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THE REYNOLDS NUMBER FOR TRANSITION ON A FLAT PLATE IN THE RAE 4--ETC(U)
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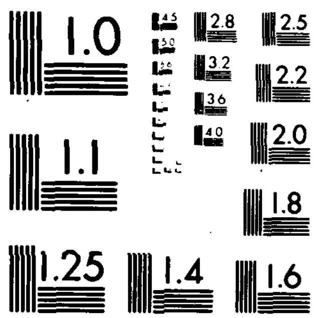

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THE REYNOLDS NUMBER FOR TRANSITION ON A FLAT PLATE IN THE RAE 4 ft x 3 ft LOW TURBULENCE WIND TUNNEL

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SUMMARY

Reynolds numbers for transition on a flat plate measured in two brief series of tests in the RAE 4 ft x 3 ft tunnel with two different screen arrangements in the settling chamber are presented. In the two series the transition Reynolds number varies in magnitude in opposite senses with tunnel speed but the same trend is indicated for the variation with turbulence level. At the lowest level of turbulence achieved, the transition Reynolds number approaches 6 million, and according to Mack's calculations, this would correspond to a value of n of 13 for the e^n method.

e to the N power

1 INTRODUCTION

It was intended, after the completion and initial calibration of the RAE 4 ft x 3 ft Low Turbulence Wind Tunnel[1] in 1946, that one of the first investigations to be made should be into the effects of turbulence level in the free-stream on the transition from laminar to turbulent flow of the boundary layer on a flat plate. It was also intended to investigate the effects of changes of pressure gradient on transition and provision was made for a flexible roof along the tunnel working section above the flat plate which was mounted parallel to the tunnel centre-line but below it to accommodate the flexible roof. A very preliminary investigation was, in fact, made by the first author but not completed, as the interest in the tunnel became concentrated on measuring the very low levels of turbulence in the stream[2,3]. Subsequently, a further and much more thorough investigation was undertaken by the second author with an 'optimum' arrangement of the tunnel turbulence damping screens. For a variety of reasons this second investigation became rather extended and was also not completed. The transition position was determined by traversing a surface pitot tube mounted on a carriage spanning the tunnel. The primary reason for the extension of the time-scale of the experiment was the need to establish a configuration which minimized the interference effects of the carriage and to determine the range of transition positions, and thus tunnel speed, for which the interference effects could be neglected. It was also felt that it was necessary to investigate thoroughly the nature of the turbulence and noise in the tunnel to make possible any understanding of the differences between the results and those of Schubauer and Skramstadt[4]. Subsequent investigations elsewhere, for example those of Spangler and Wells[5], have reinforced this view. Nevertheless, because of the increased interest in recent years in establishing requirements for the quality of flow in wind tunnels, it has been considered to be worth putting on record the results from the 4 ft x 3 ft tunnel.

2 THE 4 ft x 3 ft WIND TUNNEL

The wind tunnel and the properties of its flow have been fully described in Refs 1, 2 and 3, and some details only are given here. Fig 1 shows a drawing of the tunnel. The main features are the large contraction ratio of 31.2 to 1 and the provision of up to nine wire gauze screens in the settling chamber in addition to the three fitted as part of the 'diffuser-resistance' combination which forms the rapid expansion up to the settling chamber. To obtain good quality flow throughout the tunnel circuit the angles for the first and second diffusers were chosen to have, what was at the time of erection of the tunnel, the unusually small angle of 5^{o}. The tunnel can be run either with the working section vented to atmospheric pressure, or with the observation chamber, which surrounds the working section, sealed and the return circuit vented at a location between the third and fourth corners. The latter mode of operation is preferred because it reduces the potential for flow leakage out of the return circuit. This leakage in the former mode, indirectly, affects the flow in the working section and first diffuser, because of the compensating incoming flow into the vent holes at the end of the working section. The tests described here were made with the return circuit vented to atmosphere.

3 DESCRIPTION OF TESTS

As noted in the introduction the tests were made on a flat plate, the upper surface of which was the working surface, mounted horizontally but below the centre-line of the tunnel. A flexible plywood plate supported on jacking screws formed a false roof to the tunnel and provided a means of adjusting the pressure gradient along the flat plate. To enable pressure probes to be traversed these were mounted on a carriage which spanned the tunnel and ran on rails attached to the sidewalls. An arrangement of cords and pulleys enabled the carriage to be traversed without stopping the tunnel. The pressure distribution along the flat plate was measured by traversing a small static tube shaped so that its forward part maintained close contact with the surface of the plate during the course of a traverse.

The plate initially designed for the experiments had an upper surface of aluminium bonded to a plywood base. This construction gave a good surface finish but unfortunately the nose shape proved to be unsatisfactory. At the nose the undersurface was flat and the upper surface curved in cross-section over the first 12 in with a radius of curvature of about 4 ft. With this design there was inevitably an overshoot in velocity towards the downstream end of the curved region, and it was considered that the subsequent adverse pressure gradient would affect the position of transition to an unknown extent. A second plate was therefore manufactured but the complications of the aluminium bonding were avoided and the surface was of wood varnished or painted (at various stages of the tests) to give a good surface finish. The leading edge of the plate, of length 12 in was made removable so that various forms could be tested. The form used in the first transition tests was that of a wedge with a flat upper surface. The total length of the plate was 8 ft. As a further means of controlling the pressure gradient, in addition to the use of the flexible roof, a flap was fitted on an extension to the trailing edge of the plate. This flap exerted a powerful control on the location of the stagnation point in the region of the plate leading edge. It was adjusted so that the stagnation point was at a small distance aft of the leading edge on the flat upper (working) surface.

Some preliminary tests were made with this wooden plate. For these tests all nine damping screens were fitted in the tunnel settling chamber. These tests are termed 'Series I' in the remainder of this Memorandum. The wooden plate was, however, considered to be unsatisfactory for an extensive investigation and a further plate was designed and manufactured. This plate was made from two pieces of 4 ft square 'bakelized paper board' $\frac{3}{8}$ in thick. This material was chosen as having a good and robust surface in the 'as-manufactured' condition. The joint between the boards was made by grooving the abutting ends of the boards and inserting a metal tongue held in place by screws tapped into the boards and tongue. The leading edge of the plate was symmetrical in this case, the sections over the first 6 in consisting of two circular arcs. The second series of tests (Series II) described here were made with this plate. The Series II tests also made use of an extension to the trailing edge of the plate fitted with a flap. In the Series I tests the plate had been mounted with its leading edge 7 in downstream of the start of the working section. This put the leading edge in a region where a pressure gradient existed in the empty tunnel and for the Series II tests this distance was increased to 27 in.

In both series of tests the location of transition was determined by traversing a pitot tube along the plate in contact with its surface. The forward part of the pitot tube was made from 1 mm tubing flattened to give an external height of 0.020 in. Some check tests were made by means of surface oilflow techniques.

4 RESULTS

The pressure distribution along the plate in the Series I tests is shown in Fig 2 expressed as q_1/q_0, the local kinetic pressure divided by the kinetic pressure in the empty tunnel. A mildly favourable gradient occurred over the forward half of the plate and the traverse made off the centre-line indicates some small spanwise non-uniformity over the forward part. Three sets of measurements, at nominal speeds of 100, 140 and 160 ft/s, made with the traversing surface pitot tube are given in Fig 3 in terms of q_s/q_1, the kinetic pressure indicated by the surface tube divided by the local freestream kinetic pressure. These traverses were made on the plate centre-line. A simple traverse made at 140 ft/s 10 in off the centre-line agreed closely with that on the centre-line. From Fig 3 the values of x_1 and x_2, the distances from the leading edge of the plate for the beginning and end of the transition region, have been taken. For the beginning, x_1 has been taken at the point of intersection of faired lines through the measurements in the laminar region and the transitional region, and for the end, x_2 has been taken as the point of maximum reading. For the measurements at 100 ft/s the value of x_2 is ill-defined. The reasons for this were not explored but a plausible exploration may be that the proximity of the carriage to the flap fitted at the end of the plate extension resulted in some interference with the flow. The Reynolds numbers for the beginning and end of transition, based on the values of x_1, x_2 and the local unit Reynolds number are shown in Fig 4. Re_{x_1} and Re_{x_2} show a small increase with increase of tunnel speed, and over the range covered have values greater than the 'limiting' values of 2.8 and 3.9 million formed by Schubauer and Skramstadt.

The variation with tunnel speed of the three components of turbulence on the tunnel centre-line (in the empty tunnel) at a position corresponding to x = 59 in is given in Fig 5. The measurements are extracted from Ref 2 and were made subsequent to the transition tests. This Figure shows that there is an increase in the level of all three components as speed is reduced from 160-100 ft/s and the obvious inference is that the reduction in transition Reynolds number over this speed range is related to the increase in turbulence. However, as pointed out in Ref 2, the energy in the turbulence is contained mainly at the low frequency end of the spectrum where its influence on the stability of a laminar boundary layer might be expected to be significant only at Reynolds numbers very much higher than obtainable on the flat plate. Thus attempts to relate overall levels of turbulence to transition Reynolds numbers may be misleading. A further point to be noted[2] is that the low levels of turbulence extended over a central region only about 20 in x 15 in in the cross-section of the working section. Spectra for speeds of 100 and 160 ft/s are shown in Fig 6 demonstrating the concentration of the energy at low frequencies. Some peaks corresponding to the fan fundamental frequency (1/10 times the fan speed in rev/min gives frequency in cycles/s since the fan has six blades) and multiples of this frequency can be identified in the spectra, but these do not occur consistently.

Measurements of noise in the working section made with a special microphone positioned on the tunnel centre-line were also reported in Ref 2. The particle velocity deduced, assuming plane waves, is shown in Fig 7, and frequency spectra, in which the fan fundamental frequency and second harmonic are strongly marked, are reproduced in Fig 8. Also shown in Fig 7 is the rms total turbulence, conventionally expressed as $\left[\frac{1}{3}(u'^2 + u'^2 + w'^2)\right]^{\frac{1}{2}}$, for the tunnel with 3+9 screens (Series I) and also with 3+3 screens (Series II). The levels of noise and turbulence compared rather arbitrarily in this way are of similar magnitudes but comparison of the spectra shows, as might be expected, that the noise contribution is at somewhat higher frequencies than the turbulence contribution.

Some results from the Series II tests are summarized in Figs 9, 10 and 11. Because of the change in the shape of the leading edge of the plate and its position from that used in Series I the acceleration of the airstream in the leading-edge region is greater but occurs over a shorter length and leads to a suction peak followed by a short region of adverse pressure gradient. The gradient is mildly favourable over the remainder of the plate apart from a perturbation in the vicinity of the joint. The variation of transition Reynolds number with tunnel speed (Fig 11) is quite different from that in the Series I tests. At 160 ft/s the values of Re_{x_1} and Re_{x_2} are slightly greater than for Series I but in the Series II tests Re_{x_1} shows a monotonic decrease with increase of tunnel speed over the whole range from 120-200 ft/s. Re_{x_2} follows the same trend over the speed range for which it was determined. (The usable length of the plate was too small to allow its determination at the lower speeds.) Again the inference can be readily drawn that the transition Reynolds number correlates with the turbulence level. On the other hand, it is necessary to consider the possible influence of the pressure gradients along the plates which differ in the two series. At 160 ft/s Series II gives a slightly larger transition Reynolds number than Series I. For Series I the pressure gradient is entirely favourable up to $x = x_1$ whereas for Series II the pressure gradient is small apart from two short regions of adverse pressure gradient, near the nose and just upstream of $x = x_1$. Thus the pressure gradients might be expected to have the opposite effect to that observed (as also might the stream turbulence on the basis of the rms level). At the lowest speed (100 ft/s for Series I and 120 ft/s for Series II) the pressure gradients are respectively adverse and favourable at the transition point so that the lower transition Reynolds number for Series I is in accordance with the expected effect of pressure gradient. At the higher speeds for Series II the pressure gradient is also favourable at the transition point but of smaller magnitude than for the lower speeds. It seems unlikely that the increase, almost twofold, in transition Reynolds number with reduction in speed from 200-120 ft/s can be directly attributed to the small change in pressure gradient. Thus on the basis of qualitative arguments it appears improbable that the pressure gradients have a controlling influence.

The three components of turbulence are shown in Fig 12. The variations of the turbulence components with speed are quite different from those for 3+9 screens shown in Fig 5. Explanations for the features and differences are advanced in Refs 2 and 3. The two main reasons are (1) the interaction of the screens in the settling chamber with the curved flow there in promoting an unstable velocity profile on the curved walls in the initial region of the contraction cone and (2) the influence of fluctuation of the transition point on the tunnel walls on the flow in the working section. The effect of the first of these reduces as the number of screens in the settling chamber is reduced but, of course, the damping effect of the screens on the mainstream turbulence is then reduced. An optimum number of screens is thus indicated and this number was considered to be 3, the number chosen for the Series II tests. The reduction in the number of screens also increased the area of the cross-section of the tunnel over which low turbulence existed to about 25 in x 20 in. The influence of the tunnel wall boundary layer was reduced by fitting a trip wire in the downstream part of the contraction cone.

Some measurements of spectra were made during the course of the Series II experiments. The longitudinal component was measured at a point 3 in above the plate and 18 in downstream of the leading edge. The hot wire was supported on the carriage used to traverse the surface pitot tube and, despite efforts to provide isolation against vibration, the results may contain some spurious peaks from this source. The lateral components were measured upstream of the plate with the wire mounted on a wooden strut as used for the measurements of Refs 2 and 3. The incomplete set of results obtained is shown in Fig 13. The spectra contain many contributions at discrete frequencies the sources of which can be identified with any confidence only in a few instances. For example the fan fundamental frequency appears clearly in the longitudinal and transverse components at 160 ft/s but not in the vertical component and also appears in the two available components at 220 ft/s. On the other hand the peaks occurring at frequencies in the vicinity of 200 Hz have not been identified. For comparison the spectra for the tunnel with 3+2 screens from Ref 3 are reproduced in Fig 15. The differences are striking and show, with the exception of the vertical component, the reduction in the low frequency content for the configuration (3+3 screens) used for the Series II tests.

The measured variation with turbulence level of the Reynolds number for the onset of transition is shown in Fig 14. Also shown are the results of Schubauer and Skramstadt and the range of results obtained by Spangler and Wells[5] is also indicated. Spangler and Wells showed the quite different response of the transition Reynolds number to the apparent variation in turbulence level when this was caused by sound of some given frequency or by genuine turbulence produced by grids. Different combinations of sound and turbulence produced variations lying within the hatched area. These experiments make it appear futile to attempt to draw any facile conclusions from a plot such as Fig 14.. However it is interesting to note that the present results and those of Schubauer and Skramstadt do tend to form a continuous curve, though this may be fortuitous since there is no region of overlap. It is also unlikely that both sets of results contain the same mix of acoustic and turbulence disturbances or that the influences of the pressure gradients along the plates are the same for all the experiments. Nevertheless the results do show that the indication of Schubauer and Skramstadt of a plateau in the effect of turbulence level may have been an accidental consequence of the particular mix of disturbances in the NBS tunnel and that it is worth trying to achieve levels of turbulence well below the accepted 0.08% if uncontaminated transition is an aim*.

On the basis of the Schubauer and Skramstadt measurements Mack[6] produced a semi-impirical correlation using an 'e^n method'. The component n is related to a Reynolds number by means of the envelope curve for maximum amplification according to linear stability theory and Mack then determined n as a function of turbulence level T by fitting to the results of Schubauer and Skramstadt for values of T greater than 0.1%. For zero pressure gradient the envelope curve may be approximated by the equation

$$n = \frac{2}{3}\left(\frac{Re_x^{\frac{1}{2}}}{100} - 4.5\right)$$

and this leads to

$$n = -8.43 - 2.4 \ln T \quad .$$

The curve shown in Fig 14 is derived from these two equations. It is interesting to note that at the lowest turbulence level of the present results (0.013%) the

* It is interesting to note that the transition prediction method recently proposed by Wilcox[7] predicts, for a disturbance frequency which matches the results of Ref 4, a rapid rise in transition Reynolds number for turbulence levels below 0.02%.

measured transition Reynolds number is close to Mack's curve, but it is probably unhelpful to attempt to draw any conclusions in the somewhat superficial context of the present Memorandum, other than to remark that for this point n has a value of 13.

5 CONCLUDING REMARKS

Reynolds numbers for transition on a flat plate measured in two brief test series in the RAE 4 ft x 3 ft tunnel with two different screen arrangements in the settling chamber have been presented. In the two series the transition Reynolds number varies in magnitude in opposite senses with tunnel speed but the same trend is indicated in the variation with turbulence level. At the lowest level of turbulence achieved the transition Reynolds number approaches 6 million and, according to Mack's calculations, this would correspond to a value of n of 13 for the 'e^n method'.

REFERENCES

No.	Author	Title, etc
1	H.B. Squire K.G. Winter	The Royal Aircraft Establishment 4 ft x 3 ft Experimental Low Turbulence Wind Tunnel. Part I General flow characteristics. R&M 2690 (1948)
2	H. Schutz K.G. Winter	The RAE 4 ft x 3 ft Experimental Low Turbulence Wind Tunnel. Part II Measurements of turbulence intensity and noise in the working section. R&M 2905 (1951)
3	H. Schutz	The RAE 4 ft x 3 ft Experimental Low Turbulence Wind Tunnel. * Part IV Further turbulence measurements. R&M 3261 (1953)
4	G.B. Schubauer H.K. Skramstadt	Laminar boundary layer oscillations and transition on a flat plate. NACA Report 909 (1948)
5	J.G. Spangler C.S. Wells	Effect of freestream disturbances on boundary layer transition. AIAA J, Vol 6, p 543 (1968)
6	L.M. Mack	Transition prediction and linear stability theory. Paper No.1, AGARD-CP-224 (1977)
7	D.C. Wilcox	Development of an alternative to the e^9 procedure for predicting boundary layer transition. DCW Industries Inc, DCW-R-23-01 (1979)

* There is no Part III in the R&M series. Parts II and III of the original RAE reports are incorporated in Part II.

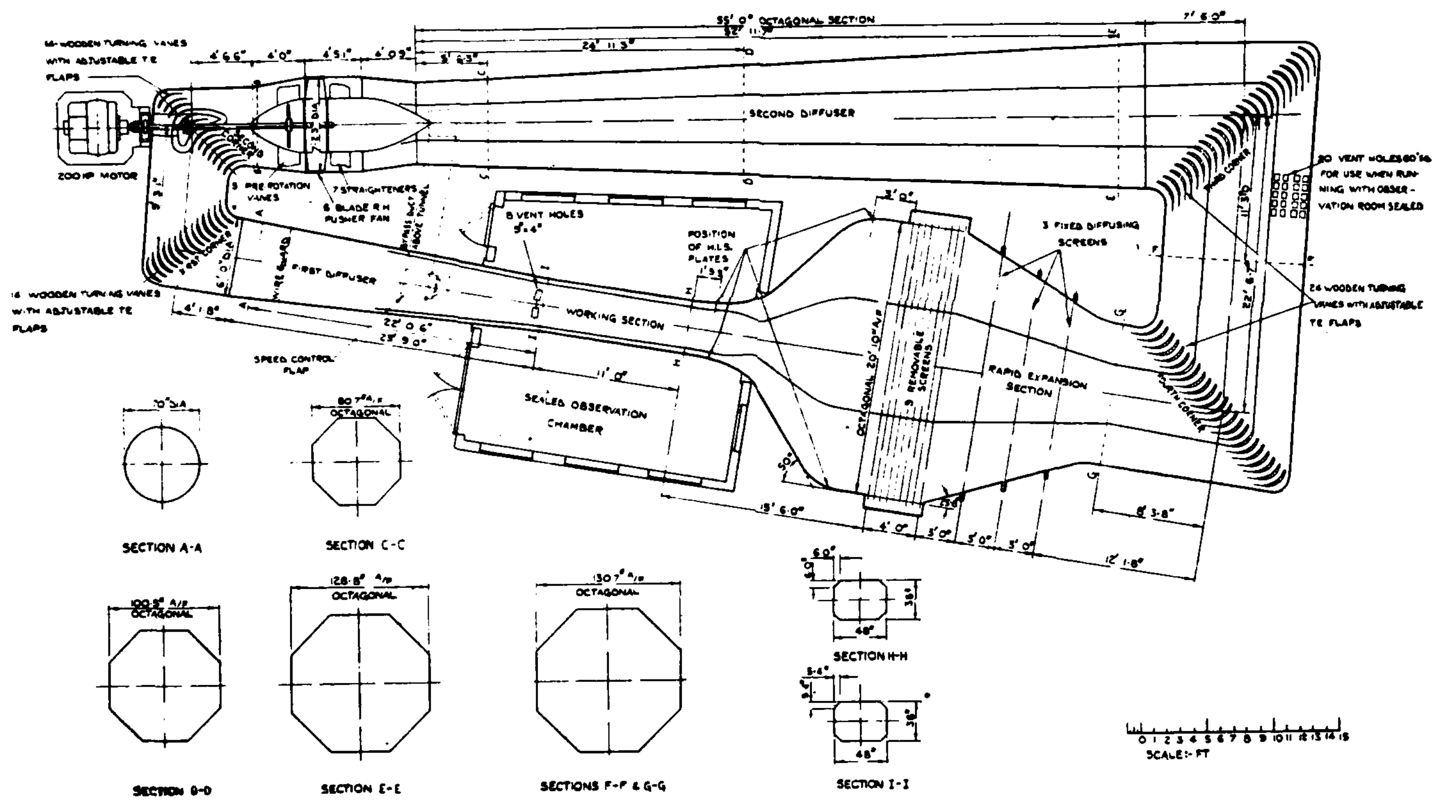


Fig 1 4 x 3ft wind tunnel, RAE. Sectional plan on tunnel centre-line.

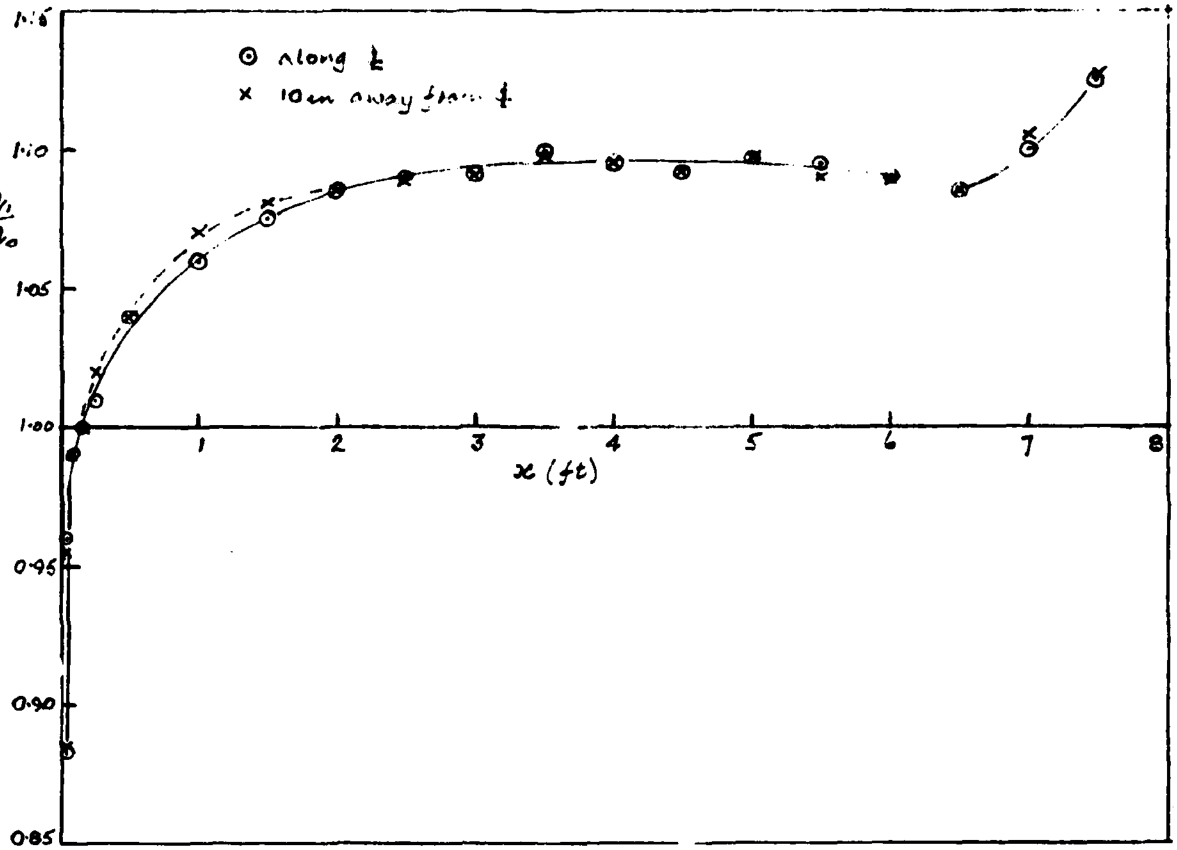


Fig 2 Pressure distribution along plate at U_0 = 100 ft/s - Series I

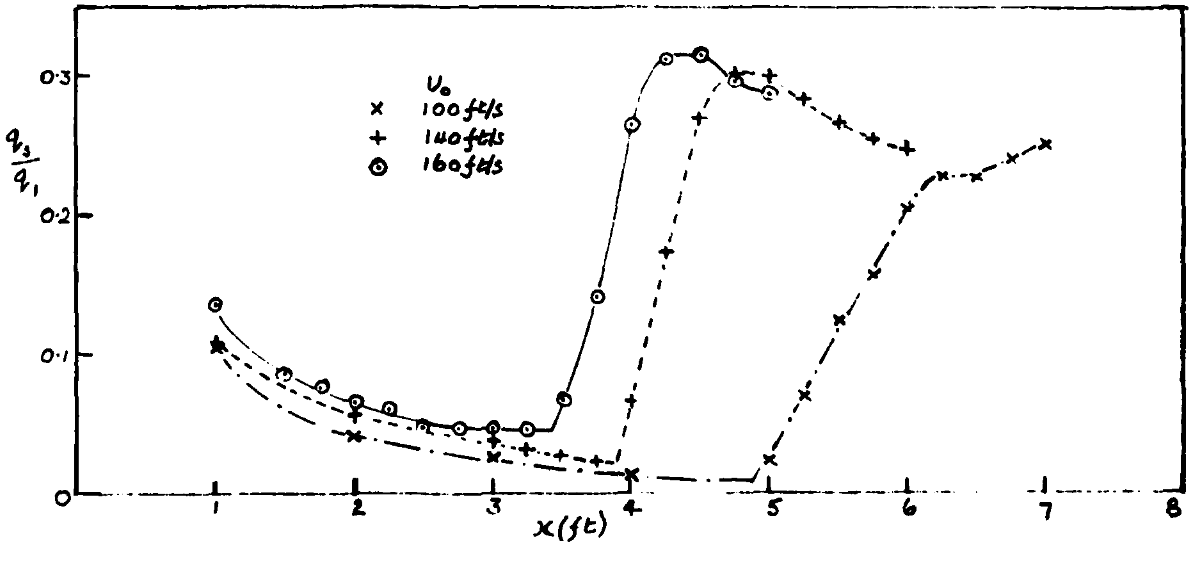


Fig 3 Pressure indicated by surface pitot tube - Series I

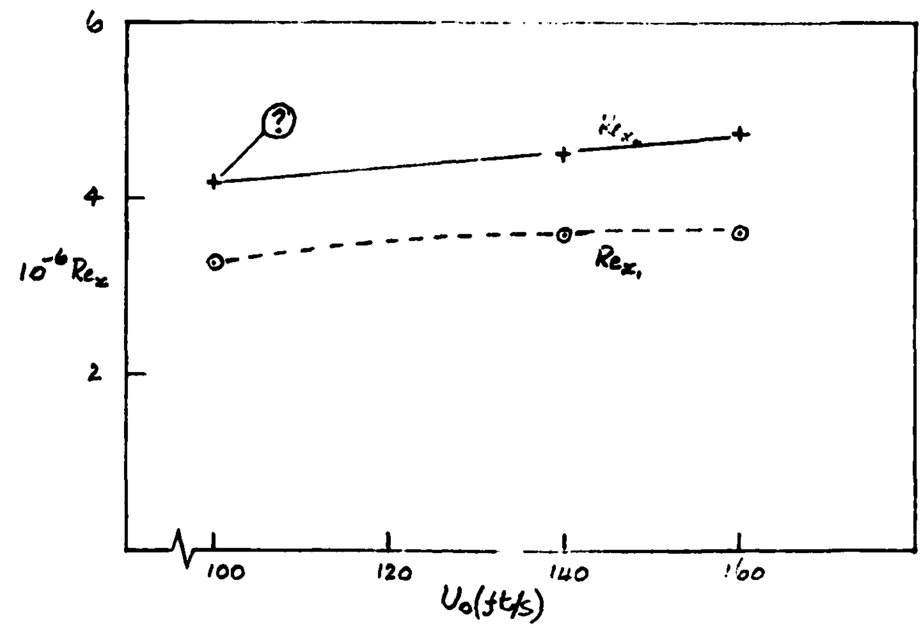


Fig 4 Transition Reynolds number - Series I

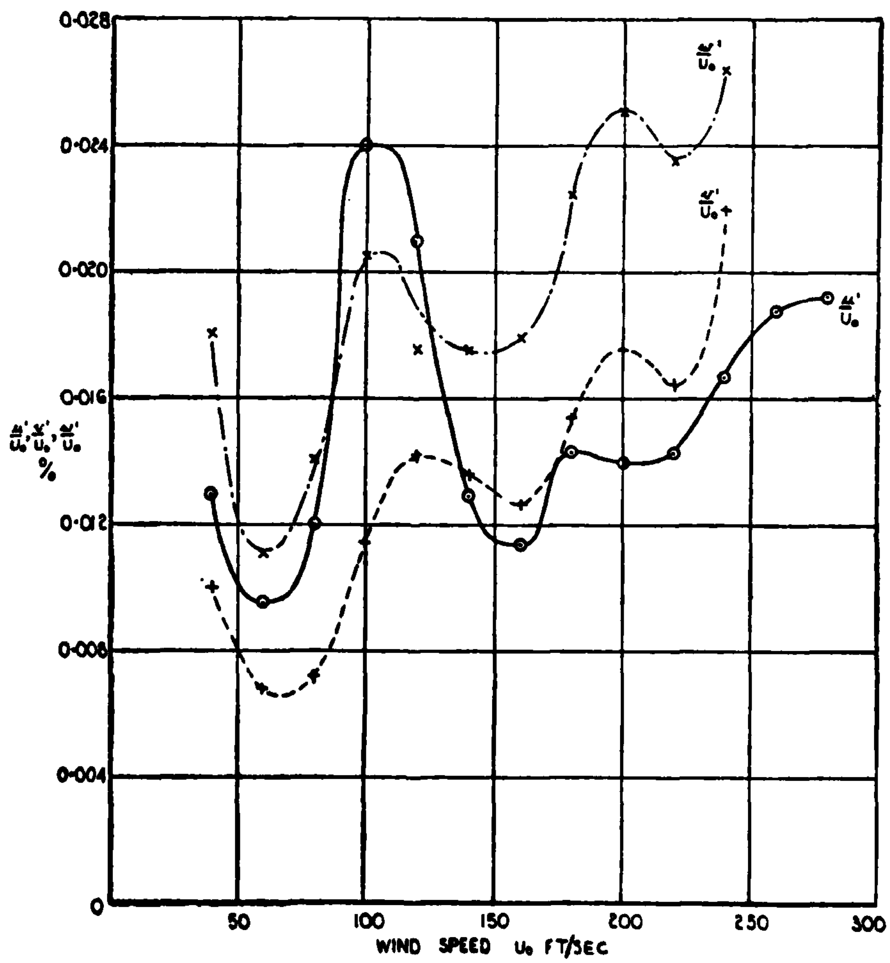
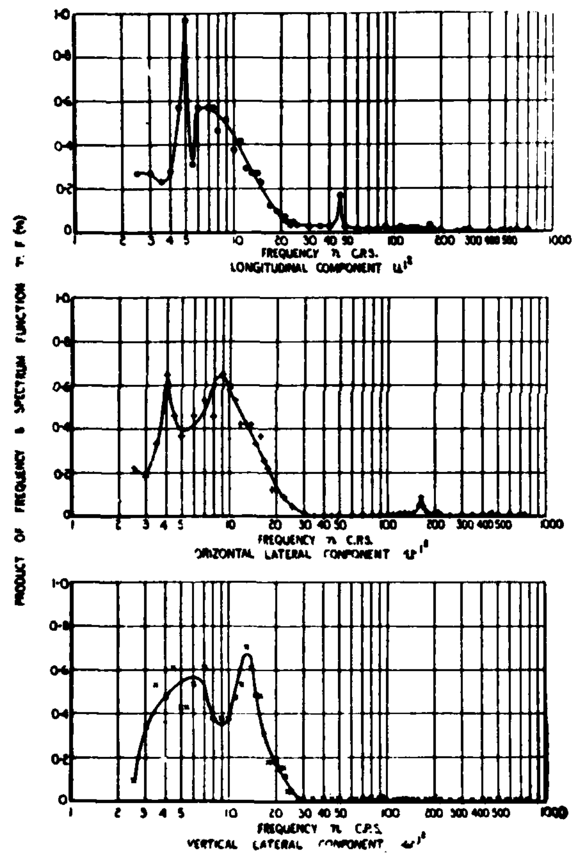
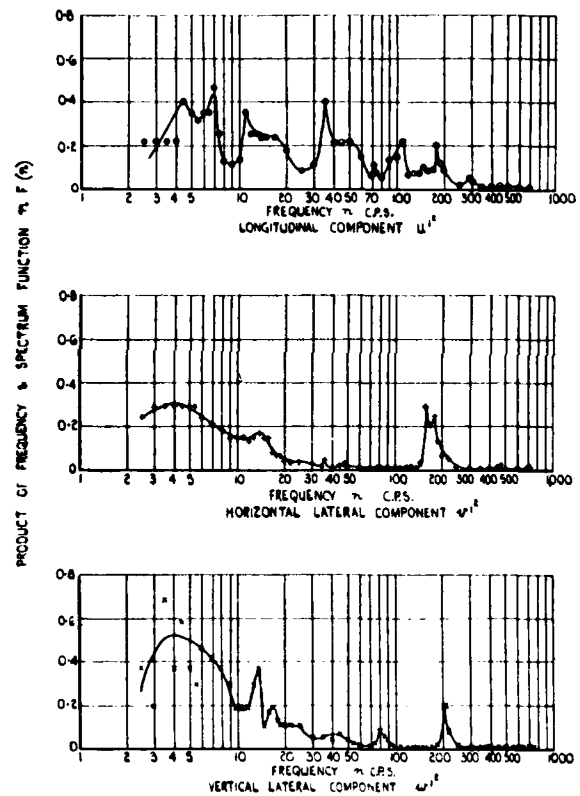


Fig 5 Turbulence components in working section: 3+9 screens. Measurements made on the tunnel centre-line



(a) U_0 = 100 ft/s. Fan speed = 230 rev/min



(b) U_0 = 160 ft/s. Fan speed = 360 rev/min

Fig 6 Frequency spectra of the three turbulence components on the centre-line of the tunnel

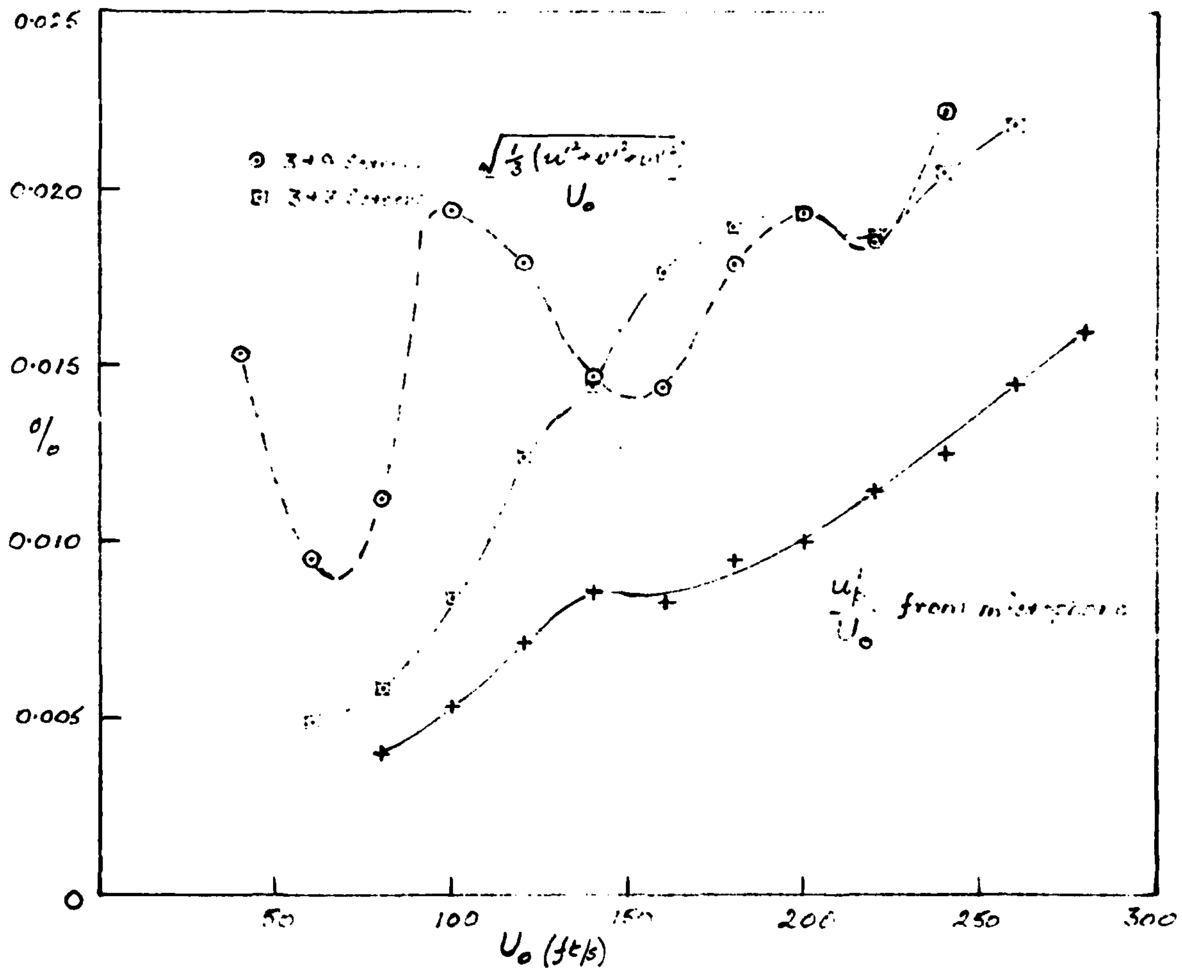
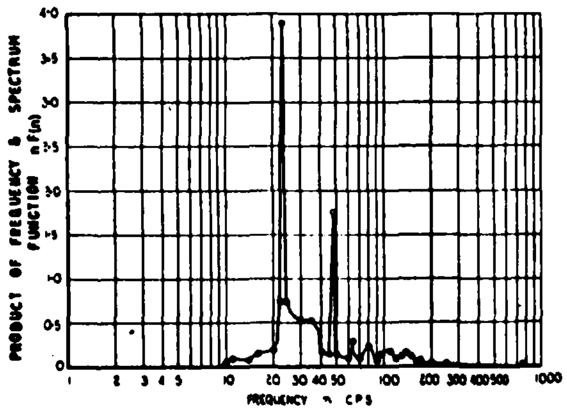
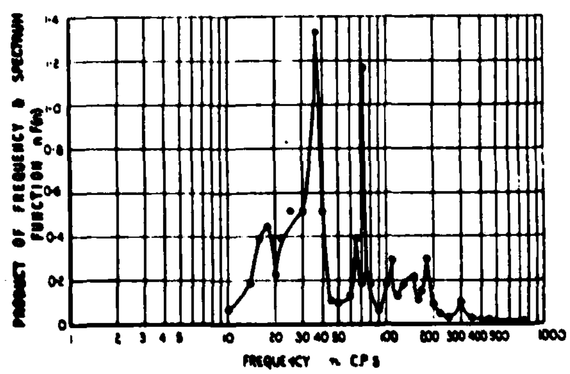


Fig 7 Comparison of turbulence intensity and noise



(a) U_0 = 100 ft/s.
Fan speed = 230 rev/min.



(b) U_0 = 160 ft/s.
Fan speed = 360 rev/min.

Fig 8 Frequency spectra of noise in centre of working-section

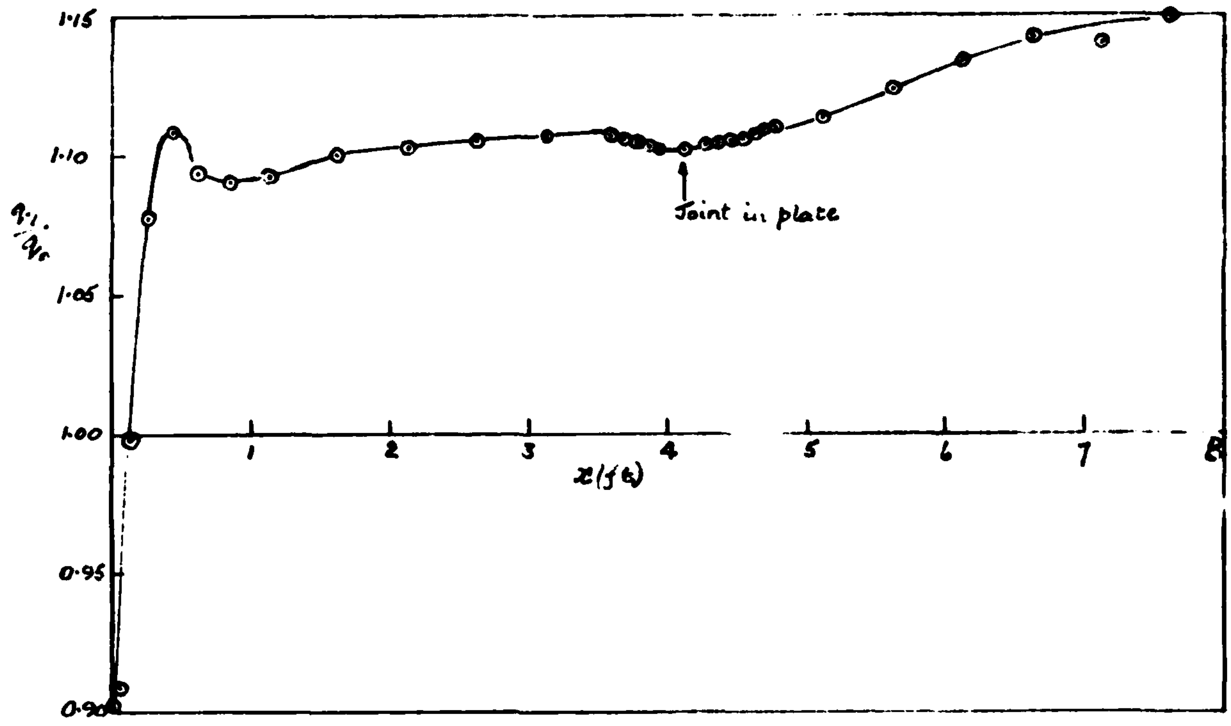


Fig 9 Pressure distribution along plate at U_0 = 160 ft/s - Series II

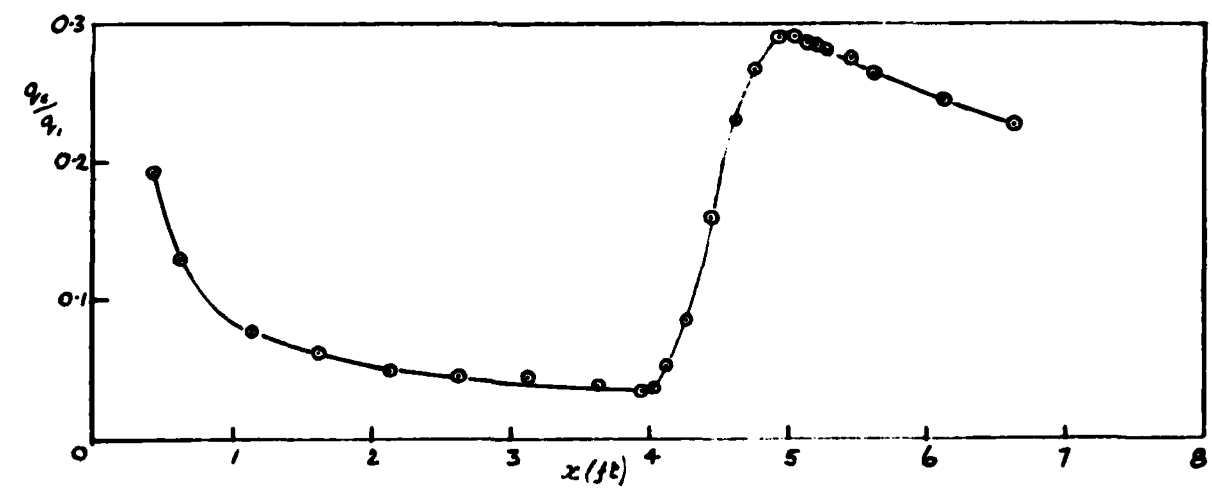


Fig 10 Pressure indicated by surface pitot tube at U_0 = 160 ft/s - Series II

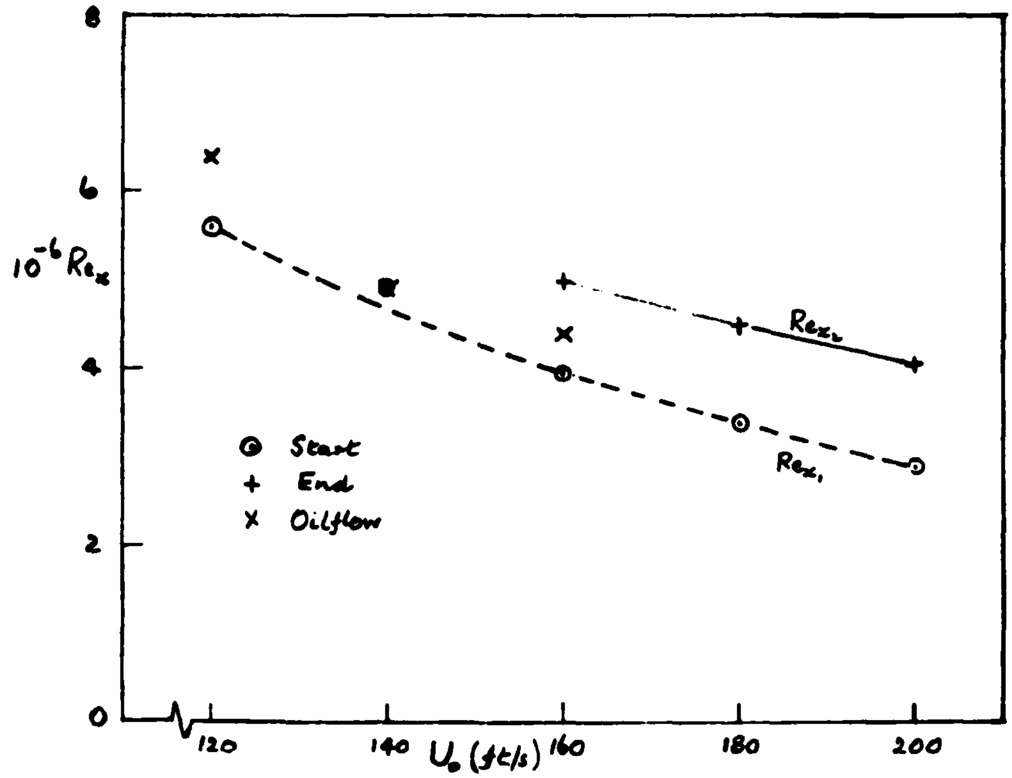


Fig 11 Transition Reynolds number - Series II

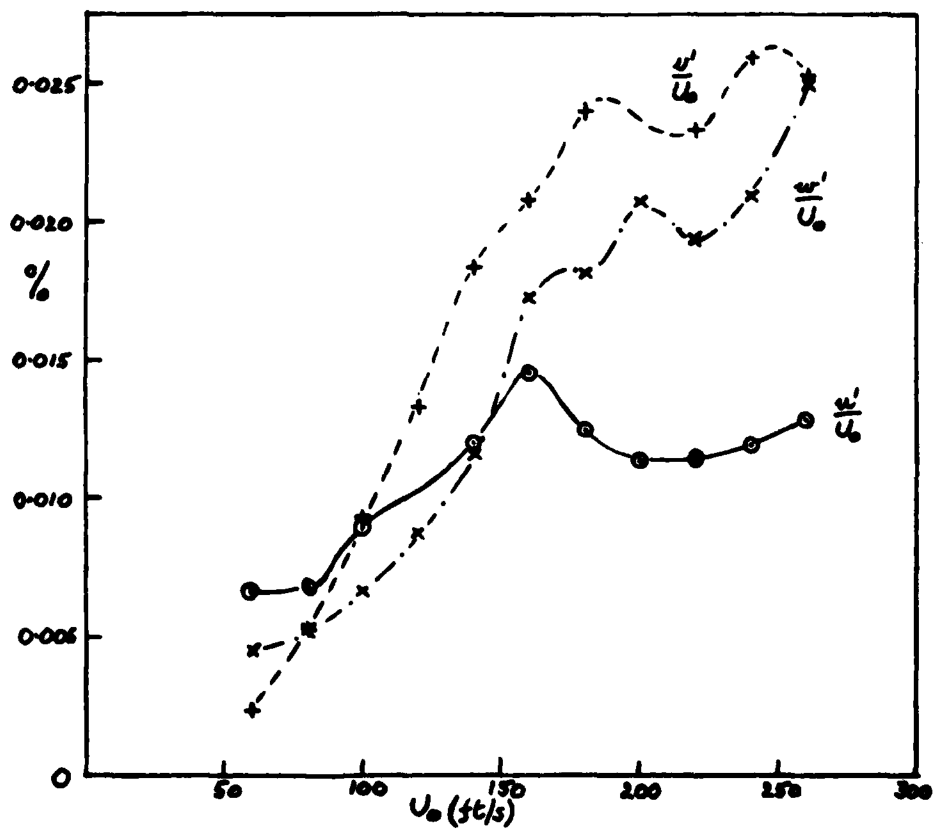


Fig 12 Turbulence components 3+3 screens

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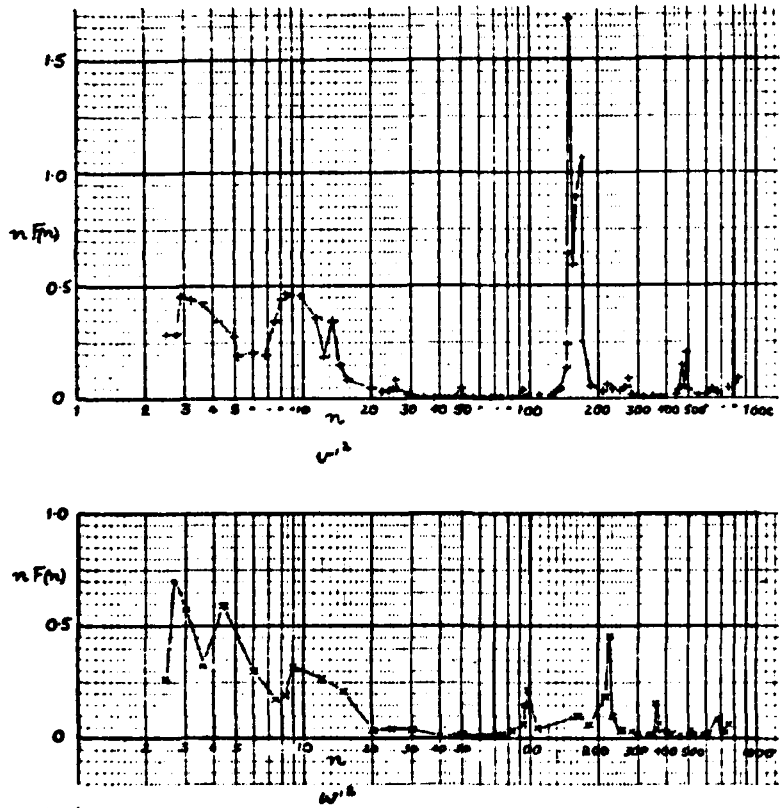
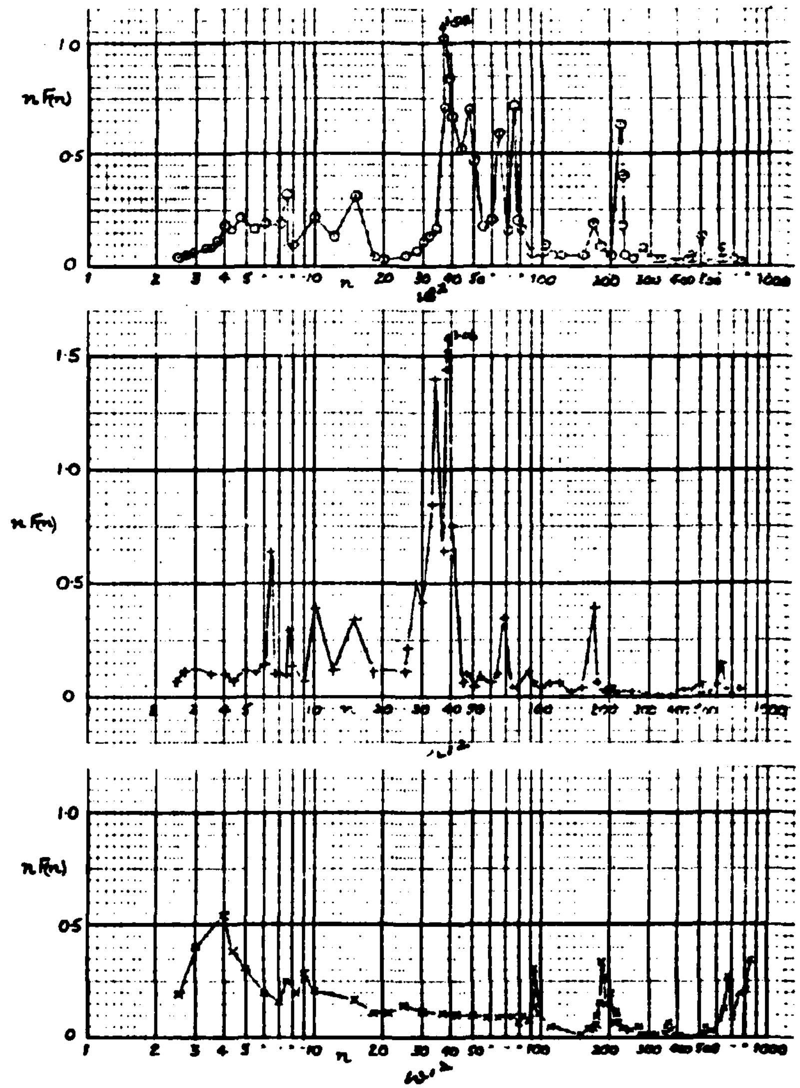


(a) U_0 = 100 ft/s. Fan speed ≏ 255 rev/min.



(b) U_0 = 160 ft/s. Fan speed ≏ 390 rev/min.

Fig 13 Frequency spectra of turbulence components. 3 + 3 screens.

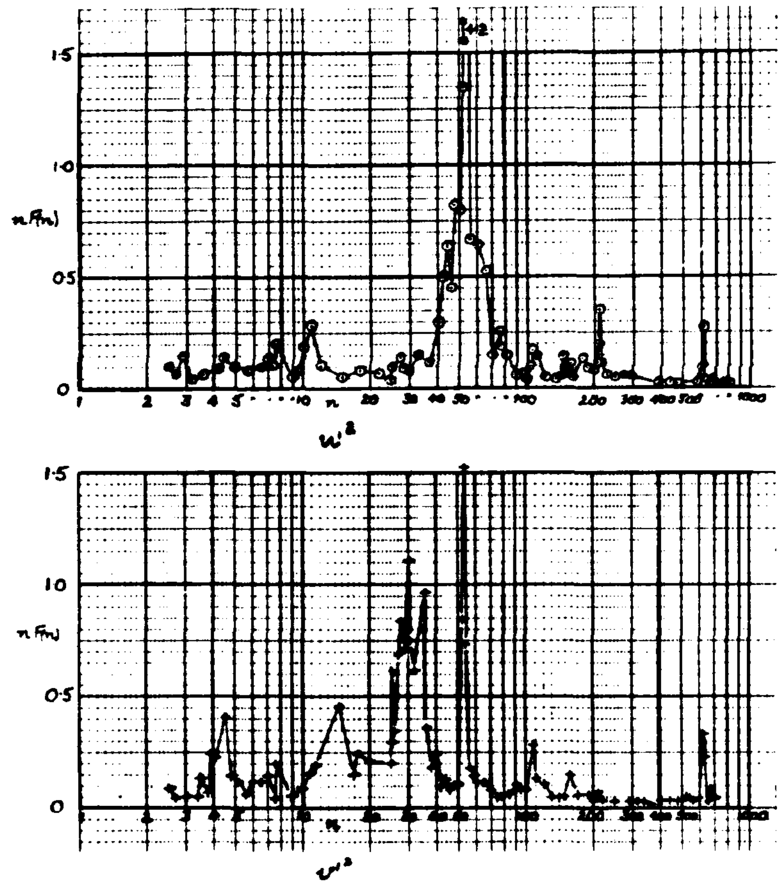


Fig 13 (c) U_0 = 220 ft/s. Fan speed ≏ 525 rev/min.

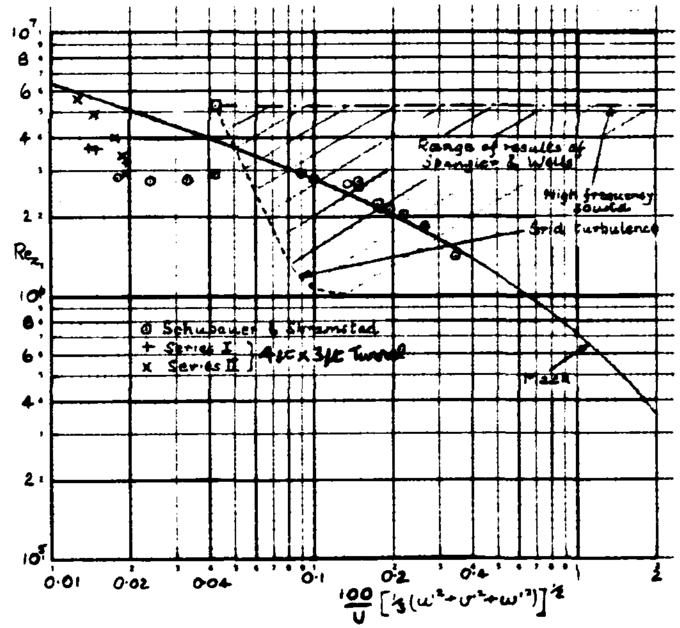


Fig 14 Variation of Reynolds number for onset of transition with turbulence level

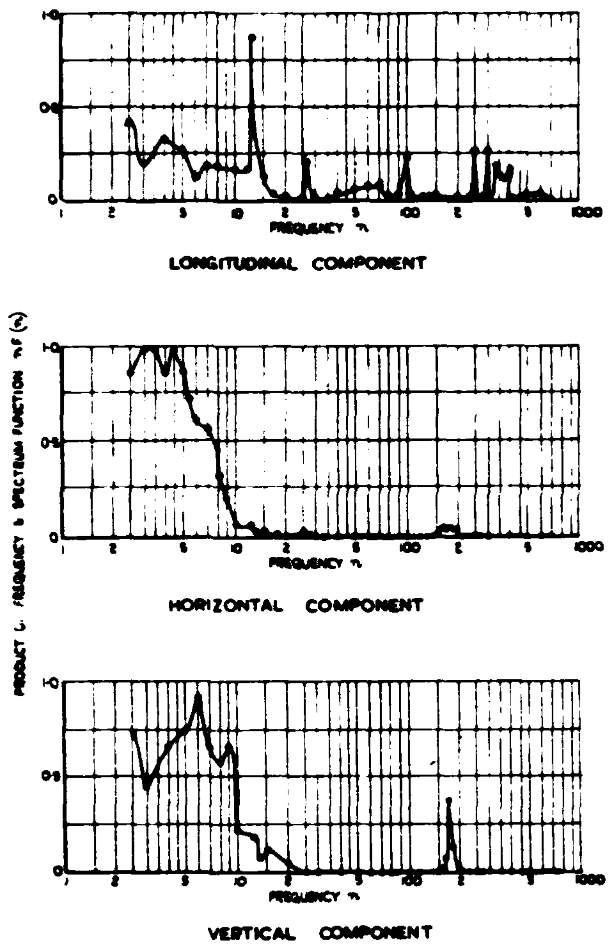


Fig 15 (a) Frequency spectra of all three components in working section with two screens in the bulge. Speed 60 ft/s. Fan fundamental frequency 13.2 cps.

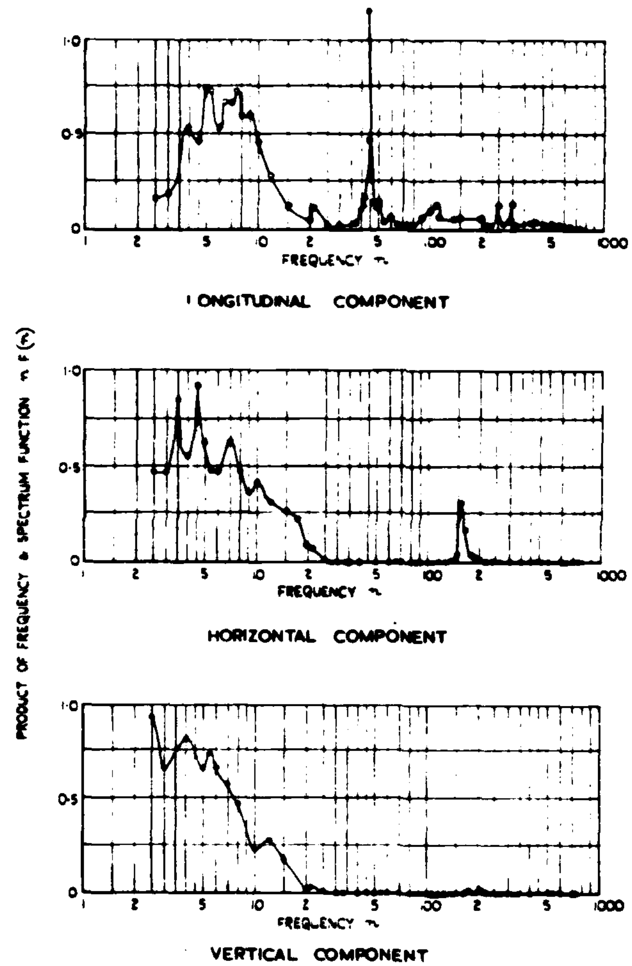


Fig 15 (b) *Frequency spectra of all three components in* working section with two screens in the bulge. Speed 100 ft/s. Fan fundamental frequency 21.7 cps.

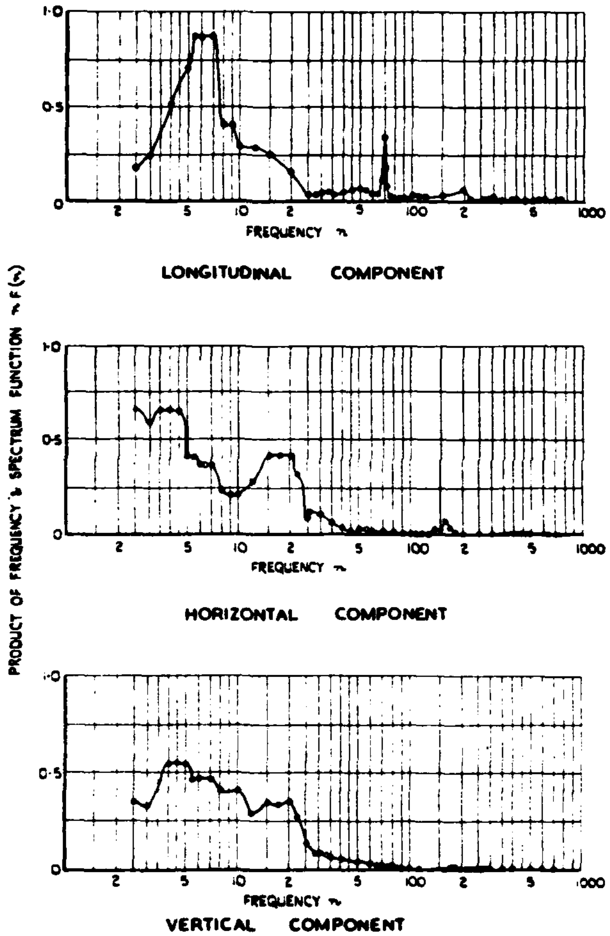


Fig 15 (c) Frequency spectra of all three components in working section with two screens in the bulge. Speed 160 ft/s. Fan fundamental frequency 35 cps.

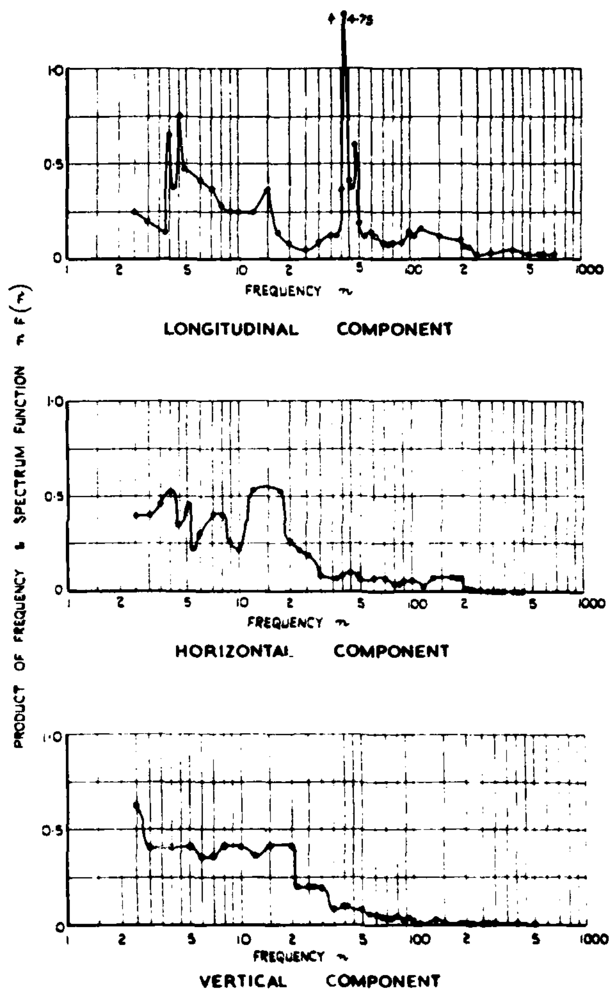


Fig 15 (d) Frequency spectra of all three components in working section with two screens in the bulge. Speed 200 ft/s. Fan fundamental frequency 43.7 cps.

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UNCLASSIFIED TITLE

THE REYNOLDS NUMBER FOR TRANSITION ON A FLAT PLATE IN THE RAE 4 FT X

ABSTRACT

(U) REYNOLDS NUMBERS FOR TRANSITION ON A FLAT PLATE MEASURED IN TWO
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Boundary layer TRANSITIONS

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TERMS NOT FOUND DURING LEXICAL DICT

TRANSITION REYNOLDS NUMBER APPROACHES 6
4 FT X 3 FT TUNNEL

4 FT X 3

OUP 000000

ON A FLAT PLATE IN THE RAE 4 FT X 3 FT LOWTURBULENCE WIND TUNNEL.

ON ON A FLAT PLATE MEASURED IN TWO BRIEF SERIES OF TESTS IN THE RAE 4 FT X 3 FT TUNNE
EMENTS IN THE SETTLING CHAMBER ARE PRESENTED. IN THE TWO SERIES THE TRANSITION REYNOL
PPOSITE SENSES WITH TUNNEL SPEED BUT THE SAME TREND IS INDICATED FOR THE VARIATION WI
LEVEL OF TURBULENCE ACHIEVED, THE TRANSITION REYNOLDS NUMBER APPROACHES 6 MILLION. A
S, THIS WOULD CORRESPOND TO A VALUE OF N OF 13 FOR THE E TO THE N POWER METHOD. (AUTH

INDEX TERMS ASSIGNED

N POWER
USE POWER

REYNOLDS NUMBERS
USE NUMBERS
REYNOLDS NUMBER

TUNNEL SPEED
USE TUNNELS
VELOCITY

TURBULENCE LEVEL
USE TURBULENCE

TERMS NOT FOUND DURING LEXICAL DICTIONARY MATCH PROCESS

CHES 6 4 FT X 3 FT

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNLIMITED

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17. Abstract

Reynolds numbers for transition on a flat plate measured in two brief series of tests in the RAE 4 ft x 3 ft tunnel with two different screen arrangements in the settling chamber are presented. In the two series the transition Reynolds number varies in magnitude in opposite senses with tunnel speed but the same trend is indicated for the variation with turbulence level. At the lowest level of turbulence achieved, the transition Reynolds number approaches 6 million, and according to Mack's calculations, this would correspond to a value of n of 13 for the 'e^n method'.

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