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Some Investigations into the Spanwise Non-Uniformity of Nominally Two-Dimensional Incompressible Boundary Layers Downstream of Gauze Screens

By B. G. de Bray

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By B. G. de Bray

Reports and Memoranda No. 3578*
July, 1967

Summary.

This Report describes investigations on spanwise non-uniformity in boundary-layer flow at low subsonic speeds over a range of experimental conditions, covering particularly the effect of varying number and open-air ratio of screens, type of honeycomb, flow contraction, surface curvature, and downstream position of measuring plane. Regions with laminar and turbulent boundary layers were investigated.

Bradshaw's investigations into the effect of open-area ratio are confirmed. The conclusion is drawn that in a boundary-layer tunnel, where spanwise uniformity is essential, at least the two downstream screens should have open-area ratios ~~less~~ greater than 0·57. The Report also recommends the use of a high-quality honeycomb downstream of the screens.

Whilst open-area ratios greater than 0·57 are also advisable for new general-purpose tunnels, the Report suggests that the cost of changing the screens of existing tunnels is scarcely justifiable economically.

CONTENTS

*Replaces A.R.C. 29 271.

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1. *Introduction.*

Many investigators have reported the existence of spanwise non-uniformity in boundary layers in wind tunnels and similar apparatus, even when considerable care was taken to achieve two-dimensional geometry. Head and Rechenberg[3] and Fernholz[2] found this in circular pipes; Bradshaw[1] and Patel[7] on the walls of two-dimensional tunnels; and Fernholz and Patel on plates and aerofoils inserted in tunnels.

Klebanoff, Tidstrom and Sargent[6] showed that three-dimensional effects in turbulent boundary layers were initiated by the mechanism of transition, whether natural or forced. Doubt is thrown upon this as the cause of the above non-uniformities by the experiments of Bradshaw, who showed that the magnitude of the variations was critically dependent upon the characteristic of the gauze screens upstream of the measuring positions.

Klebanoff and Tidstrom had found screen-induced non-uniformities in their earlier work on transition[5] and minimised these by changing the screens. In the present work, non-uniformities were found in laminar as well as turbulent boundary layers.

Bradshaw stated that screens with an open-area ratio less than about 0·57 (corresponding to a pressure drop of about $1{\cdot}6q$ at 12 ft/sec) produce spatial instability sufficient to cause these effects.

The present investigation is aimed at assessing the importance of the type of screen for use in wind tunnels for various purposes. Many general-purpose tunnels are in existence with $2q$ to $2\frac{1}{2}q$ screens, since such high-loss screens have been considered to give the most economic arrangement for reducing upstream variations in longitudinal and transverse velocities, both mean and fluctuating. These screens, however, themselves produce non-uniformities as described by Bradshaw, so that a re-assessment of screen selection considerations seems desirable.

In the present experiments, spanwise boundary-layer non-uniformity was investigated at low subsonic speeds for a wide range of conditions, using Preston-tube traverses.

All the experiments were done in one tunnel (a two-dimensional blower tunnel designed for boundary-layer research) but by the use of vertical and horizontal central flat plates and a central flat splitter extending upstream to the gauzes the following variations were investigated, in addition to changing the open-area ratio and number of screens and the type of honeycomb:

(a) Flow contraction in the plane of the test surface, by comparing vertical and horizontal flat plates.
(b) Surface curvature of the contraction wall, by comparing rear wall with splitter.
(c) Continuity of surface from screen, by comparing flat plate in test section with splitter.
(d) Distance of measurement plane from screens along direction of flow.

It will be seen (Section 2 and 3) that spanwise non-uniformities, dependent upon the arrangement of screens and honeycomb, were found with all these arrangements. The implication is that non-uniformities in the air-flow outside the boundary layer, produced by the screens, persist into the test section and cause irregularities of the boundary layer in any object placed in it. Further, the close similarity in the pattern of boundary-layer non-uniformity found by taking traverses at various distances in the flow direction along a tunnel wall, for example, suggests the possibility that such variations are related to a persistent pattern in the free stream. Some experiments to investigate this possibility are described in Section 4.

2. *Experiments.*

The wind tunnel used was the 5 ft x 1 ft blower tunnel of the Cambridge University Engineering Laboratory. Fig. 1 shows the downstream portion of the tunnel. Immediately upstream of screen 1 is a transition section 4 ft long from the 5 ft dia. fan section to 5 ft square. The centrebody of the axial-flow fan extends to screen 1. The contraction is two-dimensional based on the equation for the half-width $y = 5/2 - 2x/5 + (\sin 2\pi x/5)/\pi$, x and y being in ft. The front 5 ft wide wall of the test section is flexible.

Two types of screen were used:

Type *O* 31 swg by 24 mesh, open-area ratio 0·520

Type *N* 28 swg by 16 mesh, open-area ratio 0·600.

Nearly all the experiments were done with a honeycomb having $\frac{3}{4}$ in. hexagon cells 6 in. long made of Kraft paper, built up from 3 ft x 1 ft slabs. The junctions between the slabs were imperfect resulting in lack of parallelism of the passages of adjacent slabs; as much as 2 deg error was measured. For a few final experiments this honeycomb was replaced by a much more accurate aluminium one with 5/16 in. hexagon cells 3 in. long and no joints.

Fig. 1 also shows the vertical central plate, the vertical central splitter, and the horizontal central plate in its three positions. All these were $\frac{3}{4}$ in. thick with semi-elliptic noses (in the case of the splitter the nose was upstream of the last screen) and tapered trailing edges.

The vertical walls and the splitter plate were fitted with rough strips for transition in the transverse plane of the end of the contraction. Transition devices on the flat plates, when used, were of wire or nylon mono-filament underneath Sellotape.

All boundary layer traverses were done at one of the transverse planes A, B, C or D. The traversing head carried a Preston tube and a static tube, both 0·043 in. dia., side by side and 0·5 in. apart, both in contact with the surface. Vertical traversing was restricted to the middle 3 ft (approximately) of the 5 ft tunnel height, and horizontal traversing to the middle 9 in. of the 12 in. width.

Normally only the differential pressure across the two tubes was measured, but some checks with separate readings were done to show that the spanwise variations in static pressure were insufficient to cause any inaccuracies. Readings were taken at spanwise intervals of 0·2 in. or 0·4 in. on the 5 ft wide surfaces and 0·1 in. on the 1 ft wide surfaces. Pressures were read in mm alcohol at 10 deg slope.

For measurements on the rigid rear tunnel wall and on the splitter plate, the flexible wall was adjusted to give zero longitudinal pressure gradient. With the vertical plate, the wall was adjusted to give a favourable pressure gradient over the upstream 6 in. to avoid a separation bubble. Over the rest of the plate the gradient was adjusted as required (Table 1). With the horizontal plate, the walls were parallel and the plate itself adjusted to a small angle to give zero pressure gradient (except at the nose).

All readings were taken at a nominal tunnel velocity of 42·2 ft/sec, (Re/ft 0·27 x 10^6).

3. *Discussion of Results.*

Table 1 lists the traverses measured and the Figure numbers in which they are plotted. It also gives the mean values and the scatter of the pressure readings (Preston – static). The scatter of the turbulent-friction coefficients are slightly less than those of the pressures since $\tau_0 \propto (P-p)^{7/8}$ (Ref. 8), but pressure readings are adequate for comparisons. The traverses are plotted in Figs. 2 to 8. In these Figs. the ordinate ΔP is equal to 69·7 x ΔC_p (as defined at the foot of Table 1).

3.1. *Effect of Type of Honeycomb.*

All traverses, except those plotted in Fig. 3, were done with the $\frac{3}{4}$ in. mesh paper honeycomb. Irregularities arising from this honeycomb are shown in the traverses done with only one screen (which is upstream of the honeycomb), i.e. numbers 2(a), 4(a) and 5(a). These all show large variations with 6 in. to 12 in. pitch, which do not appear with corresponding traverses with the aluminium honeycomb, curve 3(a), nor in any traverse where there are two screens downstream, such as 2(b) and (c), 4(b) and (c), 5(b) and (c). It is concluded that comparisons made with all screens in place are not invalidated by the rather poor flow uniformity from the $\frac{3}{4}$ in. paper honeycomb. This is supported by comparing curves 2(b) with 3(b), and 2(c) with 3(c); the similarity between these pairs of curves, in spite of the widely different honeycomb quality upstream of them, clearly show that they are predominantly screen patterns and not honeycomb patterns.

3.2. *Effect of Screen Type.*

Comparing graph (b) with (c), in Figs. 2, 3, 4 and 5 shows that the 0·520 open-area ratio screens (0) caused variations at about 2 in. pitch which were two to three times as large as those found with 0·600 open-area ratio screens (*N*). The 0 screens in fact gave little or no improvement in overall variation from the $\frac{3}{4}$ in. honeycomb in spite of its poor quality. They made the flow from the 5/16 in. honeycomb much worse. Thus Bradshaw's findings on the effect of screen open-area ratios are confirmed, as are Patel's findings that minimum spanwise variations are obtained by using a high-quality honeycomb downstream of any screens.

Graph 2(d) shows that the last screen has greater effect on the pattern than the other screens. The graphs in Figs. 2, 3 and 5 are for turbulent boundary layers after fixed transition, whereas those of Fig. 4 are for laminar layers (confirmed by china clay and stethoscope techniques), so the conclusion as regards the effect of type of screen appears to be quite general. Further, the fact that the laminar layers show larger variations (both in magnitude and as percentage of the mean) than the turbulent layers further downstream, and also have points of similarity in their patterns (*cf.* corresponding graphs in Figs. 4 and 5), clearly indicates that these variations do not originate at the transition devices.

Various transition devices were experimented with on the vertical plate with zero pressure gradient. The pattern downstream, Fig. 5(b), was practically unaffected by changing transition wire size from 0·031 to 0·055 in. dia. and its position from $\frac{1}{2}$ in. to 12 in. from the leading edge; the use of a serrated strip 0·032 in. thick with $\frac{1}{4}$ in. pitch saw tooth serrations on its upstream edge, did not affect this very persistent pattern. Klebanoff and Tidstrom[5] found that a screen-induced pattern was not affected by making a new surface and a new leading edge on their flat plate.

The type of screen is thus seen to be the major controlling factor in the flow variations.

3.3. *Effect of Flow Contraction in the Plane of the Test Surface.*

These and subsequent tests were done with the $\frac{3}{4}$ in. honeycomb and 0·520 open-area screens (type 0) only.

It has been suggested that the shape of the contraction in a general-purpose tunnel would cause a reduction in pitch of spatial non-uniformities due to the screens and hence reduction in their amplitude due to increased mixing between high and low-velocity regions, as compared with results obtained in boundary-layer tunnels with two-dimensional contractions.

Comparative tests on vertical and horizontal central plates are shown in Figs. 4 and 5, curves (b) and (d); Fig. 4 is for laminar layers 12 in. from the leading edge and Fig. 5 for turbulent layers after forced transition, 42 in. from the leading edge. (Transition wire at 12 in. from leading edge). The graphs for the horizontal plate are drawn both with the actual z scale and with this opened up five times, the contraction ratio. The pitch of the predominant variations is reduced (roughly halved) but not in proportion to the contraction ratio, and the amplitudes are reduced, but the percentage variations are practically identical, the mean values being smaller on the horizontal plate. The reason for the thicker boundary layers on the horizontal plate was not established, but there may have been a short bubble near the leading edge, which was avoided with the vertical plate by using the flexible wall as already stated.

A similar comparison using the vertical and horizontal tunnel walls was invalidated by strong corner effects extending the full 12 in. width of the horizontal wall.

3.4. *Effect of Surface Curvature.*

The possibility of spanwise variations being affected by wall curvature by a mechanism similar to that producing Goertler vortices, was investigated by comparing traverses on the rear wall (downstream of the curved contraction wall) with those on the flat splitter, both forward and aft of the transition strips, (Fig. 6). Both surfaces were continuous to upstream of the last screen.

The variations on the splitter were from $\frac{1}{2}$ to 2/3 of those at corresponding transverse planes on the rear wall. This difference is not conclusive as the degree of non-uniformity fed on to the two surfaces by the screen may not have been identical.

Though there may be differences in the flow pattern through the honeycomb in the plane of the splitter as compared with the rear wall, tests already described show that such differences are unlikely to persist through the two screens downstream. Hence it would appear that the differences in non-uniformity between the splitter and the rear wall are due to wall curvature.

3.5. *Effect of Surface Continuity from the Screens.*

Comparison of traverses in plane C on the vertical plate and plane B on the splitter, Fig. 5 graph (b), and Fig. 6, graph (d), show that the plate had 20 per cent larger variations but expressed as a percentage of the mean values the variations on the plate were less, (since the plate had a thinner boundary layer giving a higher mean pressure reading). This comparison is not strictly valid owing to the different traversing planes. Moving the plate bodily upstream so that the traversing planes coincided would be expected to increase the variations on it, based on measurements described in the next Section for the horizontal plate. If the increase were the same as found for the latter plate, corresponding variations would become about 50 per cent higher for the plate than for the splitter (equal values expressed as a percentage of the mean).

3.6. *Effect of Distance of Measurement Plane from Screens* (*with* $\partial P/\partial x = 0$).

3.6.1. *Turbulent boundary layer on horizontal flat plate placed at various positions along test section.*

Fig. 5, graphs (d), (e), (f), compare measurements at planes B, C, D, Fig. 1, all at 42 in. from the leading edge, the plate being moved to the required position.

The mean pressure reading remained substantially constant as would be expected and the variations fell only from $\pm 6{\cdot}7$ per cent to $+5$ per cent in a distance of 5 ft.

3.6.2. *Developing turbulent layer on rear wall.*

Traverses at planes B, C and D, Fig. 3(b), (d) and (e), show that as the turbulent layer became thicker the magnitude of the spatial variations decreased in proportion to the mean value of the pressure readings, so that the percentage variation remained constant. The similarity of these three traverse patterns is very marked.

This similarity (in pattern and percentage variation) even extends to a traverse forward of the roughness strip at the end of the contraction, Fig. 6(a). However it cannot be deduced from this test that a pattern persists through transition because the forward boundary layer was not fully laminar ($H = 1{\cdot}85$). Tests on the vertical plate, however, do show some similarity in such patterns, as already mentioned.

3.7. *Effect of Pressure Gradient. Tests on Vertical Flat Plate Using Flexible Wall.*

3.7.1. *Fixed transition, fixed distance from transition to measuring plane.* Traverses at plane C with the static pressure gradient $\frac{\partial P/\partial x}{\rho U^2}$ on the rear 36 in. of the 48 in. chord plate adjusted to values from $-0{\cdot}121$ to $+0{\cdot}118$ per foot, caused negligible change in the variation of the boundary-layer pressure readings when expressed as percentages of the mean pressures, although these mean values changed by a factor of two. The general shape of the curves, Fig. 7(a), (b), was not greatly affected by the pressure gradient.

3.7.2. *Free transition at varying distance from measuring plane.* For these tests transition was detected using the china-clay technique. Positive pressure gradients were used to give transition from 24 in. to 42 in. from the leading edge. In the latter position the measuring plane (C) was in the transition region. Fig. 8 shows four traverses also a curve giving the position of the transition for traverse (d).

The very large variations in pressure readings in the transition region and the very large extent to which they are reduced as transition moves forwards under increasing adverse pressure gradients, is noticeable. The similarity between curves (a) and (b), (c) and (d) indicates the transition is not complete at curve (c). After it is complete the rate of reduction of amplitude of the variations with distance downstream of transition is very much reduced, as shown by curves (a) and (b).

Fernholz found a similar effect with free transition in a circular pipe having a variable adverse pressure gradient; also upon an aerofoil spanning a wind tunnel, again with free transition.

4. *Correlation between Non-Uniformity in Boundary Layer and in Free Stream.*

Bradshaw has shown that variations of the type described in this Report could be caused by very small variations in flow direction (of the order of 0·05 deg) initiated by the screens. These must persist in the free stream through the contraction and test section in order to cause variations in the boundary layer of any object placed in the test section.

These small directional variations would be very difficult to measure. They could be accompanied by small changes in U- component of velocity and in turbulence, both being more readily measured. Possible correlation between free stream and boundary-layer variations was investigated at the rear wall of the tunnel, traverse B, by mounting an additional total head tube, identical with the Preston tube and directly above it at various distances from the wall, up to about 2δ. The longitudinal turbulence $\sqrt{\overline{u^2}}/U$ was also measured at this maximum distance. The results (Fig. 9) show that the pattern of non-uniformity given by the Preston tube persists through the inner three-quarters of the boundary layer, but then falls off rapidly to the edge of the layer. When the amplitude of the variation is expressed as a fraction of the mean value $(\overline{P_T - p}$ = total pressure – static pressure), the curve is somewhat similar to the intermittency curve of Klebanoff[4] shown by the dotted line.

Measurements at about $1{\cdot}5\delta$ and 2δ show very slight variations which are spatially out-of-phase with the much larger variations in the boundary layer. The former are consistent with, and smaller than, variations in the semi-width of the channel outside the boundary-layer due to variations in displacement thickness along the traverse. No evidence can therefore be derived as to any interaction between the boundary layer and free stream, from this test.

The results of a further test, in which the free stream was deliberately made non-uniform, are shown in Fig. 10. Using the imperfect $\frac{3}{4}$ in. honeycomb with no screens downstream, (the single screen being upstream), the longitudinal turbulence and U-component velocity in mid-stream of the empty tunnel at position B varied as shown (± 32 per cent turbulence, ± 5 per cent U).

Now putting in the central vertical plate, some correlation with Preston tube traverses at positions B and C, and with transition position as indicated by china clay, is evident. The regions of high free-stream turbulence ($z = 4$ in. and 16 in.) show early transition, and high c_f values in both laminar and turbulent regions. In fact the laminar traverse could well result from a combination of the variations of turbulence and mean velocity, high c_f values occurring at peaks of both these variables. The turbulent traverse with fixed transition, 29 in. further downstream, is a close copy of the laminar traverse; closer than was obtained at corresponding traverses with a more uniform free stream (compare corresponding curves

(b) and (c), Figs. 4 and 5). This is some evidence that this very non-uniform free stream is exerting some control over the boundary-layer variations while flowing over the plate, as well as initiating these variations near the leading edge.

The correspondence between traverse C after free transition and the free-stream turbulence may be partly fortuitous as the low c_f region ($z = 9$ in.) may be due to incomplete transition.

There is no conclusive evidence from these tests that the slight variations in the free-stream which one would consider reasonable in a wind tunnel have a controlling effect on the spanwise variations across a boundary layer, other than that of initiating such variations at the leading edge, or at the screen itself in the case of a continuous wall.

5. *Conclusions.*

The conclusions given below refer to the fractional variations in boundary-layer pressure readings (as given for example in the last column of Table 1).

(i) Non-uniformities in the air-flow downstream of the gauze screens persist through the contraction and test section. Although not measurable themselves by normal techniques, they react on the boundary layer on the tunnel walls or on any object placed in the tunnel, causing substantial spanwise variations in the boundary layer.

(ii) The honeycomb mesh and directional uniformity has a powerful influence on the magnitude of the boundary-layer variations, but only if there are no screens downstream of the honeycomb. In the present tests, two screens of open-area ratio either 0·520 or 0·600 were sufficient to eliminate very large variations due to an imperfect honeycomb. However, the screens impress their own pattern of non-uniformity.

(iii) The type of screen is the main controlling factor for non-uniformity in conventional tunnels. Screens with an open-area ratio of 0·520 gave considerably greater non-uniformity than those with a ratio of 0·600. This confirms the findings of Bradshaw who gave a minimum ratio of 0·570 for 'good' screens.

(iv) With more than one screen, the open-area ratio of the downstream screen has the most effect.

(v) A high-quality honeycomb of fine mesh (5/16″ in these tests) gave much better results than either of the screens used.

(vi) The effect of the shape of the contraction, i.e. whether two-dimensional as usual in boundary-layer tunnels, as compared with three-dimensional as generally used in general-purpose tunnels, is small.

(vii) Some evidence was found that wall curvature had a substantial effect in increasing the non-uniformity.

(viii) There was little difference in the variation in the boundary layer of a central flat plate in the test section, and that of a central splitter extending upstream through the contraction and the last screen.

(ix) The effect of distance along the tunnel from the screens to the measuring plane was very small, both for a continuous wall and for a given flat plate placed in various positions along the test section.

This conclusion applies to turbulent boundary layers and is independent of the distance from transition to the measuring plane.

(x) The effect of pressure gradient along a flat surface, with fixed transition, was negligible.

(xi) When pressure gradient is used to control the position of free transition, boundary-layer non-uniformity is strongly influenced by the closeness of transition to the measuring plane. The non-uniformity increases markedly in the transition region.

(xiii) Laminar boundary layers showed greater fractional variations than the turbulent boundary layers further downstream on the same surfaces, but the patterns of the variations had points of similarity. A given honeycomb and screen arrangement tended to impose a given pattern form on both laminar and turbulent layers.

The conclusions given above are consistent with the existence, in the free air-stream, of a system of trailing vortices originating at the screens. This system persists through the contraction and test section and interacts with the boundary layer on every surface within the tunnel.

A possible cause of this vortex system is shown in Fig. 11, vortices of opposite sign originating at adjacent meshes, and this fine-mesh system becoming coarser as it flows downstream by the grouping together of bundles of vortices (bundles of five are shown).

A smoke-tunnel test on an enlarged model of a section of a screen would throw light on this conjecture.

The similarity between the curves of intermittency and fractional changes in pressure readings at different depths in the boundary layer (Fig. 9) may not be coincidental. Both are measures of the degree of non-uniformity; one a temporal non-uniformity when spatial variations (across the flow parallel to the wall) are ignored, and the other a spatial non-uniformity when temporal variations are evened out by the measuring system used (liquid-filled manometers with long connecting tubes).

6. *Acknowledgements.*

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APPENDIX

Choice of Screen and Honeycomb Arrangements for Low-Speed Wind Tunnels.

A.1. *Boundary layer tunnels.*

Since spanwise uniformity is a prime requirement, open-area ratios less than 0·57 should be avoided for the two downstream screens at least.

In existing tunnels, such a change of the two downstream screens is unlikely to have any marked effect on the turbulence level. In the present tunnel the measured turbulence level $\left(\sqrt{\overline{u^2}}/U\right)$ in the centre of the test section was only increased by 3 per cent with a complete change of screens from 0·52 to 0·60 ratio.

Optimum spanwise uniformity is obtained by having a high-quality honeycomb downstream of the screens, the main purpose of the latter being to reduce variations in mean longitudinal velocity to a low level. This arrangement, however, would probably necessitate a longer settling length to obtain a given turbulence level in the test position. For the same reason, a honeycomb in this position should be of fine mesh.

A.2. *General purpose tunnels.*

The majority of work in these tunnels is done on models suspended near the axis of the test section. Such models generally have large pressure gradients and in cases where boundary-layer behaviour is important transition is usually produced artificially.

The present work indicates that percentage spanwise variations in the boundary layer on such models are less than those found on tunnel walls, (about one-third) except in the laminar and transition regions which are generally of limited extent. It does not appear that the three-dimensional contraction which is usual in this type of tunnel plays a significant part in this difference.

While it would be advisable to use a large ($\nless 0{\cdot}57$) open-area ratio downstream screen in new tunnels, it seems doubtful whether the cost of changing screens on existing tunnels, particularly large ones, would be justified. A further factor supporting this conclusion is the large distance from the screens to the model in large tunnels, though the effect of this in allowing diffusion of irregularities appears to be small.

These conclusions should be applicable to larger tunnels than that used in the present experiments, since the *screen* Reynolds Number is not affected by tunnel size, but only by the mesh size and the air velocity at the screens.

TABLE 1

Particulars of Tests.

Fig. No.	Graph	Tunnel		Traverse				Values		
		H'comb	Screens	Surface	Posn.[1]	Transn.	$\frac{\partial P/\partial x^2}{\rho U^2}$	ΔC_{pMean}[2]	$\pm\Delta C_p$	$\pm$%
2	a	$\frac{3}{4}''$	1,*O*	Rear wall	*B*	Fixed[4]	0	0·281	0·059	21
	b		3,*O*					0·287	0·055	19
	c		3,*N*					0·293	0·024	8·5
	d		2,*O*+1,*N*					0·287	0·034	12
3	a	5/16"	1,*O*	Rear wall	*B*	Fixed[4]	0	0·278	0·016	5·2
	b		3,*O*		*B*			0·280	0·053	19
	c		3,*N*		*B*			0·281	0·020	7·3
	d		3,*O*		*C*			0·258	0·047	18
	e		3,*O*		*D*			0·233	0·044	19
4	a	$\frac{3}{4}''$	1,*O*	Vertical plate	*B*	—	0	0·265	0·040	15
	b		3,*O*					0·240	0·057	23
	c		3,*N*					0·227	0·023	10
	d		3,*O*	Horiz. plate				0·138	0·034	25
5	a	$\frac{3}{4}''$	1,*O*	Vertical plate	*C*	Fixed[5]	0	0·410	0·032	7·7
	b		3,*O*					0·390	0·027	6·8
	c		3,*N*					0·390	0·012	3·1
	d		3,*O*	Horizontal plate	*B*			0·315	0·021	6·7
	e		3,*O*		*C*			0·321	0·016	5·0
	f		3,*O*		*D*			0·333	0·017	5·0
6	a	$\frac{3}{4}''$	3,*O*	Rear wall	*A*	Fixed[4]	0	0·253	0·046	18
	b			Splitter	*A*			0·214	0·026	12
	c			Rear wall	*B*			0·287	0·055	19
	d			Splitter	*B*			0·261	0·023	9·2
7	a	$\frac{3}{4}''$	3,*O*	Vertical plate	*C*	Fixed[5]	−0·121	0·569	0·044	7·8
	b						+0·118	0·304	0·024	8·0
8	a	$\frac{3}{4}''$	3,*O*	Vertical plate	*C*	Free	+0·118	0·367	0·013	3·5
	b						+0·075	0·466	0·019	4·0
	c						+0·069	0·510	0·057	11
	d						+0·060	0·275	0·122	44
	e						+0·060	—	—	—

NOTES

1 *See* Fig. 1.

2 Per foot.

3 $\Delta C_p = \frac{\text{Pressure difference (Preston − static)}}{\text{Tunnel contraction pressure difference}}$.

4 Roughness strip at end of contraction.

5 0·055" wire at 12" from L.E.

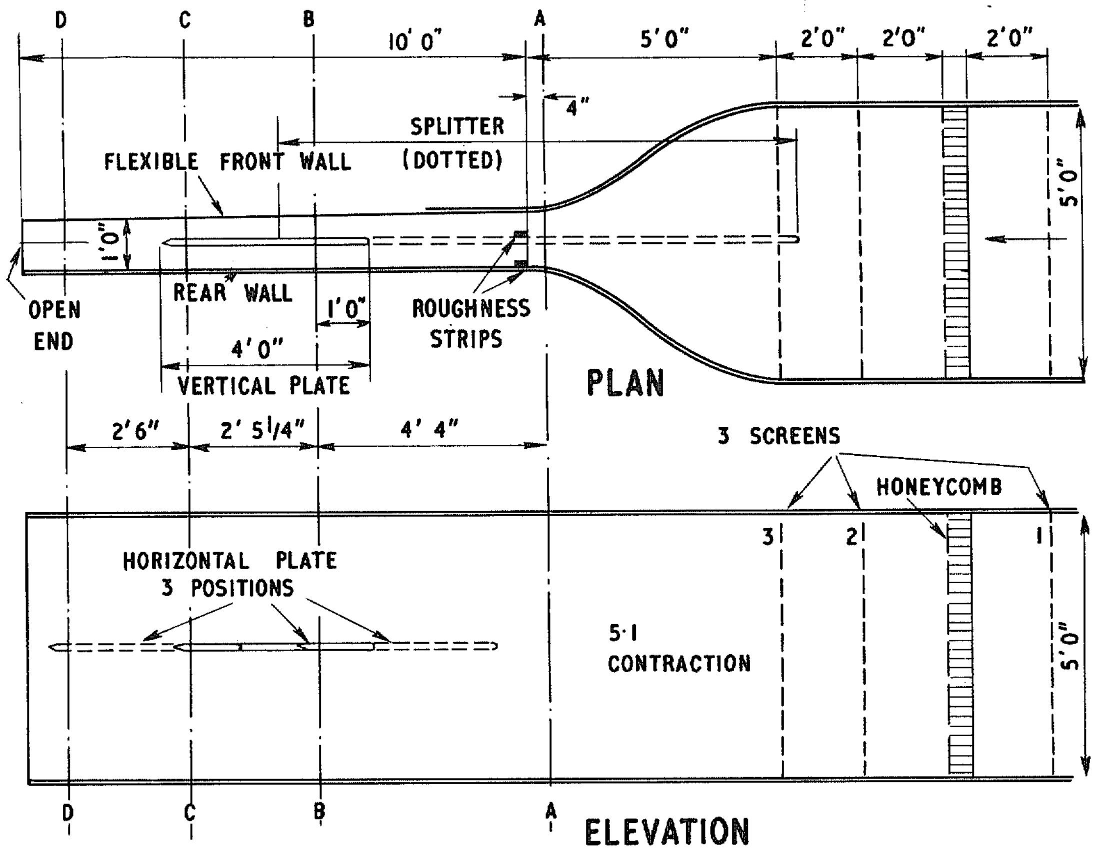

FIG. 1. Tunnel layout.

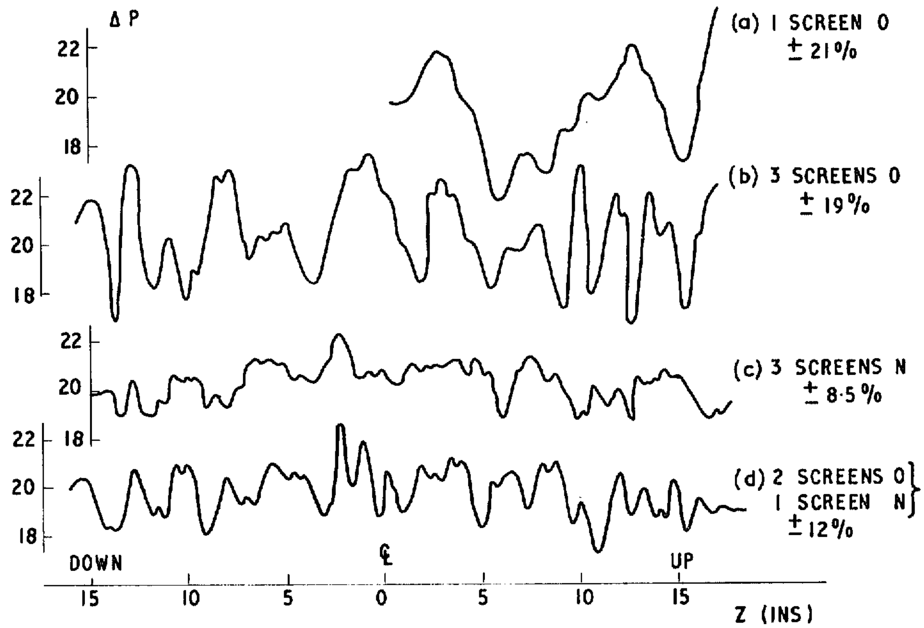

FIG. 2. Rear wall. Traverse B.

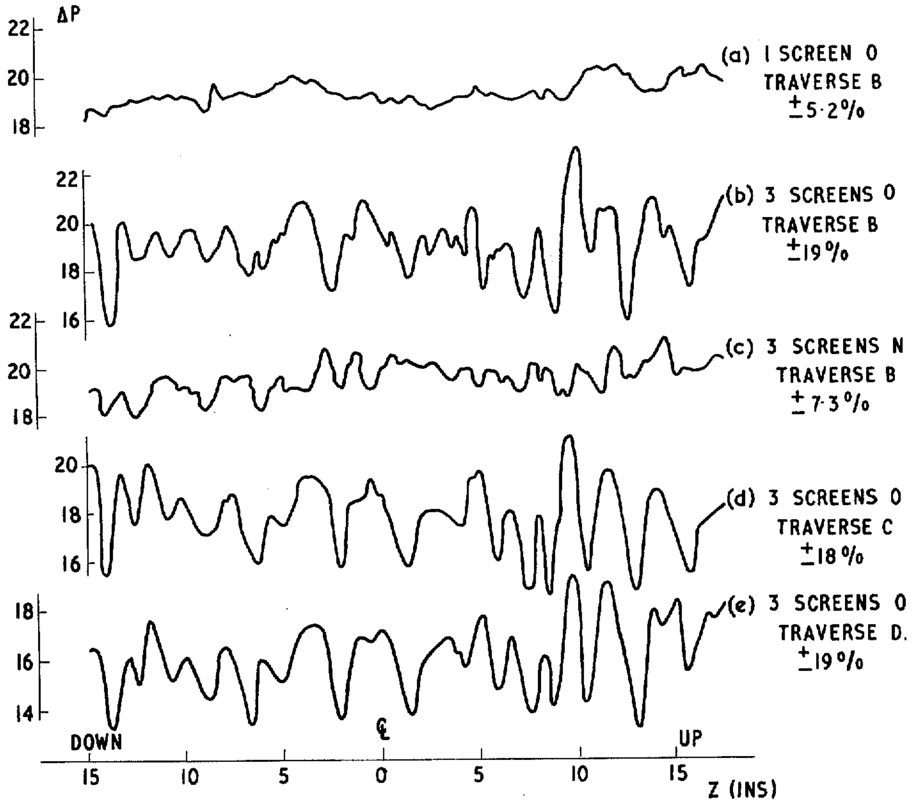

FIG. 3. Rear wall. New honeycomb.

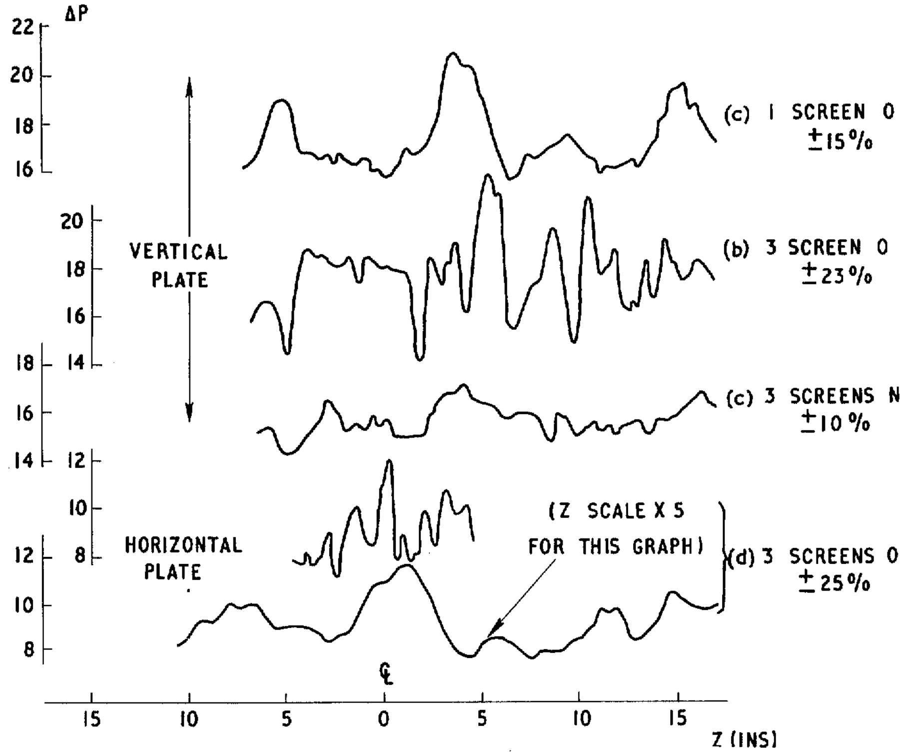

FIG. 4. Central plates. Traverse B (laminar).

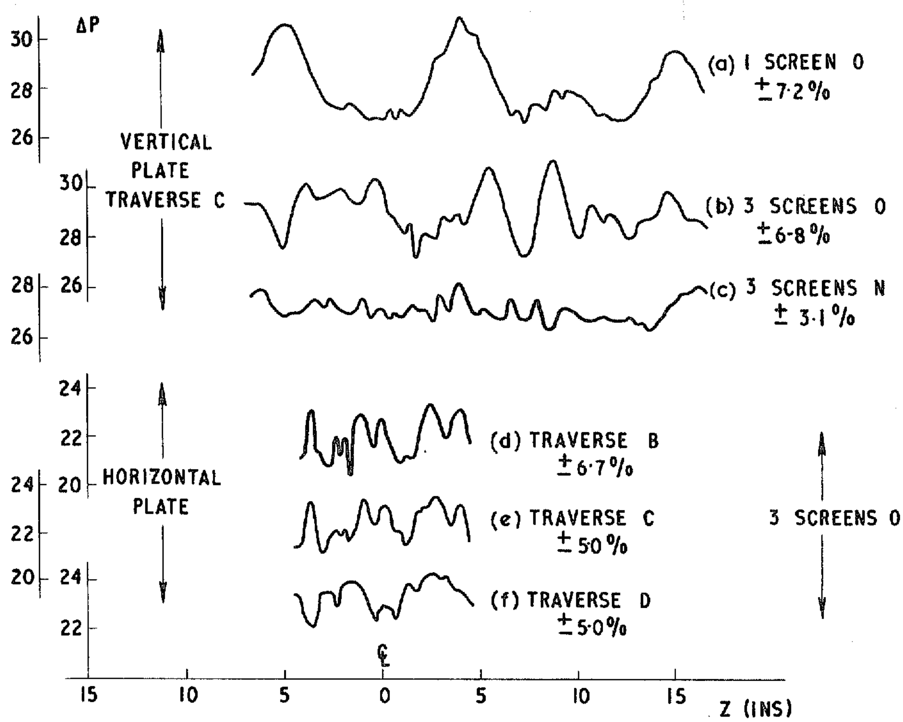

FIG. 5. Central plates. Turbulent traverses. Fixed transition $\delta P/\delta x = 0$.

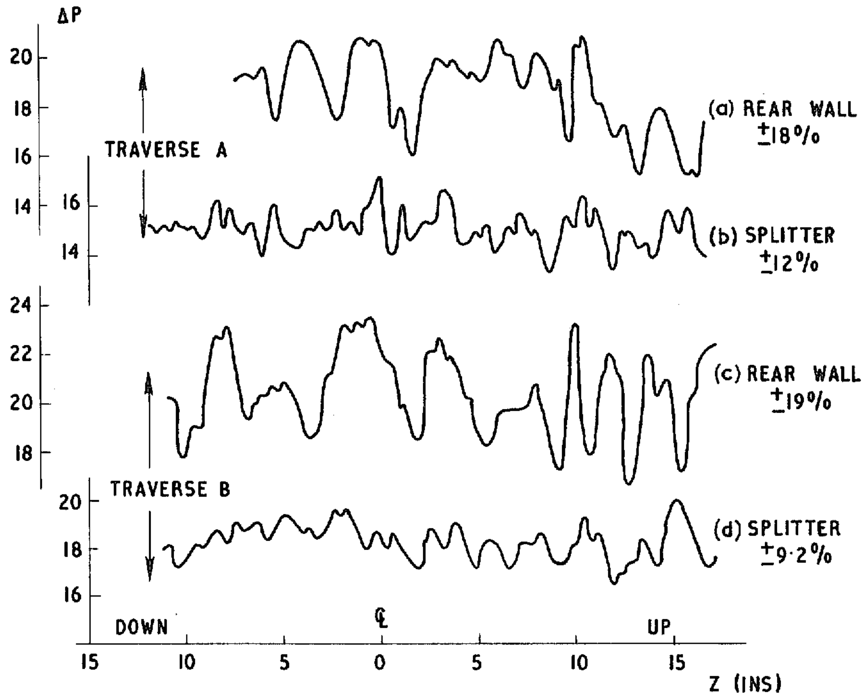

FIG. 6. Traverses on rear wall and splitter. 3 screens O.

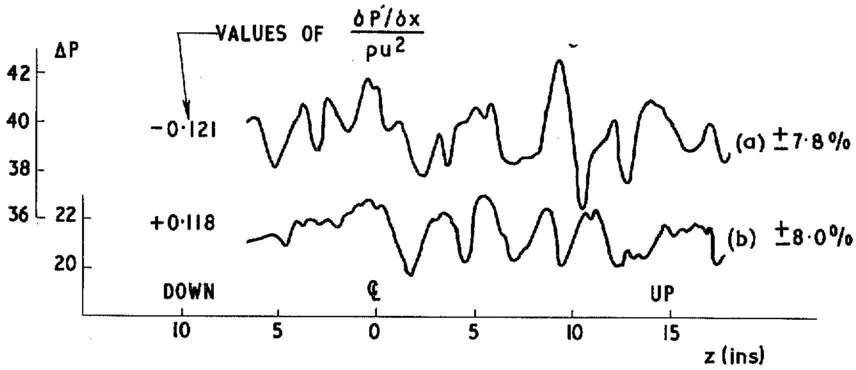

FIG. 7. Traverses C on vertical plate. 3 screens 0. Effect of pressure gradient. Fixed transition.

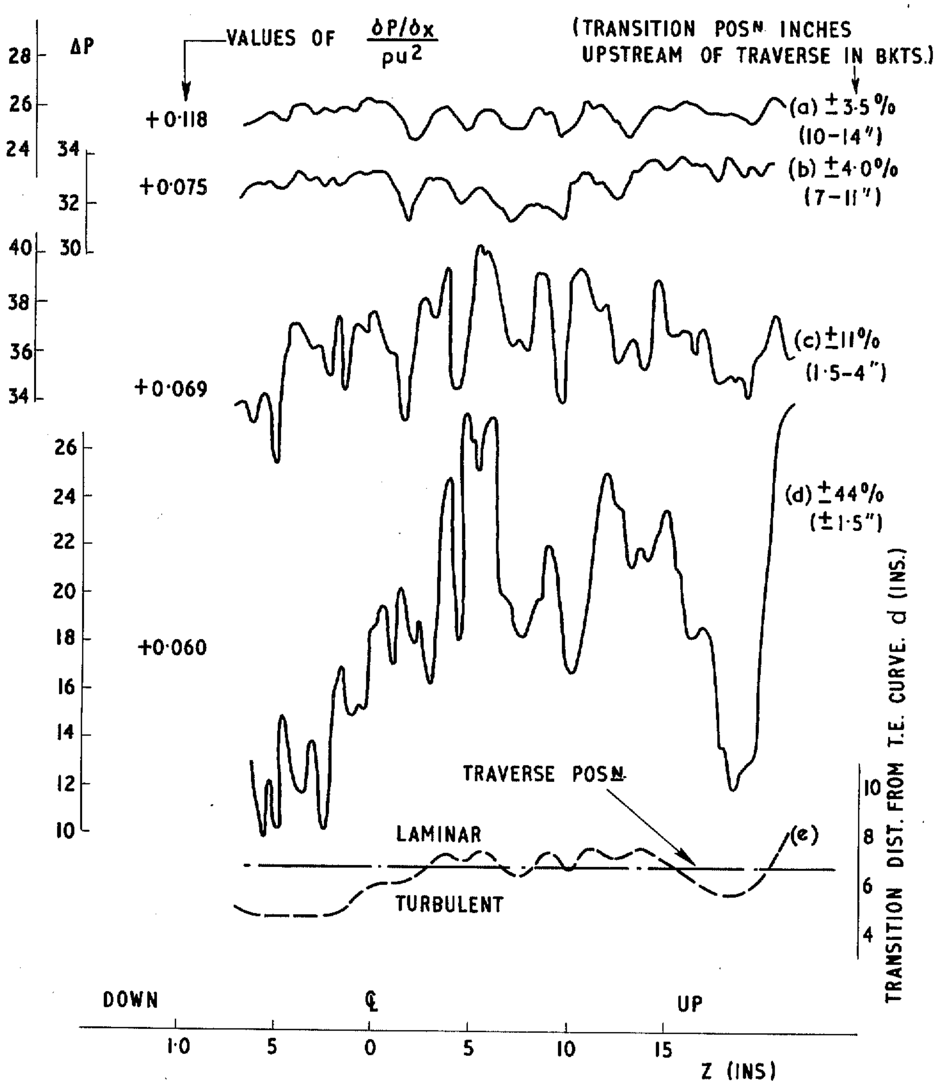

FIG. 8. Traverses C on vertical plate. 3 screens 0. Effect of pressure gradient. Free transition.

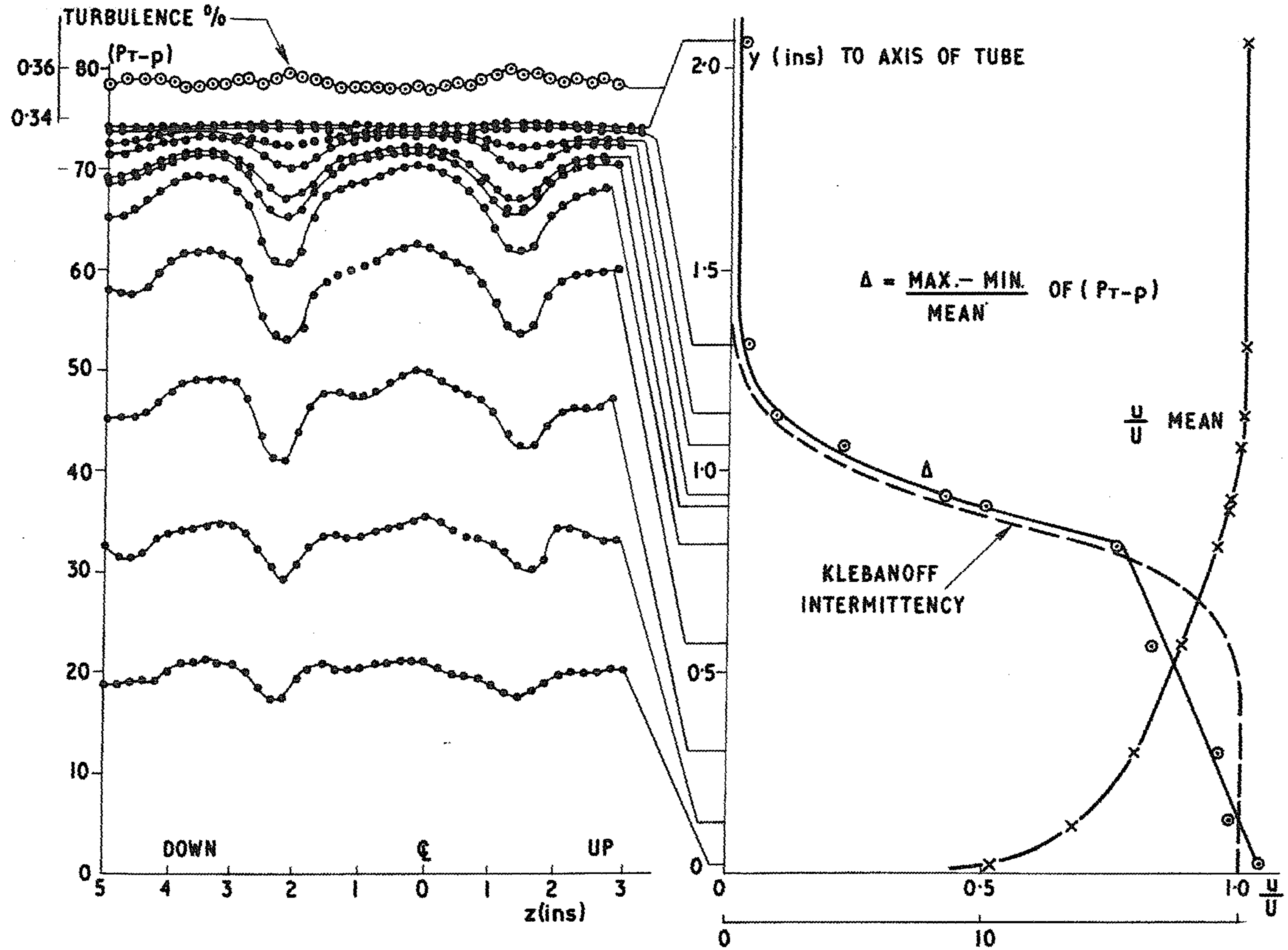

FIG. 9. Rear wall. Traverse B with total head tube. 3 screen 0. 5/16 in. hor-

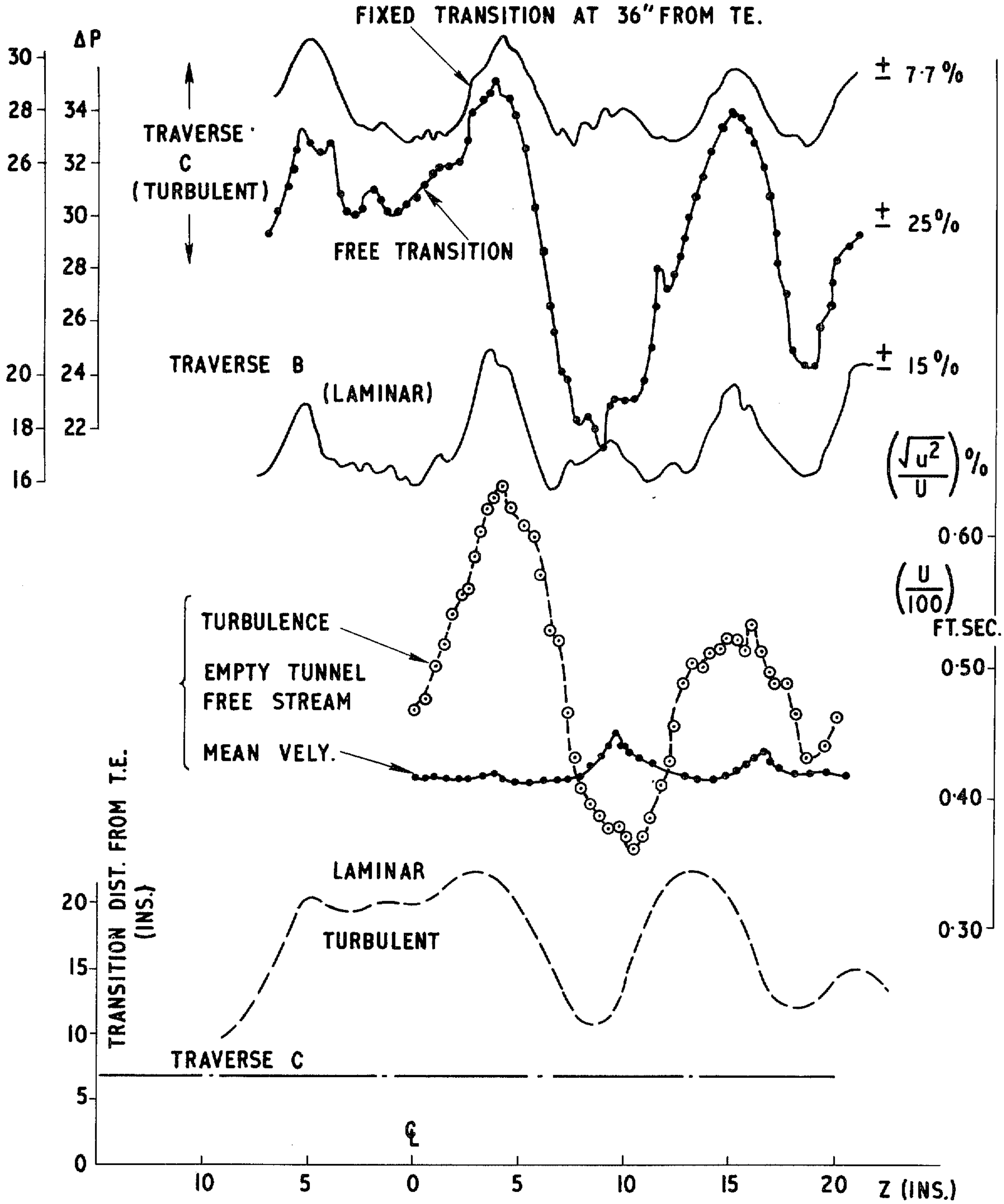

FIG. 10. Vertical flat plate. 1 screen 0, $\frac{3}{4}$ in. honeycomb.

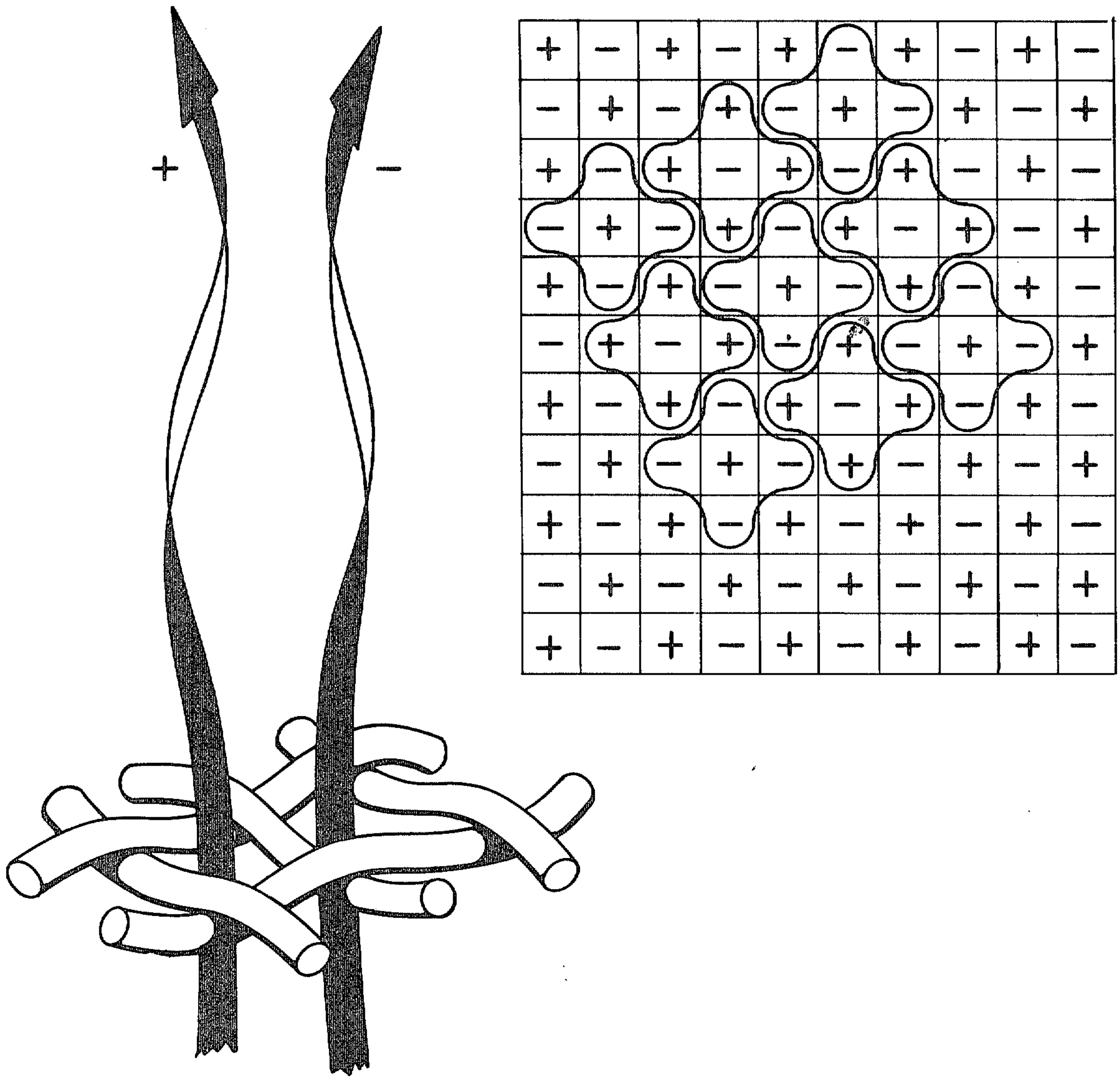

FIG. 11. Vortex formation at wire screen.

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