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Summary.—This note describes current experiments on laminar-boundary-layer control by suction through perforations. No attempt was made to obtain full-chord laminar flow, as this had been shown previously to be a natural consequence of applying a suitable suction distribution, providing turbulent wedges did not result from oversuction. In the present tests, the main aim therefore was to determine the flow rates at which such wedges appeared for different arrangements of perforations. In order to simplify the test procedure, most of the results were obtained using one or more closely spaced rows of perforations at a single chordwise station on an otherwise plain wing. A method is given, supported by some experimental evidence, for predicting the perforation spacing which would be required in a full-chord application from the results thus obtained at a single chordwise station.

With all the configurations tested, a limiting suction rate was found above which turbulent wedges appeared, causing premature transition. This limit exhibited an adverse Reynolds-number effect and also made it essential to use a uniform backing to obtain a satisfactory performance. It is suggested that flow curvature under three-dimensional conditions may further restrict the suction rates which could be used.

Because of the adverse Reynolds-number effect, the present tests needed to be extended to cover flight values of U_0/ν. A short programme of tests will cover the practicable diameter range with different geometrical configurations to provide two-dimensional data. If these tests are successful, the logical next step would be for an aircraft designer to choose a configuration based on the wind-tunnel results and prove it under flight conditions.

1. *Introduction.*—During the tests described in Ref. 1, some initial experiments were carried out on the control of the laminar boundary layer on the Handley-Page laminar-flow wing by suction through perforations drilled in the wing surface. At each chordwise suction station, suction was applied through a spanwise multi-row strip consisting of several rows of closely spaced holes backed tightly with felt; consecutive stations were located at 6 per cent intervals chordwise. The tests successfully demonstrated that, at zero incidence, the laminar boundary layer could be preserved over at least part of the wing chord, up to a Reynolds number per foot chord, U_0/ν, of about $1 \cdot 9 \times 10^6$.

In view of the large number of parameters involved (*e.g.*, the geometry of the perforation pattern, boundary-layer thickness, pressure gradient, and Reynolds number) these initial tests were not very systematic, and were largely intended to establish that control of the laminar boundary layer by suction through perforations was aerodynamically feasible. It was clear that much further work was required to produce the data needed for a practical application, and research has proceeded both at the National Physical Laboratory and at the Royal Aircraft Establishment to provide these data. The R.A.E. contribution since the work of Ref. 1, is described in this note.

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The N.P.L. and R.A.E. have approached the subject somewhat differently. The N.P.L. has made a systematic study of the discrete strip method outlined above, and it is probable that the multi-row strips of closely spaced holes, which form the basis of the N.P.L. experiments, will be developed into a satisfactory scheme attractive to designers. The R.A.E. approach has tended to cover a wider range of geometrical patterns varying from these multi-row strips to a uniform distribution of holes. The two programmes were complementary and have tended to overlap. It is hoped that it will prove possible to select suitable arrangements for a particular case from the joint results.

In the R.A.E. tests, it was assumed that calculations could be made in a particular case to give the required chordwise distribution of suction. Such a method has already been developed[2] and proved in flight[3] for distributed suction through a porous material. For the case when suction was applied at discrete chordwise stations, the results of Ref. 4 suggested that it was then satisfactory to choose the suction distribution so as to maintain a sufficiently low constant value of $R_{\delta*}$ ahead of each suction station. It was therefore necessary to obtain experimental data showing the suction quantities which could safely† be applied with various configurations. With this information, it is a straightforward matter to deduce the density of perforations required at different chordwise stations to provide the calculated chordwise suction distribution.

Apart from the selection of a suitable surface configuration, the main problem confronting a practical application is the difficulty of providing adequate resistance for the perforations. Particularly under full-scale conditions, the mean velocity which can be used is small and the resulting mean pressure drop across the hole is therefore very small relative to the free-stream dynamic pressure. Thus any small local surface-pressure variations can be sufficient to cause wide variations in the inflow velocity through individual holes, unless each hole, or each small group of holes, is provided with additional resistance before being joined to a common manifold inside the wing. Such velocity variations may be sufficient to cause turbulent wedges due to over-suction at particular holes, although the mean velocity is well below the critical velocity. Felt had been used in the initial tests of Ref. 1 to provide this resistance, but would not be suitable for a practical application. The N.P.L. used cellular backing‡ for this purpose. At the R.A.E. the problem was different; practical model considerations made it necessary to increase mechanically the resistance of each hole separately, which resulted in the alternative satisfactory system of backing described in this note.

A subsidiary problem will be the application of results obtained under two-dimensional conditions to a three-dimensional design. Two-dimensional tests show that too high a suction rate causes wedges of turbulence, so that there is an upper limit to the suction rate which may be applied; a possible reason for the limit is discussed in this note, which, if correct, gives some grounds for anticipating a further restriction on suction rates under three-dimensional conditions.

The main objects of the resulting test programme were, on the basis of the above:

(*a*) To see whether a practicable arrangement of holes could be found on a two-dimensional wing, with the holes placed in simplified strips, containing one or two rows in each strip, directly connected to spanwise suction ducts. With such a configuration, the effect of chordwise pressure gradients would be mainly avoided, and it was hoped to avoid the necessity for providing any additional resistance. Even if such a scheme had been successful under two-dimensional conditions, frequent spanwise compartmenting would be required in an application to a three-dimensional wing.

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† When too large a suction rate was applied, it was found that turbulent wedges were set up at individual holes (*see* section 4.2).

‡ The grouping of several surface holes into one cell directly fitted to the underside of the surface skin. One high-resistance hole leads from each of these cells to a common manifold. The successful design of the cell depends on a knowledge of the suction rates to be applied and on the external chordwise and spanwise pressure variations over the extent of the cell.

(*b*) To evaluate the performance of a single hole with different geometric configurations of neighbouring holes; in particular, to determine the upper limit to the inflow velocity ratio, and the Reynolds-number effect on this limit. Individual holes were backed mechanically (as described in section 4.3) to ensure that velocity variations from one hole to another were negligible, and the upper limit was therefore attained simultaneously at each hole. The tests were restricted to one hole diameter size only, 0·052 in. (No. 55 drill). The diameter chosen was thought to be within the suitable practical range; the effect of hole diameter is to be included in the final series of tests (not yet done).

A preliminary analysis only is possible at this stage, and final conclusions must await the completion of the experiment.

2. *Model Details.*—The original version of the Handley-Page laminar-flow model has already been described in Refs. 1 and 4. Relevant details of the modified model are given in Table 1 and Figs. 1 and 2 of this note. The wing has a 12-per-cent–thick NACA 63_1–012 symmetrical section (with a slightly extended nose), and spans the tunnel vertically. The test surface covered the centre 4 ft of the wing span, and this part of the wing was provided with an undrilled smooth Duralumin skin of 0·080 in. thickness (14 standard wire gauge), extending from near the leading edge to about mid-chord (*see* Fig. 1). Under the skin, the method of internal construction illustrated in the lower half of Fig. 1 afforded 16 separate chordwise stations through which suction could be applied. The suction stations extended from 14·5 per cent chord to 49·2 per cent chord. At each station, about 1·5 in. chordwise could be used to drill holes through the skin into the main suction duct, which was connected by metering holes to a secondary duct (*see* Fig. 1). The secondary ducts were connected separately to the suction pump through orifice plates and gate valves as previously. About two-thirds of the local wing surface was thus available for drilling holes into the main ducts, and the model was suitable for testing a range of hole configurations. As it was initially hoped that it would be possible to use holes without any backing resistance, the main suction ducts were divided by spacers into several spanwise compartments, each about 7 in. long, to try to ensure a uniform overall spanwise velocity distribution. Perforation patterns were drilled through the wing surface on site using jig plates taped to the wing.

The tests were carried out in the R.A.E. No. 2, $11\frac{1}{2}$ ft × $8\frac{1}{2}$ ft Wind Tunnel between March and August, 1954.

3. *Tests on Plain Wing.*—Before any perforation patterns were drilled on the wing, the effect of wind speed on the plain-wing transition position was found over an incidence range using paraffin on china clay as an indicator. The surface condition was poor at first because of local flats above the heads of countersunk screws which had been filled with paraffin wax. These flats caused a wavy transition front, about 4 per cent less laminar flow occurring in line with each chordwise row of screws. After the screw-heads had been refilled with oil-paint filler, and several coats of paint sprayed on and rubbed down, the transition front became reasonably straight with about 2 per cent chordwise variation across the four-foot test span.

The variation of the mean transition position with wind speed and incidence is given in Fig. 3. From $\alpha = 0$ deg to $\alpha = 1$ deg the variation with wind speed was gradual but above $\alpha = 1$ deg there was an abrupt forward movement at a speed which decreased as the incidence was increased. Surface pressure distributions measured by static creeper traverses are shown in Fig. 4 at $\alpha = 0$ deg, 1 deg, 2 deg. By $\alpha = 2$ deg, a local negative pressure peak followed by a local adverse pressure gradient had developed near the leading edge, and this was probably responsible for the abrupt forward movement noted above. To avoid possibly misleading results, most of the subsequent tests were made at $\alpha = 0$ deg and $\alpha = 1$ deg.

In addition to these paraffin observations, a stethoscope was used to determine the transition front. For a given model configuration, as it was moved chordwise towards the trailing edge the stethoscope detected three distinct regions, namely laminar (faint hiss), intermittent (bursts of noise, similar to the sound of a motorboat) and turbulent (loud roar). The intermittent region was about 2 per cent chord in extent. The paraffin boundary was found to be somewhere in the intermittent region, the precise position depending on the running time allowed. Some uncertainty in the paraffin pictures was not important as they were only used to obtain the overall effect of wind speed and incidence on the mean transition position. On the other hand the stethoscope was later found to be preferable for tests with perforations at a given point on the wing, as the wind speed and the suction quantity could then be varied continuously.

4. *Tests with Suction Applied Through Perforations.*—4.1. *Effect of the Presence of Perforations on the Plain-Wing Transition Position.*—The presence of an arrangement of open holes (with zero suction) ahead of the plain-wing transition position caused a reduction in the extent of laminar flow. Even with optimum flow quantities, the presence of perforations at one chordwise station still caused in general a net reduction in the extent of laminar flow; net gains in the extent of laminar flow could only be obtained when suction was applied at several chordwise stations or distributed uniformly over a large part of the chord. This loss due to the presence of the perforations is probably best taken into account by regarding the 'holes open, zero suction' transition position as a new datum. The amount of forward movement was partially determined by the quantity of inflow and outflow occurring, and so could be reduced to a certain extent by increasing the resistance of the holes (*see* in particular Fig. 5c).

4.2. *Results of Tests without 'Backing Holes'.*—As stated in the introduction, the first aim of the present tests was to determine whether single or double rows could be made to work without any additional backing, the holes being drilled directly into a spanwise compartment of about 7 in. span. It was thought possible that the local spanwise and chordwise surface-pressure variations might be small enough over this restricted area to permit a sufficiently uniform inflow through individual holes with optimum flow quantities. Surface-pressure traverses indicated that such pressure variations were reasonably small over the extent of the test specimen, being only of the order $0 \cdot 0025 \times \frac{1}{2}\rho U_0^2$. However, it was found that the maximum flow quantities which could be used, without turbulent wedges resulting from over-suction at particular holes, were so small that the mean pressure drop across the skin was only of the same order as the local surface-pressure variations, even at low tunnel speeds. Hence 100 per cent variations in the inflow velocity could occur at different holes. As the speed was increased, the maximum usable flow quantities decreased (*see* section 4.4) and therefore such velocity variations became correspondingly worse.

The idea of using rows of unbacked holes was therefore abandoned, after tests had been made over the practicable diameter range. Some of the results obtained are shown in Figs. 5a to 5c and are discussed in the next section. They emphasised the need for a carefully designed backing system as an essential preliminary to tests on different geometric configurations.

4.3. *Effect of 'Backing Holes' on the Performance of Perforations.*—The tests described in the previous section showed that it was essential to increase the mean pressure drop across the holes. The skin could not be removed easily to insert some form of resistance directly below the surface, so that the pressure drop could only be augmented by increasing the jet velocity at the bottom of each hole. The surface holes, 0·052 in. diameter, were therefore drilled to 0·05 in. depth, and connected individually by 0·021 in. diameter 'backing holes' to the suction compartment inside the wing through the remaining 0·03 in. thickness of the skin (*see* Fig. 2a). The throttling effect of the small holes increased the jet velocity by a factor of $(0 \cdot 052/0 \cdot 021)^2 \simeq 6$ and therefore the mean pressure drop by about 36. With zero suction, the additional resistance decreased by a factor 6 the mass inflow and outflow through individual holes and improved the zero suction datum (*see* Fig. 5c with $C_Q' = 0$); with a given total suction quantity, the mean pressure drop across the skin decreased the effect of local pressure variations and hence the variations in the flow through individual holes.

The effect of using the 0·021 in.-diameter holes as a resistance backing for the main surface 0·052 in.-diameter holes can be seen in Figs. 5a and 5b for a single row and in Fig. 5c for a multiple row arrangement. When the holes were drilled straight through the skin to the compartment with no resistance backing, stethoscope and paraffin evaporation tests indicated large spanwise variations in the behaviour of the test specimen, both with zero suction and with optimum flow quantities, the performance deteriorating with increasing Reynolds number. However, when ' backing holes ' were present, the spanwise variations became negligible and there was now, for low suction rates, a linear increase with (v_0/U_0)† in the extent of laminar flow over the datum position with zero suction. The critical value for (v_0/U_0), called hereafter $(v_0/U_0)_{\text{crit}}$, increased substantially and the breakdown was more severe, as would be expected with a more uniform flow distribution. $(v_0/U_0)_{\text{crit}}$ again decreased rapidly as the wind speed was increased.

Thus, in contrast to the wide variations in the aerodynamic behaviour which occurred without ' backing holes ', the performance with ' backing holes ' was repeatable and showed that a successful form of mechanical backing had been devised.

It was appreciated that the presence of the ' backing holes ' might affect the critical inflow ratio, $(v_0/U_0)_{\text{crit}}$, for an individual hole. To minimise any such effect, the depth of the 0·052 in.-diameter surface holes had been made as large as possible, about equal to the diameter. As the results obtained with ' backing holes ' closely resemble the results which were obtained by the N.P.L. with a form of cellular backing, it seems unlikely that the presence of the ' backing holes ' affected the aerodynamic behaviour of individual holes; the actual system of backing used was probably unimportant as long as it performed successfully its function of ensuring inflow uniformity.

At this point, it is appropriate to discuss the two mechanical systems of backing which have been suggested. The method of increasing the resistance of the surface perforations by means of ' backing holes ' is the case of the cellular system when the number of holes to each cell is reduced to one. The main advantage is that it is ideal in the sense that each hole is provided separately with adequate resistance, so that the ducting required below the surface skin can be very simple, probably on the lines of the sandwich skin construction developed by Messrs. Handley Page, Ltd., and used on the tunnel model. However, such compound holes are more liable to block or ice-up, although the blockage of an occasional hole would not be expected to affect the overall performance of a system of perforations. In addition, the surface skin is more difficult to produce than a simple perforated sheet. In the cellular system which is being developed at the N.P.L., about 10 holes are connected directly to a common cell just below the surface, and a single hole joins each cell to the suction manifold. The pressure drop between the cell and the manifold is of much higher order than the mean pressure drop across the perforated surface skin, and ensures that the total flow through the different cells can be closely controlled. Large variations in the inflow velocity through the various holes of a cell may still occur if the surface-pressure variations over the extent of a cell are of the same order as the mean pressure drop across the perforated skin. The perforated skin is easier to produce but there is the complication of providing a suitable cellular backing and the difficulties of bonding the backing to the surface skin. There is less chance of blockage of the surface holes, but all the holes of a cell cease to function if the control hole at the bottom of the cell becomes blocked. In the above tests without ' backing holes ', fifty to a hundred holes were connected directly to a suction duct in a very simple version of a cellular backing.

4.4. *Results of Tests with ' Backing Holes '*.—In the main set of tests, which are described in this section, no attempt was made to obtain full-chord laminar flow. This had been shown previously [1,4] to be a natural consequence of applying a suitable suction distribution, providing turbulent wedges did not result from over-suction through particular holes. The aim of the tests, therefore, was to determine the flow rates at which such wedges appeared for different arrangements of perforations. In order to simplify the test procedure, most of the results were obtained using one or more closely spaced rows of holes at a single chordwise station on an otherwise plain wing. A method is given in the next section for predicting from the results thus

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† The ratio between the mean inflow velocity through the surface hole, $v_0 = \frac{Q_{(\text{cu ft/sec per hole})}}{(\pi D^2/4)_{\text{sq ft}}}$, and the wind speed U_0 (ft/sec).

obtained at a single chordwise station, the perforation spacing which would be required in a full-chord application. The method is supported by the results of the final series of tests described in this section in which perforations were spread over 25 per cent of the wing chord.

The usual suction coefficient, C_Q, is essentially arbitrary, as it is based on the wing chord, unless a full-chord configuration is under consideration. A C_Q' based on a nominal one-foot chord (*see* notation) has therefore been used in the analysis when comparing the total flow quantities for different configurations. However, the test results are generally better expressed in terms of the upper limit, $(v_0/U_0)_{\text{crit}}$, for the ratio of mean inflow velocity to the wind speed, since an estimate can be directly made from $(v_0/U_0)_{\text{crit}}$ (*see* section 5) of the density of perforations which would be required for a particular application, on the assumption that the chordwise suction distribution required to maintain laminar flow can be calculated in advance.

In view of the tests described in the last section, 0·021 in.-diameter 'backing holes' were used throughout to augment the resistance of the surface perforations and hence make the inflow velocities through individual holes more uniform. To simplify the test programme, only one diameter size, 0·052 in., was used for the surface perforations. This size was within the likely practical range (the effect of diameter size over this range will be included in a later series of tests). The test configurations, consisting of 6 in.-span samples of each perforation pattern, were located well forward on the wing surface, generally at 14·5 per cent chord or 21·6 per cent chord, mainly because it was found to be desirable to commence suction some distance ahead of the plain-wing transition, at a point where the laminar boundary layer was stable to small disturbances. (When suction was commenced immediately ahead of the plain-wing transition, the more unstable boundary layer was extremely sensitive to suction through the perforations.) Each of the above chordwise stations was well ahead of the natural transition position, and comparative tests (*see* discussion below of Fig. 8) showed that slightly larger suction quantities could be applied through the same perforation pattern at the further aft station, due to the increased boundary-layer thickness relative to hole diameter. Thus, if the same pattern were located much further aft on the wing, in a slightly thicker boundary layer which had been stabilized and thinned by the application of suction at preceding rows of perforations, we would expect at most a small further increase in the suction quantities which could be applied.

Most of the results were obtained using the stethoscope as this was found to be quicker and more reliable than the evaporation technique when detailed results were required for a small region of the wing surface. In addition, the use of the stethoscope permitted results to be obtained for a continuous variation of wind speed and flow quantity, which would not have been possible with an evaporation technique. In particular, the value of $(v_0/U_0)_{\text{crit}}$ could be determined accurately. Check tests with paraffin were made occasionally to confirm the trend of stethoscope results.

The tests were limited to $U_0 = 200$ ft/sec for two reasons. Firstly, the present stethoscope rig was unsuitable at higher speeds (for reasons of safety and audibility). Secondly, Plasticine was used to obtain a variety of configurations by blocking up certain holes already drilled and the resulting surface was considered too rough for use above 200 ft/sec. The results, however, show such an adverse scale effect on $(v_0/U_0)_{\text{crit}}$, that it would appear desirable to extend the tests to cover the probable flight requirements for U_0/ν and thus avoid the necessity for extrapolation.

The results are presented in figure form, and only a preliminary analysis is attempted at this stage.

The lower halves of Figs. 5a and 5b show, at two wind speeds, the effect of suction through a single row of holes at 21·6 per cent chord. The results are typical of those obtained in these tests. There was initially a linear variation of transition position with (v_0/U_0) followed by a sharp cut-off above $(v_0/U_0)_{\text{crit}}$ (or equally well $C_{Q\,\text{crit}}'$). This cut-off occurred at progressively lower values for (v_0/U_0) as the wind speed was increased, so that there was an adverse Reynolds-number effect. The upper portions of each figure were obtained without 'backing holes', *see* section 4.3, and need not be considered here. In Fig. 6, the effect is shown of adding successive rows to the configuration used in Figs. 5a and 5b. The chordwise pitch, 0·125 in., of rows was the same as the spanwise pitch between holes (*see* Fig. 2b). The results are shown for three wind speeds; for simplicity, one curve only has been drawn in each case, representing the laminar-intermittent boundary (Figs. 5a and 5b show both the laminar-intermittent and the intermittent-turbulent boundaries). It can be seen that with one row only the extent of laminar flow increased linearly with (v_0/U_0) at a rate roughly independent of the wind speed until the critical value, $(v_0/U_0)_{\text{crit}}$, was exceeded, when transition moved forward violently. $(v_0/U_0)_{\text{crit}}$ decreased with increasing wind speed, as did the maximum increment in the chordwise extent of laminar flow, $\Delta L_{\max}$. With two rows, the maximum gain, $\Delta L_{\max}$, was doubled and $(v_0/U_0)_{\text{crit}}$ was increased. With three rows, the transition curve exhibited a flat top, showing that there was a limit to the extent of laminar flow which could be obtained with suction at the one chordwise station only. Analysis of the adverse Reynolds-number effect shows that $(v_0/U_0)_{\text{crit}}$ was roughly proportional to U_0^{-1} for each configuration.

Figs. 7a and 7b show results for a similar configuration at 14·5 per cent chord. In this case further rows were added, which extended the range of total flow quantities over which the maximum increment in laminar flow, $\Delta L_{\max}$, was obtained but did not extend the value of $\Delta L_{\max}$ above the three-row value. In Fig. 7a, the results have been plotted against the total C_Q' for N rows. Increasing the number of rows above three extended the maximum total flow quantity which could be applied, whilst the performance at low total flow rates was unchanged. In Fig. 7b the results have been plotted against (v_0/U_0) and C_Q' per row; this shows the improvement in the performance at low values of (v_0/U_0).

In Fig. 8 the results for a single row of perforations at 14·5 per cent chord and at 21·6 per cent chord have been compared. The value of $(v_0/U_0)_{\text{crit}}$ was larger at the further aft station because of the favourable effect of an increase in boundary-layer thickness relative to hole diameter. Comparison of the results for three rows at 14·5 per cent chord (Fig. 7b) and 21·6 per cent (Fig. 6) confirm this effect on $(v_0/U_0)_{\text{crit}}$. Calculations of boundary-layer development based on observed pressure distributions (by method of Ref. 5) showed that the boundary-layer displacement Reynolds number was 25 per cent greater at 21·6 per cent chord than at 14·5 per cent chord (*see* following Table).

In an application, most of the perforation patterns would be located further aft on a wing. However, the thinning effect of suction at preceding rows of perforations would tend to reduce the chordwise variations in displacement thickness. Thus, in the initial N.P.L. tests on this wing (Ref. 4), with optimum flow quantities for full-chord laminar flow applied at 10 chordwise stations through Porosint strip inserts, the measured values of R_{δ^*} ahead of each station tended to remain constant from 20 per cent chord onwards (*see* following table). The mean value of R_{δ^*} (2127 at 120 ft/sec) was therefore not much larger than the calculated plain-wing value at 21·6 per cent chord in the present tests (1810), so that the results obtained at this station may be directly applied with confidence to a full-chord application (Fig. 8 suggests that such an increase in R_{δ^*} from 1810 to 2127 would lead to an increase in $(v_0/U_0)_{\text{crit}}$ of at most 10 per cent, which is not very important in view of the large safety margin which it would be desirable to allow in practice). It may be noted that great simplification of test procedure results if only one chordwise suction station need be used.

Fig. 9 shows that a small incidence change did not affect the performance of a single row. This is not surprising, as the following table shows that the corresponding change in R_{δ^*} was small.

The value of 2·4 used for the spanwise pitch-diameter ratio in the above tests was as small as was considered tolerable in a practical application (*see* Fig. 2c). The main advantages of increasing P_s/D are structural. If the space between adjacent holes is increased, the strength of the skin is increased and the provision of a suitable backing becomes easier. Fig. 10 shows the effect of varying P_s/D on the performance of a single row. As P_s/D was increased, the upper diagram shows that the $C'_{Q\,\text{crit}}$ for the row tended asymptotically to zero, as would be expected. But the lower diagram shows that the upper limit to the flow rate into a particular hole, $(v_0/U_0)_{\text{crit}}$, actually increased as P_s/D was increased. Thus, the performance of an individual hole tended

Table of Boundary-Layer Displacement Reynolds Number

$U_0 = 120$ ft/sec

Tests of Ref. 4, Model 1 (Table 4) Total $C_Q = 0 \cdot 00041$, 95 per cent laminar flow			Present tests (perforations drilled at one station)		
Incidence (deg)	Chordwise station (per cent chord)	Measured value of R_{δ^*}	Incidence (deg)	Chordwise station (per cent chord)	Calculated value of R_{δ^*}
0	10 (Upstream of strip 1)	1130	0	10	1090
	20 (Upstream of strip 2)	1780		14·5	1450
	30 (Upstream of strip 3)	2050		21·6	1810
	39 (Upstream of strip 4)	1960	1	21·6	1940
	48 (Upstream of strip 5)	2180			
	56·5 (Upstream of strip 6)	2300			
	64·5 (Upstream of strip 7)	2160			
	71·5 (Upstream of strip 8)	2450			
	78 (Upstream of strip 9)	2190			
	84 (Upstream of strip 10)	2070			
	Average ahead of strips 2 to 10	2127			

to improve as its spanwise neighbours were moved further away. As, in an application, an increased value for P_s/D would be compensated by an increase in the total number of rows, it is the value for $(v_0/U_0)_{\text{crit}}$, rather than $C'_{Q\,\text{crit}}$ per row, which is important. Fig. 10 also shows that the effect of P_s/D on the performance of a single row depended on the Reynolds number. On increasing P_s/D from 2·4 to 9·6, $(v_0/U_0)_{\text{crit}}$ increased by 150 per cent at 100 ft/sec, but only increased by 70 per cent at 200 ft/sec. This emphasises the need for results to be obtained at the highest value of U_0/ν which is likely to be used in full-scale applications.

It will be noted that $(v_0/U_0)_{\text{crit}}$ is shown in Fig. 10 to increase again below $P_s/D = 2 \cdot 4$. This result has been obtained in the corresponding N.P.L. tests with a single row of very closely spaced holes; presumably, such a configuration tends to act like a continuous spanwise slot as P_s/D is decreased. This is an additional reason why the present tests need to be extended to cover the full speed range, as the value of P_s/D at which $(v_0/U_0)_{\text{crit}}$ is a minimum will probably depend on the relative values of the hole diameter and the displacement thickness.

Fig. 11 shows the corresponding transition curves at $U_0 = 150$ ft/sec. With two rows of holes at $P_s/D = 9 \cdot 6$, at a given total flow quantity, there was more extensive laminar flow than with one row at $P_s/D = 4 \cdot 8$, although the same total number of holes was used; also, the value for $(v_0/U_0)_{\text{crit}}$ was larger in the former case. Similarly, two rows at $P_s/D = 4 \cdot 8$ were slightly superior to one row at $P_s/D = 2 \cdot 4$. These results showed that it was possible to obtain at least as good a performance with the same total number of holes if they were spaced out more widely both spanwise and chordwise. It would be worthwhile, then, to compare the relative performance of, for example, 3 rows at $P_s/D = 2 \cdot 4$, 6 rows at $P_s/D = 4 \cdot 8$, and 9 rows at $P_s/D = 7 \cdot 2$, as all these configurations use the same total number of holes. Since the effect of geometry on maximum inflow velocity decreased with increasing test speed (*see* Fig. 10 and previous paragraph), it would be essential to test at higher wind speeds in case the P_s/D effect reverses. If, as is suggested by Fig. 10, the maximum inflow velocity was found to become virtually independent of surface geometry as the speed was increased, then the hole geometry could be arbitrarily chosen without affecting the aerodynamic performance under full-scale conditions (*N.B.* Fig. 10 includes results for one diameter size only. The effect of geometry at a given wind speed will also depend on the diameter).

In the tests described so far, several rows of closely spaced holes were located at a single chordwise station. It has already been pointed out (in the discussion of Fig. 8) that the test procedure is greatly simplified if most of the results can be obtained in this manner. It was desirable to show that the answers thus obtained could be used to design a suitable arrangement of perforations extending over an appreciable portion of the wing chord. The pattern of holes used in the final series of tests therefore consisted of a succession of single rows spread uniformly over 25 per cent of the wing chord, with a relatively large distance between rows. In the first tests, each row consisted of 0·052 in.-diameter backed holes at 0·125 in. pitch spanwise (Fig. 2d). As shown in the following table, two values for the chordwise pitch between rows were tried. Because of the adverse Reynolds-number effect on $(v_0/U_0)_{\text{crit}}$, it was found that the chordwise pitch had to be decreased as the wind speed was increased. Thus, a chordwise pitch of 4·5 in. was satisfactory at 100 ft/sec and marginal at 150 ft/sec, whilst a pitch of 2·25 in. was satisfactory at 150 ft/sec and marginal at 200 ft/sec. The performance of the configuration was considered satisfactory if there was extensive laminar flow beyond the last row over a range of suction rates, so that the extent of laminar flow could have been further increased by adding additional rows of perforations at the same chordwise pitch. Optimum quantities were not determined, but the values of $(v_0/U_0)_{\text{crit}}$ at the different rows were found to be of the same order as the values for a single row at 21·6 per cent chord. This test is summarized in the following table:

Chordwise spacing of successive rows (in.)	Local density of perforations (per cent)	Extent in chord (per cent)	Number of rows	Performance
4·5	0·375	21·6 to 44·6	6	Satisfactory at 100 ft/sec Marginal at 150 ft/sec
2·25	0·75	21·6 to 46·9	12	Satisfactory at 150 ft/sec Marginal at 200 ft/sec

The chordwise spacing of 2·25 in., which was satisfactory up to 150 ft/sec, is seen to correspond to a local density of perforations of 0·75 per cent. In the next section, the results obtained at a single chordwise station are used to estimate the minimum density of perforations which is likely to be required in a full-chord application. At 150 ft/sec, the estimated density is 0·7 per cent and agrees well with the figure found necessary in the tests just described. It is therefore suggested that the results obtained in tests at a single chordwise station may be used to estimate the density of perforations which would be required for a full-chord application.

A further test was also carried out with the hole configuration for uniformly distributed suction shown in Fig. 2e. The hole density was 0·75 per cent, as in the above test with $P_c = 2 \cdot 25$ in., and it was expected that the configuration would behave in a similar way. However, since every third row had to be drilled directly into a secondary duct through a double skin, the suction distribution was far from ideal and breakdowns occurred at isolated holes at very low flow rates. The test was inconclusive and it is hoped to try out the configuration again in the final series of tests.

5. *Discussion of Full-Scale Hole Spacing.*—To preserve full-chord laminar flow by strip suction or uniformly distributed suction through a perforated wing surface, inflow quantities equivalent to a mean inflow rate of about 0·0005 through a porous skin will be required towards the trailing edge[1, 2, 4]. This figure will not vary greatly with U_0/ν. Let us consider the case $U_0 = 200$ ft/sec at sea level, for which $U_0/\nu = 1 \cdot 25 \times 10^6$ (equivalent to 450 ft/sec at 30,000 ft). It was shown in section 4.4 that the boundary-layer displacement thickness would tend to remain constant on such a wing from about 20 per cent chord onwards, so that the test results obtained at 21·6 per cent chord can be used in the present analysis. From Fig. 5b, we see that the value of $(v_0/U_0)_{\text{crit}}$ exceeded 0·05 at 200 ft/sec for a single row of closely spaced holes at 21·6 per cent chord. The value of $(v_0/U_0)_{\text{crit}}$ was also larger than 0·05 for all the other geometrical configurations tested at this chordwise station, so that 0·05 could always be used safely. By division, the density of perforations required to apply a mean inflow rate of 0·0005 is:

$$P = \frac{0 \cdot 0005}{0 \cdot 05} = 1 \text{ per cent.}$$

At $U_0 = 150$ ft/sec, the same procedure leads to a smaller density:

$$P = \frac{0 \cdot 0005}{0 \cdot 07} \simeq 0 \cdot 7 \text{ per cent.}$$

As this figure agrees closely with the density found necessary at $U_0 = 150$ ft/sec in the tests described in section 4.4 with perforations extending over 25 per cent of the wing chord, the suggested method for interpreting the results obtained at a single chordwise station appears to be satisfactory.

At higher values of U_0/ν, with a safety factor to allow for imperfections in the backing, it would appear that 3 per cent to 4 per cent of the surface might have to be perforated in a practical application. This figure is not unreasonable. For instance, in the previous tests with strip suction[1], 12·5 per cent of the wing area was occupied by Porosint inserts.

In terms of the spanwise pitch, P_s, between adjacent holes and the average chordwise pitch, P_c, of successive rows:

$$P = \frac{\pi}{4} \frac{D^2}{P_s P_c} \, .$$

$$\text{With} \qquad P = 0 \cdot 03, \quad \left(\frac{P_s}{D}\right) \times \left(\frac{P_c}{D}\right) = 26 \cdot 2 \, .$$

This, for instance, would entail rows of 0·052 in.-diameter holes at 0·5 in. intervals with the holes of each row pitched at 0·14 in.

Current N.P.L. experiments suggest that if a smaller hole diameter was used, the total number of holes required would be increased, but the total perforated area could be decreased.

6. *Future Programme.*—In a later series of tests to conclude this investigation, the aims would be twofold, namely :

(*a*) Extend the present results to slightly higher values of U_0/ν, to cover the probable range for cruising conditions, and avoid the necessity for extrapolation, because of the unpredictable Reynolds-number effect. It is hoped to obtain data showing the relative merits of a few different geometric configurations using the same number of holes. The effect of hole diameter would be obtained over the practicable range of hole diameter, assumed to be 1/32 in. to 1/16 in.

(*b*) Determine what kinds of backing are suitable under flight conditions. It is hoped that some form of cellular backing will prove successful, with about 10 holes to each cell, as used in current N.P.L. Tests. It may be necessary to reduce the number of holes to each cell because of adverse Reynolds-number effect. With the larger hole sizes, it may even be necessary to back individual holes, as was done for convenience in the present tests.

7. *Possible Explanation for the Existence of* $(v_0/U_0)_{\text{crit}}$.—The occurrence of a critical value of (v_0/U_0) is thought to be due to the spanwise cyclic variations of surface pressure induced by suction through a row of perforations. Such surface-pressure variations normal to the free-stream direction would result in inherently unstable secondary velocity profiles near the edges of the holes, as are encountered on swept wings[6]. Whenever the characteristic Reynolds number, $\chi = v_{\max}\delta/\nu$, exceeded a value of about 125, these profiles would be expected to break down with the formation of vortices along stream, two contra-rotating vortices being shed by each hole; the associated forward movements of transition would be expected to be violent. In the present tests, striation traces were observed in the laminar boundary layer behind the holes at high suction rates, and the stethoscope indicated flow disturbances just aft of the holes in the laminar boundary layer. The observed forward movements of transition at the critical flow conditions were violent. Thus the experimental evidence was consistent with this explanation.

Mr. Hooper, of Messrs. Fairey Aviation Co. Ltd., kindly agreed to obtain some secondary velocity profiles on his large-scale perforation model to see whether this explanation was in fact correct and he has been able to measure secondary velocity profiles of the required order.

Care will therefore be needed when applying results obtained under two-dimensional conditions to the three-dimensional flow on a wing or body. Consider, for instance, a wing on which some flow curvature exists. Then there will already be a pressure gradient, normal to the local free-stream direction, which may be superimposed on the cyclic variation due to the perforations, tending to increase the strength of the secondary flow on one side of a hole and tending to reduce it on the other side. The critical value of χ will consequently be attained at lower values of (v_0/U_0) than in the corresponding two-dimensional case. Thus, for a given hole diameter, the number of perforations required to apply a given total amount of suction would have to be correspondingly increased, in order to keep below a reduced maximum value of (v_0/U_0). When the flow curvature present was large, this effect might conceivably be sufficient to render the use of perforations impracticable.

8. *Conclusions.*—This note describes current experiments on laminar–boundary-layer control by suction through perforations. No attempt was made to obtain full-chord laminar flow, as this had been shown previously to be a natural consequence of applying a suitable suction distribution, providing turbulent wedges did not result from over-suction. In the present tests, the main aim therefore was to determine the flow rates at which such wedges appeared for different arrangements of perforations. In order to simplify the test procedure, most of the results were obtained using one or more closely spaced rows of perforations at a single chordwise station on an otherwise plain wing. A method is given, supported by some experimental evidence, for predicting the perforation spacing which would be required in a full-chord application from the results thus obtained at a single chordwise station.

With all the configurations tested, a limiting suction rate was found above which turbulent wedges appeared causing premature transition. This limit exhibited an adverse Reynolds-number effect and also made it essential to use a uniform backing to obtain a satisfactory performance. It is suggested that flow curvature under three-dimensional conditions may further restrict the suction rates which could be used.

Because of the adverse Reynolds-number effect, the present tests need to be extended to cover flight values of U_0/ν. A short programme of tests will cover the practicable diameter range with different geometrical configurations to provide two-dimensional data. If these tests are successful, the logical next step would be for an aircraft designer to choose a configuration based on the wind-tunnel results and prove it under flight conditions.

NOTATION

c		Wing chord (ft)
C_Q	$=$	$Q/(U_0 c)$ Suction coefficient based on a wing chord c
C'_Q	$=$	$\frac{Q}{U_0 1}$ Suction coefficient based on nominal 1-ft chord
$C'_{Q\,\mathrm{crit}}$		C'_Q value at which forward movements of transition occur
D		Hole diameter at surface (ft)
P		Proportion of local wing surface which is perforated
P_s		Spanwise pitch of centres of adjacent spanwise perforations
P_c		Chordwise pitch of successive rows
Q		Rate of flow (cu ft/sec/ft span)
$v_{\max}$		Maximum value of the component of the boundary-layer velocity normal to the local streamline direction just outside the boundary layer (ft/sec)
v_0	$=$	$\frac{Q_{\text{per hole}}}{(\pi D^2)/4}$ Inflow velocity through a hole (ft/sec)
$\frac{v_0}{U_0}$		Inflow velocity ratio
$\left(\frac{v_0}{U_0}\right)_{\mathrm{crit}}$		Value of (v_0/U_0) above which forward movements of transition occur
R_{δ^*}		Boundary-layer displacement Reynolds number
s		Span of test specimen (ft)
U_0		Wind speed (ft/sec)
α		Wind incidence (deg)
δ		Boundary-layer thickness
δ^*		Boundary-layer displacement thickness
$\Delta L_{\max}$		Maximum increment in laminar flow
θ		Boundary-layer momentum thickness
χ	$=$	$\frac{v_{\max}\,\delta}{\nu}$ Secondary-flow Reynolds number
ν		Kinematic viscosity

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5	B. Thwaites	Approximate calculations of the laminar boundary layer. Aero. Quart. Vol. 1. pp. 245 to 280. 1949.
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TABLE 1

Model and Test Details

Wind tunnel: R.A.E. No. 2 $11\frac{1}{2} \times 8\frac{1}{2}$ ft

Turbulence level: (data from R.A.E. Tech. Note Aero. 1991)

Wind speed:	U_0	100 ft/sec	200 ft/sec	300 ft/sec	400 ft/sec
Turbulence:	$(u'/U_0)\%$	0·03	0·05	0·075	0·125

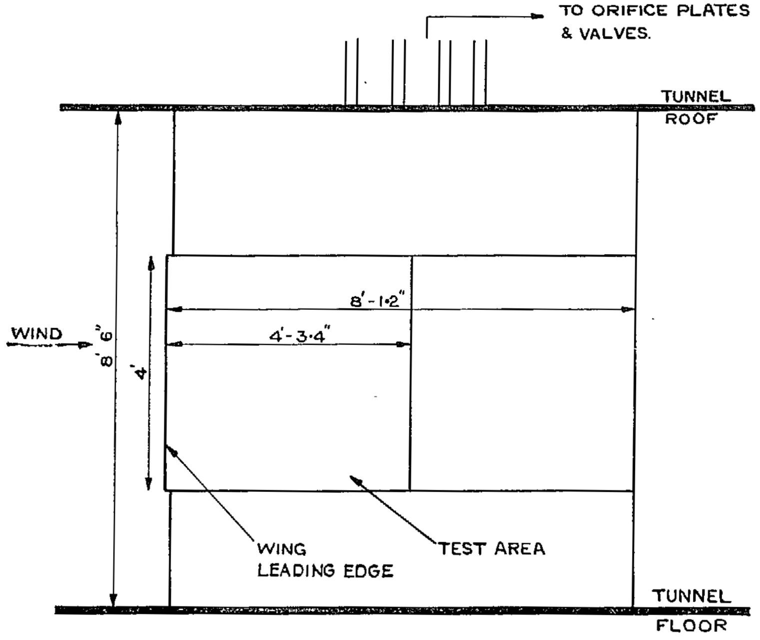
Bad peak of 0·10 at 160 ft/sec

Wing:
chord: 8·097 ft
span: 8·5 ft (spanning tunnel vertically)
thickness: 12 per cent
section: NACA 63_1–012

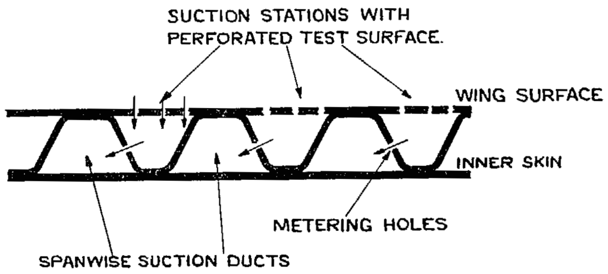
Suction stations:

No.	1	2	3	4	5	6	7	8
(x/c) per cent	14·5	16·9	19·3	21·6	23·9	26·2	28·5	30·8
No.	9	10	11	12	13	14	15	16
(x/c) per cent	33·1	35·4	37·7	40·0	42·3	44·6	46·9	49·2

At each station, about 1·6 per cent chordwise is available for drilling perforation patterns; consecutive stations are separated by about 0·8 per cent chordwise of plain wing not suitable for perforations.

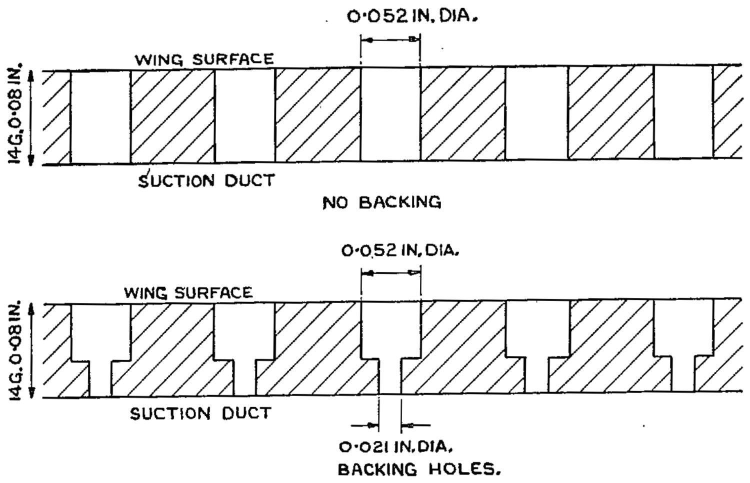


INSTALLATION OF MODEL IN TUNNEL.

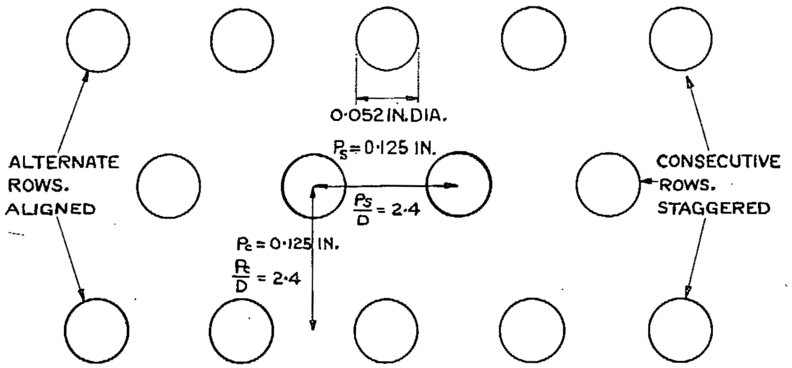


METHOD OF WING SURFACE CONSTRUCTION

Fig. 1. Model details.



(a) CROSS-SECTIONS OF THE SURFACE SKIN SHOWING DETAILS OF BACKING HOLES.



(b) GEOMETRY OF NORMAL MULTIPLE ROW ARRANGEMENT.

Figs. 2a and 2b. Details of perforations.

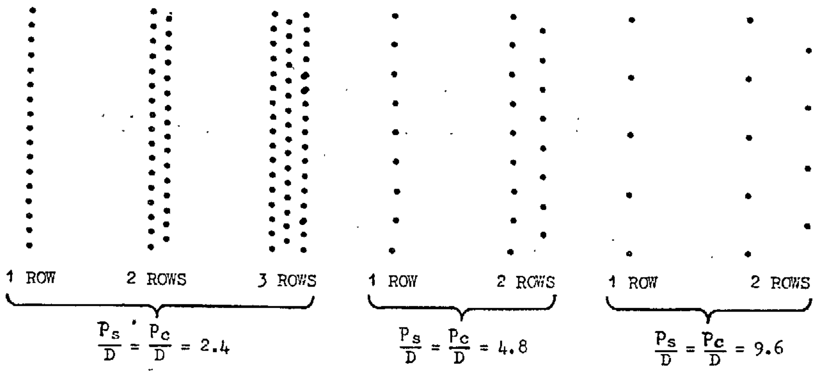


FIG.2c. SOME OF THE DIFFERENT TEST CONFIGURATIONS USED IN THE TESTS AT ONE CHORDWISE STATION

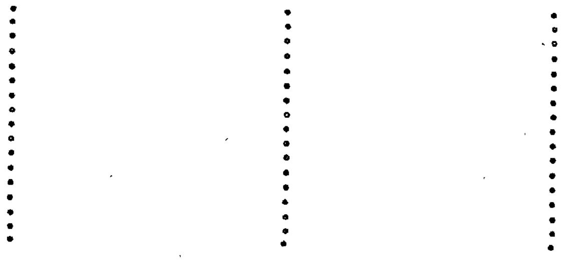


FIG.2d. SUCCESSION OF SINGLE ROWS $\left\{\frac{P_s}{D} = 2.4, \frac{P_c}{D} = 43.2\right\}$

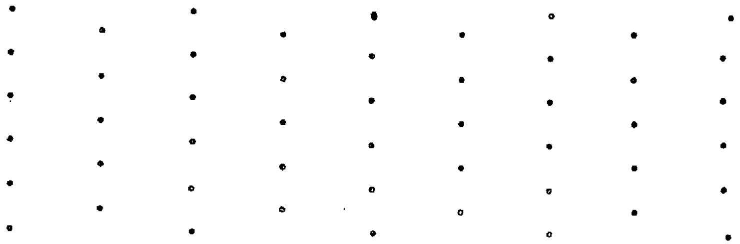


FIG.2e. DISTRIBUTED SUCTION CONFIGURATION $\left\{\frac{P_s}{D} = 7.2, \frac{P_c}{D} = 14.4\right\}$

FIGS. 2c to 2e. Details of perforations.

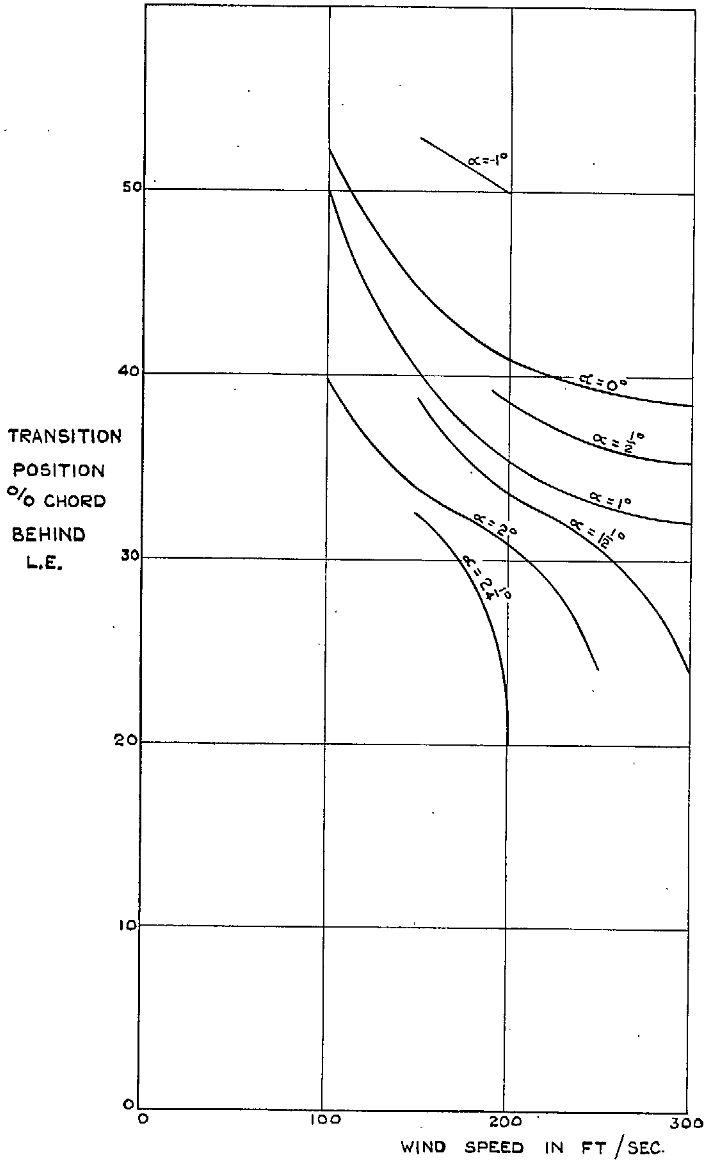


FIG. 3. Effect of wind speed on plain wing transition position. Test surface is upper surface.

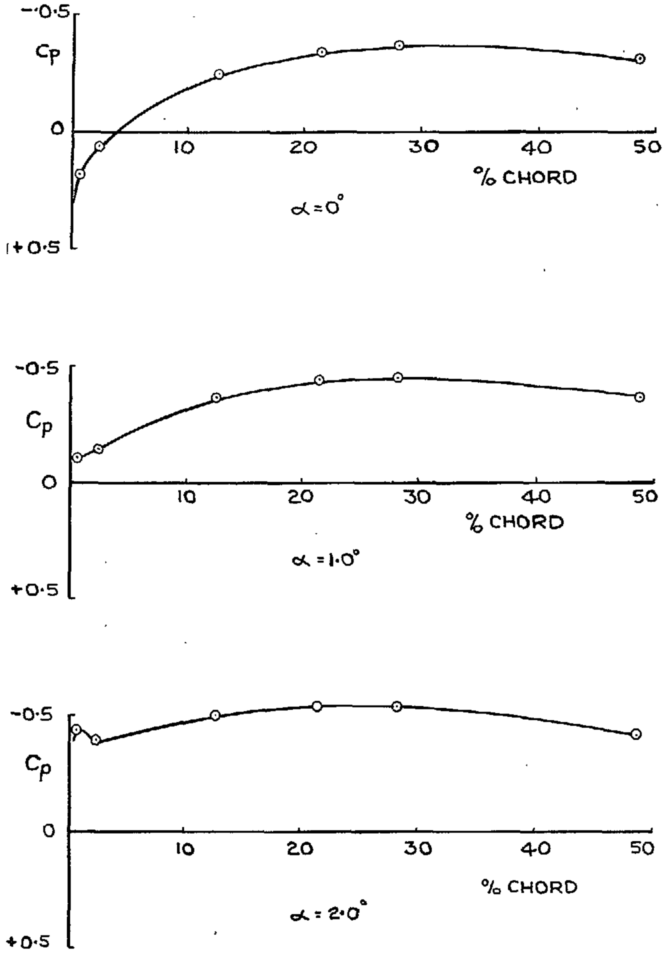


Fig. 4. Surface-pressure distributions at $\alpha = 0$ deg, $1{\cdot}0$ deg, $2{\cdot}0$ deg.

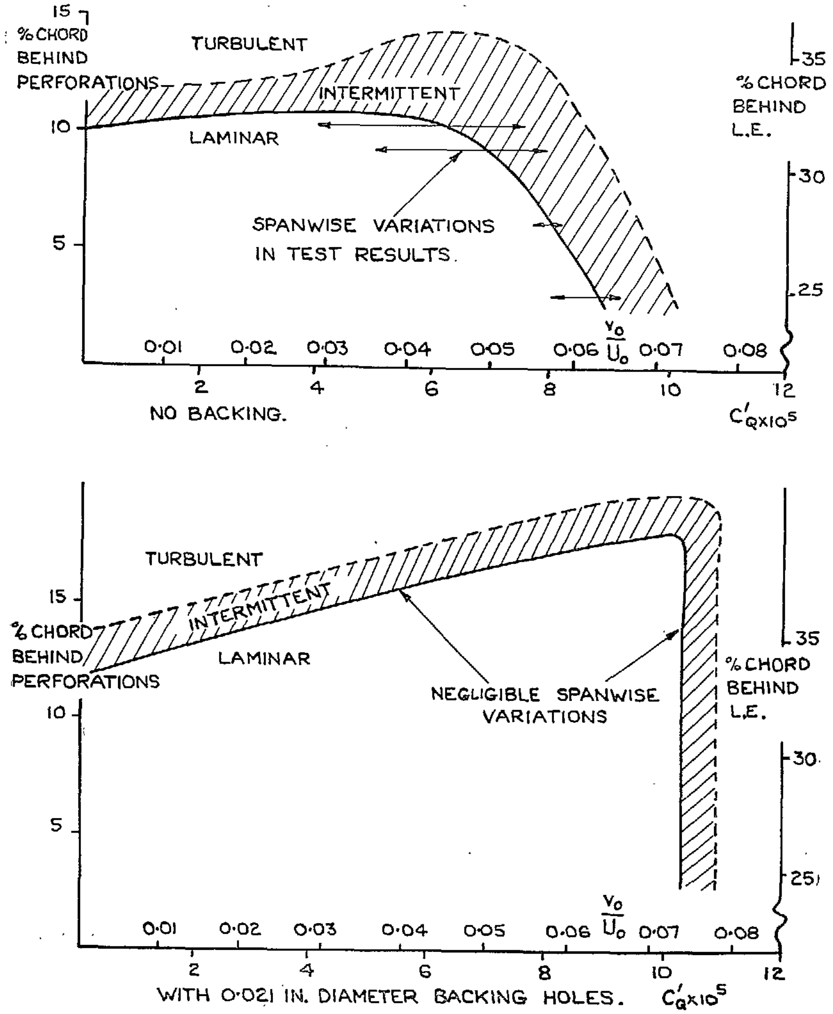
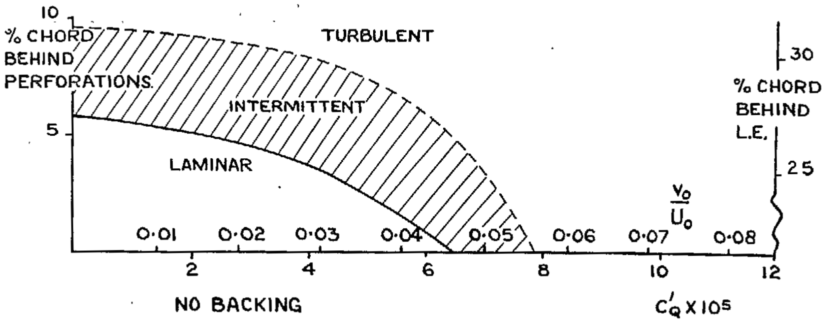
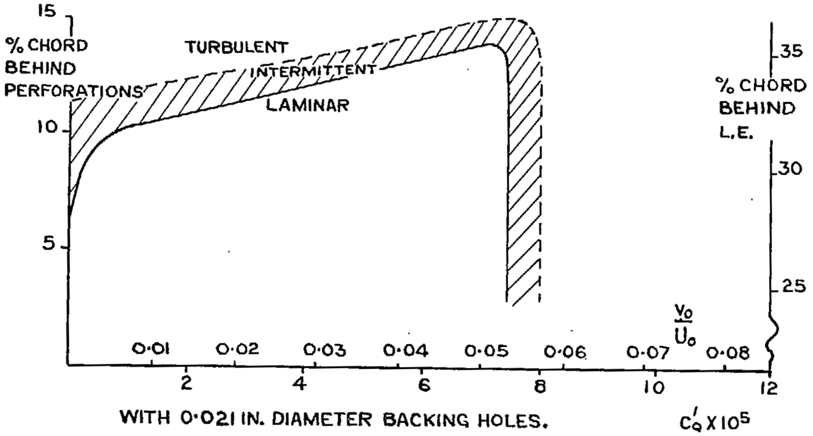


Fig. 5a. Effect of backing holes on the performance of a single row at $\alpha = 0$ deg, $U_0 = 150$ ft/sec. Single row at $21{\cdot}6$ per cent chord of $0{\cdot}052$ in.-diameter holes at $0{\cdot}125$ in. pitch spanwise.



NO BACKING



WITH 0·021 IN. DIAMETER BACKING HOLES.

FIG. 5b. Effect of backing holes on the performance of a single row at $\alpha = 0$ deg, $U_0 = 200$ ft/sec. Single row at 21·6 per cent chord of 0·052 in.-diameter holes at 0·125 in. pitch spanwise.

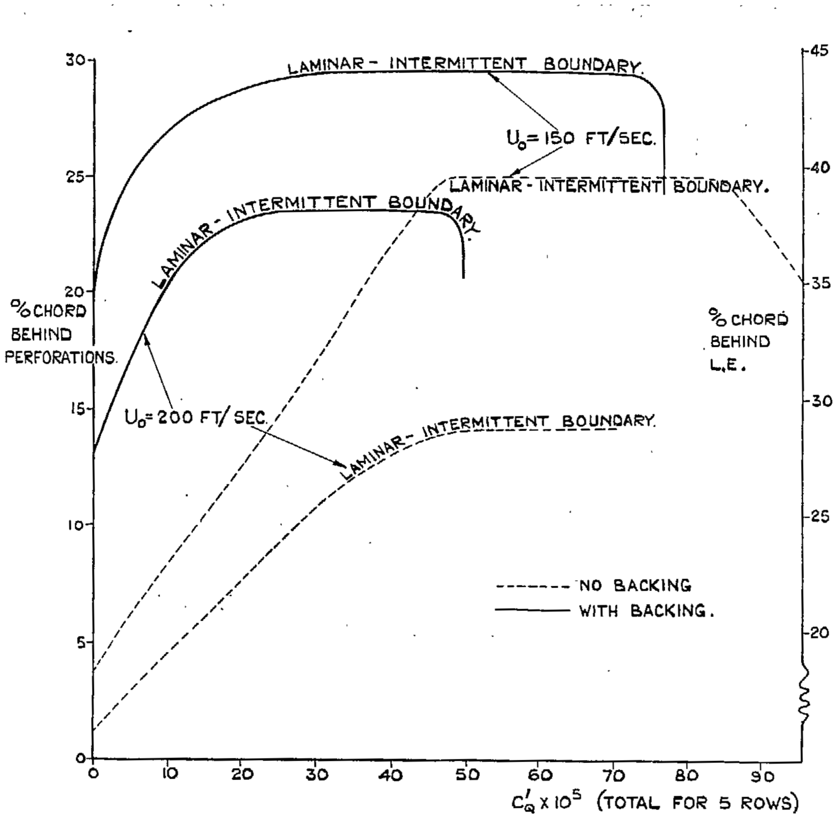
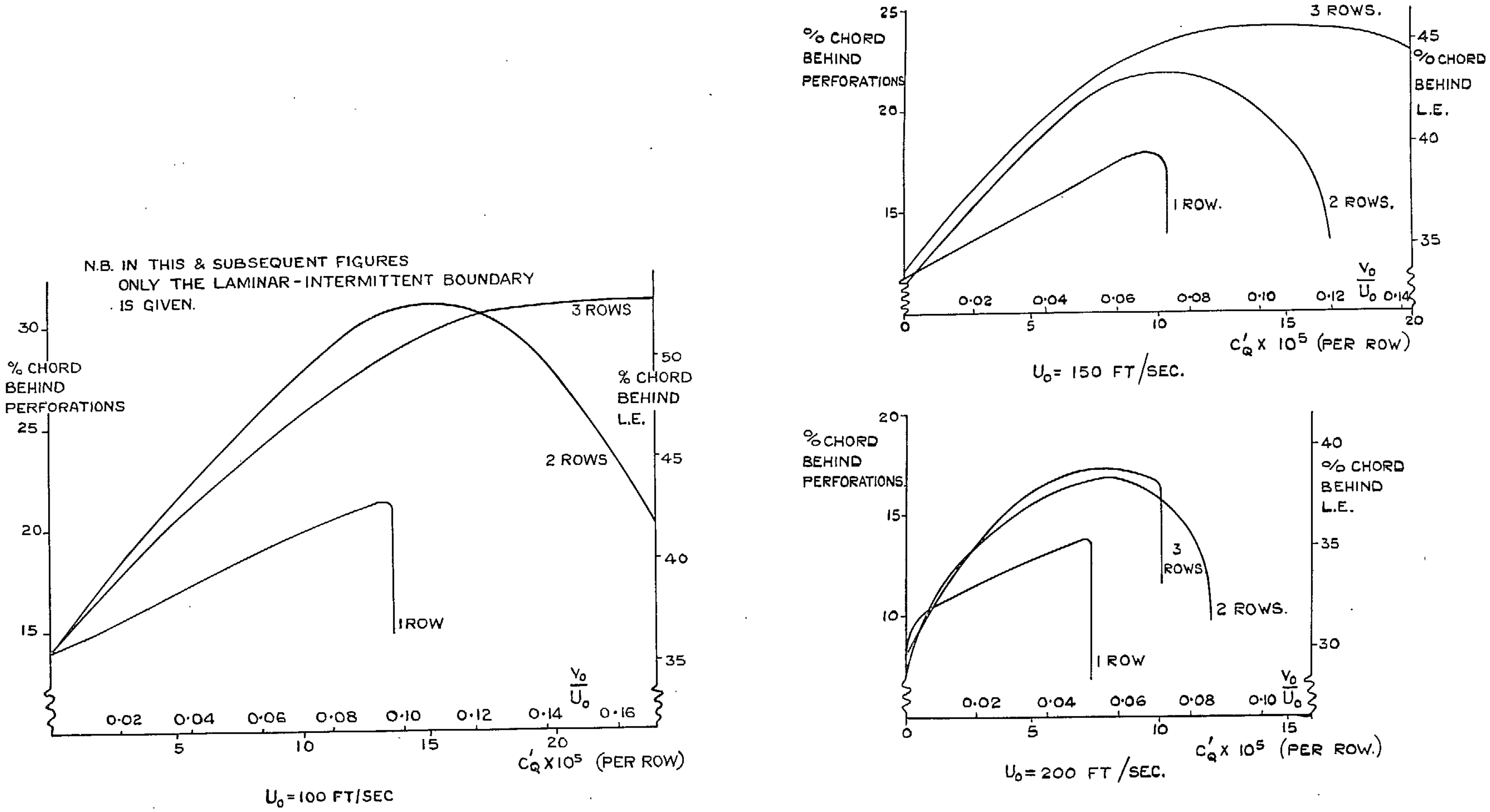


FIG. 5c. Effect of backing on the performance of 5 rows at $\alpha = 0$ deg, $U_0 = 150$, 200 ft/sec. 5 rows at 14·5 per cent chord of 0·052 in.-diameter holes at 0·125 in. pitch spanwise. Consecutive rows at 0·125 in. pitch and staggered.



N.B. IN THIS & SUBSEQUENT FIGURES ONLY THE LAMINAR-INTERMITTENT BOUNDARY IS GIVEN.

FIG. 6. Performance of N rows of perforations at 21·6 per cent chord. $\alpha = 0$ deg. N rows at 21·6 per cent chord of 0·052 in.-diameter 'backed holes' at 0·125 in. pitch spanwise. Consecutive rows at 0·125 in. pitch and staggered.

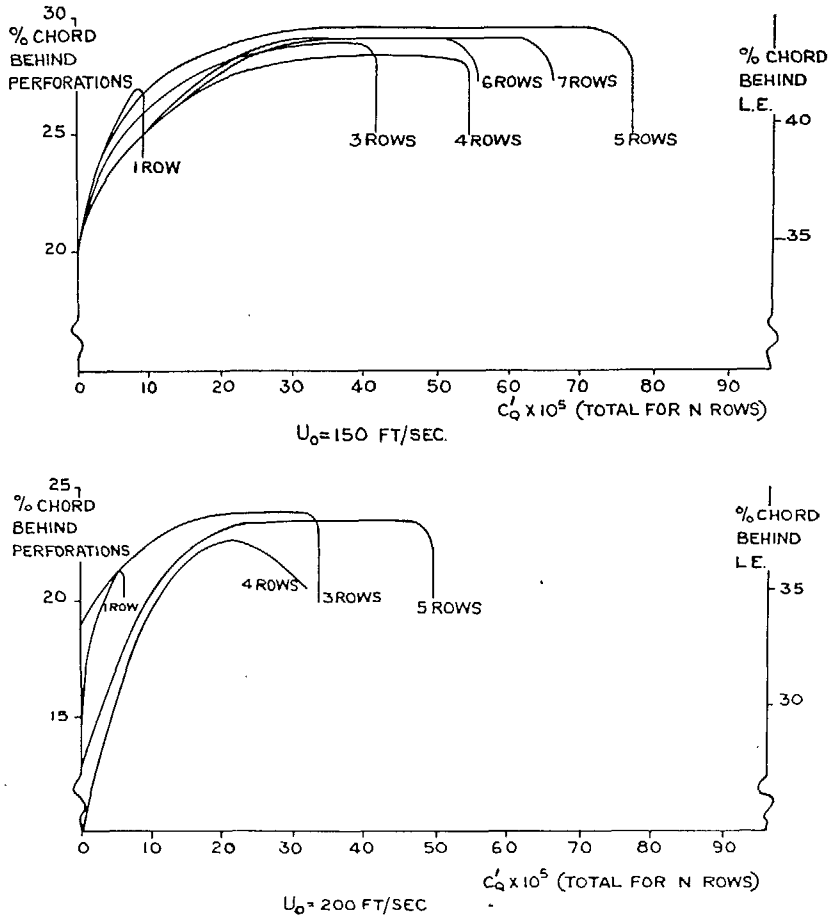


FIG. 7a. Performance of N rows of perforations at 14·5 per cent chord. $\alpha = 0$ deg. N rows at 14·5 per cent chord of 0·052 in.-diameter 'backed holes' at 0·125 in. pitch spanwise. Consecutive rows at 0·125 in. pitch and staggered.

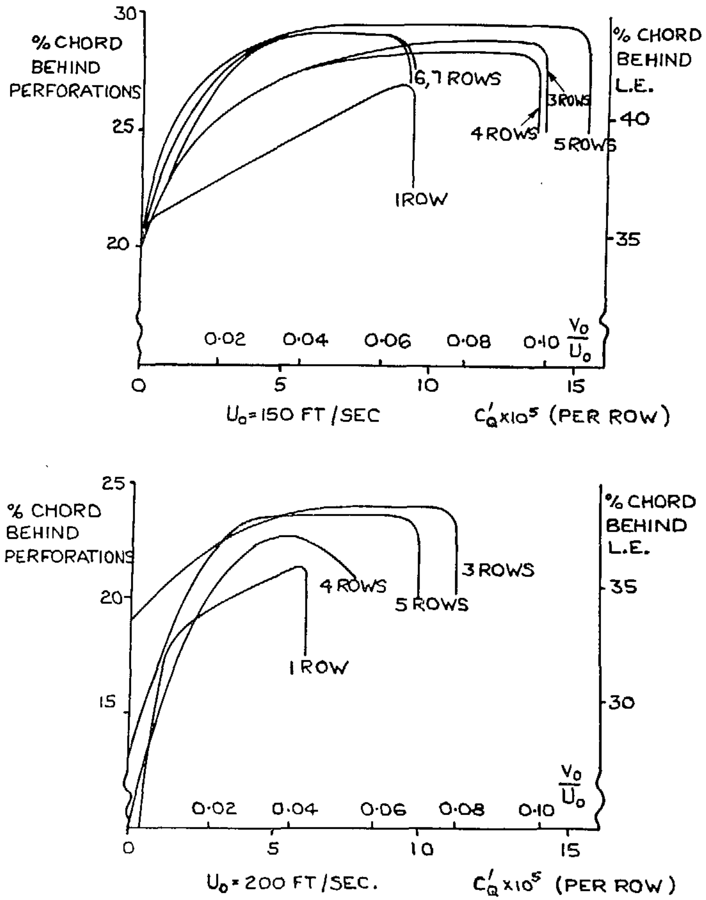


FIG. 7b. Performance of N rows of perforations at 14·5 per cent chord. N rows at 14·5 per cent chord of 0·052 in.-diameter 'backed holes' at 0·125 in. pitch spanwise. Consecutive rows at 0·125 in. pitch and staggered.

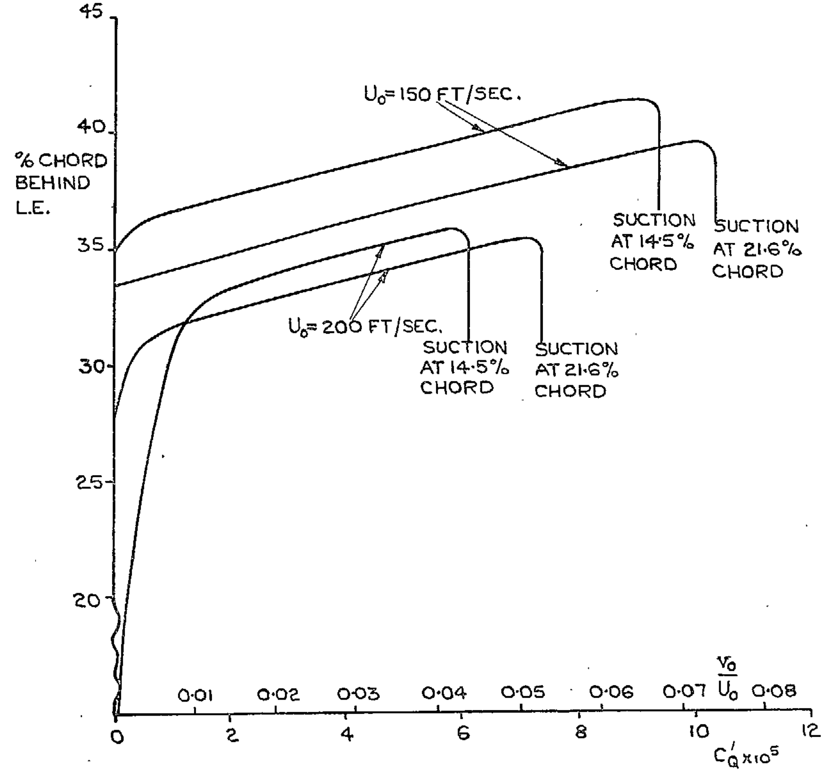


FIG. 8. The effect of chordwise location on the performance of a single row of perforations. $\alpha = 0$ deg. Single row of 0·052 in.-diameter 'backed holes' at 0·125 in. pitch spanwise located at 14·5 and 21·6 per cent chord.

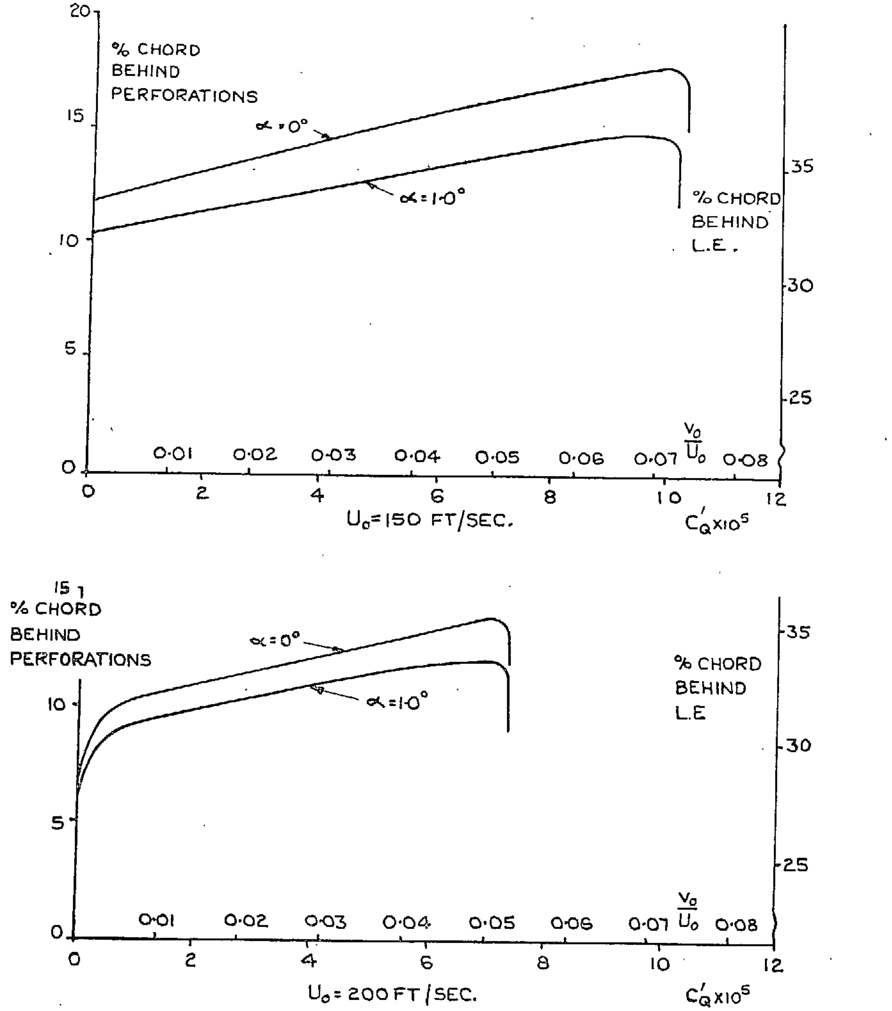


FIG. 9. Effect of incidence on the performance of a single row. Single row at 21·6 per cent chord of 0·052 in.-diameter 'backed holes' at 0·125 in. pitch spanwise.

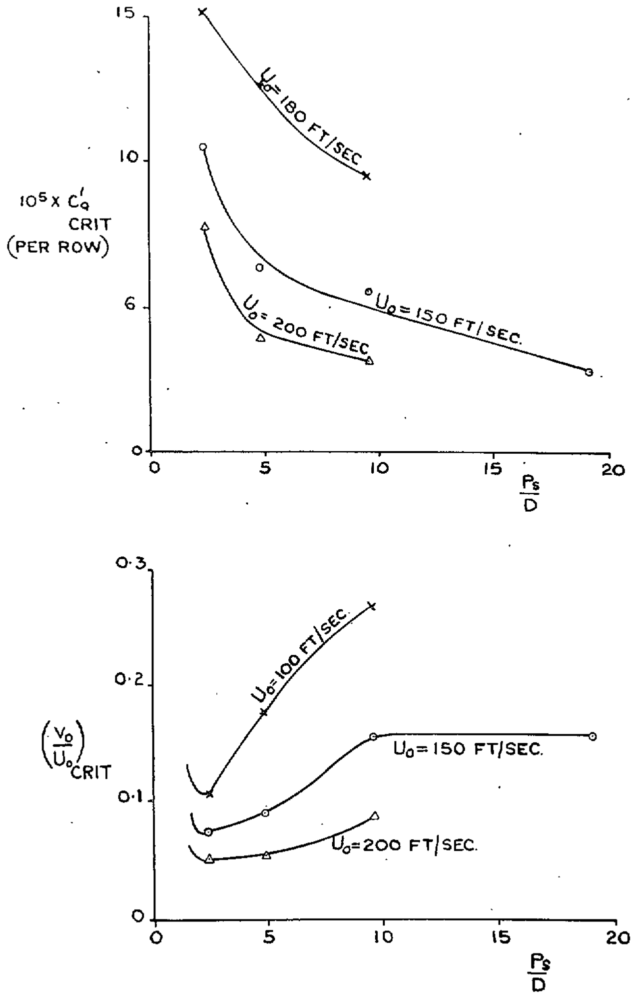


FIG. 10. Effect of P_s/D on $C'_{Q\,\mathrm{crit}}$ and $(v_0/U_0)_{\mathrm{crit}}$. Single row of 0·052 in.-diameter ' backed holes '.

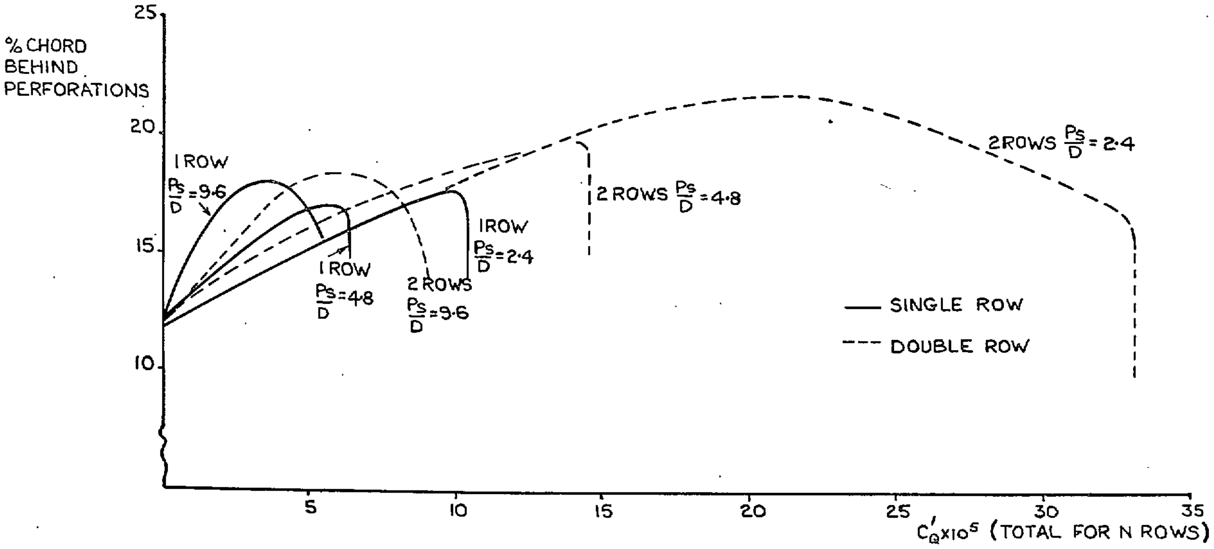


FIG. 11. Effect of spanwise pitch on the performance of single and double rows. 0·052 in.-diameter ' backed holes '. U_0 = 150 ft/sec.

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