R. & M. No. 3261

MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

The R.A.E. 4-ft x 3-ft Experimental Low-Turbulence Wind Tunnel
Part IV. Further Turbulence Measurements

By

H. SCHUH, Dr.rer.nat.

LONDON: HER MAJESTY'S STATIONERY OFFICE
1962
PRICE £1 0s. 0d. NET

The R.A.E. 4-ft × 3-ft Experimental Low-Turbulence Wind Tunnel
Part IV. Further Turbulence Measurements

By

H. Schuh, Dr.rer.nat.

Communicated by the Principal Director of Scientific Research (Air), Ministry of Supply

Reports and Memoranda No. 3261*

June, 1953

Summary.—Further measurements of turbulence in the working section are given with 2 and 3 screens in the bulge.

The extended region of high intensity turbulence near the walls of the working section, which was observed with 9 screens in the bulge, disappeared when the number of screens was reduced from 9 to 2 or 3. The longitudinal component of turbulence is approximately independent of the number of screens; the lateral component does not change, if the number of screens is reduced from 9 to 3, but increases by a factor 2·5 to 3, if the number of screens is further reduced from 3 to 2.

In order to explain the origin of the turbulence in the working section, further turbulence measurements have been made at the end of the second diffuser, before the rapid expansion and in the bulge.

The intensities of turbulence are about 12 per cent of mean speed at the end of the second diffuser and drop to about 4 to 6 per cent before the rapid expansion.

However, this turbulence seems to be reduced by the screens in the rapid expansion and in the bulge below the level of disturbances set up by inhomogeneities of the last screen. These disturbances are the origin of the lateral components of turbulence in the working section.

The extended region of high intensity turbulence near the walls of the working section is connected with the existence of a return flow in the bulge, but several possible explanations exist as to how this produces the region of high intensity turbulence in the working section.

1. *Introduction.*—In two previous Reports[1,2] turbulence measurements in this tunnel have been described; the results of the first Report are partly obsolete, since the equipment then available did not record very low frequencies, which contribute materially to the total intensity of turbulence. The second Report[2] deals with measurements of turbulence and sound in the working section, which were made after the necessary improvements in equipment had been effected; but no explanation was given of the origin of turbulence, or of certain other features, among them a big region of high intensity turbulence near the walls of the working section. Since this tunnel was mainly built in order to gain experience in low-turbulence wind tunnels, it appeared desirable to continue the investigations, in order to provide data for the design of new tunnels or the improvement of existing tunnels. For this purpose further measurements were

* Previously issued as R.A.E. Report No. Aero. 2494—A.R.C. 16,363.

made in the working section; the influence of the number of screens in the bulge on the turbulence in the working section was studied, and the intensity and scale of turbulence was measured at the end of the second diffuser and at various places downstream and in the bulge.

In the course of these investigations a number of interesting problems of fluid motion were encountered. As far as time permitted and facilities existed, these problems have been clarified. One of the difficulties encountered was, for instance, the size of the bulge and the screens, which made detailed flow investigations in the bulge difficult; changing screens of 22-ft × 22-ft size was a major operation, involving also risks of damaging the screens and it had to be restricted to a number of essential cases. Although not every detail could be explained, most of the characteristic features and the origin of the turbulence in this tunnel could be clarified.

2. *Measurements in the Working Section.*—2.1. *Nine Screens in the Bulge.*—2.1.1. *Exploration of the region of high intensity turbulence near the walls of the working section.*—Intensity and frequency spectra of all three components have already been measured, and the results are given in Ref. 3. A big region of high intensity turbulence near the walls of the working section was also mentioned in Ref. 3; this will now be investigated in more detail. The intensity of turbulence measured on a vertical traverse from the centre-line across the lower part of the working section is shown in Fig. 1. The traverse was made at the 'standard' position, about 6 ft downstream of the beginning of the working section, which in turn is defined by a line G–G in the sectional plan of the tunnel in Ref. 1. The thickness of the boundary layer on the floor of the working section was about 1 in. and 2 in. at tunnel speeds of 60 f.p.s. and 100 to 180 f.p.s. respectively. The low level of turbulence of 0·01 to 0·02 per cent intensity, as exists in the middle of the working section extends only 8 in. from the centre-line; over the remaining 10 in. the intensity varies from 0·1 to 1 per cent, agreeing with previous measurements[3], where the low intensity core was only 20-in. × 16-in. out of a total area of 48-in. × 36-in. In order to find the origin of this region of high intensity turbulence, similar traverses were made farther upstream. At the beginning of the working section, this region is only slightly smaller than at the 'standard' position (Fig. 2), except for the lowest speed of 60 f.p.s. The boundary-layer thickness at the floor was 0·3 in. for 60 f.p.s. and 0·8 in. for 100 to 180 f.p.s. Although these measurements suggest that the boundary-layer thickness at the beginning of the working section is only about 1/3 of the thickness at the standard position, the extent of the region of high intensity turbulence at speeds greater than 100 f.p.s. is much the same for both traverses, implying that the boundary layer alone cannot be responsible for the increased intensity near the wall. There is a maximum in intensity of turbulence outside the boundary layer in Fig. 2 and this feature is more apparent in Fig. 3a, which was obtained by a traverse* in the contraction of the tunnel. It is also difficult to see how turbulence, spreading from a turbulent boundary layer, could have a maximum outside the boundary layer. A discussion about the origin of the high intensity turbulence near the walls is given in Section 7.

2.1.2. *Boundary-layer transition-point fluctuations on the tunnel walls.*—The tunnel contraction has a high area ratio and a short length, so that the boundary layers on its walls are subjected to a powerful favourable pressure gradient; they consequently remain laminar as far as the beginning of the working section, transition occurring some distance downstream. Experiments made by Hall[4] and Schubauer[13] have shown that the transition on a smooth flat plate fluctuates to a considerable extent. Such fluctuations on the walls of a wind-tunnel working section would lead to fluctuations of the displacement thickness of the turbulent boundary layer, and a corresponding fluctuation in the effective cross-sectional area of the tunnel, which could contribute to the longitudinal component of the turbulence.

* The path followed on this traverse is given in Fig. 3b. A traverse can be defined by a line, which is everywhere normal to the local streamlines. Since the flow in the central part of the contraction approximates to the flow in a cone, produced by a point source at the apex of the cone, the surfaces normal to the streamlines will be approximately spherical with their centre at the point C in Fig. 3b. For practical reasons the traverse was made along two straight lines, suitably joined, one normal to the walls, the other normal to the centre-line.

It is interesting to calculate roughly, whether this kind of fluctuation could be of the same order as the measured turbulence. Denote the length of turbulent boundary layer by x, its displacement thickness by δ_1 and the cross-sectional area and circumference of the working section by A and C respectively. The boundary-layer thickness is assumed to be proportional to its length, which is a sufficiently accurate approximation for the present purpose. Then

$$\frac{\Delta\delta_1}{\delta_1} = \frac{\Delta x}{x} .$$

The fluctuations of transition point are not likely to occur on the whole circumference simultaneously, but rather in patches, whose average size may be $1/m$ of the whole circumference. The change of effective cross-section due to fluctuations of one patch is

$$\Delta A = \Delta\delta_1 \frac{C}{m} = \frac{\Delta x}{x} \delta_1 \frac{C}{m} .$$

Assuming the volume of air flowing through the tunnel to be constant,* the corresponding fluctuation in longitudinal velocity is given by

$$\frac{\Delta u}{u} = \frac{\Delta A}{A} = \frac{\Delta x}{Ax} \delta_1 \frac{C}{m} .$$

Assuming the velocity fluctuations to be sinusoidal with time, it is more convenient to introduce R.M.S. values of u by the relation :

$$u' = \frac{\Delta u}{\sqrt{2}} .$$

Now the symbol Δ applied to any quantity means the maximum amplitude of that quantity. The fluctuations of the individual patches are assumed to be independent of each other ; then the resulting velocity fluctuation is obtained by summing the squares of the individual contributions.

$$\frac{u'}{u} = \frac{1}{\sqrt{2}} \frac{\Delta x}{x} \frac{\delta_1 C}{A\sqrt{m}} . \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

$m = 4$ may be taken as a rough approximation, because the cross-section is rectangular with sides not differing much from each other. With $C = 14$ ft, $A = 12$ ft^2, $x = 5$ ft, $\Delta x = 0\cdot5$ ft, $\delta_1 = 0\cdot2$ in., Equation (1) yields

$$\frac{u'}{u} = 0\cdot07 \text{ per cent.}$$

This is about the right order of magnitude, and proves that the fluctuations of transition point contribute to the longitudinal component of turbulence. Better numerical agreement with measurements could be obtained, if more details of the fluctuations of transition point were known, and some of the assumptions of the preceding analysis were refined.

An experimental proof of this theory is easily made by fixing a transition wire on the tunnel wall. This was done and the position of the wire is shown in Fig. 4b.

In Fig. 4a the turbulence intensities are given as a function of wind speed, with and without a transition wire. It is particularly interesting to observe how the large peak at 110 f.p.s. disappears, when the transition wire is introduced.

For comparison, the particle velocity of noise measured with a hot-wire microphone in the middle of the tunnel is also plotted in Fig. 4a (*see* also Fig. 11 of Ref. 3). With the transition wire on the tunnel walls, the longitudinal component is mainly due to noise.

---

* With fluctuations of speed, fluctuations of the energy losses in the working section also occur, and consequently the volume of air flowing through the tunnel is, strictly speaking, not constant. However, since the losses in the working section are about 1/5 of the total[1] and considering some rough data on the fan characteristics, the changes in volume of flow can for the present purpose be neglected.

All the measurements, mentioned so far, were made at the standard position of the working section (marked (1) in Fig. 4b). The hot wire was also moved to the beginning of the working section (marked (2) in Fig. 4b). Compared with the results obtained in the standard position, it will be seen that the peak intensity occurs at a higher wind speed and with greatly reduced magnitude. The distribution of turbulence along the tunnel axis is shown in Fig. 5.

Corresponding observations of the flow pattern by an oil-film technique were made on the floor of the tunnel and they will be described in detail in Section 2.2.1. According to these observations the centre of the fluctuating transition region is about 2·5 ft and 1·5 ft downstream of the beginning of the working section at speeds of 60 and 100 f.p.s. respectively. The extent of the region is 1 ft and 2 ft for the two speeds. Since the influence of fluctuations of transition point will reach the centre-line only some distance downstream of where the fluctuations occur, the turbulence at the beginning of the working section will consist almost wholly of sound. Farther downstream, an increase to the level in the working section will take place. For speeds of 140 f.p.s. and 180 f.p.s., where practically the whole of the boundary layer is turbulent, the intensity remains approximately constant along the tunnel axis.

2.2. *Two Screens in the Bulge.*—It was thought that the high number of screens in the bulge might have been responsible for the region of high intensity turbulence in the working section.

In order to test this suggestion, 7 screens were removed from the bulge, so that only the first and the last screen remained. The effect of this change is described below.

2.2.1. *Intensity and frequency spectra of the longitudinal components of turbulence on the centre-line.*—The intensity of the longitudinal component of turbulence, without a transition wire on the tunnel wall (Fig. 6), remains almost the same, if compared with the corresponding curve in Fig. 4a ; the main difference is a shift of the characteristic peak from 110 to 160 f.p.s. This peak can again be eliminated by fixing a transition wire on the tunnel wall. At 200 f.p.s. a jump in the intensity of turbulence occurred, which is indicated by an isolated point. It appeared, when the speed of 200 f.p.s. was approached from lower speeds, but not if it was approached from higher speeds. Measurements at the beginning of the working section show a slight shift of the peak to higher speeds, but above 160 f.p.s. the intensity is higher than at the standard position. There is however a tendency for all three curves to become equal at the highest speed. It is not clear why the intensity at the beginning of the working section should be appreciably higher at high speeds than that at the standard position both with and without a transition wire.

An oil-film technique was used for investigating fluctuations of transition point. A thin layer of a mixture of oil with a white paint was applied to the floor of the working section. Air moving past this layer set up small waves, whose wave length depended on the state of the boundary layer. If it was turbulent, the wave length was much shorter than in the laminar state. So regions of laminar and turbulent flow could be distinguished, and even fluctuations of transition point could be seen, since their frequency was rather low. The results of the observations are shown in Fig. 7. Checks were made to ensure that the oil film itself did not materially disturb the boundary layer. There is a spread of turbulence from the corners of the working section, which is clearly visible at speeds of 60 and 80 f.p.s. With increasing speed the region, within which the transition point fluctuates, becomes larger in size and at the same time moves upstream until the contraction is reached. Here the boundary layer is stabilised by a strong favourable pressure gradient and consequently a further increase in speed reduces the extent of the fluctuations, until they finally disappear at sufficiently high speeds. The contribution to the longitudinal component of turbulence depends on the extent of these fluctuations and the curve of intensity *vs.* speed in Fig. 6 shows corresponding features. The maximum in intensity at 160 f.p.s. (Fig. 6) agrees well with the observed maximum of the extent of the fluctuations of transition point at 160 to 180 f.p.s. Finally the conclusion about the origin of the longitudinal component of turbulence is similar as in Section 2.1.2. Without a transition wire, there is a strong contribution due to fluctuations of the transition point below 200 f.p.s. with a characteristic peak at 160 f.p.s. With a transition wire on the tunnel walls, the longitudinal component of turbulence is mainly due to noise.

Frequency spectra are given in Figs. 9, 10, 11 and 12 and in each of these figures, the longitudinal component is shown by the top picture ; these pictures are similar in shape to those with all 9 screens in the bulge (*see* Figs. 4, 5, 6 and 7 of Ref. 3). There are also peaks at the fan fundamental frequency and its second harmonics.

2.2.2. *Intensity and frequency spectra of the lateral components.*—The intensity of the lateral components was increased considerably by removing the 7 middle screens in the bulge (Fig. 8) and it is now about $2\frac{1}{2}$ to 3 times as much as it was previously with all 9 screens in the bulge. A peculiar feature shown in Fig. 8 is the jumps in intensity, which occur at certain speeds, most of them at 180 f.p.s., but some were also observed at 200 f.p.s. (not shown in Fig. 8). There is a hysteresis effect, so that intensities measured with increasing wind speed are higher than those with decreasing wind speed. In Fig. 8 the direction of wind speed is indicated by arrows. Although this effect was observed with both components, a complete run with increasing and decreasing wind speed was made with the horizontal component only. There were also some changes in intensity, if measurements were made on different days (*see* Fig. 8), but the order of magnitude of the intensities remained the same. Various checks on the measuring equipment ruled out any faults there, so that these changes seemed genuine.

Frequency analyses of the lateral components (Figs. 9, 10, 11 and 12) revealed no striking changes, in comparison with measurements made with all 9 screens in the bulge.

2.2.3. *Traverse across the working section of the longitudinal and lateral components.*—The distribution of turbulence across the working section is considerably improved by removing the 7 middle screens in the bulge. A vertical traverse of the longitudinal component (Fig. 13) revealed that the width of the region of high intensity turbulence near each wall was reduced from about 10 in. to 4 in. ; the latter figure is considered due to the spread of turbulence from the boundary layer on the walls, which was 2 in. thick.

Similar conditions were found with a horizontal traverse (Fig. 14).

The area containing a level of turbulence as low as on the centre-line is now about 38-in. × 28-in. out of a total area of 48-in. × 36-in.

Vertical traverses of the vertical turbulence component showed considerable variation in intensity across the tunnel. The curves in Fig. 15 simply connect the measured points, but there may be further local variations in intensity than are shown by the curves. A wire support, suitable for working a continuous traverse, is difficult to design, since the requirements for its rigidity are rather severe when lateral components are measured. Therefore a much simpler method was employed : a number of holes were drilled in the supporting strut and the base for the wire holder was fitted into these holes. Measurements could therefore only be made at a limited number of points, not too close together. The roughness in intensity distribution is a characteristic of the lateral turbulence component.

The lateral components of turbulence spread farther from the walls than the longitudinal components. Fig. 13 shows that there is a particularly large spread of turbulence near the floor at a speed of 60 f.p.s. At this speed the transition-point fluctuations on the walls of the working section occur in the neighbourhood of the measuring station, and consequently the turbulence intensity at this wind speed increases more as the wall is approached than it does at other speeds.

2.2.4. *Correlation measurements.*—The correlation* of the longitudinal component across the working section was measured with two wires equidistant from, but on opposite sides of, the

* The correlation of longitudinal component is defined by $K = \overline{u_1 u_2}/u_1' u_2'$, where $\overline{u_1 u_2}$ is the average product of u_1 and u_2 taken over a sufficiently long time, with u_1' and u_2' being the R.M.S. intensities of u_1 and u_2. u_1 and u_2 are the instantaneous values of velocities in two places, which are a distance y apart. Consequently K is a function of y.

tunnel centre-line. The results (Fig. 16) are rather similar to those with 9 screens[3] in the bulge except at 200 f.p.s., where the correlation drops at small distances to values lower than that for other speeds. At zero distance the correlation should of course be $1 \cdot 0$ by definition. Extrapolating the curves in Fig. 16 to zero yields, however, this value only for the smallest speed of 60 f.p.s. There is evidence that this deficiency may be due to the impact on the wires of dust particles in the air. This explanation is supported by observations made early in the morning which resulted in turbulence intensities some 10 per cent lower than those measured later in the day, when the tunnel had been run for some hours. The apparent intensity of turbulence at a speed of 60 f.p.s. was considerably increased, if the tunnel had just before run at top speed ; however if the tunnel were stopped for a quarter of an hour the original low values of intensity were repeated. The explanation is that, at high speed, more dust is stirred up in the tunnel than at low speeds, and that the dust suspended in the air takes some time to settle down after stopping the tunnel. However, the high correlation over most of the working section suggests that the error involved by this type of dust effect is not very large, probably not more than 10 to 20 per cent (*see* Appendix I). An error of this magnitude is however tolerable.

The correlation of the lateral components was measured by using two inclined wires and the method is described in Appendix II. Since these experiments require considerable time, only the correlation of the vertical component along a horizontal line in the middle of the tunnel has been measured. The correlation curve in Fig. 17 does not fall continuously with increasing distance, but decreases in a wave form with a considerable number of maxima and minima. A correlation of lateral components has not been measured previously, but this peculiar shape of correlation function could hardly be expected with turbulence behind grids or in pipes. Indeed, at the end of the long diffuser, the shape of the correlation function of the lateral components is quite similar to that of the longitudinal component (Figs. 30 and 31). Here the correlation of both components decreases continuously with increasing distance between the two wires.

When measurements in the bulge are described in Section 5, an explanation of this peculiar type of correlation function will be given.

2.2.5. *Influence of vent holes on the turbulence intensity in the working section.*—It has already been mentioned in Ref. 2 that vent holes in the working section provide a means of reducing the turbulence due to sound. It is well known that sound waves in a tube are reduced in intensity by holes in the tube, which provide an outlet for acoustic energy. There are two groups of holes in the wind tunnel (*see* Fig. 1 of Ref. 1) : one at the end of the working section, which consists of 8 holes, each with an area of 9-in. × 4-in. ; the other in the return circuit of the tunnel between the third and the fourth corner with 20 holes, each 6-in. × 6-in. Measurements have been made, usually with all holes at both places open. In order to demonstrate the efficiency of the holes in reducing the intensity of sound in the wind tunnel, each group of holes was closed in turn. This resulted in an increase in intensity of sound (Fig. 18) and in the measured ' turbulence '. However, this increase is only appreciable at speeds above 160 f.p.s., when it amounts to from 50 to 100 per cent. Obviously below 160 f.p.s. the ' turbulence ' due to fluctuations of transition point is much larger than that due to sound, so that an increase in the intensity of the latter has only little effect on the measured turbulence.

2.3. *Three Screens in the Bulge.*—As has been shown in Section 2.2 the distribution of turbulence across the working section was improved by reducing the number of screens in the bulge from 9 to 2, but the lateral components of turbulence were increased by a factor 2 to 3. It seemed therefore likely that 2 screens in the bulge are not sufficient and consequently one more screen was added ; the second screen was chosen.

2.3.1. *Intensity of the longitudinal component of turbulence.*—There is little change resulting from the addition of one more screen in the bulge (*see* Fig. 19), as would be expected from previous measurements, where the removal of 7 screens had a negligible effect. The characteristic peak in intensity is now lower.

2.3.2. *Intensity of lateral component of turbulence.*—The intensities of the lateral components decreased appreciably by adding one more screen in the bulge and were almost as low as they were with all 9 screens in the bulge (*see* Figs. 20 and 21). There is the same systematic difference between the measurements made with increasing and decreasing wind speed (*see* Fig. 21). The change in sign at low speeds of the difference between the curves of increasing speed and decreasing speed is probably due to the dynamic dust effect. In Section 2.2.4, it was mentioned that the intensity of turbulence at low speeds increased appreciably if the tunnel had previously run at top speed, owing to an increased amount of dust in the tunnel. Similar conditions exist in the present case, if a curve is measured with decreasing wind speed. In previous measurements, with 2 screens in the bulge, the intensity of the lateral component was much higher, so that the influence of the dust effect was not noticeable.

2.3.3. *Traverse of the longitudinal and the lateral components of turbulence across the working section.*—The intensity of the longitudinal component in a vertical traverse at the standard position (Fig. 22) is approximately the same as with 2 screens in the bulge, but the intensity is a little higher near the roof.

Similar conditions exist for a horizontal traverse, where the regions near the walls are shown in Fig. 24a.

As far as the longitudinal component is concerned, the area of tunnel with the same low level of turbulence as on the centre-line is about 25-in. × 38-in. out of a total of 36-in. × 48-in.

Traverses of the vertical component are shown in Fig. 23. Here the local variations in intensity are larger, especially near the side walls.

The area of low turbulence is smaller for the lateral components than for the longitudinal component.

2.3.4. *Correlation measurements.*—An attempt was made to measure the correlation of the lateral components only, but the results were inconsistent. However, there was an indication that the correlation curve would be similar to that in Fig. 17.

3. *Measurements at the End of the Second Diffuser.*—In order to trace the origin of the turbulence in the working section, measurements were made upstream at various parts of the tunnel commencing at the end of the second diffuser.

3.1. *Intensity and Frequency Spectra of the Three Components of Turbulence.*—In Fig. 25 the intensity of the three components on the centre-line is rather high (about 12 per cent), and approximately equal for all three components. It is roughly constant with speed and falls only slightly at low speeds. (In Fig. 25, U_0 is the speed in the working section and U the local speed at the end of the diffuser.) The diffuser has an effective angle of 5 deg (*see* Ref. 1).

The frequency spectra (Figs. 26, 27, 28 and 29) show that almost all the energy is concentrated below about 30 c.p.s. The lowest frequency at which the analyser could be read was about $2 \cdot 5$ c.p.s., but it is apparent from the frequency spectra at low speeds that considerable contributions arise from frequencies much smaller than $2 \cdot 5$ c.p.s. The amplifier for measuring turbulence was used here without a transformer, and the cut-off frequency was about $0 \cdot 7$ c.p.s. The apparent decrease of turbulence intensity in Fig. 25, at local speeds below 14 f.p.s., may be due to the fact that frequencies below $0 \cdot 7$ c.p.s. contributed to the total intensity to a noticeable extent.

3.2. *Traverse across Tunnel Section.*—In order to save time, measurements were made only at a few points on a vertical line from the centre-line to the tunnel floor, in order to give some estimate of the distribution of turbulence across the tunnel. The results are given in Table 1 and it is seen, that the intensity remained roughly constant for the lateral component, while there is a slight increase near the walls for the longitudinal component. There is some scatter in the measured points, owing to difficulties of obtaining a reliable mean reading, the frequencies involved being rather low.

It is interesting to compare these results with measurements in a pipe of constant cross-section.* Here the intensity of longitudinal component was about 3 per cent on the centre-line and reached a maximum of 8 per cent near the walls. On the other hand, the intensities in a jet mixing with air at rest reach values of 15 to 20 per cent, so that the diffuser seems to be midway between the pipe flow and the free turbulence in a jet.

3.3. *Correlation Measurements.*—The correlation of longitudinal components as a function of the distance between two wires is given in Fig. 30. There is a slight influence of speed in so far as the correlation is slightly less at low speeds. This may be explained by the fact that some wind fluctuations, at very low frequencies, are not recorded by the amplifier as already mentioned above. Checks at a few points indicated that the correlation curves for a horizontal and a vertical traverse are very nearly the same. From Fig. 30 a length can be derived, usually called the scale of turbulence, and defined by

$$L = \int_0^\infty K \, dy ,$$

where K is the correlation function as defined in Section 2.2.4. L is some measure of the average eddy size. The correlation of longitudinal component $L^{(u)}$ is about $3 \cdot 4$, $4 \cdot 2$ and $5 \cdot 5$ in. for 60, 100 and 160 to 220 f.p.s.

The correlation of the vertical component of turbulence did not seem to depend on speed, and the points can be represented by one curve (Fig. 31). The corresponding scale of lateral component is about $2 \cdot 4$ in., or, expressed as a fraction of the diameter of an equivalent conical diffuser, is $0 \cdot 0182$.

The scale of the lateral component of turbulence is important in those cases, where the intensity of the lateral component is reduced by a honeycomb, since the cell size must be smaller than the scale of turbulence, if the honeycomb is to be effective.

4. *Measurements between the End of the Second Diffuser and the Rapid Expansion.*—The cross-section of the tunnel remains constant from the end of the second diffuser, just before the third turning vanes, to the beginning of the rapid expansion (*see* Fig. 1 of Ref. 1). Since the turbulence on the centre-line is appreciably higher at the end of the diffuser than in a pipe (*see* Section 3.2), it may be expected that the turbulence decreases on the centre-line after the air passes from the end of the diffuser into that part of the tunnel where the cross-section is constant.

When the turbulence passes through the rather closely spaced turning vanes of chord to gap ratio 4 : 1, these act partly as a honeycomb for the horizontal component of turbulence, since the turning vanes are vertical ; at the same time the turbulence of all three components is increased by contributions of the turbulent boundary layer on the turning vanes and the wake behind them.

The distribution of intensity of turbulence along the tunnel axis depends therefore on :

(*a*) the decrease of intensity due to the change of flow from the diffuser to a pipe of constant cross-section ;

(*b*) an increase due to turning vanes ; and

(*c*) a decrease due to turning vanes in the horizontal component only.

Measurements of the intensity of turbulence were made behind the third turning vanes, and before and after the fourth turning vanes. These positions are indicated in Fig. 32 and in Table 2, where the distance from the end of the diffuser is given in feet and in fractions of the diameter of an equivalent tube D. The result of these measurements of the intensity of

* See Goldstein : Modern Developments in Fluid Dynamics. Vol. II. p. 398.

turbulence is given in Table 3 as a fraction of the intensity at the end of the diffuser. All three components decrease in intensity in the direction of flow, except the longitudinal component between positions (3) and (4). Between these stations, the lateral components decrease much less than between the other positions. The explanation is that both turning vanes, which lie between positions (1) and (2) and between (3) and (4), are shedding turbulence ; but in the first case the level of the oncoming turbulence is higher than in the second case and consequently, as the turbulence shed from the turning vanes is in both cases the same, its influence appears to be larger in the second case. In position (4), the horizontal component is smaller than the vertical component (Fig. 34), which is thought to be due to the vertical vanes acting as a honeycomb for the horizontal component, but not for the vertical component. The intensity of turbulence before the expansion is about 4 to 6 per cent for all three components.

With a view to the uneven distribution of lateral components across the working section, a vertical traverse was made in position (4) at rather close intervals, in order to find whether similar features of the lateral components could be detected here. Fig. 33 shows some variation in intensity, but far less than in the working section (Fig. 23). Since the turbulence before the expansion differs from the turbulence in the working section, by an appreciable contribution, at frequencies above 20 c.p.s., an electric filter was incorporated in the amplifier, which cut off all fluctuations above 20 c.p.s., so that the intensities labelled 'with filter' in Fig. 33 were comparable in frequency to those in the working section. But even so the variations in intensity were much less than in the working section (Fig. 23).

5. *Measurements in the Bulge.*—5.1. *Turbulence Measurements near Centre-line with Two Screens in the Bulge.*—Measurements were made with a big wooden strut erected in the bulge behind the screens. An existing strut was used, which was not sufficiently long, so that the nearest position to the centre-line, at which measurements could be made, was about 17½ in. below. The intensities of all three components are roughly equal, as shown in Fig. 35. All three components were measured with continuously increasing wind speed and there is a tendency at a speed of 200 f.p.s. for measurements not to fit into the curve through the other points.

A comparison with turbulence measurements in the working section and before the expansion is of interest. According to Prandtl[5] the reduction of turbulence passing through a contraction is different for longitudinal and lateral components ; for the longitudinal component it is

$$\frac{u_1'}{U_1}\Big/\frac{u_2'}{U_2} = \left(\frac{U_2}{U_1}\right)^2 , \qquad \qquad (2)$$

where u_1' and u_2' are the turbulence intensities, U_1 and U_2 the corresponding values of mean speed. The formula is expressed here for convenience as the ratio of intensities relative to the mean speed, in the same way as all the turbulence measurements are given in this Report. The corresponding expression for the lateral component is

$$\frac{v_1'}{U_1}\Big/\frac{v_2'}{U_2} = \sqrt{\frac{U_2}{U_1}} , \qquad \qquad (3)$$

with v_1' and v_2' as the lateral components of turbulence. In this tunnel U_2/U_1 is about 1/25* near the centre-line, if U_1 is the mean speed in the bulge and U_2 in the working section.

In Fig. 8 the lateral components calculated by (3) from the measurements given in Fig. 35 agree well with the measurements in the working section. Unfortunately both measurements in the working section and in the bulge were not made exactly on the same streamline, and since the variation in lateral component in the working section (Fig. 15) is considerable, the good agreement between measured and calculated values in Fig. 8 cannot be given full weight, but it proves at least that Equation (3) provides the correct order of magnitude for the effect of contraction.

---

* Referred to the ratio of the cross-section of the working section to that of the bulge, the ratio would be 1/30·5 ; however, near the centre-line at a distance of 30 to 40 in. from the last screen the flow in the bulge has already been accelerated and here the ratio is about 1/25. This ratio was used throughout the Report.

According to (2) the reduction of longitudinal component is about 1/600, and so large that the turbulence in the bulge could not contribute to the turbulence in the working section. This confirms that the longitudinal component in the working section is mainly due to fluctuations of the transition point and noise, as was already mentioned in Section 2.2.1.

Turning now to a comparison between the turbulence in the bulge and at a position just ahead of the rapid expansion, we note three effects :

(*a*) reduction of turbulence by natural decay ;

(*b*) reduction of turbulence by passing through screens ;

(*c*) the effect of rapid expansion.

Effect (*a*) is rather difficult to estimate, since the law of natural decay of turbulence is not known in this case. Although the intensity of turbulence has been measured at a number of positions between the end of the second diffuser and before the rapid expansion, it is almost impossible to extrapolate the further decay of turbulence from these measurements, since at each of the turning vanes fresh turbulence has been added to the turbulence from the flow in the diffuser. Both kinds of turbulence differ appreciably in scale (' eddy size '), as is obvious when considering the small size of the boundary layer on the turning vanes compared with the scale of turbulence at the end of the diffuser ; moreover, the rate of decay depends on the scale of turbulence. Therefore only a guess can be made with regard to the reduction of turbulence by natural decay and it is assumed to be of the order of 2 to 4.

The second influence, the reduction of turbulence by screens, has been investigated theoretically by G. I. Taylor and G. K. Batchelor[6] and experimentally by Schubauer, Spangenberg and Klebanoff[7]. In agreement with both theory and experiment, the lateral components are reduced by a factor

$$r_v = \frac{1 \cdot 1}{\sqrt{(1 + k)}}, \qquad (4)$$

where k is the resistance coefficient of the screens. For the longitudinal component, the reduction is given by the theory as*

$$r_u = \frac{1 + \alpha - \alpha k}{1 + \alpha + k}\,; \qquad \alpha = \frac{1 \cdot 1}{\sqrt{(1 + k)}}, \qquad (5)$$

whereas the measurements of Ref. 7 can be represented by the following formula

$$r_u = \frac{1}{\sqrt{(1 + k)}}. \qquad (6)$$

The difference between theory and experiment is appreciable for large values of k and may amount to a factor 10 to 100 for a number of dense screens. The theory appears to predict quite accurately the reduction of small variations in mean speed according to the experiments of Schubauer[7]. If the turbulence is composed of very low frequencies, the law of reduction of *mean* speed (Equation (5)) will be valid instead of Equation (6). Schubauer used, in his experiments, turbulence with a scale of the longitudinal component of 0·4 in., whereas the corresponding scale at the end of the second diffuser was from 3·5 in. to 5·5 in. in the present tunnel. Since the scale of turbulence in this tunnel is larger than that in Ref. 6, and, since the speed in the bulge of this tunnel is smaller than in Schubauer's experiments, the frequencies of the turbulence will be much lower here than in Ref. 7. Hence Schubauer's formula (6) may not be applicable, and values between those of Equations (5) and (6) may be valid for the reduction of turbulence in the bulge of this tunnel. In the following discussion, both limiting cases were distinguished by ' dynamic ' and ' static ' reduction coefficients ($r^{(D)}$ and $r^{(S)}$). The reduction of turbulence has been calculated for all three components, and, in the case of the longitudinal component, also for the ' static ' and ' dynamic ' case. Three separate cases

* Equation (5) is valid for the reduction of small disturbances of mean speed; it is however also a good approximation for the reduction of isotropic turbulence.

for 2, 3 and 9 screens in the bulge were considered. The screen resistance was calculated from Ref. 8. The result is shown in Table 4, where R_u and R_v mean the total reduction of longitudinal and lateral components respectively by all the screens. (D) and (S) denote dynamic and static cases. As all the screens are placed a distance apart, which is large compared with the mesh size of the screens, the total reduction of turbulence is the product sum of the reduction of the individual screens. For instance

$$R_u^{(D)} = \Pi \left(\frac{1}{\sqrt{(1+k)}} \right) . \quad \ldots \quad (7)$$

The variation with speed arises from the variation of k with Reynolds number as given in Ref. 8, and it is also shown in Table 4 for each screen separately. The screens in the rapid expansion are all of the same kind of 0·0095 in. wire diameter and 0·033 in. mesh size, but the local speed is different for each of the three screens; consequently their respective values of k differ. The screens in the bulge were of 0·017 in. wire diameter and 0·05 in. mesh size. The big difference between 'static' and 'dynamic' overall reduction of the longitudinal component is rather striking. With all 9 screens in the bulge the overall reduction would be so high, that the measured turbulence in the bulge or in the working section could not be explained by any turbulence coming from upstream. This fact will be used in Section 6 as a strong argument in explaining the nature of the lateral components.

In order to calculate the influence of the rapid expansion on the turbulence, Equations (2) and (3) are assumed to be valid. The ratio of speed before, to speed after, the expansion is about 3.

In Table 5 the ratio of intensity of turbulence after and before the rapid expansion is given for each of the two effects mentioned below:

TABLE 5

Influence due to:	*Longitudinal component*	*Lateral component*
Natural decay	1/3	1/3
Rapid expansion	9	$\sqrt{3}$

The value for the reduction due to natural decay is rather an arbitrary mean between the values of 2 and 4, which were previously mentioned. The rapid expansion increases both components, if they are expressed as a fraction of mean speed, since the effect of a rapid expansion is the opposite to that of a contraction.

It is now possible to calculate the turbulence in the bulge from the measured values before the rapid expansion. Mean values of turbulence intensity of about 5·4, 4 and 4·6 per cent are assumed for the longitudinal, horizontal and vertical components of turbulence (u', v' and w'). Using values from Tables 4 and 5 for the reduction of turbulence due to all three influences (a) to (c) as listed in Section 4, we obtain the following values, assuming two screens in the bulge:

TABLE 6

Speed in working section	u' (*per cent*)	v' (*per cent*)	w' (*per cent*)
60	0·32	0·072	0·083
100	0·38	0·096	0·110
160	0·59	0·132	0·150
220	0·70	0·17	0·200

In calculating u' in this table, the dynamic coefficient of reduction of u' in Table 4 has been used; the values for the static reduction would be practically zero. Comparing these results with Fig. 35 the calculated values of u' are larger than the measured values, whereas the calculated lateral components are smaller. The measured intensities of all three components rise much more steeply than the calculated values; this is explained by the fact that the screens operate below their critical Reynolds number at low speeds. Under these conditions the reduction coefficients r_u and r_v differ from Equations (4) and (6) and they drop with decreasing speed as has been shown by Schubauer[7]. Since the amount of reduction of turbulence by natural decay is uncertain, no definite conclusion can be drawn from this comparison between calculated and measured intensities in the case of two screens in the bulge.

The correlation measurements are more useful. The correlation of the longitudinal component between two wires at some distance apart was measured with one wire fixed and the other travelling horizontally (Fig. 36) or vertically (Fig. 37). The fixed wire was about $17\frac{1}{2}$ in. vertically below the centre-line. In the horizontal traverse the movable wire travelled from left to right, when facing the direction of flow, in the vertical traverse vertically downwards. Comparison with Fig. 30 shows that the correlation curve is entirely different in the bulge, correlation zero being reached in all curves at a distance between $0 \cdot 2$ and $0 \cdot 4$ in., which is very short compared with Fig. 30. Even negative values of correlation are reached in the bulge.

It was not possible to measure the correlation of lateral components, for reasons given in Appendix II ; but the correlation between longitudinal and lateral component was measured (Fig. 38) ; this was rather high in places. Since no correlation between lateral and longitudinal component was observed near the centre-line at the end of the diffuser, as could be expected, these measurements in the bulge strongly suggest that there is an appreciable contribution to the lateral component, whose origin is not the diffuser. The same conclusion also holds for the longitudinal component. This argument will be expanded in Section 6.2.

5.2. *Measurements of the Mean Flow in the Bulge.*—In connection with the abnormal spread of turbulence in the working section, the mean flow in the bulge was investigated more closely.

Observations showed that with all 9 screens in the bulge, there was a return flow near the walls of the bulge whose extent is roughly indicated in Fig. 39. The return flow seemed to exist even through the last screen. There was no return flow, if the number of screens was reduced to 2 or 3.

The mean speed distribution across the bulge, and about 30 in. downstream of the last screen, was measured for the cases of 9 and 2 screens in the bulge. In the former case (Fig. 40) there is a small local peak near the walls, which is thought to be due to the displacement of streamlines, caused by the return flow. There is a gradual fall from the maximum on the centre-line towards the walls for 2 screens in the bulge (Fig. 41), in which case there is no return flow on the tunnel walls. Since the traverses were made in a place where the contraction already affects the flow, a constant velocity profile could hardly be expected, certainly not for potential flow. With two screens in the bulge measurements were also made about 7 in. behind the last screen (Fig. 42). Being farther away from the contraction, the velocity distribution is rather flat with minor local variations.

If a screen is inserted in a flow with curved streamlines, there will, in general, be vorticity in the mean flow. This is confirmed by measurements of the total head distribution. In Figs. 43 and 44, the difference between the total head at any point and at the centre-line, at different distances from the wall, is shown.

With 9 screens in the bulge, the total head rises continuously up to the turbulent-mixing zone of the return flow, when it falls rapidly. The vorticity, which is equal to the gradient of the total head, reaches a maximum at both sides of the maximum of the total head. With two screens in the bulge, and in the absence of any return flow, there is no sharp drop in total head near the walls.

6. *Explanation of the Origin of Turbulence in the Working Section.*—Measurements in the working section were sufficient to explain the origin of the longitudinal component of turbulence ; this explanation has been given in Ref. 3 and in Section 2.1.2. However, it requires more elaborate arguments to explain the origin of the lateral components. Hence the case of the longitudinal component is mainly summarized here, whereas a full discussion is given of the origin of the lateral components.

6.1. *Longitudinal Component of Turbulence.*—In Section 2.1.2 and in Ref. 3, the origin of the longitudinal component was explained by fluctuations of transition point and noise, which were predominant below a speed of about 150 f.p.s. and above 150 f.p.s. respectively. The fluctuation of transition point was directly observed by using an oil-film technique (Section 2.1.2). The influence on turbulence intensity was proved by fixing a transition wire on the tunnel wall (Section 2.1.2). Pressure fluctuations were measured by a hot-wire microphone of special design, placed in the middle of the tunnel. The corresponding particle velocities agreed well with the velocity fluctuations at speeds above 150 f.p.s. (Ref. 3). Opening and closing the two sets of holes in the return circuit, and at the end of the working section, had a marked influence on the velocity fluctuations above 150 f.p.s. This could only be explained by assuming the velocity fluctuations to consist of sound at that speed range. The longitudinal component of turbulence showed a high degree of correlation across the working section for all speeds. This is consistent with the longitudinal component of turbulence being caused by fluctuations of transition point and noise. That no contribution comes from upstream is proved by applying the formula for reduction of turbulence due to a contraction (Equation (2)) to the measurements in the bulge ; the resulting turbulence intensities from that source would be too small to contribute to the longitudinal component in the working section, provided there is no interchange of turbulent energy from one component to the other.

6.2. *Lateral Component of Turbulence.*—Comparison of intensity of lateral components can be made for the following three cases, which differ by the number of screens in the bulge :

(*a*) 9 screens,

(*b*) 3 screens,

(*c*) 2 screens.

The lateral intensities of the turbulence in the working section for these three cases can be found in Ref. 3 and in Figs. 8, 20 and 21 of this Paper. Although in cases (*a*) and (*b*) there was a difference of 6 screens in the bulge, the intensity of the lateral components has hardly changed. If the turbulence had its origin upstream of the screens, there would be a change in intensities by a factor, which varies between 260 and 76 according to speed (*see* Table 4). This is a strong argument for assuming the last screen to be the source of the lateral component in the case of all 9 screens in the bulge.

If there is hardly any change in intensity between the case with 9 and with 3 screens in the bulge, and if with 9 screens the intensity is mainly due to turbulence shed from the last screen, then it follows that the intensity with 3 screens in the bulge is also mainly due to turbulence shed from the last screen.

It would seem, at first, as if the difference in intensity by a factor 2 to 3 between cases (*b*) and (*c*) was mainly due to more turbulence from upstream being transmitted through the screens. However, a strong argument against this is found in Fig. 17, where the shape of the correlation function of the lateral component in the working section is entirely different from that at the end of the second diffuser (Fig. 31). Another argument is a considerable variation of the intensity of lateral component across the working section and the absence of such variation before the rapid expansion (compare Fig. 15 and Fig. 33). Measurements of correlation of the longitudinal component in the bulge (Figs. 36 and 37) were of a similar nature to those for the lateral component in the working section and entirely different from those at the end of the second diffuser. There was also, in the bulge, a correlation between longitudinal and lateral components of turbulence near the centre-line, whereas no such correlations could be found at the end of the second diffuser.

The obvious conclusion is that disturbances with this peculiar characteristic are shed from the last screen and possibly also from preceding screens. It could not be the ordinary turbulence shed from any screen, since its scale would be much smaller than that measured in Figs. 36 and 37 and its decay is so rapid that it would not be observed in the working section (*see* Ref. 7).

The possible nature of this type of disturbance is now discussed. An inhomogeneity in the screens is accompanied by local variations in resistance coefficients and these result in corresponding variations in local mean speed. If all speeds are taken relative to the mean speed, these variations in mean speed represent local jets. Now it is known that jets are unstable if their Reynolds number is above a very low critical value. However, experiments of Homan[9], on wakes behind cylinders, indicate that at low Reynolds number (and since the speed in the bulge is small, this applies here), the wake is initially deformed to a wave form. This corresponds to laminar oscillations in the boundary layer on a flat plate, which precede transition to turbulence. Since the settling length behind the screens is rather short, these laminar oscillations have not enough time to build up to intensities so high that transition to turbulence occurs, before they pass through the contraction. The contraction stabilizes these jets by reducing all differences in mean speed to about 1/600 of their original values. The flow is then stable. This explanation would account for the low frequency of the lateral components, since by analogy with laminar oscillations in the boundary layer on a flat plate the frequencies involved would be low. It remains to be explained why the difference in intensity of lateral component in the working section between 2 and 3 screens is so large. It is thought that the intensity of the laminar oscillations depends on the magnitude of initial disturbances approaching the last screen. These are larger in the case of 2 screens than in the case of 3 screens in the bulge.

Schubauer[7] has found similar disturbances behind screens, which he also attributed to irregularities of the screen. Schubauer thought that the pattern of variations of mean speed, set up by these irregularities, is agitated by the oncoming turbulence, which was rather high, *i.e.*, of the order of 1 per cent. However, with all nine screens in the bulge, the turbulence approaching the last screen could be only the ordinary turbulence shed by the preceding screen ; it would be composed of rather high frequencies owing to the small mesh size of the screens, and it is difficult to see how this could result in velocity fluctuations of the low frequencies observed in the working section, unless there were already an instability of flow, which had a selective effect on the disturbances. It is likely that, with a high intensity turbulence approaching the last screen, Schubauer's explanation is valid, whereas with very low levels of oncoming turbulence, the instability of flow has to be taken into account.

The difference between measurements made with increasing speed and those made with decreasing speed in Figs. 8 and 21 would be more likely to occur in a flow which is unstable.

Local variations in turbulence can be explained by local variations in resistance coefficient.

7. *Discussion of the Region of High Intensity Turbulence near the Walls of the Working Section.*— It has been shown in previous sections that the region of high intensity turbulence in the working section occurs when a return flow exists in the bulge. The region of return flow in the bulge extends about 2 in. to 3 in. from the walls and turbulent mixing occurs at the interface of forward and return flow. Measurements (Fig. 45) showed that the intensity of turbulence reaches values as high as 15 per cent of the local mean speed in a region where the mean speed has not yet fallen appreciably (*see* Fig. 46). Farther downstream the return flow ends at the beginning of the contraction. On a streamline close to the interface between forward and return flow, but in the region of forward flow, the turbulence will be fed by the instability of the interface ; but later, when passing into the contraction it will be close to the wall and will therefore be damped. This would result in a distribution of turbulence similar to that shown in Figs. 2 and 3, where the maximum of turbulence intensity is some distance from the wall. In passing through the contraction (effective ratio 25 : 1) the longitudinal component of turbulence* is reduced by a factor 1/600 (*see* Section 5) and on the basis of this figure the high intensity turbulence at the beginning of the working section could not be explained by turbulence in the bulge. However, the lateral components are only reduced by a factor 5 in passing through the contraction and with a high intensity turbulence it is likely that the longitudinal component would receive energy from the lateral components. For instance, the turbulence intensity is 3 per cent in

* All turbulence intensities are here relative to the local mean speed.

Fig. 45 at a distance of 20 in. from the wall at a speed of 180 f.p.s. ; from this figure the intensity at the beginning of the working section was calculated by allowing for the influence of the contraction according to Equations (2) and (3) and assuming all three components to be equal in the bulge. It is further assumed that all three components remain equal in passing through the contraction by exchanging their energy, although the effect of the contraction is selective on longitudinal and lateral components. The result was an intensity of 0·5 per cent and it compares with the measured value of 0·7 per cent at a distance of 4 in. from the wall, which is about 1/5 of the corresponding distance in the bulge. But for points closer to the wall agreement was not so good, probably owing to the presence of the walls.

The region of high intensity turbulence can also be explained by assuming an instability of flow. Liepmann[10] has recently summarized the various cases of instability. In most of these cases the flow consists of parallel streamlines, and the stability criterion can be expressed in terms of certain characteristics of the velocity profile. This is however impossible in a more general case, where the streamlines are curved, and Liepmann suggested that the stability criterion should be expressed in terms of vorticity. In applications, the distinction between two-dimensional and three-dimensional disturbances is not important. It is sufficient to consider three basic cases :

A. Dynamic instability :

(*a*) due to a maximum in vorticity distribution ;

(*b*) due to vorticity in a flow with curved streamlines ;

B. Viscous instability.

Case A(*a*) was investigated by Rayleigh[11] and Tollmien[12] for the case of a parallel flow and then the instability criterion is a point of inflection in the velocity profile, which is equivalent to a maximum in vorticity distribution. Case A(*b*) was also investigated by Rayleigh[11]. If the streamlines are circles, the flow is stable or unstable, if the square of the circulation increases or decreases with increasing radius. However, for a general case of flow, it is again better to express the stability criterion by vorticity instead of by circulation. In Appendix III a simple rule is derived for the stability criterion : the flow along a curved streamline is dynamically stable at any point where the vorticity of a fluid particle has the same direction of rotation as the radius vector from the centre of curvature of the streamline to the fluid particle.

Now the stability of flow in the bulge will be discussed. The vorticity can be expressed by the gradient of the total head as

$$\gamma = -\frac{1}{u\zeta}\frac{dP}{dy}, \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (8)$$

where P is the total head, y the distance from the wall of the tunnel. From Figs. 43 and 44 it can be seen that there is a maximum in vorticity between the centre-line of the tunnel and the peak of total head. Whether there is another maximum of vorticity near the walls cannot be decided, since the measurements in Figs. 43 and 44 were not made sufficiently close to the walls. However, there is at least one maximum of vorticity and hence instability of the type A(*a*) exists. Instability of the type A(*b*) also exists. Since the total head does not change along streamlines, Fig. 43 will also give the distribution farther downstream, where the curvature of the walls is larger than in the cross-section, where the measurements of Fig. 43 were taken. The vorticity is negative near the walls in the bulge according to Fig. 43 and Equation (8). Fig. 47 shows the direction of streamlines and the system of co-ordinates used, and it is seen that the radius vector from the centre of curvature to a fluid particle near the concave wall has a positive direction of rotation. The vorticity near the walls being negative, an instability exists here. This type of instability would give rise to additional velocities normal to the walls, which could be quite strong, since the high intensity turbulence near the walls represents a high initial disturbance for the instability of flow.

In conclusion, it can be said that the return flow in the bulge is ultimately responsible for the abnormal spread of turbulence in the working section. But it is not quite clear, whether the high intensity turbulence in the bulge connected with the return flow is simply swept downstream into the working section ; in this case the longitudinal component would have to receive almost all its energy from the lateral components in order to explain the measured intensity of longitudinal component at the beginning of the working section. There is also the possibility of two types of instability of flow, which are caused by the vorticity of mean flow and the influence of the return flow on the distribution of vorticity. From the present measurements it is not possible to assess the contribution from each of the three possible explanations.

Something remains to be said about the origin of the return flow. Observations indicated that the return flow extended upstream through the last screen. When the first and the last of the 9 screens (Fig. 1 of Ref. 1) were in the bulge, there was no return flow and it was the same with the first, the second and the last screen in. In the first case there was a distance of about 4 ft between the two screens, in the second case the distance between the first and the second screen was $\frac{1}{2}$ ft and between the second and the last screen $3\frac{1}{2}$ ft. It is assumed that a separation of the boundary layer and a region of strong adverse pressure gradient after separation is necessary to create a return flow. Since the contraction is very rapid, an extended region of adverse pressure gradient certainly exists on the walls of the bulge downstream of the last screen. Since the wind speed immediately behind the last screen is almost uniform (Fig. 42) and the total head increases towards the wall of the bulge, it follows that there is a radial increase in pressure behind *and* before the last screen. Since the wall of the bulge is straight upstream of the last screen, there will be an adverse pressure gradient on the walls. So conditions favourable to a separation exist ahead of the last screen, and it can be concluded, that the proximity of one or more screens to the last screen creates flow conditions, which actually set up the return flow in the bulge. Details of these flow conditions are not yet clear.

8. *Conclusions.*—Some conclusions are drawn from the turbulence measurements, which might help in the design of a low-turbulence wind tunnel.

There is at present little information about the amount of reduction of turbulence which is desirable in a low-turbulence wind tunnel. Experiments of Schubauer and Skramstad[13] showed that in the case investigated, a decrease of turbulence below 0·1 per cent would not affect the position of the transition point in the boundary layer on a flat plate. In this tunnel a level of turbulence of about 0·02 to 0·03 per cent for all three components was achieved with three screens in the tunnel. Although few data have been published about turbulence in other wind tunnels, the intensity of longitudinal component in this tunnel seems to be of about the same order of magnitude as in other low-turbulence tunnels, but the lateral component is probably lower than in other tunnels. Since the longitudinal component is mainly due to noise at full tunnel speed, it is not surprising that a similar level of that component is reached in various tunnels ; in all these tunnels the main effort was to reduce the turbulence coming from upstream and these efforts being successful, there remains only noise, whose particle velocity is registered by the hot wire in the same way as ' genuine ' turbulence. However, it was found, in this tunnel, that vent holes in the tunnel provided some powerful means of reducing noise. These vent holes exist at two places in the tunnel, one at the end of the working section, the other between the third and fourth turning vanes. These vent holes act as acoustic filters. Sound can be attenuated in a tube by holes connected to a cavity. The dimensions of the hole and the cavity define a resonance frequency, below which frequency sound is attenuated. In this tunnel the cavity was in one case infinite (vent holes in return circuit), and in the other case (vent holes in working section) sufficiently large to suppress most of the low frequencies. A further reduction of noise could be achieved by one or more sets of holes, each at least one tunnel diameter distant from the other and connected to a separate cavity. These acoustic ' filters ' are only effective for sound of a wave length larger than the diameter of the tube, *i.e.*, of the tunnel. However, in this tunnel the noise was of sufficiently long wavelength for these filters to be effective.

With 9 screens in the bulge, the high intensity turbulence spreading over a considerable part of the working section needs some attention. This seemed to occur when more than one screen was too close to a rather sudden contraction. It is unlikely that this danger would arise in a conventional design with a more gradual contraction and a longer settling chamber. Some guide as to when this danger arises may be found by observing that this phenomenon was absent when the first, second and ninth of the movable screens were installed in the bulge.

The next problem discussed is that of reducing the turbulence generated upstream of the working section. It does not seem to be generally realised that the turbulence is high (about 10 to 12 per cent of the mean speed) at the end of the second diffuser. Compared with this the additional turbulence shed by the following turning vanes is small, if the turning vanes are closely spaced (in this tunnel chord to gap ratio 4 : 1). The turbulence entering the settling chamber or a rapid expansion will be about 4 to 6 per cent for all three components. The reduction of turbulence can be achieved by

(*a*) natural decay of turbulence,

(*b*) screens or honeycomb,

(*c*) a sufficiently large contraction ratio.

With settling chambers of normal length, the natural decay of turbulence originating from the second diffuser is slow and the turbulence at the end of the settling chamber would not have decayed to much less than half of its initial value. Consequently the main reduction of turbulence has to be achieved by screens or honeycomb and a sufficiently large contraction ratio.

An investigation of the size of the bulge and number of screens necessary to achieve a desired level of turbulence in the working section follows. We neglect the natural decay of turbulence from the beginning of the rapid expansion to the beginning of the working section, and assume that a rapid expansion and a contraction have opposite effects on turbulence intensities. Then the overall effect of rapid expansion and contraction will only depend on the ratio of area at the beginning of the rapid expansion and of the working section, which is 8·5 : 1 for this tunnel. It is assumed that a turbulence level of 0·02 to 0·03 per cent is desired in the working section and that the turbulence level at the beginning of the rapid expansion is 4 per cent of the mean speed. Three screens are installed in the rapid expansion in the same places as in this tunnel, where the increase in area of cross-section is 0·086, 0·358 and 0·664 times that of the total increase of the area between the beginning of the expansion and the bulge. The number of screens and their resistance coefficient is arbitrary, provided that the same total reduction in turbulence results. A reason for choosing screen resistance coefficients between 1 and 2 is given later. The results of this calculation are given in Table 7, where the contribution to the tunnel power factor* is given for various contraction ratios. Contraction ratio means here the area ratio of bulge to working section. A contraction ratio of 8·5 : 1 means that the bulge is omitted.

So far as the longitudinal component of turbulence is concerned, a rather modest contraction ratio would be sufficient, and the bulge could be omitted without undue increase in tunnel power factor.

However, it is different with the lateral components ; here more screens are necessary, since a contraction is rather inefficient in reducing lateral components of turbulence. In order to keep the losses due to the screens sufficiently small, the size of the bulge has to be increased. At the design stage of this tunnel, the law for the reduction of turbulence by screens was not known ; the tunnel was designed therefore for a power factor of about 0·3 with 12 screens in the rapid expansion and bulge ; it was intended to find the necessary number of screens by experiment. But with sufficient data about reduction of turbulence by screens now available, a contraction ratio of 14 : 1 seems to be sufficient, since the contribution of screens to the power

* The contribution to the power factor by one screen is $k(U/U_0)^2$, if k is the screen resistance, U the mean speed at the screen and U_0 the speed in the working section. The speed at the screen is assumed to be constant over the whole screen.

factor is in this case 0·098 (*see* Table 7) and thereby the total power factor would not be increased materially above 0·30* (*see* Ref. 1). Whether still smaller contraction ratios are practicable depends on the balance between capital costs and running costs.

It is also worth considering the installation of a honeycomb for reducing lateral components. The efficiency of a honeycomb of blockage ratio 0·721 (= ratio of free-passage area to total area) was investigated by Schultz-Grunow and Wieghardt[14]. In these experiments a honeycomb was placed at an oblique angle to a stream of parallel flow and the resulting deflection was measured as well as the losses due to the honeycomb. These data on mean flow can be applied to the reduction of the lateral component of turbulence, if the cell size of the honeycomb is small compared with the average eddy size of the oncoming turbulence. In Ref. 14 it was found that a ratio of cell size d to depth t, of the honeycomb, of about 1 : 4 to 1 : 5, removes the lateral component of the oncoming turbulence and that the loss coefficient was given by

$$k = 0\cdot045\,\frac{t}{d} + 0\cdot31$$

and was almost independent of Reynolds number for Reynolds numbers of more than 5000 ($R = \bar{u}d/\nu$, $\bar{u}$ = speed of oncoming airstream). This is derived from measurements with a blockage factor 0·721. The resistance coefficient of the honeycomb for $t/d = 4$ is

$$k = 0\cdot5\,,$$

which compares favourably with the overall resistance coefficient of the screens necessary to reduce the lateral components of turbulence to the desired level (*see* Table 7). But it must be ensured that the turbulence shed from the honeycomb is sufficiently reduced by natural decay not to increase the turbulence in the working section. With screens this is no problem, since their mesh size is so small that the turbulence decays rapidly enough. But with the larger cell size of a honeycomb, an estimate has to be made of the permissible size of the cells.

As a rough estimate, we assume the decay law of turbulence behind grids to be applicable to a honeycomb. We assume that an intensity of longitudinal component of turbulence of 0·1 per cent is desired just before the contraction. It can be found from the measurements of Townsend[15], on the decay of turbulence behind grids, that this level of 0·1 per cent is reached at

$$\frac{x}{M} = 1200\,,$$

where x is the distance from the screen and M, the cell size, may be identified with d for the honeycomb. Since a settling length of 20 ft is available in this tunnel, the cell size of the honeycomb should be 0·2 in. This size is also small compared with the scale of the lateral component at the end of the second diffuser, which was about 2·4 in. By using a honeycomb, the same low level of turbulence as exists in this tunnel could be achieved without the bulge. It would be necessary however to install some screens for reducing the longitudinal component of turbulence (*see* Table 7); for instance, 3 screens of resistance coefficient $k = 1$. This combination of honeycomb plus 3 screens would only contribute about 0·05 to the power factor of the tunnel (3 screens each of $k = 1$ and the honeycomb $k = 0\cdot5$). However, whether this is practicable or not depends on the cost of a honeycomb of rather small cell size compared with the saving made by replacing a rapid expansion and a bulge by a settling chamber of constant cross-section.

Another important problem relates to the disturbances set up by screens and honeycombs. All efforts to reduce the turbulence coming from upstream are in vain, if new disturbances are set up by the devices which are supposed to reduce turbulence. We mean by these disturbances, not the normal turbulence shed by screens or honeycombs, which either decays sufficiently quickly or otherwise has been taken into account, but the disturbances set up by an inhomogeneity

---

* With 12 screens in the bulge and a contraction ratio of 30·5 : 1 the contribution to the power factor was 0·065 and the total power factor was 0·3 as already mentioned.

of screens, which were discussed in Section 6.2. This type of disturbance has a slow rate of decay ; in fact it did not seem to decay noticeably in this tunnel. The only way of reducing these disturbances would be through a contraction, but this is not very efficient in reducing the intensity of lateral component and would not amount to much for a reasonable contraction ratio. Hence the importance of using screens as homogeneous as possible. Dryden[16] reported large variations in intensity of turbulence in the working section, which were reduced considerably by replacing the last screen by one with a smaller resistance coefficient k. Investigating the efficiency of screens in damping turbulence, Schubauer[7] classified the screens he used into normal and abnormal. The latter type introduced additional disturbances in the air flow. In Schubauer's list of screens, the denser screens show more tendency to abnormal behaviour than the less dense ones and the limit seems to be roughly at $k = 2$. It therefore seems advisable to use screens with k between 1 and 2. It was found in Section 6.2 that the disturbances shed by the last screen depended also on the intensity of disturbances approaching the last screen. Hence it will be advisable to put in one or two extra screens in addition to the number that is necessary for reducing the turbulence coming from upstream.

The screens in this tunnel were made in one piece ; but serious disturbances could be expected, if there are seams in the screens. It would appear that a honeycomb could be made more homogeneous than a screen, although the cost of construction may then be rather high. However, more research is needed about this type of disturbance, before the relative merits of screens or honeycomb for reducing lateral component of turbulence can be assessed.

9. *Summary of Turbulence Measurements in the Tunnel.*—The following is a summary not only of this Report, but also of Ref. 3.

(1) The intensity of turbulence at the end of the second diffuser is about 10 to 12 per cent of the mean speed and is almost constant over the cross-section. It differs from the intensity in a pipe of constant cross-section, which increases from about 4 per cent on the centre-line to about 8 per cent near the wall. The scale* of the longitudinal component is about 3·4, 4·2 and 5·5 in. for speeds of 7·1, 14·1 and 18·8 to 25·9 f.p.s. respectively. The corresponding speeds in the working section are 60, 100 and 160 to 220 f.p.s. The scale of lateral component is 2·4 in. for all speeds. The cross-section at the end of the diffuser was octagonal with a diameter of 132·3 in. for the equivalent circular cross-section. The turbulence is almost entirely composed of frequencies below 30 c.p.s. for all three components.

(2) The contribution from the turning vanes following the diffuser does not materially increase the level of turbulence from the end of the second diffuser.

(3) Before the rapid expansion, the level of turbulence is about 4 to 6 per cent for all three components.

(4) With two screens in the bulge, the intensity of turbulence for all three components in the bulge is about 0·025 per cent at a speed of 1·92 f.p.s. (60 f.p.s.)† and rises rapidly to about 0·3 per cent at 4·8 f.p.s. (150 f.p.s.).† For higher speeds the intensities fluctuate, but do not increase materially. The shape of the correlation curve for the longitudinal component is quite different from that at the end of the second diffuser. It even reaches negative values. The scale is of the order of 0·2 in. There is also a considerable correlation between longitudinal and lateral components near the centre-line, which was not observed at the end of the second diffuser.

(5) Intensities of turbulence were measured in the working section with :

(*a*) 2 screens in the bulge,

(*b*) 3 screens in the bulge,

(*c*) 9 screens in the bulge.

* The scale of turbulence can be roughly interpreted as an average eddy size. An accurate definition of the term is given in Sections 2.2.4 and 3.3.

† Speeds in brackets refer to the working section.

The longitudinal component was roughly the same for all three cases, ranging from 0·006 per cent to about 0·02 per cent for speeds of 60 f.p.s. to 260 f.p.s. At a certain speed there was a characteristic peak which changed in intensity over long periods. The intensity of the lateral component was approximately the same in cases (*b*) and (*c*) and amounted to 0·005 per cent at 60 f.p.s. and rose to about 0·02 per cent at a speed of 160 f.p.s. and then remained constant; but the intensity of the lateral component was appreciably higher in case (*a*) with an intensity of 0·01 per cent at 60 f.p.s. rising to between 0·05 and 0·06 per cent at 160 f.p.s. and then remaining approximately constant.

(6) Noise measurements were made in the working section with all 9 screens in the bulge. There was good agreement with the longitudinal component of turbulence above a speed of 160 f.p.s. Below that speed the noise expressed in terms of the particle velocity was less than the measured turbulence.

(7) The characteristic peak in the curve of intensity of turbulence *vs.* speed is due to fluctuations of transition point of the boundary layer on the tunnel wall; this was proved by fixing a transition wire at the beginning of the working section. With this arrangement the intensities below 160 f.p.s. were considerably reduced and the peak in intensity was eliminated.

(8) The correlation of longitudinal component was high across a considerable part of the working section, confirming that the longitudinal component of turbulence is either due to fluctuations of transition point or noise. The correlation of lateral component is entirely different. With two screens in the bulge, it drops rather quickly with a wave form superimposed on a continuously falling curve.

(9) Efficient means of reducing noise are vent holes in the tunnel circuit. The noise in the working section increased by 50 to 100 per cent when the holes at the end of the working section were closed.

(10) With all 9 screens in the bulge, an extensive region of high intensity turbulence was observed near the walls of the working section. Reduction of the number of screens in the bulge to 2 or 3 eliminated this region. A possible explanation of the origin of this region of turbulence was given in Section 7.

(11) There is reason to believe that the return flow on the walls of the bulge is connected with the extended region of high intensity turbulence in the working section. The return flow is present with 9 screens in the bulge, but absent with 2 or 3 screens in the bulge. It seems that too many screens close together and close to a rather sudden contraction may create a return flow in the bulge.

10. *Summary of Instrumentation.*—(1) The conventional type of wire holder, with the hot wire soldered to the tips of two slender needles, cannot be used for low levels of turbulence and for wind speeds of more than about 60 f.p.s., because of vibrations of the needles. Instead two prongs have been glued together by a thin piece of insulating material, so that free tips of not more than 0·16 in. remained. Thus by suitable design, no part of the wire holder had a resonance frequency within the frequency band transmitted by the amplifier, which was from 2 to 10,000 c.p.s. By calculation, the interference of the new wire holder with the flow around the hot wire was found to be not more than 1 to 2 per cent in speed. As support for the wire holder, a rigid strut, about the size of a model wing, had to be used in order to avoid vibrations of the strut. Rigidity of support is far more important with lateral than with longitudinal components of turbulence.

(2) For low levels of turbulence (below 0·1 per cent) and wind speeds up to 300 f.p.s. the hot wire used had to be short enough to take the wind forces by its own stiffness like a beam. The length of hot wires of 0·0002 in. diameter was 0·025 in. to 0·03 in. for longitudinal component wires and 0·03 in. to 0·04 in. for lateral component wires ('V' wires). Longer hot wires gave rise to spurious results, probably because of movements of the wire relative to the airflow.

(3) With short wires and low levels of turbulence, the voltages across the hot wire are so small that a transformer of ratio 1 : 25 was used at the input of the amplifier in order to increase the incoming signal sufficiently above the disturbance level of the amplifier. The frequency range of the transformer was about 2 c.p.s. to 5,000 c.p.s.

(4) A hot-wire microphone of special design was used for the measurement of noise. This microphone was made in the form of a static tube sufficiently small for the boundary layer at the pressure holes to be laminar. This instrument could be used in the middle of the tunnel, whereas a conventional microphone mounted in the wall of the working section recorded pressure fluctuations within the turbulent boundary layer on the tunnel wall as well as noise inside the tunnel.

REFERENCES

No.	*Author*	*Title, etc.*
1	H. B. Squire and K. G. Winter	The R.A.E. 4-ft × 3-ft Experimental Low Turbulence Wind Tunnel. Part I. A.R.C. R. & M. 2690. February, 1948.
2	H. Schuh and K. G. Winter	The R.A.E. 4-ft × 3-ft Experimental Low Turbulence Wind Tunnel. Part II : Measurements of longitudinal intensity of turbulence. A.R.C. 11,829. August, 1948.
3	H. Schuh and K. G. Winter	The R.A.E. 4-ft × 3-ft Experimental Low Turbulence Wind Tunnel. Part III : Measurements of turbulence intensity and noise with improved apparatus. A.R.C. R. & M. 2905. March, 1951.
4	A. A. Hall and G. S. Hislop	Experiments on the transition of the laminar boundary layer on a flat plate. A.R.C. R. & M. 1843. August, 1938.
5	L. Prandtl	Attaining a steady air stream in wind tunnels. N.A.C.A. Tech. Memo. 726. 1933.
6	G. I. Taylor and G. K. Batchelor	The effect of wire gauze on small disturbances in a uniform stream. *Quart. J. Mech. App. Math.* Vol. II. Pt. I. March, 1949. pp. 1 to 29.
7	G. B. Schubauer, W. G. Spangenberg and P. S. Klebanoff.	Aerodynamic characteristics of damping screens. N.A.C.A. Tech. Note 2001. January, 1950.
8	L. F. G. Simmons and C. F. Cowdrey	Measurements of the aerodynamic forces acting on porous screens. A.R.C. R. & M. 2276. August, 1945.
9	Homan	Forschung auf dem Gebiete des Ingenieurwesens 7. 1936. pp. 1 to 10.
10	Hans W. Liepmann	Investigation on laminar boundary-layer stability and transition on curved boundaries. A.R.C. 7,302. August, 1943.
11	J. W. S. Rayleigh	On the stability or instability of certain fluid motions. *Proc. Lond. Math. Soc.* Vol. 11. pp. 57 to 70. 1880. Vol. 19. pp. 67 to 74. 1888.
12	W. Tollmien	General instability criterion of laminar velocity distribution. N.A.C.A. Tech. Memo. 792. 1936.
13	G. B. Schubauer and H. K. Skramstad	Laminar-boundary-layer oscillations and transition on a flat plate. A.R.C. 6,777. April, 1943.
14	F. Schultz-Grunow and K. Wieghardt	Untersuchungen über die Wiekungsweise des Gleichrichters. *Luftfahrtforschung*, Vol. 17. pp. 82 to 86. 1940.
15	G. K. Batchelor and A. A. Townsend	Decay of turbulence in the final period. *Proc. Roy. Soc.* A. Vol. 194. pp. 527 to 543. 1948.
16	H. L. Dryden and G. B. Schubauer	The use of damping screens for the reduction of wind tunnel turbulence. *J. Ae. Sci.* Vol. 14. No. 4. April, 1947.

APPENDIX I

Estimate of the error due to the impact of dust on hot wires

For this estimate the following argument is used: the longitudinal component of turbulence is assumed to consist of two independent components u_A and u_B, of which the former has the correlation 1 and the latter the correlation 0, when two wires are a certain distance y apart. $u_A(0)$, $u_B(0)$ and $u_A(y)$, $u_B(y)$ are the instantaneous values of the two components on the first and the second wire respectively. The R.M.S. intensities are denoted by dashes and they are the same for each of the two wires. The correlation function is then

$$K(y) = \frac{\overline{u_1(0)\, u_2(y)}}{u'^2} = \frac{\overline{(u_A(0) + u_B(0))\,(u_A(y) + u_B(y))}}{u'^2} = \left(\frac{u_A'}{u'}\right)^2 .$$

Consequently the ratio of the component with correlation 0 to the total intensity is

$$\frac{u_B'}{u'} = \sqrt{\{1 - K(y)\}} .$$

Since $u'^2 = u_A'^2 + u_B'^2$. The error due to the impact of dust can be found by substituting into the above formula values of $K(y)$, which are obtained by extrapolating the correlation curves to $y = 0$. So the errors due to dust of 10 to 20 per cent as given in Section 2.2.3 were derived from Fig. 16.

APPENDIX II

Measurement of the correlation of the lateral components

Two inclined wires are used. One wire is fixed and the other wire is used in two positions, one where both wires are parallel and the other where the second wire has been rotated through 180 deg about an axis through the centre of the wire and parallel to the mean wind speed. The voltage on the first wire is given by

$$e_1 = A_1 \frac{u_1}{U} + B_1 \frac{v_1}{U} , \qquad (9)$$

where A_1 and B_1 are coefficients, u_1 and v_1 are the velocity fluctuations in the direction of the mean speed and normal to it in the plane of the hot wire and the mean speed. If the second wire is parallel to the first, the corresponding voltage is

$$e_{2p} = A_2 \frac{u_2}{U} + B_2 \frac{v_2}{U} . \qquad (10)$$

If now the second wire is rotated through 180 deg, the voltage in the new position is

$$e_{20} = A_2 \frac{u_2}{U} - B_2 \frac{v_2}{U} .$$

By using suitable circuits mean-square values of the sum or difference of these voltages can be measured, giving

$$S_p = (e_1 + e_{2\,p})^2 = \sum + 2\,A_1\,A_2\,\frac{\overline{u_1 u_2}}{U^2} + 2\,B_1\,B_2\,\frac{\overline{v_1 v_2}}{U^2}\,,$$

$$S_0 = (e_1 + e_{2\,0})^2 = \sum + 2\,A_1\,A_2\,\frac{\overline{u_1 u_2}}{U^2} - 2\,B_1\,B_2\,\frac{\overline{v_1 v_2}}{U^2}\,,$$

$$D_p = (e_1 - e_{2\,p})^2 = \sum - 2\,A_1\,A_2\,\frac{\overline{u_1 u_2}}{U^2} - 2\,B_1\,B_2\,\frac{\overline{v_1 v_2}}{U^2}\,,$$

$$D_0 = (e_1 - e_{2\,0})^2 = \sum - 2\,A_1\,A_2\,\frac{\overline{u_1 u_2}}{U^2} + 2\,B_1\,B_2\,\frac{\overline{v_1 v_2}}{U^2}\,,$$

where

$$\sum = \left(\frac{u_1}{U}\right)^2 \left[A_1^{\,2} + A_2^{\,2}\right] + \left(\frac{v_1}{U}\right)^2 \left[B_1^{\,2} + B_2^{\,2}\right]$$

and provided that no turbulent shear stresses are present, *i.e.*,

$$\overline{u_1 v_1} = \overline{u_2 v_2} = 0$$

and consequently also

$$\overline{u_1 v_2} = \overline{u_2 v_1} = 0\,.$$

Then the following expressions for the correlation of lateral or longitudinal components can be obtained :

$$\left.\begin{aligned} S_p - S_0 &= 4\,B_1\,B_2\,\frac{\overline{v_1 v_2}}{U^2}\,, \\ D_0 - D_p &= 4\,B_1\,B_2\,\frac{\overline{v_1 v_2}}{U^2}\,, \\ S_p - D_0 &= 4\,A_1\,A_2\,\frac{\overline{u_1 u_2}}{U^2}\,, \\ S_0 - D_p &= 4\,A_1\,A_2\,\frac{\overline{u_1 u_2}}{U^2}\,. \end{aligned}\right\} \qquad \ldots \quad (11)$$

If all the quantities S_p, S_0, D_p, D_0 are measured, then two independent combinations exist for determining each of the correlations $\overline{u_1 u_2}$ and $\overline{v_1 v_2}$. This is useful for estimating the experimental errors involved. A check on the absence of a turbulent shear stress can be made in the usual way by measuring the mean-square values of $e_{2\,p}^{\,2}$ and $e_{2\,0}^{\,2}$ with one wire only.

APPENDIX III

Stability criterion for a general flow with vorticity

The stability criterion for the particular case of a flow along circular streamlines is usually expressed in terms of circulation* and says that a motion is stable, if the square of circulation increases outwards ; or

$$\frac{d(\Gamma^2)}{dr} > 0 \text{ stable flow ,}$$

$$\frac{d(\Gamma^2)}{dr} < 0 \text{ unstable flow ,}$$

where $\Gamma = 2\pi rv$, where v is the velocity and r the radius. Since

$$\frac{1}{2\pi r}\frac{d\Gamma}{dr} = \gamma \text{ ,}$$

where γ is the vorticity, we can express the stability criterion in a slightly different form :

$$\Gamma\gamma > 0 \text{ stable flow ,}$$

$$\Gamma\gamma < 0 \text{ unstable flow .}$$

The stability depends therefore on whether Γ and γ have the same or opposite direction of rotation. For a general flow the sign of Γ is to be replaced by the sign of rotation of the radius vector from the centre of curvature of the streamline to the fluid particle. Then a simple rule for the stability can be derived : the flow along a curved streamline is dynamically stable at any point where the vorticity of a fluid particle has the same direction of rotation as the radius vector from the centre of curvature of the streamline to the fluid particle.

---

* *See,* for instance : N. A. V. Piercy : Aerodynamics. 2nd ed. p. 367.

TABLE 1

Intensities of Turbulence Across Lower Part of Second Diffuser at the End of the Diffuser

Distance below centre-line ft	u' (per cent)				v' (per cent)				w' (per cent)			
	Speed in Working Section f.p.s.				Speed in Working Section f.p.s.				Speed in Working Section f.p.s.			
	60	100	160	220	60	100	160	220	60	100	160	220
0	10·3	11·8	11·7	12·0	9·5	11·7	11·8	11·2	10·7	13·5	12·9	12·0
1·5	11·6	13·0	12·2	10·9	10·2	12·6	11·6	10·8	9·6	12·7	11·5	9·9
3·0	14·3	15·2	12·2	13·4	13·1	13·6	12·1	10·7	11·9	14·4	12·8	11·4
4·0	13·4	17·7	15·3	16·5	12·0	14·5	13·2	12·1	11·5	14·5	12·8	12·2
5·0	13·2	16·5	14·8	15·6	9·1	12·5	13·7	10·8	9·2	11·1	10·5	10·2

TABLE 2

Distance of Position of Measurements from End of Diffuser

Position	Distance x from End of Diffuser ft	$\frac{x}{D}$
1	0	0
2	14	1·25
3	24·3	2·17
4	38·6	3·45

TABLE 3

Reduction of the Three Components of Turbulence Along Axis of Tunnel

Speed in Working Section f.p.s.	$\frac{u'}{u_{(1)}'}$				$\frac{v'}{v_{(1)}'}$				$\frac{w'}{w_{(1)}'}$			
	Position				Position				Position			
	1	2	3	4	1	2	3	4	1	2	3	4
60	1·00	0·692	0·442	0·498	1·00	0·655	0·540	0·381	1·00	0·768	0·480	0·432
100	1·00	0·594	0·414	0·454	1·00	0·543	0·375	0·324	1·00	0·558	0·409	0·376
160	1·00	0·618	0·422	0·443	1·00	0·531	0·376	0·329	1·00	0·632	0·416	0·399
220	1·00	0·562	0·403	0·435	1·00	0·531	0·368	0·331	1·00	0·633	0·441	0·412

TABLE 4

Overall Reduction of Turbulence for Various Number of Screens in Bulge

Speed in Working Section f.p.s.	Number of Screens in Bulge									Fixed Screens in Rapid Expansion			Bulge
	2			3			9			1st	2nd	3rd	
	$R_u^{(S)}$	$R_u^{(D)}$	R_v	$R_u^{(S)}$	$R_u^{(D)}$	R_v	$R_u^{(S)}$	$R_u^{(D)}$	R_v	k	k	k	k
60	$-0{\cdot}74 \times 10^{-6}$	0·0188	0·0303	$+0{\cdot}98 \times 10^{-7}$	0·00752	0·0133	$+5 \times 10^{-13}$	0·0000312	0·0000973	2·96	3·28	3·48	5·34
80	$+0{\cdot}215 \times 10^{-6}$	0·0218	0·0352	$-0{\cdot}25 \times 10^{-7}$	0·00915	0·0162	$-0{\cdot}6 \times 10^{-13}$	0·0000496	0·000155	2·66	3·06	3·29	4·75
100	$-0{\cdot}035 \times 10^{-6}$	0·0247	0·0398	$+0{\cdot}0037 \times 10^{-6}$	0·0106	0·0187	$+5{\cdot}7 \times 10^{-15}$	0·0000646	0·000202	2·40	2·82	3·12	4·46
140	0	0·0327	0·0526	0	0·0149	0·0263	0	0·000132	0·000412	2·02	2·44	2·80	3·86
180	$+1{\cdot}05 \times 10^{-6}$	0·0372	0·0598	$-0{\cdot}66 \times 10^{-7}$	0·0172	0·0305	$-4{\cdot}1 \times 10^{-15}$	0·000172	0·000538	1·93	2·24	2·49	3·56
220	$+1{\cdot}44 \times 10^{-6}$	0·0438	0·0705	$-0{\cdot}62 \times 10^{-7}$	0·0212	0·0376	$-3{\cdot}9 \times 10^{-16}$	0·000278	0·000869	1·89	1·98	2·26	3·26

TABLE 7

Influence of Contraction Ratio of Bulge on Contribution of Screens to Tunnel Power Factor for a Given Turbulence Intensity in Working Section

Turbulence Intensity at Beginning of Rapid Expansion 4 per cent of Mean Speed

LONGITUDINAL COMPONENT

Overall Reduction Due to Expansion and Contraction $8 \cdot 5^2 : 1$

3 Screens of Resistance Coefficient $k = 1$

Turbulence Intensity in Working Section 0·02 per cent

Contraction Ratio of Bulge	Contribution to Tunnel Power Factor
25 : 1	0·018
14 : 1	0·029
10 : 1	0·037
8·5 : 1	0·042

LATERAL COMPONENT

Overall Reduction Due to Expansion and Contraction $\sqrt{8 \cdot 5} : 1$

7 Screens of Resistance Coefficient $k = 2$

Turbulence Intensity in Working Section 0·03 per cent

Contraction Ratio of Bulge	Contribution to Tunnel Power Factor
25 : 1	0·042
14 : 1	0·098
10 : 1	0·15
8·5 : 1	0·22

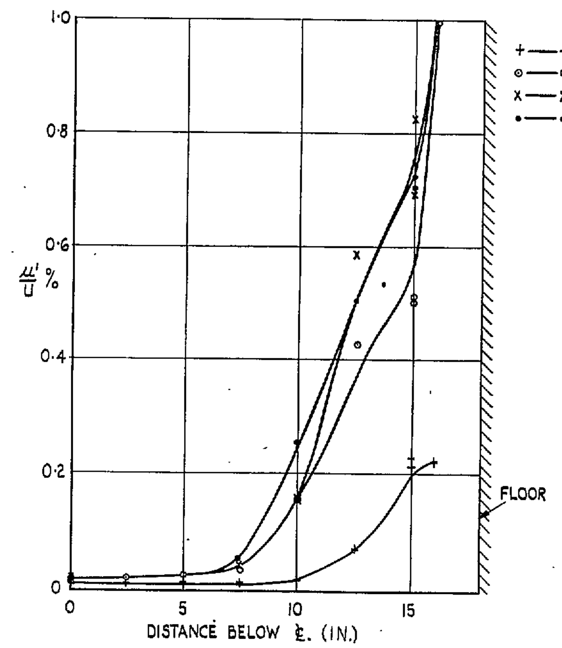

Fig. 1. At standard position.

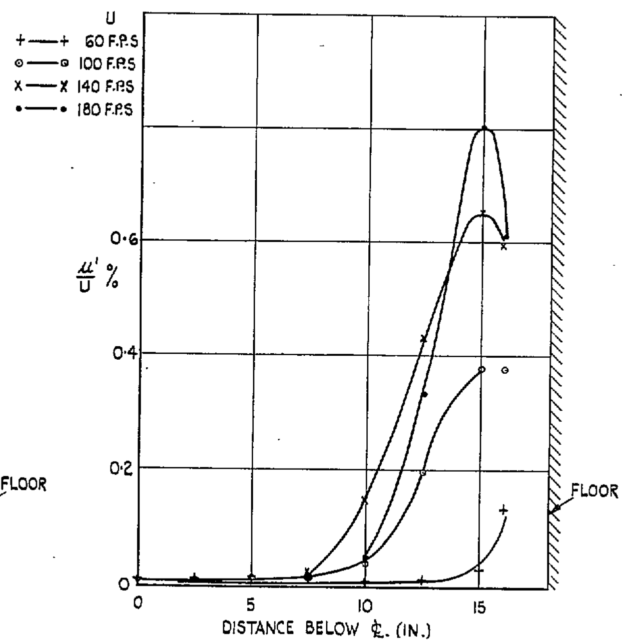

Fig. 2. At beginning of working section.

Figs. 1 and 2. Vertical traverse of longitudinal component of turbulence in working section. 9 screens in bulge.

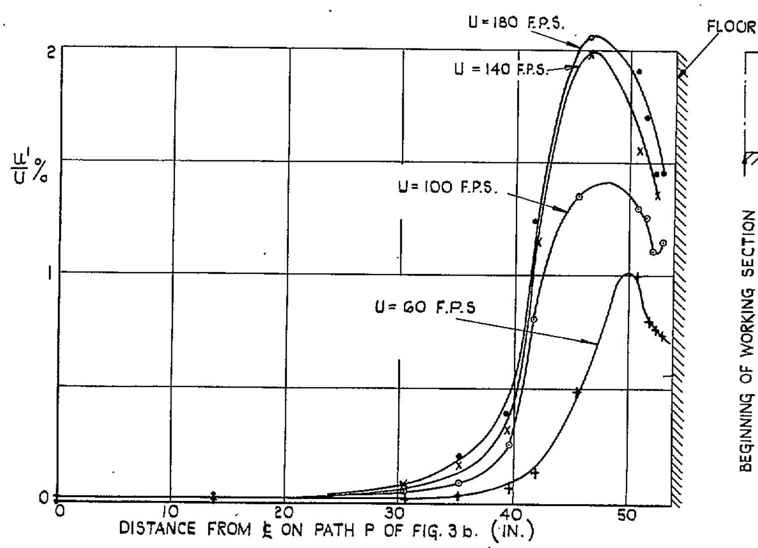

Fig. 3a. Traverse of longitudinal component of turbulence in contraction. 9 screens in bulge.

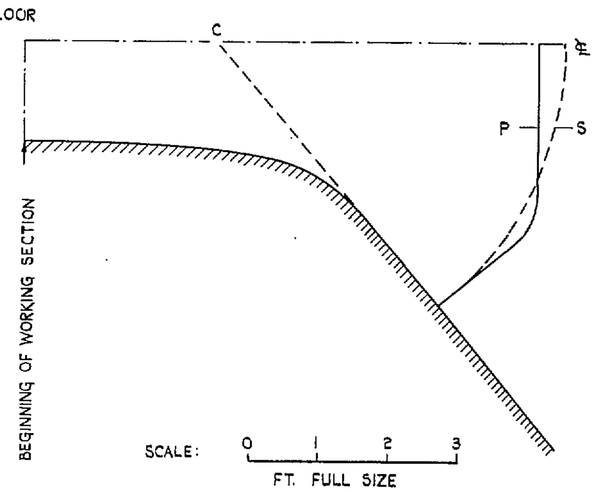

Fig. 3b. Path of traverse in contraction.

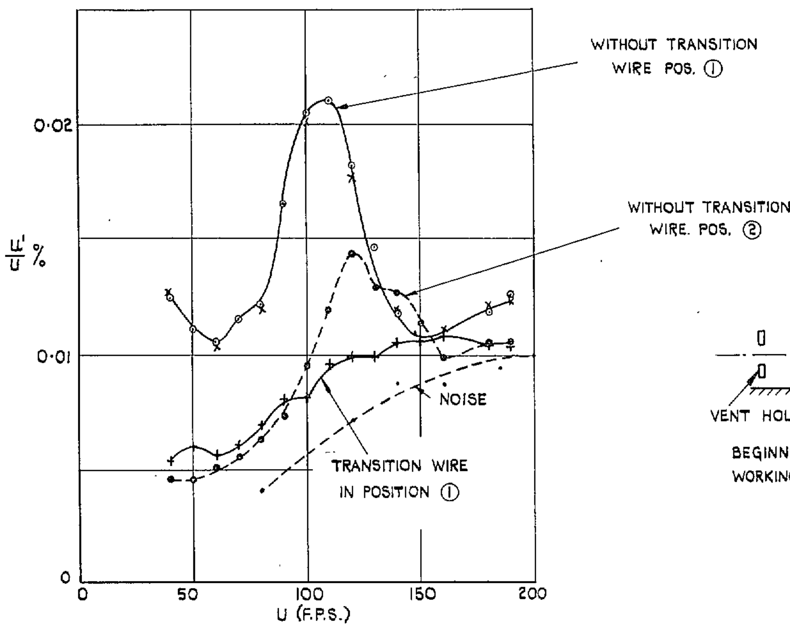

FIG. 4a. Influence of transition wire on longitudinal component of turbulence in the working section. 9 screens in the bulge (measurements made on tunnel centre-line).

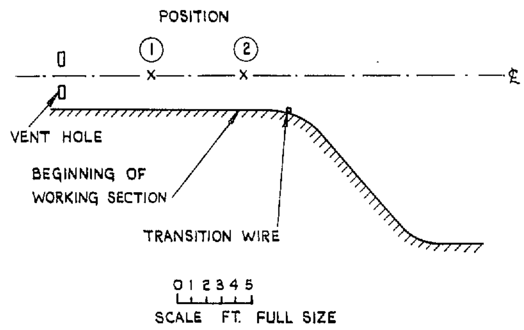

FIG. 4b. Position of transition wire on tunnel floor.

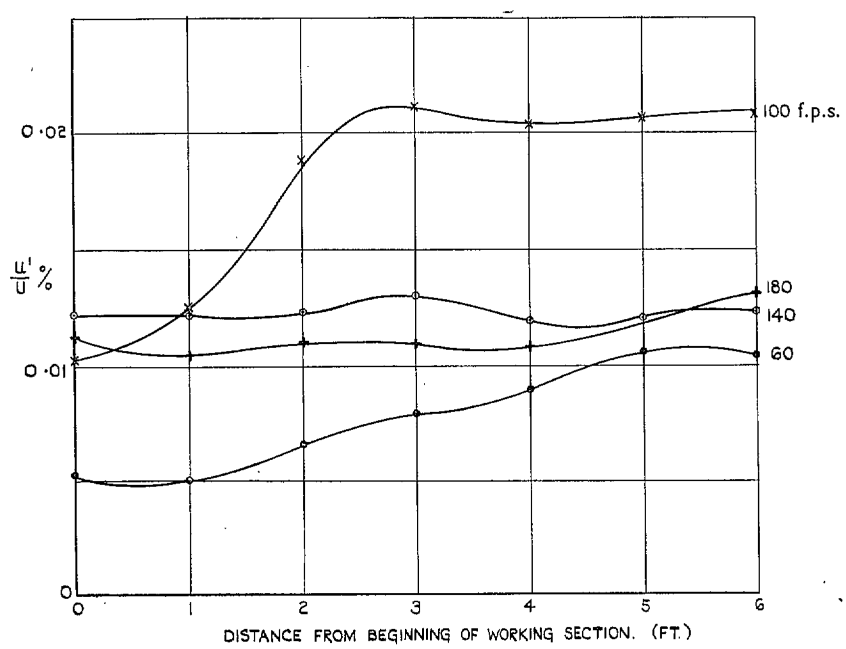

FIG. 5. Distribution of longitudinal component of turbulence along axis in working section.

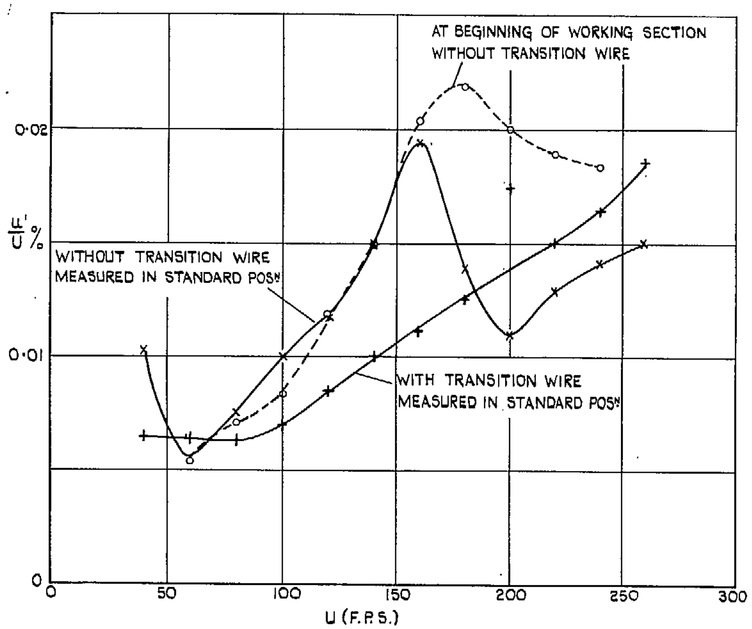

FIG. 6. Intensity of longitudinal component of turbulence in working section. 2 screens in bulge.

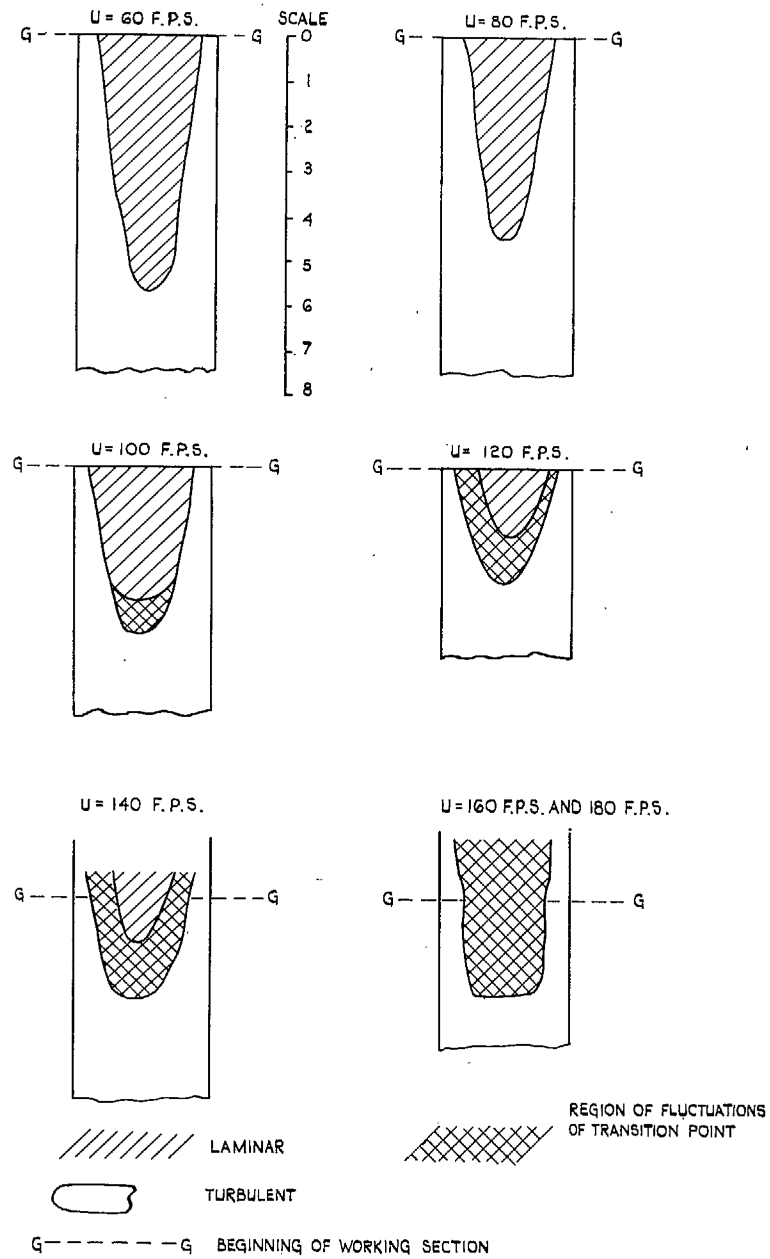

FIG. 7. State of boundary layer on floor of working section of tunnel. 2 screens in bulge.

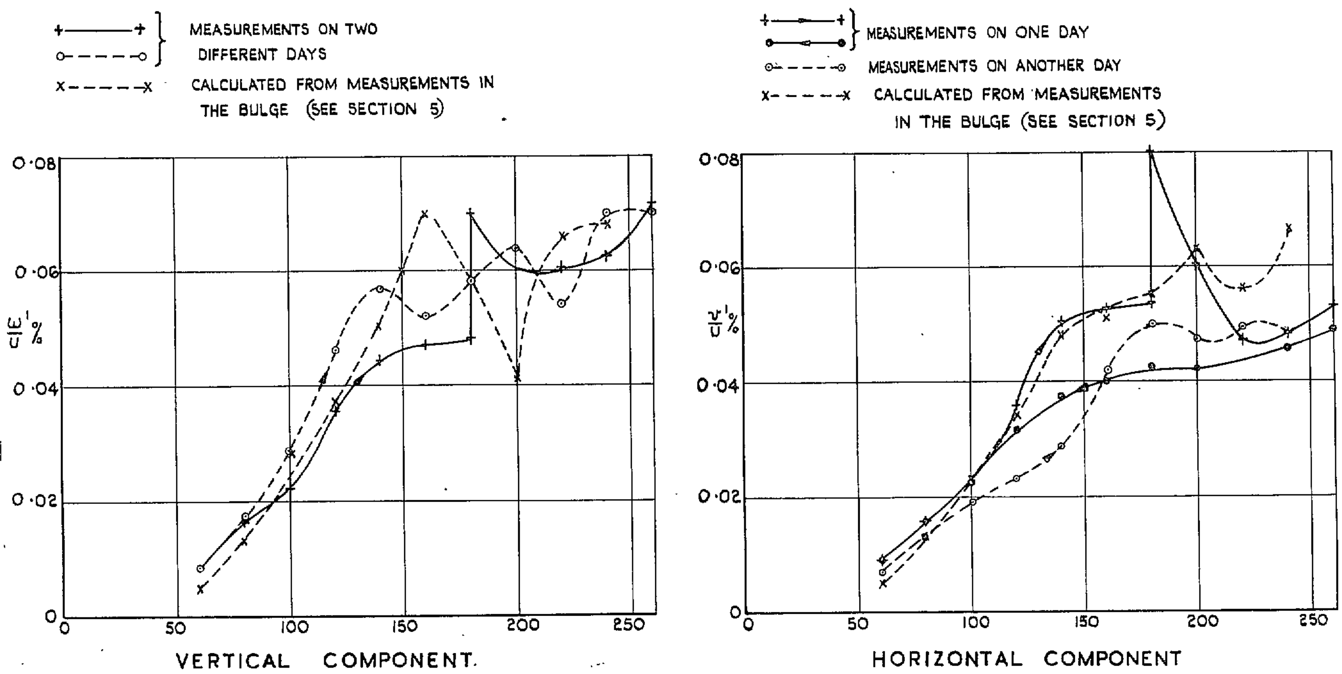

FIG. 8. Intensity of lateral component of turbulence in working section. 2 screens in bulge.

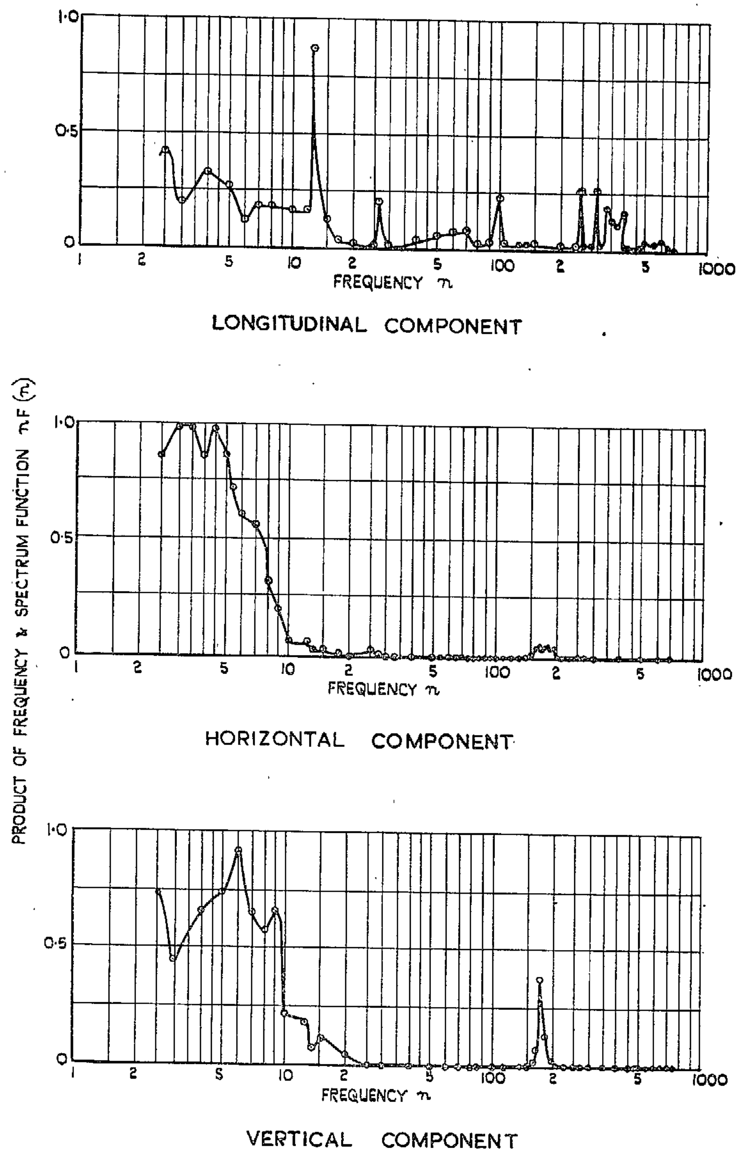

FIG. 9. Frequency spectra of all three components in working section with two screens in the bulge. Speed 60 f.p.s. Fan fundamental frequency 13·2 c.p.s.

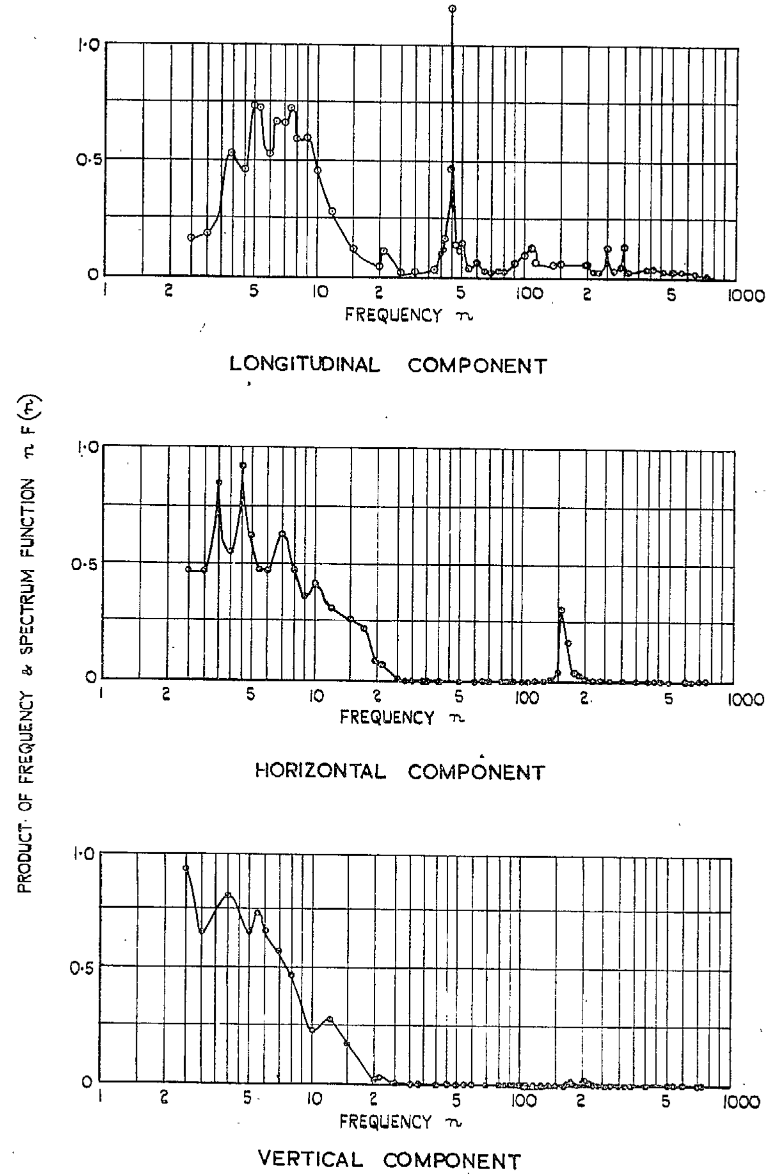

FIG. 10. Frequency spectra of all three components in working section with two screens in the bulge. Speed 100 f.p.s. Fan fundamental frequency 21·7 c.p.s.

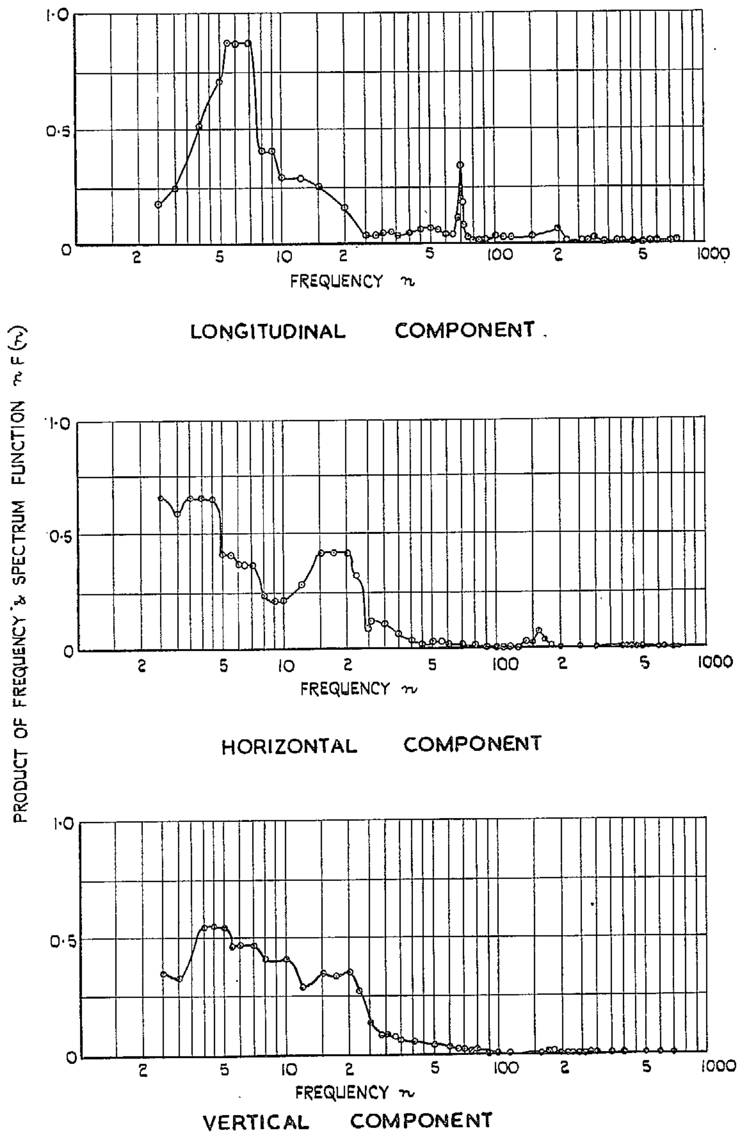

FIG. 11. Frequency spectra of all three components in working section with two screens in the bulge. Speed 160 f.p.s. Fan fundamental frequency 35 c.p.s.

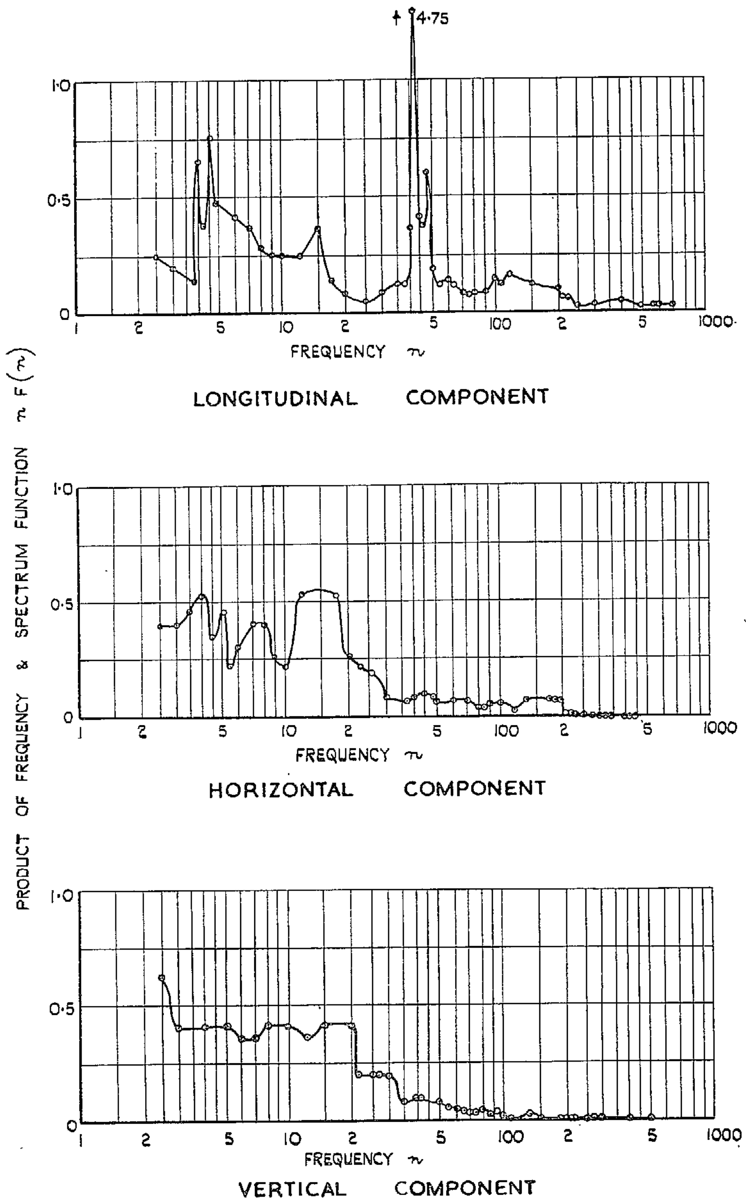

FIG. 12. Frequency spectra of all three components in working section with two screens in the bulge. Speed 200 f.p.s. Fan fundamental frequency 43·7 c.p.s.

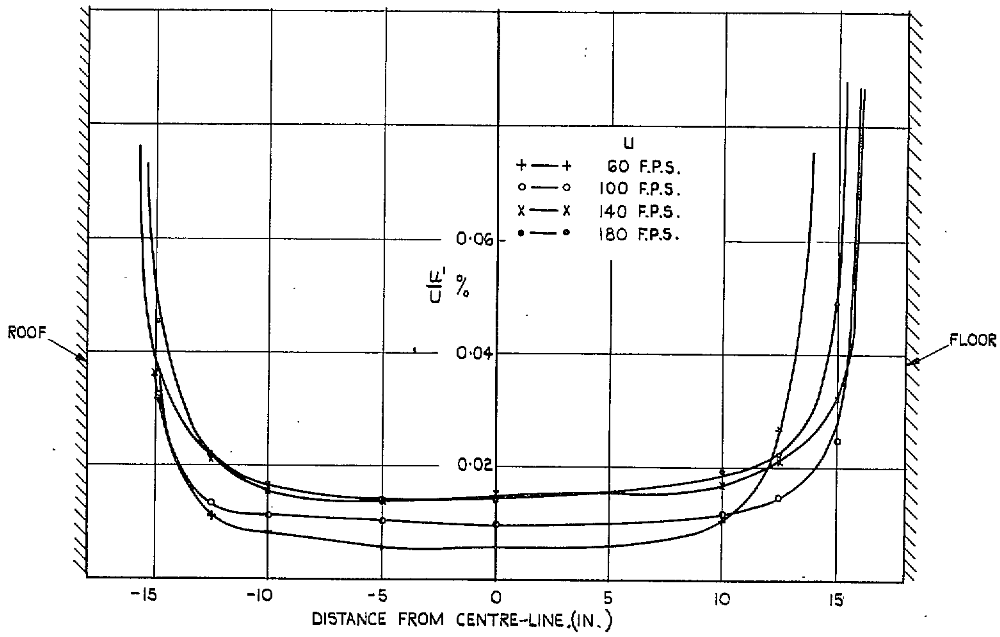

FIG. 13. Vertical traverse of longitudinal component in working section. Two screens in bulge.

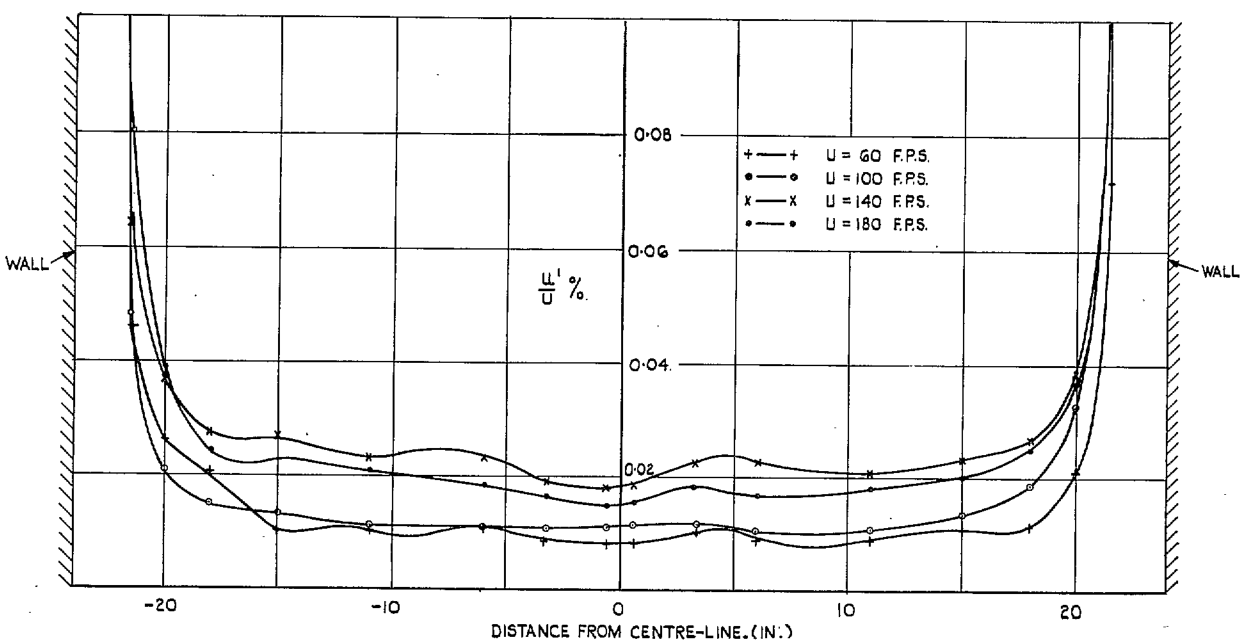

FIG. 14. Horizontal traverse of longitudinal component in working section. Two screens in bulge.

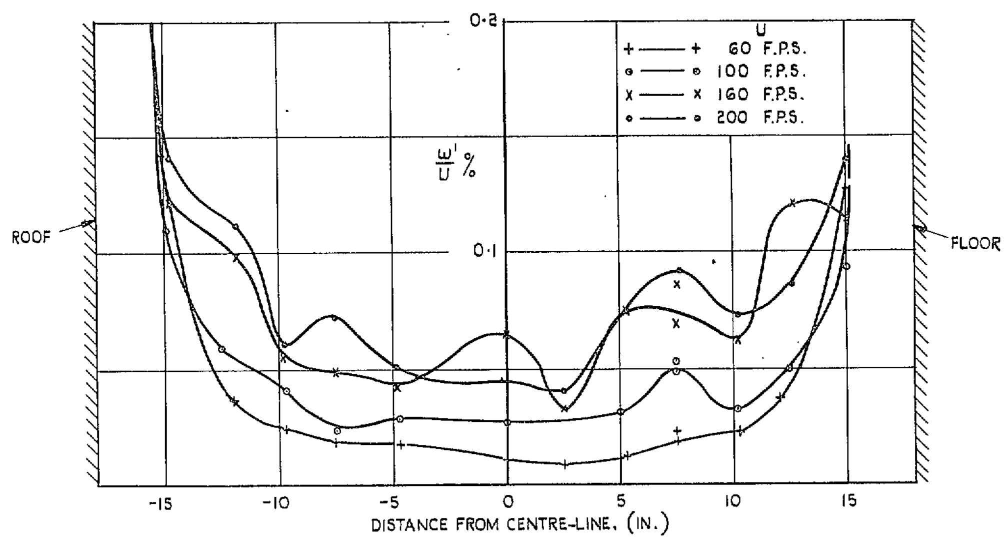

FIG. 15. Vertical traverse of vertical component in working section. Two screens in bulge.

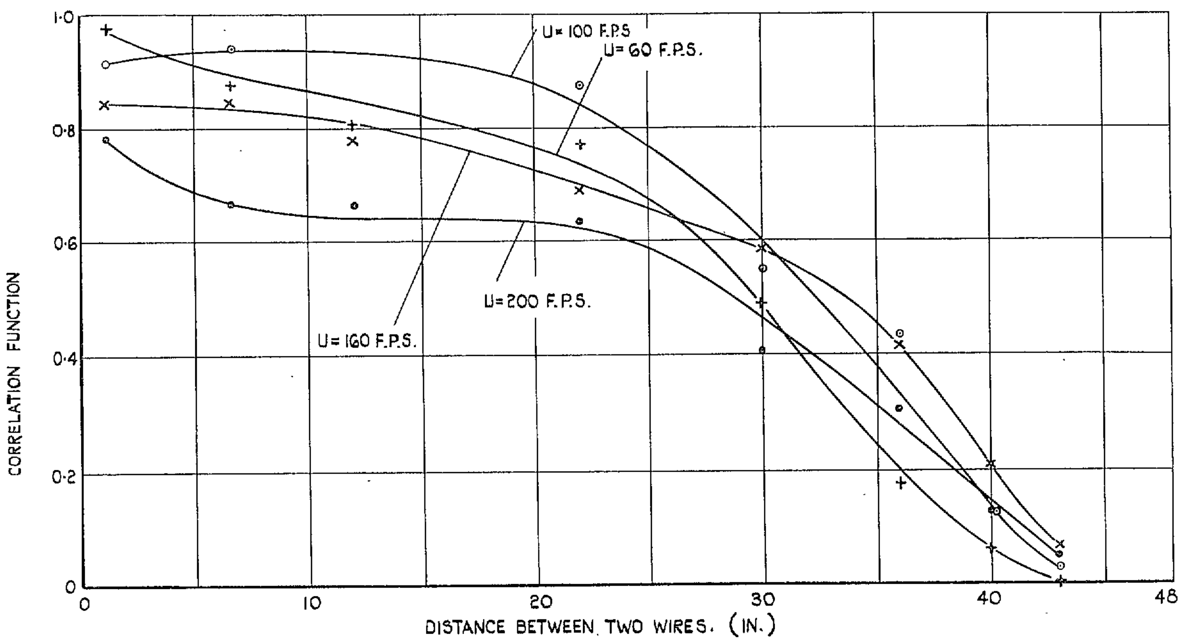

FIG. 16. Correlation of longitudinal component in working section. Two screens in bulge.

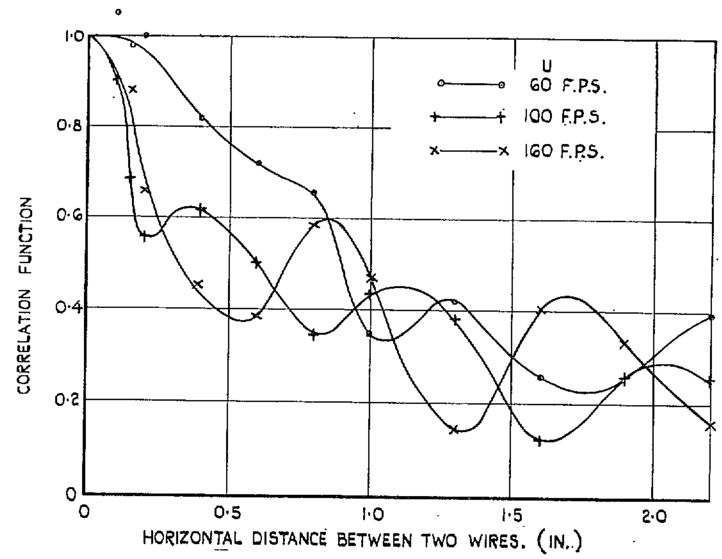

FIG. 17. Correlation of vertical component in working section. Two screens in bulge.

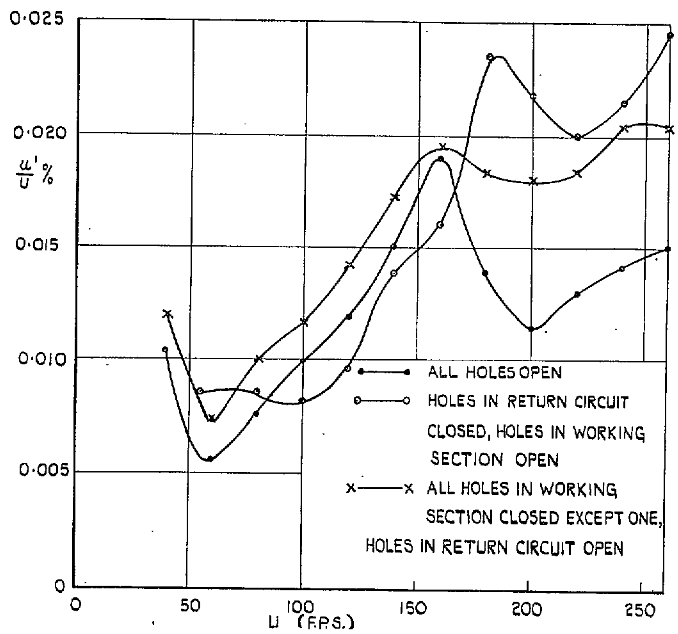

FIG. 18. Influence of vent holes on longitudinal component of turbulence in working section.

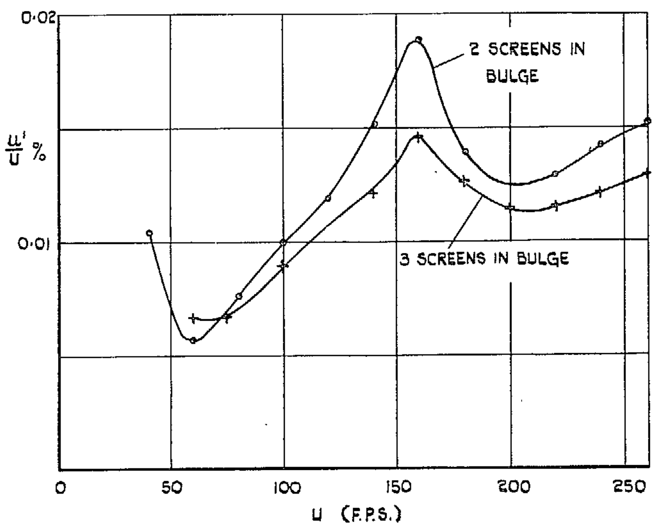

FIG. 19. Influence of number of screens in bulge on longitudinal component of turbulence in working section.

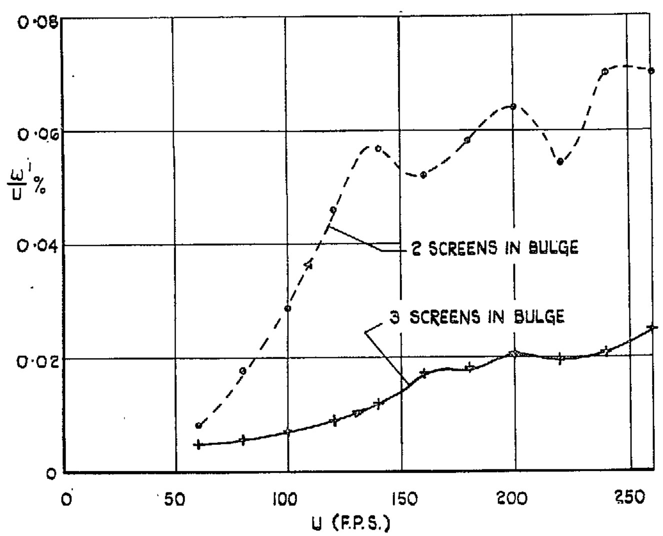

FIG. 20. Influence of number of screens in bulge on vertical component of turbulence in working section.

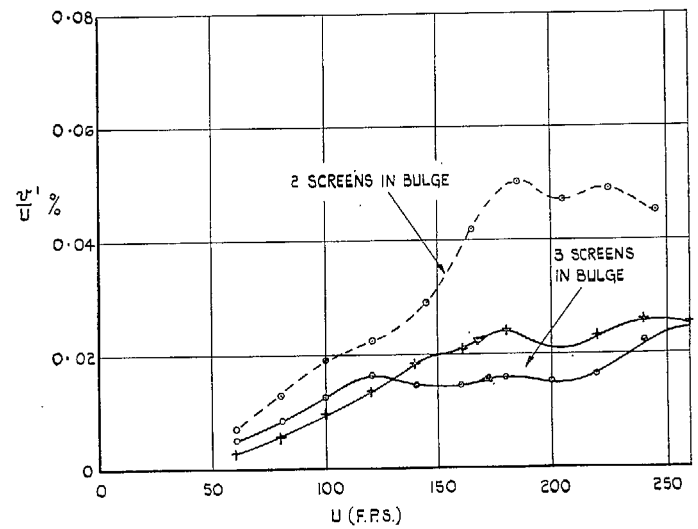

FIG. 21. Influence of number of screens in bulge on horizontal component of turbulence in working section.

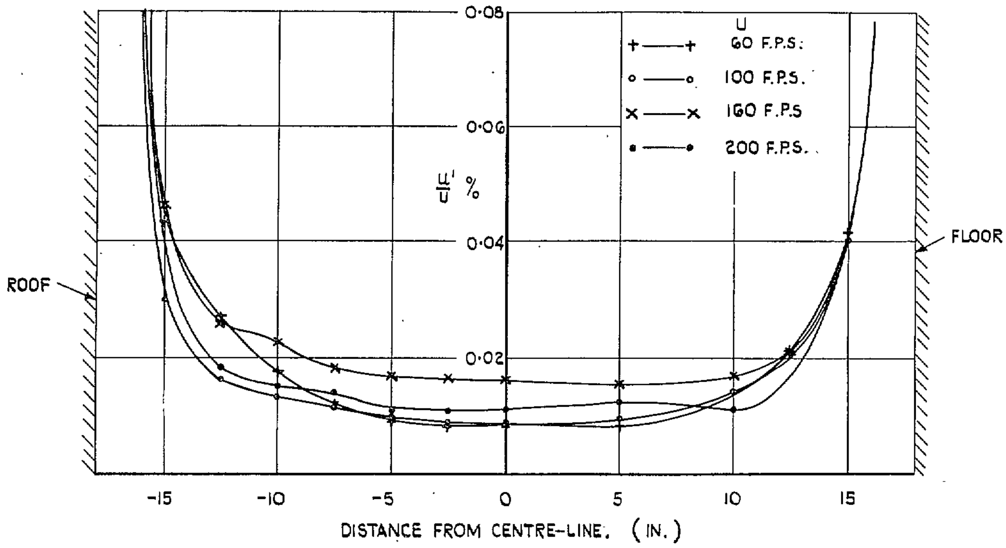

FIG. 22. Vertical traverse of longitudinal component of turbulence in working section. Three screens in bulge.

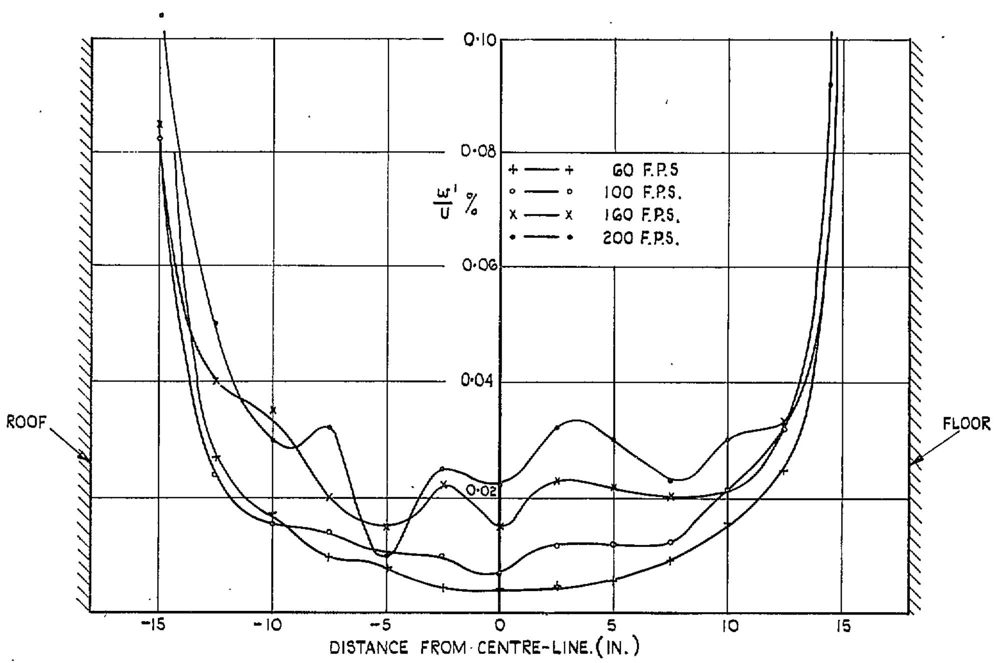

FIG. 23. Vertical traverse of vertical component of turbulence in working section. Three screens in bulge.

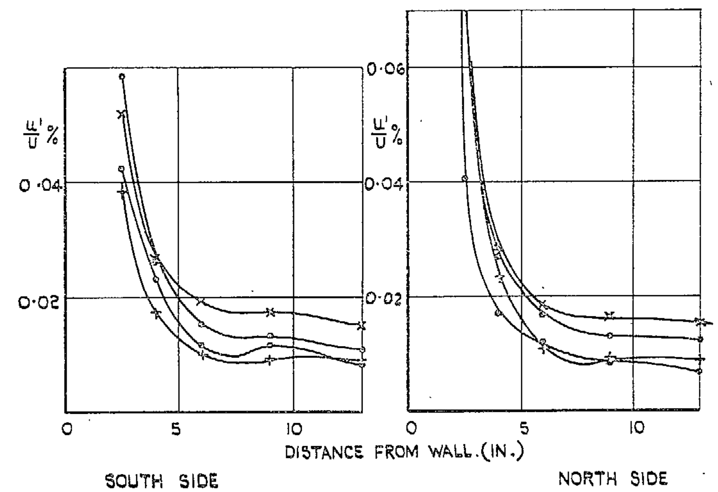

FIG. 24a. Intensity of longitudinal component of turbulence near side walls. Three screens in bulge.

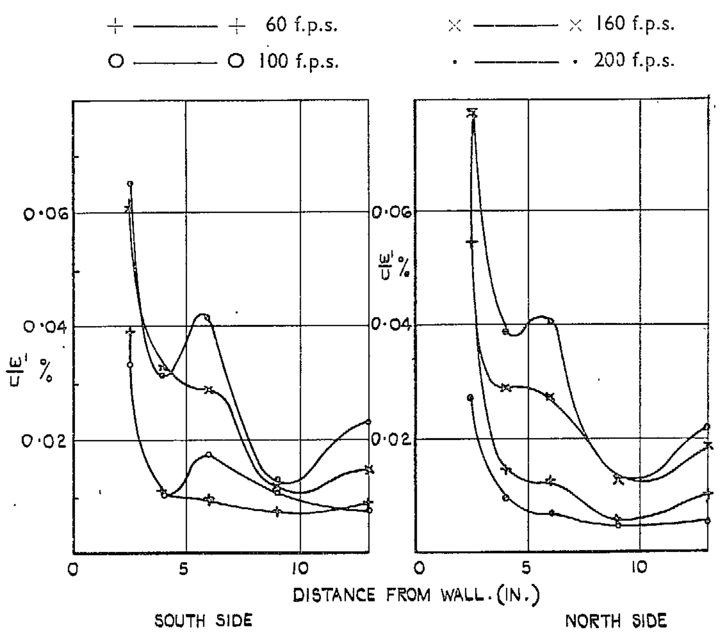

FIG. 24b. Intensity of vertical component of turbulence near side walls. Three screens in bulge.

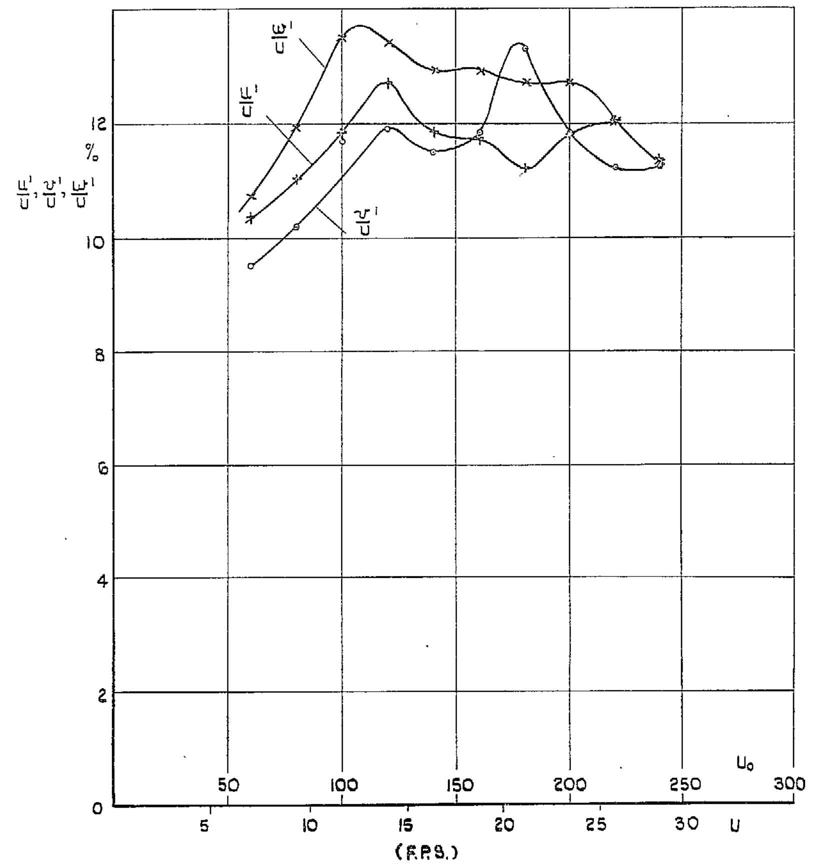

FIG. 25. Intensities of the three components of turbulence on centre-line at the end of the second diffuser.

(84222)

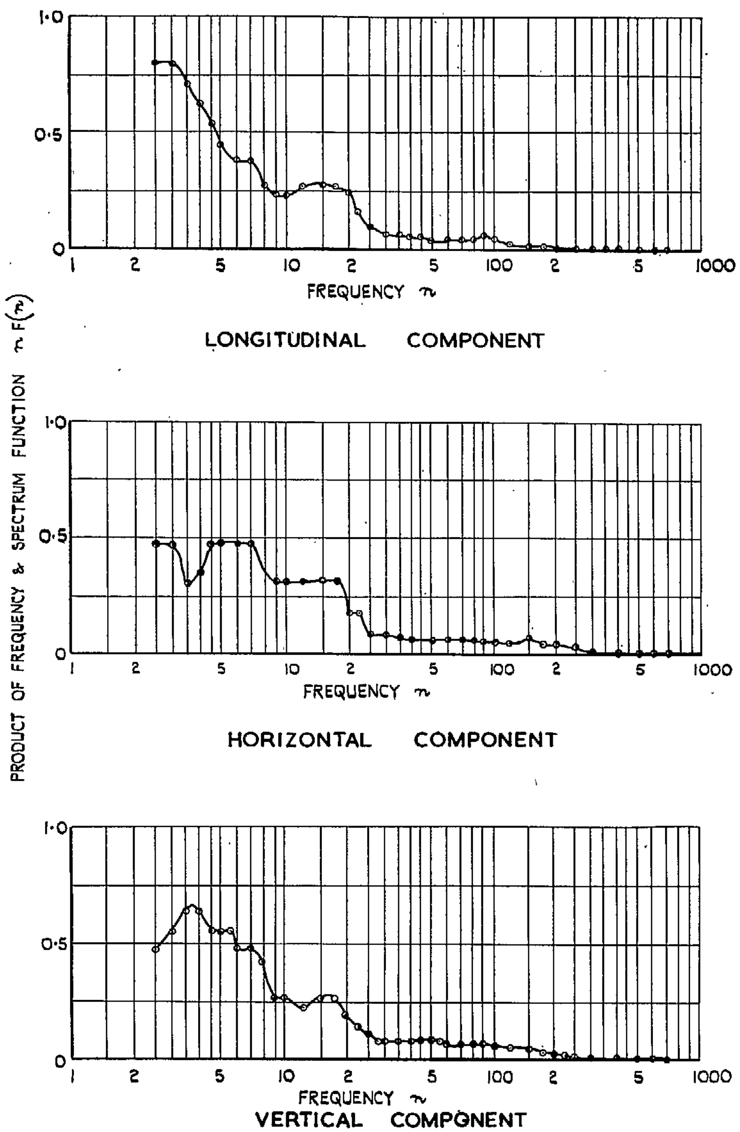

FIG. 26. Frequency spectra of all three components at the end of the second diffuser. Speed in the working section 60 f.p.s.

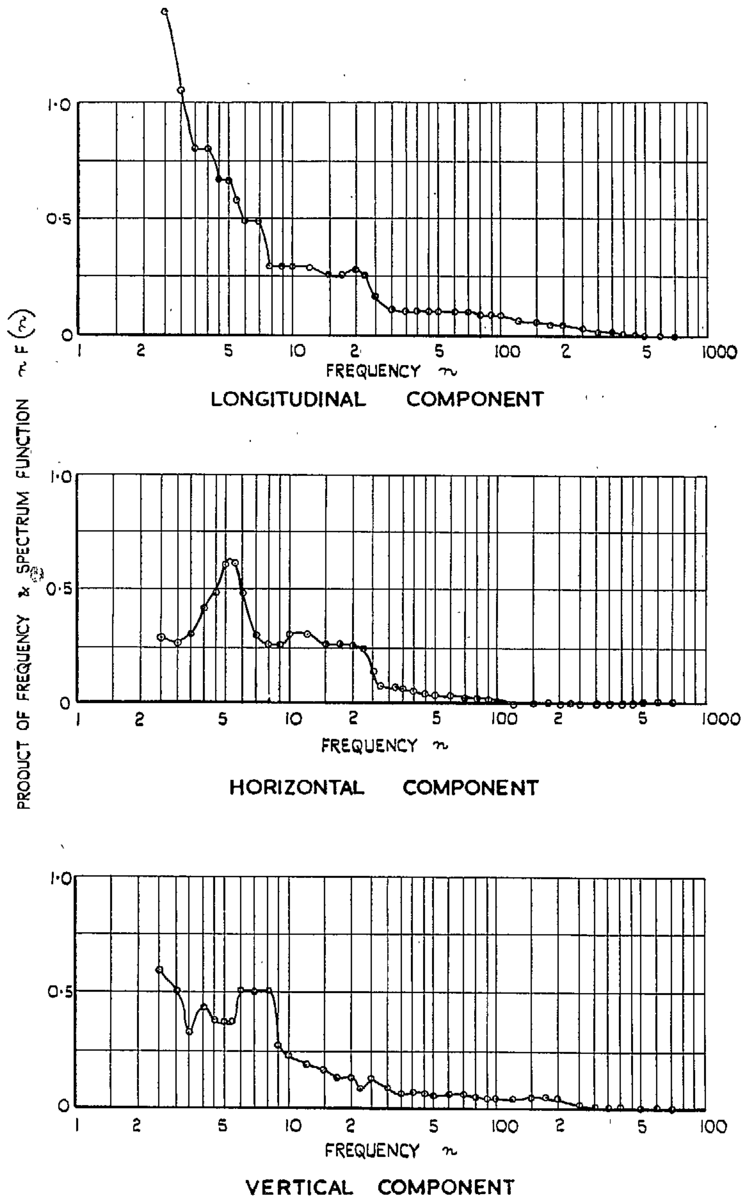

FIG. 27. Frequency spectra of all three components at the end of the second diffuser. Speed in the working section 100 f.p.s.

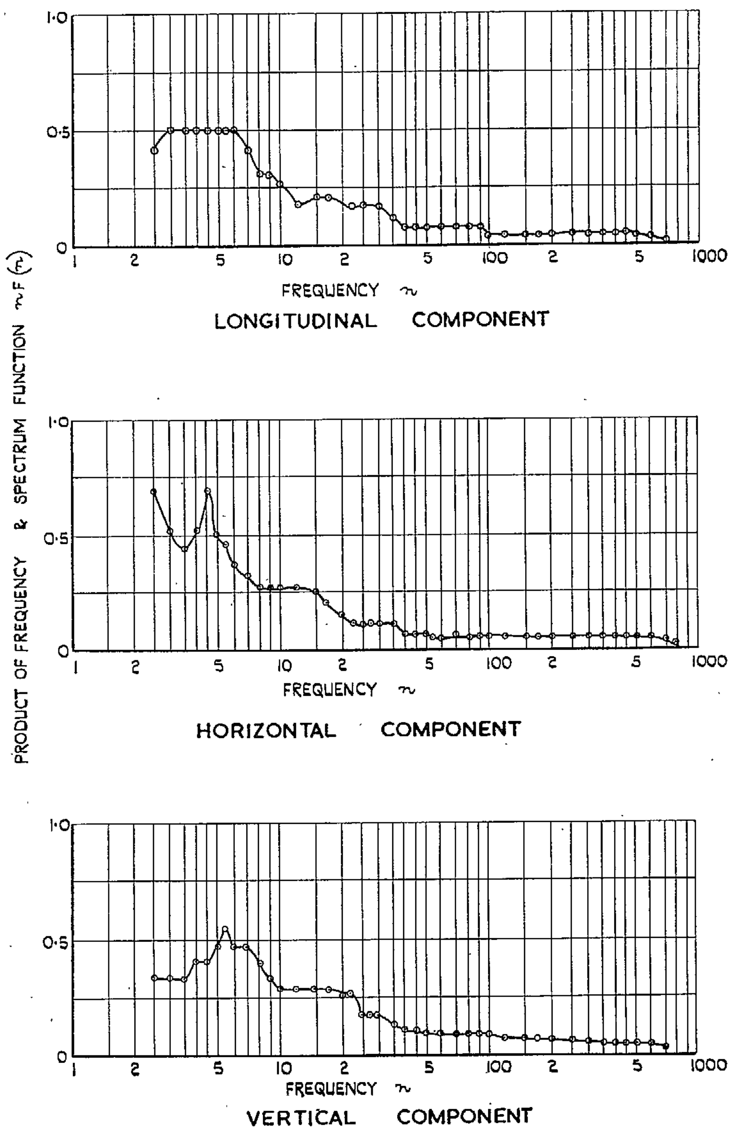

FIG. 28. Frequency spectra of all three components at the end of the second diffuser. Speed in the working section 160 f.p.s.

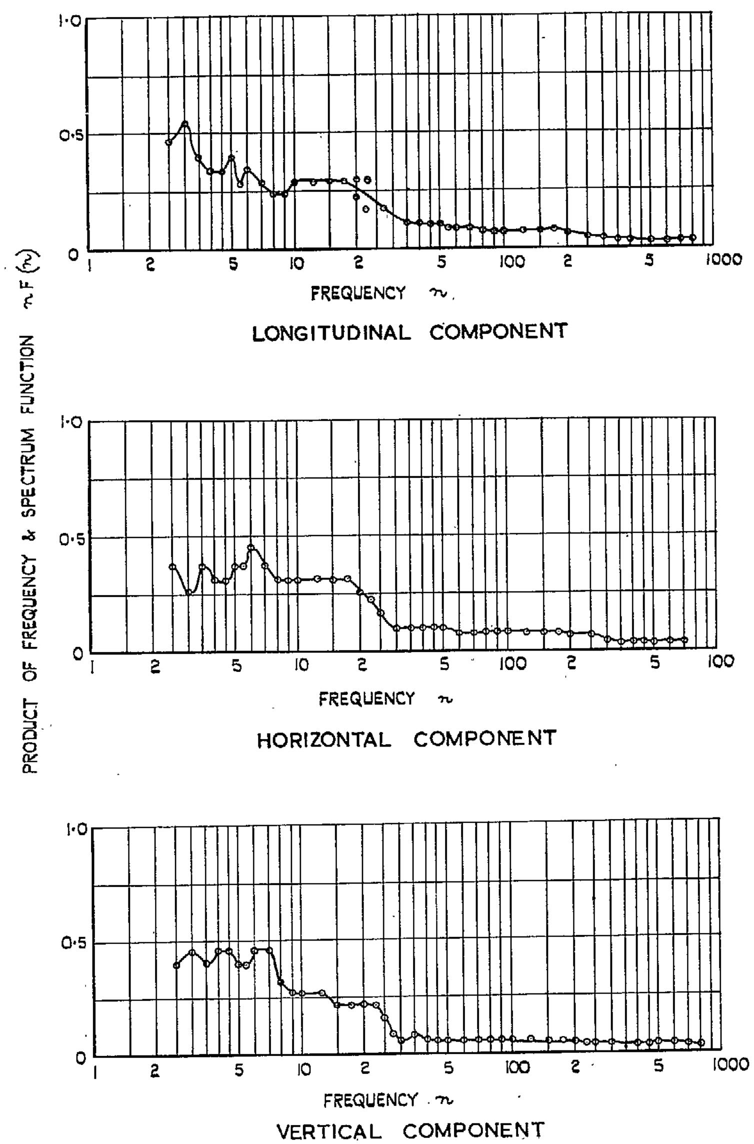

FIG. 29. Frequency spectra of all three components at the end of the second diffuser. Speed in the working section 220 f.p.s.

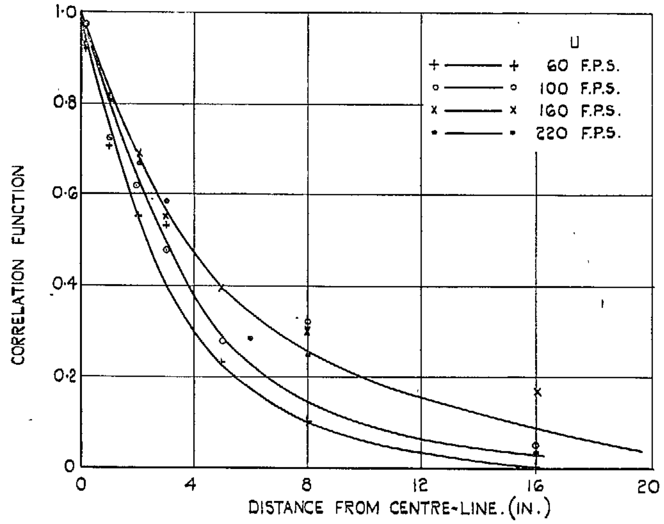

FIG. 30. Correlation of longitudinal component at end of second diffuser.

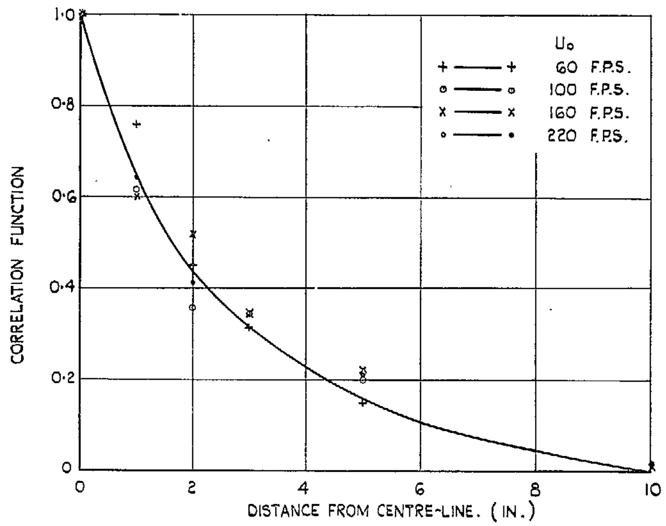

FIG. 31. Correlation of lateral component at end of second diffuser.

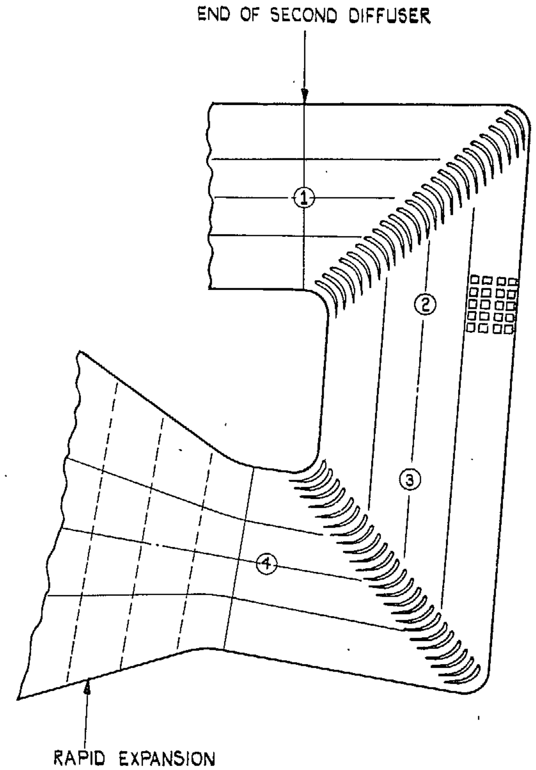

FIG. 32. Position of measurements between end of second diffuser and rapid expansion.

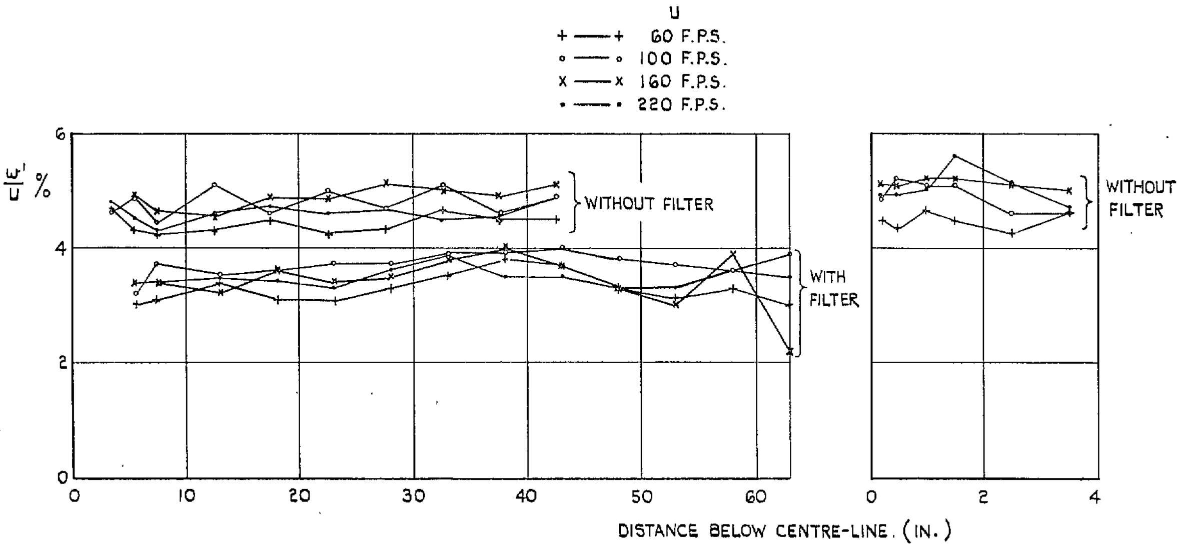

FIG. 33. Vertical traverse of vertical component of turbulence before the rapid expansion.

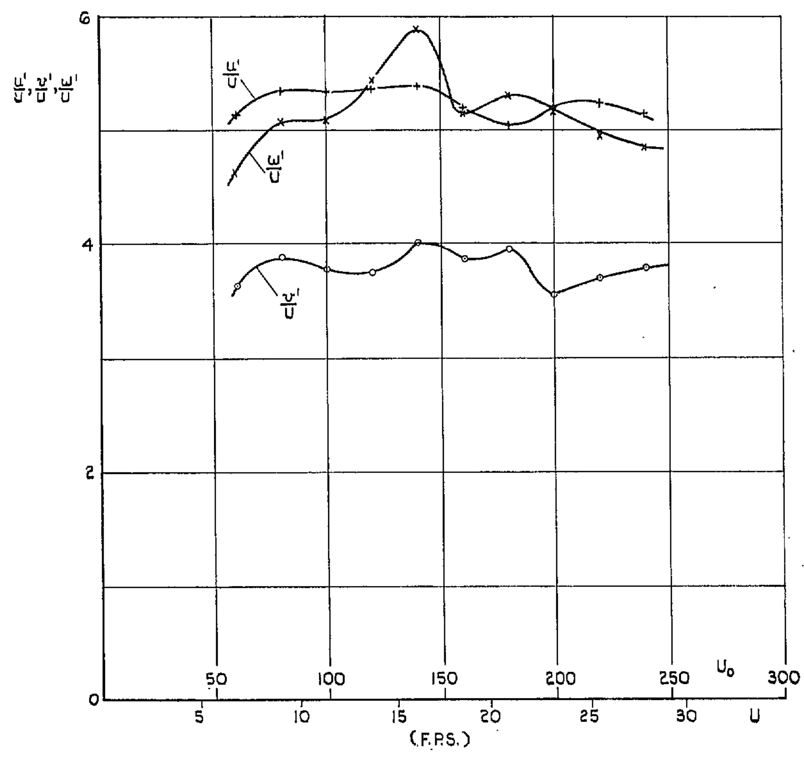

FIG. 34. Intensities of all three components of turbulence before rapid expansion.

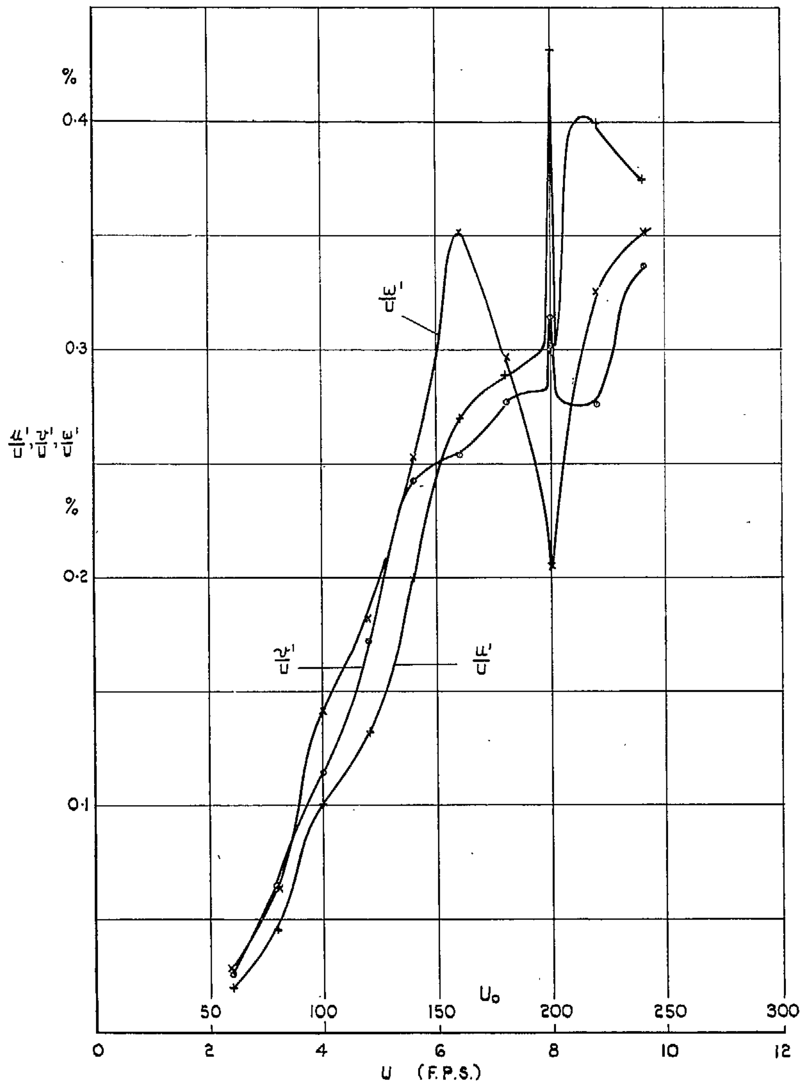

FIG. 35. Intensities of all three components of turbulence in bulge at a distance of 37 in. from the last screen. Two screens in the bulge.

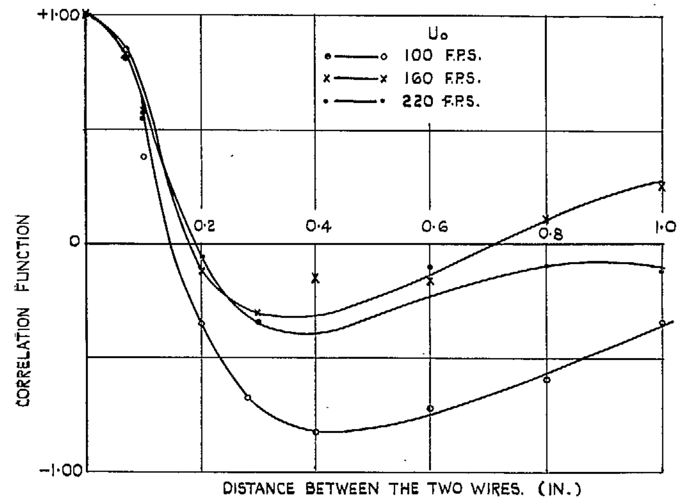

FIG. 36. Correlation of longitudinal component of turbulence along a horizontal line in the bulge 37 in. behind the last screen and 17½ in. below centre-line. Two screens in bulge.

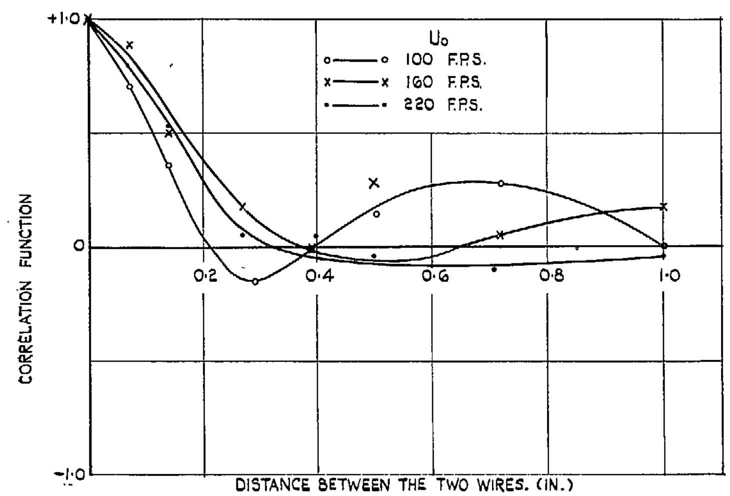

FIG. 37. Correlation of longitudinal component of turbulence along a vertical line in the bulge 37 in. behind last screen. Two screens in the bulge.

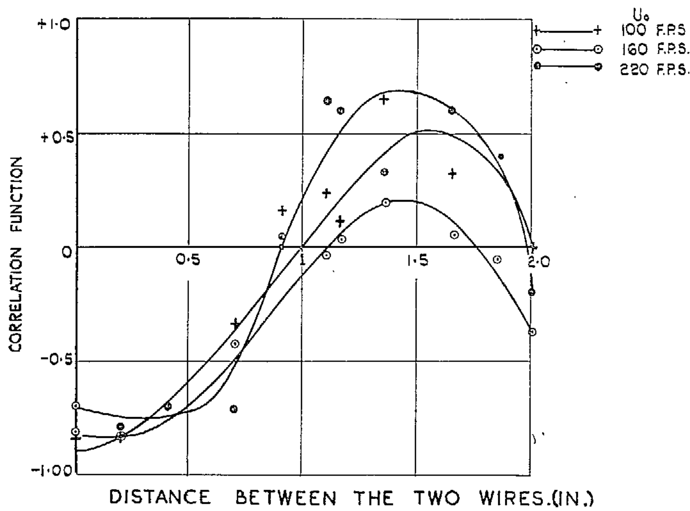

FIG. 38. Correlation of longitudinal and lateral component of turbulence in bulge 37 in. behind last screen. Two screens in bulge.

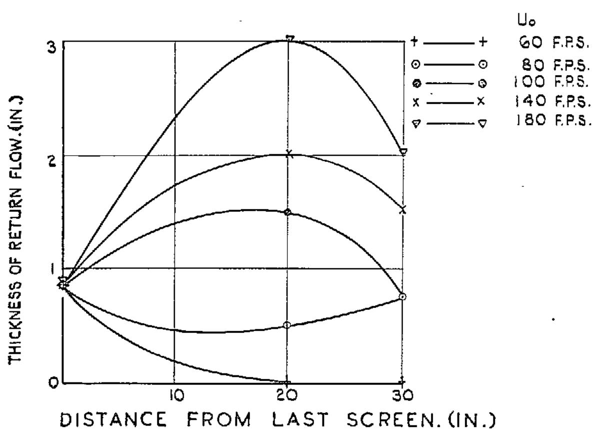

FIG. 39. Extent of return flow in bulge.

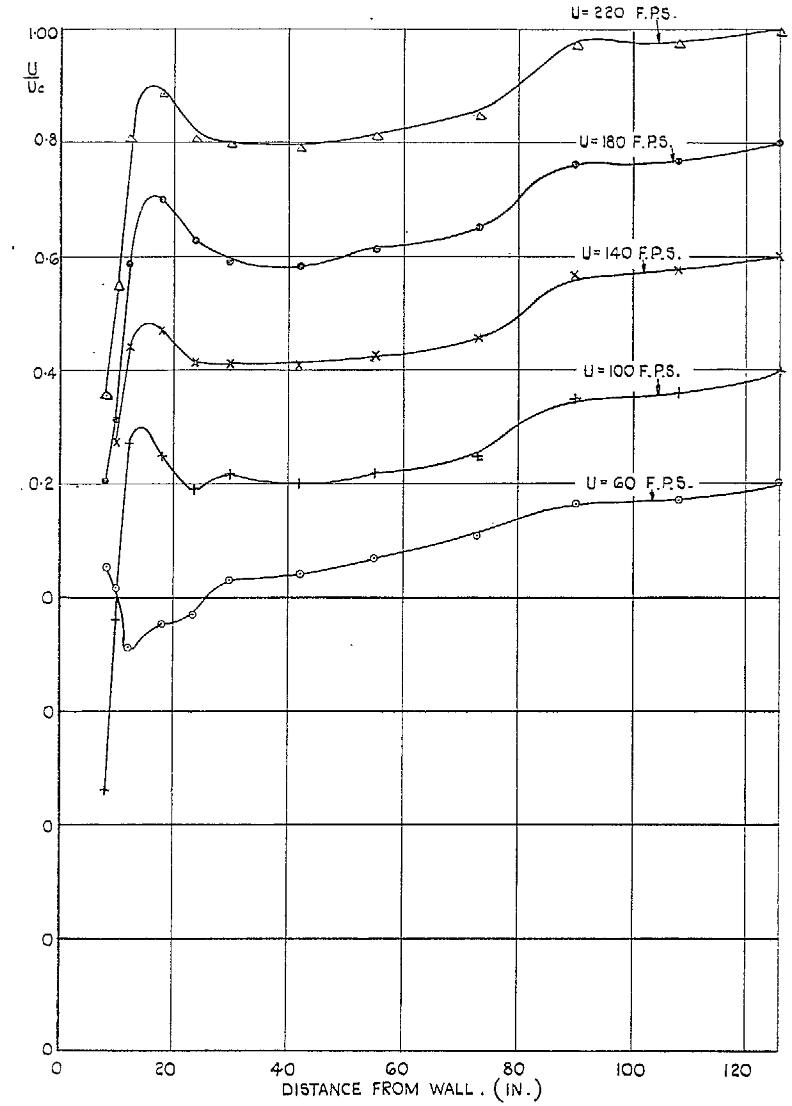

FIG. 40. Mean speed distribution in bulge 30 in. behind last screen. 9 screens in bulge.

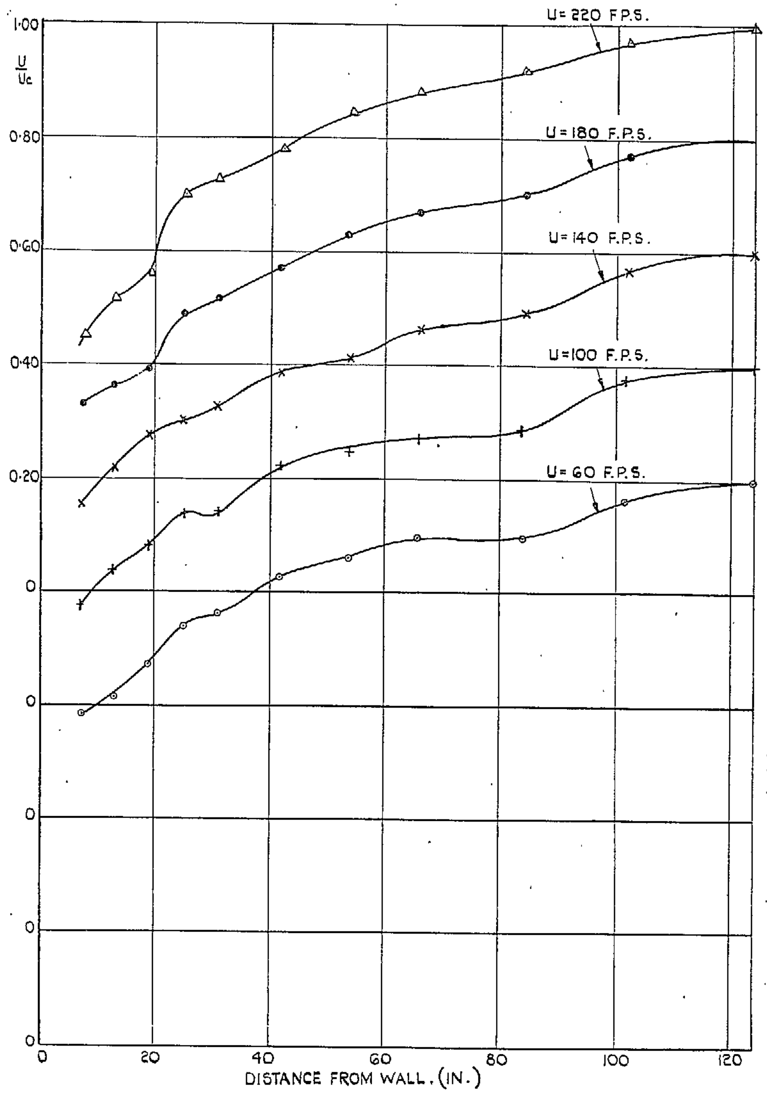

Fig. 41. Mean speed distribution in bulge 30 in. behind last screen. Two screens in bulge.

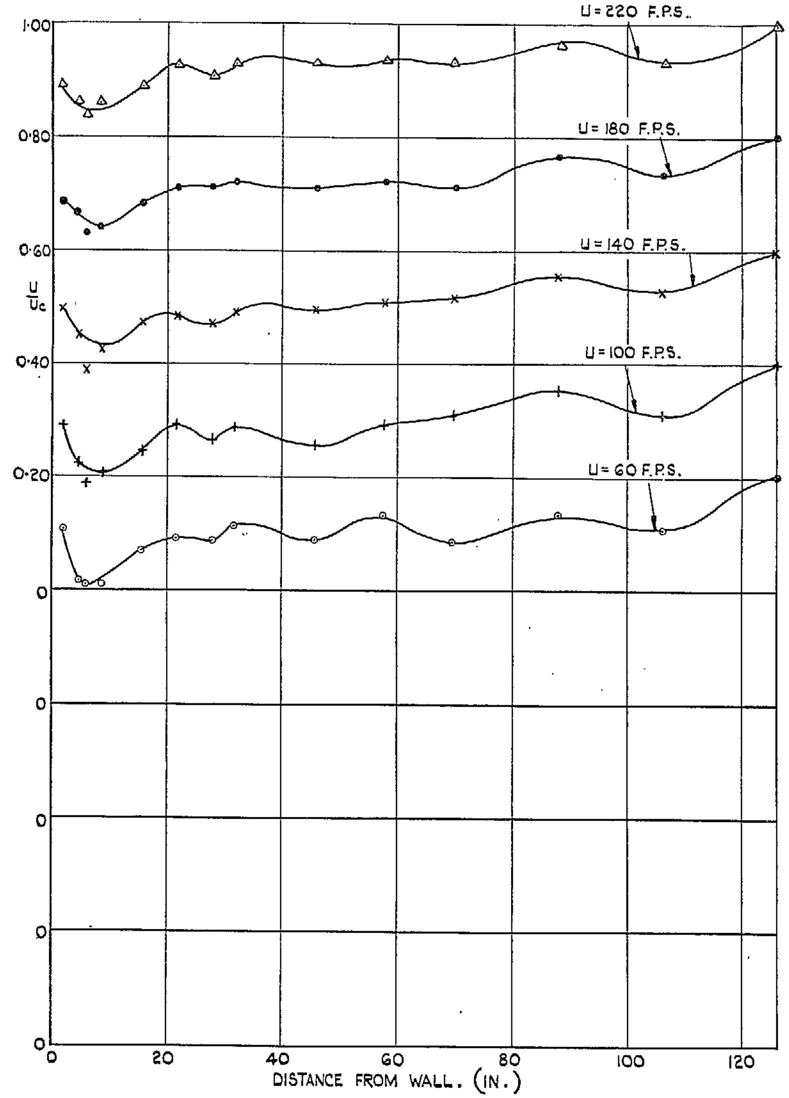

Fig. 42. Mean speed distribution in bulge 7 in. behind last screen. Two screens in bulge.

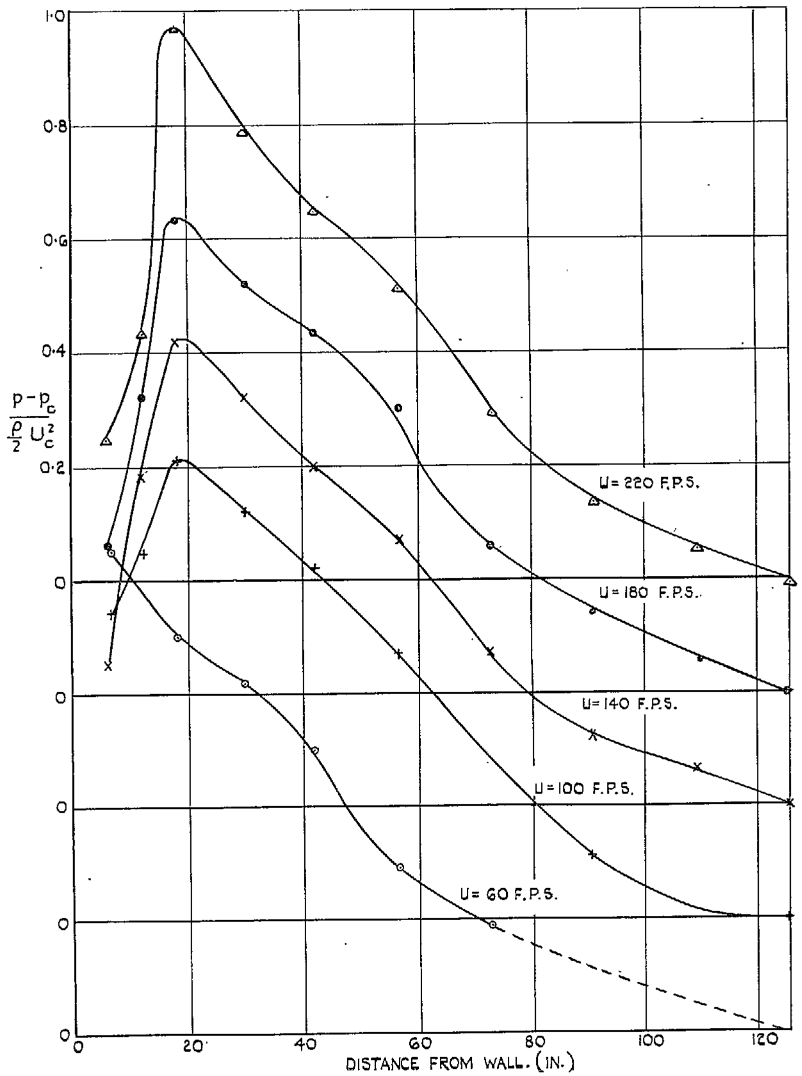

FIG. 43. Distribution of total head across lower part of bulge with 9 screens in bulge.

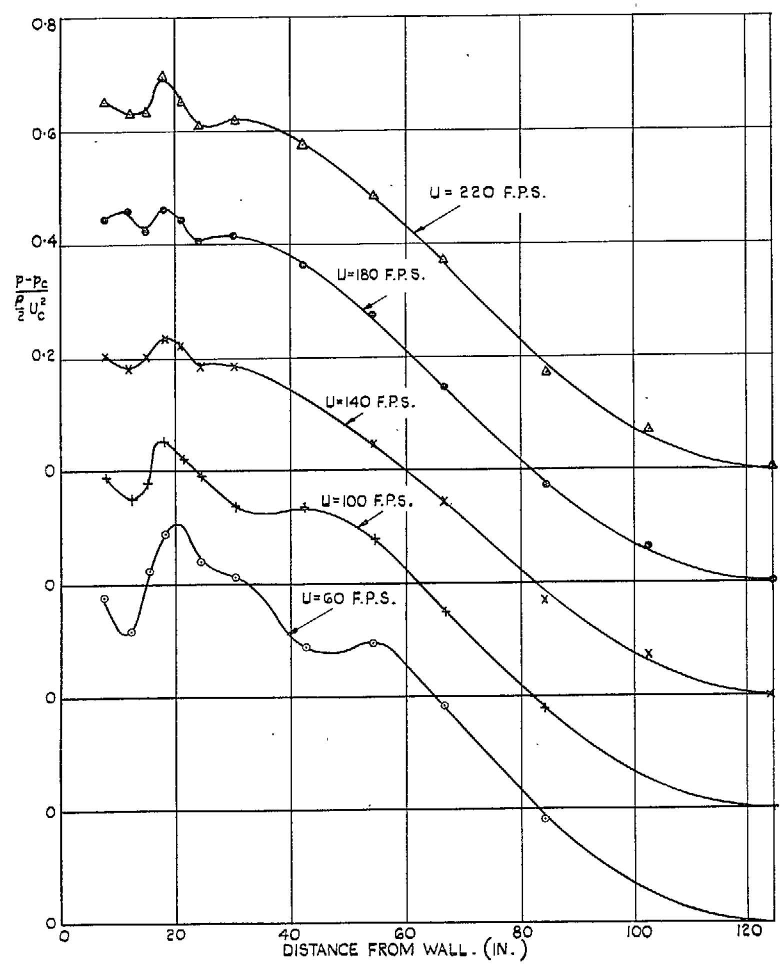

FIG. 44. Distribution of total head across lower part of bulge with 2 screens in bulge.

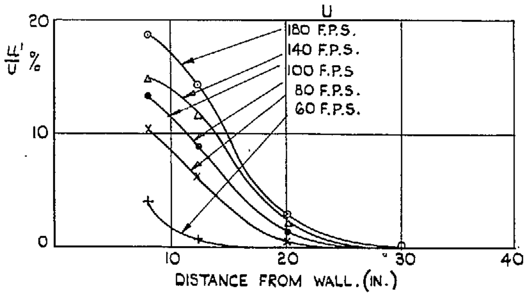

Fig. 45. Turbulence level in bulge 30 in. behind last screen. 9 screens in the bulge.

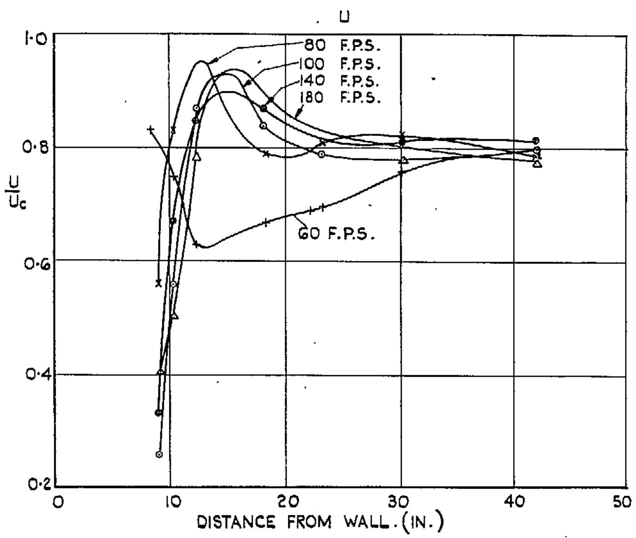

Fig. 46. Distribution of mean speed near the walls of the bulge 30 in. behind last screen. 9 screens in the bulge.

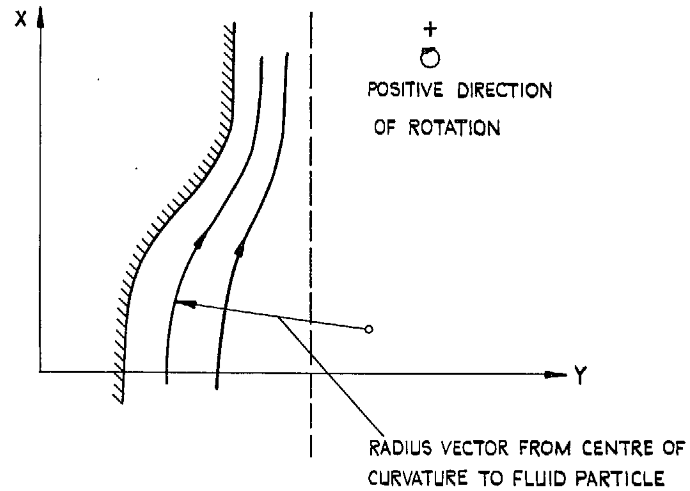

Fig. 47. Schematic diagram for discussion of stability of flow in bulge.

(84222) Wt. 67/1876 K.5 6/62 Hw.

Publications of the Aeronautical Research Council

ANNUAL TECHNICAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL (BOUND VOLUMES)

1942 Vol. I. Aero and Hydrodynamics, Aerofoils, Airscrews, Engines. 75*s.* (post 2*s.* 9*d.*)
Vol. II. Noise, Parachutes, Stability and Control, Structures, Vibration, Wind Tunnels. 47*s.* 6*d.* (post 2*s.* 3*d.*)

1943 Vol. I. Aerodynamics, Aerofoils, Airscrews. 80*s.* (post 2*s.* 6*d.*)
Vol. II. Engines, Flutter, Materials, Parachutes, Performance, Stability and Control, Structures. 90*s.* (post 2*s.* 9*d.*)

1944 Vol. I. Aero and Hydrodynamics, Aerofoils, Aircraft, Airscrews, Controls. 84*s.* (post 3*s.*)
Vol. II. Flutter and Vibration, Materials, Miscellaneous, Navigation, Parachutes, Performance, Plates and Panels, Stability, Structures, Test Equipment, Wind Tunnels. 84*s.* (post 3*s.*)

1945 Vol. I. Aero and Hydrodynamics, Aerofoils. 130*s.* (post 3*s.* 6*d.*)
Vol. II. Aircraft, Airscrews, Controls. 130*s.* (post 3*s.* 6*d.*)
Vol. III. Flutter and Vibration, Instruments, Miscellaneous, Parachutes, Plates and Panels, Propulsion. 130*s.* (post 3*s.* 3*d.*)
Vol. IV. Stability, Structures, Wind Tunnels, Wind Tunnel Technique. 130*s.* (post 3*s.* 3*d.*)

1946 Vol. I. Accidents, Aerodynamics, Aerofoils and Hydrofoils. 168*s.* (post 3*s.* 9*d.*)
Vol. II. Airscrews, Cabin Cooling, Chemical Hazards, Controls, Flames, Flutter, Helicopters, Instruments and Instrumentation, Interference, Jets, Miscellaneous, Parachutes. 168*s.* (post 3*s.* 3*d.*)
Vol. III. Performance, Propulsion, Seaplanes, Stability, Structures, Wind Tunnels. 168*s.* (post 3*s.* 6*d.*)

1947 Vol. I. Aerodynamics, Aerofoils, Aircraft. 168*s.* (post 3*s.* 9*d.*)
Vol. II. Airscrews and Rotors, Controls, Flutter, Materials, Miscellaneous, Parachutes, Propulsion, Seaplanes, Stability, Structures, Take-off and Landing. 168*s.* (post 3*s.* 9*d.*)

1948 Vol. I. Aerodynamics, Aerofoils, Aircraft, Airscrews, Controls, Flutter and Vibration, Helicopters, Instruments, Propulsion, Seaplane, Stability, Structures, Wind Tunnels. 130*s.* (post 3*s.* 3*d.*)
Vol. II. Aerodynamics, Aerofoils, Aircraft, Airscrews, Controls, Flutter and Vibration, Helicopters, Instruments, Propulsion, Seaplane, Stability, Structures, Wind Tunnels. 110*s.* (post 3*s.* 3*d.*)

Annual Reports of the Aeronautical Research Council—

1939–48 3*s.* (post 6*d.*) 1949–54 5*s.* (post 5*d.*)

Index to all Reports and Memoranda published in the Annual Technical Reports, and separately—

April, 1950 – – – – R. & M. 2600 (out of print)

Published Reports and Memoranda of the Aeronautical Research Council—

Between Nos. 2351–2449	R. & M. No. 2450	2*s.* (post 3*d.*)
Between Nos. 2451–2549	R. & M. No. 2550	2*s.* 6*d.* (post 3*d.*)
Between Nos. 2551–2649	R. & M. No. 2650	2*s.* 6*d.* (post 3*d.*)
Between Nos. 2651–2749	R. & M. No. 2750	2*s.* 6*d.* (post 3*d.*)
Between Nos. 2751–2849	R. & M. No. 2850	2*s.* 6*d.* (post 3*d.*)
Between Nos. 2851–2949	R. & M. No. 2950	3*s.* (post 3*d.*)
Between Nos. 2951–3049	R. & M. No. 3050	3*s.* 6*d.* (post 3*d.*)
Between Nos. 3051–3149	R. & M. No. 3150	3*s.* 6*d.* (post 3*d.*)

HER MAJESTY'S STATIONERY OFFICE

York House, Kingsway, London W.C.2; 423 Oxford Street, London W.1; 13a Castle Street, Edinburgh 2; 39 King Street, Manchester 2; 35 Smallbrook, Ringway, Birmingham 5; 109 St. Mary Street, Cardiff; 50 Fairfax Street, Bristol 1; 80 Chichester Street, Belfast 1, *or through any bookseller.*

S.O. Code No. 23-3261

R. & M. No. 3261