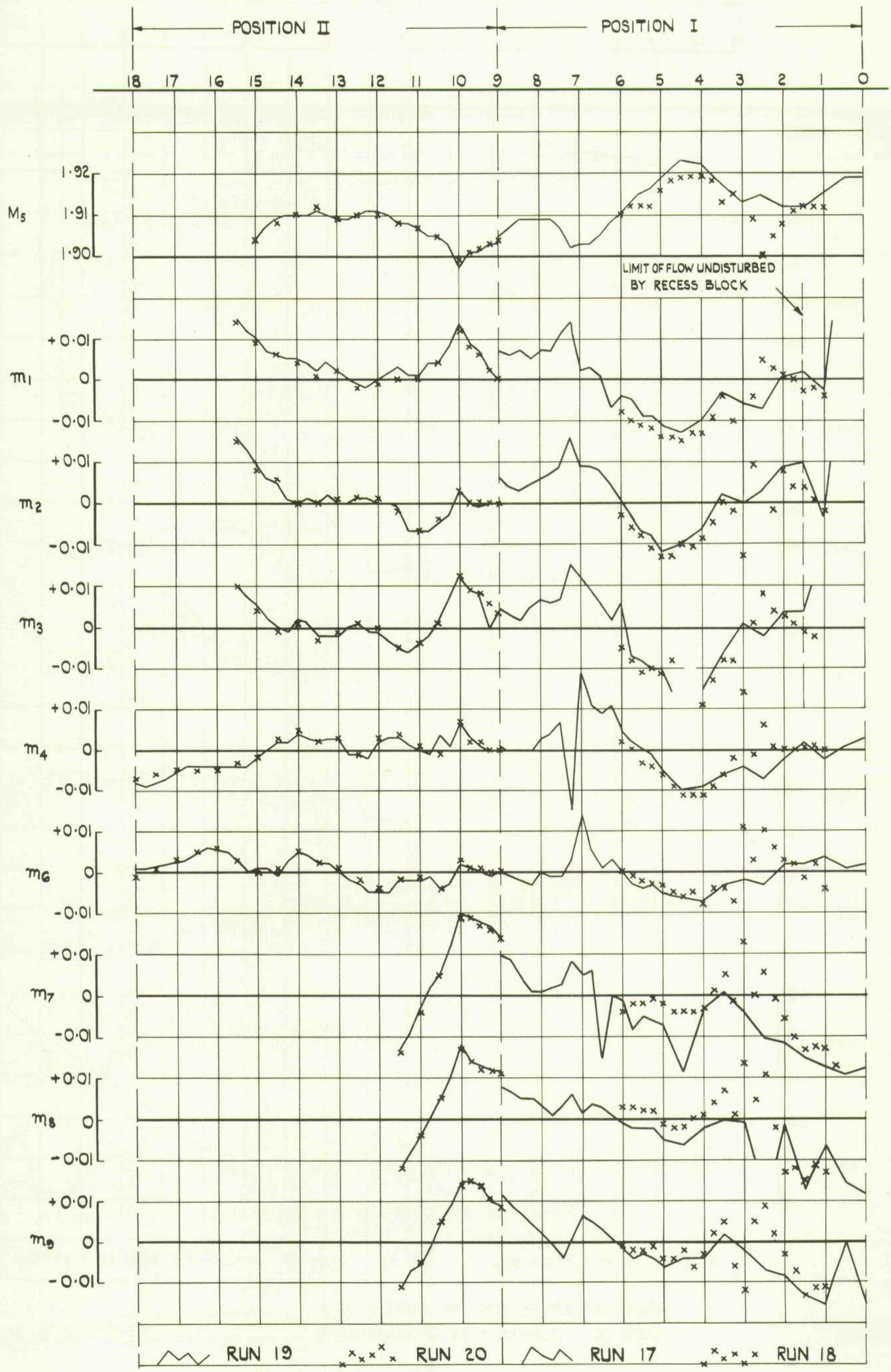

FIG. 8. (a). DISTRIBUTIONS OF MACH NUMBER DIFFERENCES m_n

$\overline{M} = 1{\cdot}9 \quad \overline{p}_o = 30 \quad \overline{T}_o = 35 \quad \overline{\Omega} = {\cdot}0001$

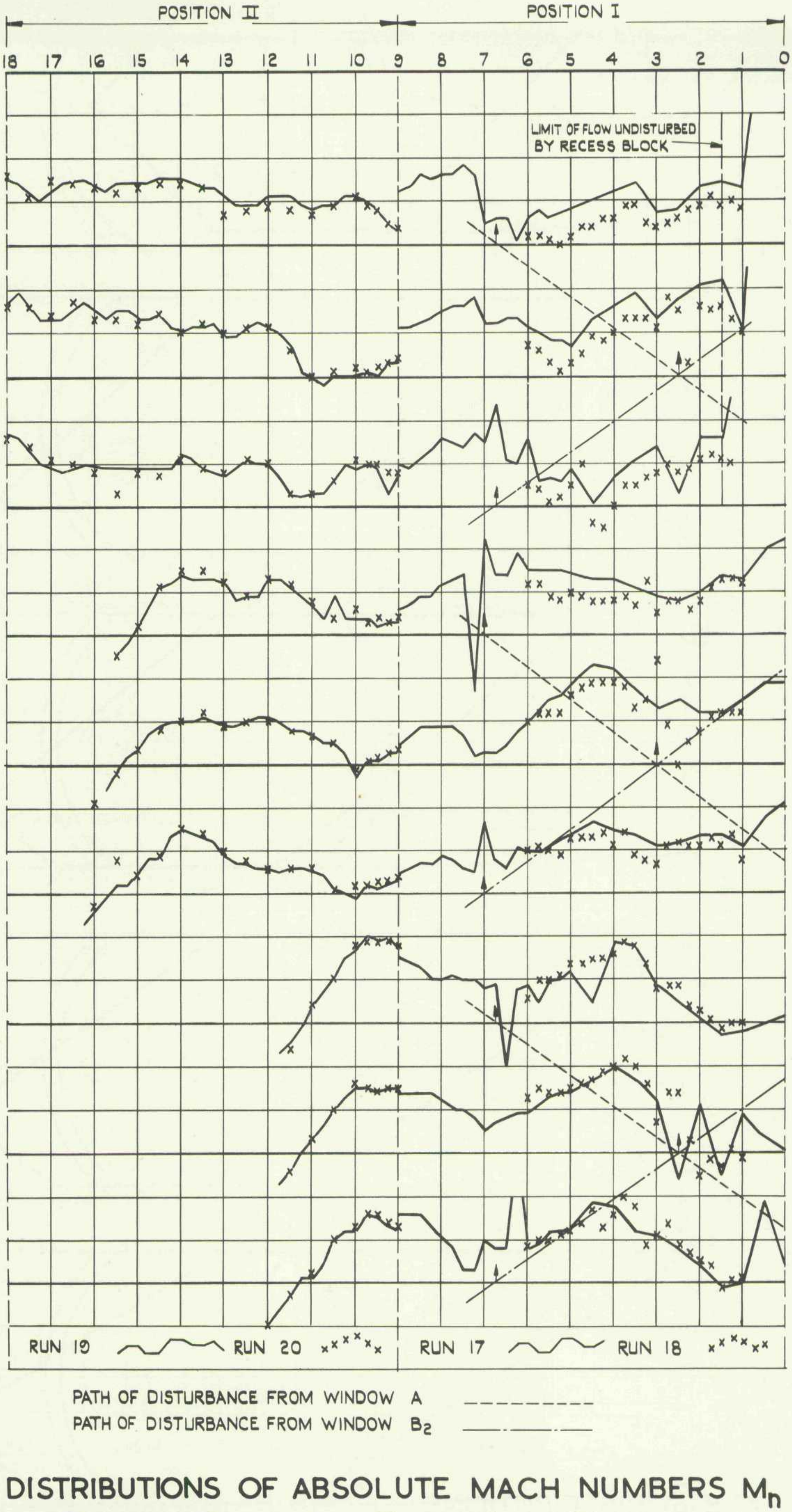

FIG. 8 (b) DISTRIBUTIONS OF ABSOLUTE MACH NUMBERS M_n

$\overline{M} = 1\cdot 9 \quad \overline{P}_o = 30'' \quad \overline{T}_o = 35\,^{\circ}C \quad \overline{\Omega} = \cdot 0001$

FIG.9

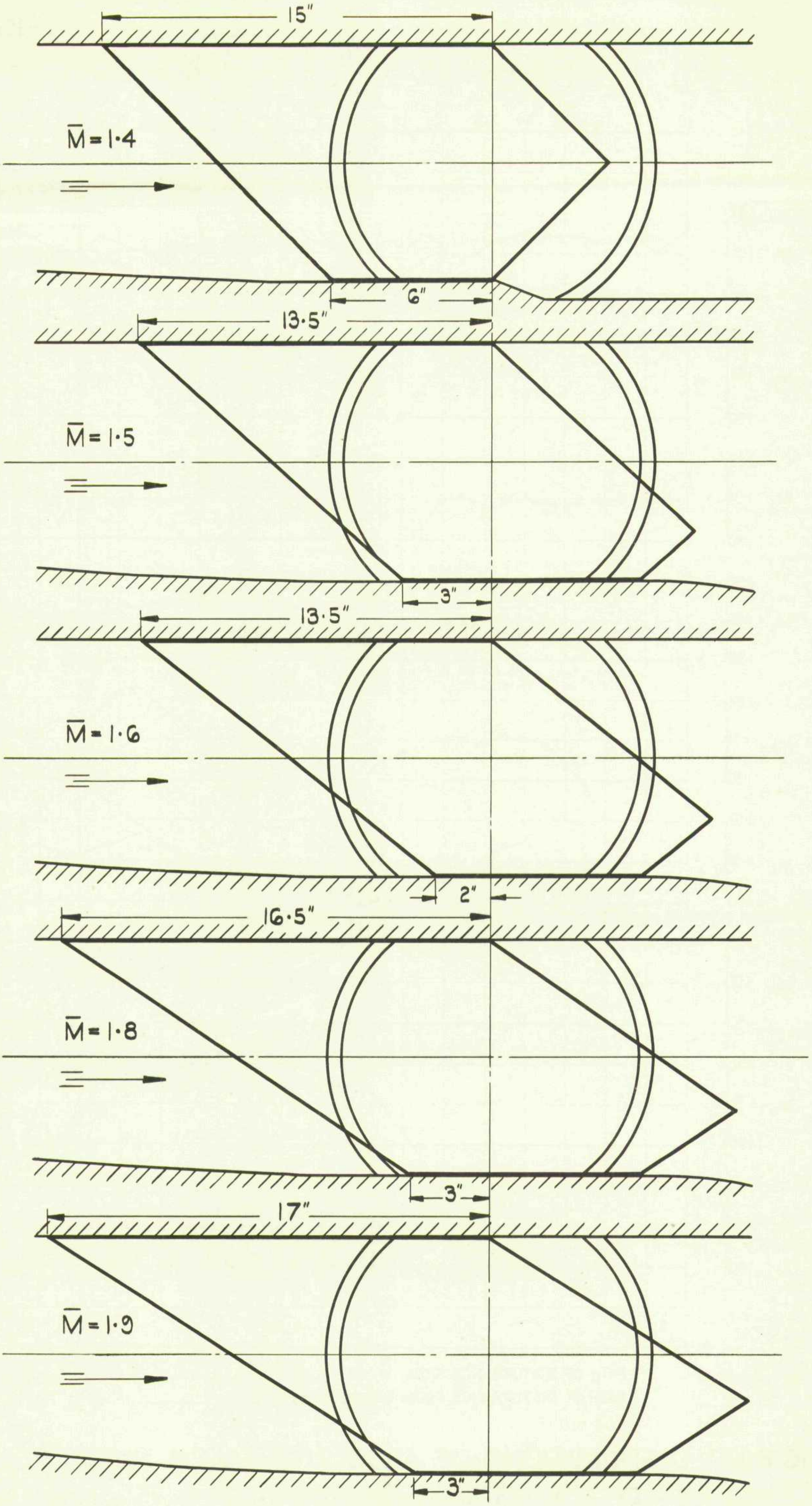

FIG.9 INDICATION OF WORKING SECTION BOUNDARIES.

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