R. & M. No. 3083
(17,707)
A.R.C. Technical Report

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

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LONDON: HER MAJESTY'S STATIONERY OFFICE
1958
PRICE 10*s* 6*d* NET

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COMMUNICATED BY THE DIRECTOR-GENERAL OF SCIENTIFIC RESEARCH (AIR),
MINISTRY OF SUPPLY

Reports and Memoranda No. 3083*
June, 1955

Summary.—Wind-tunnel tests are described in which suction is applied at perforated strips, as an alternative to porous strips or slots, in order to maintain a laminar boundary layer. A test was first carried out on a single row of perforations on a cambered plate, as a preliminary to the main tests which were performed on strips of multiple rows of perforations drilled through the surface of a low-drag-type aerofoil 13 per cent thick and of 5-ft chord.

Up to a wind speed of 180 ft/sec it has been ascertained that suction may be safely applied to extend laminar flow provided the ratio of hole diameter to boundary-layer displacement thickness is less than 2, the ratio of hole pitch to diameter is less than 3 and there are at least three rows of holes in the strip. With less than three rows, the criteria are much more restrictive. It is possible to extend laminar flow by suction through perforations whose diameters and pitches exceed these values slightly, but only with the risk that excessive suction quantities will produce wedges of turbulent boundary layer originating at the holes.

A uniform distribution of suction through the holes was necessary. This was successfully obtained by two methods, the use of cells and throttle holes, and with tapered holes. In particular, tests were carried out on some panels supplied by Handley Page, Ltd., in which the cells and tapered holes had been constructed by commercial methods, and the suction distribution proved satisfactory.

The resistance of some of the cellular arrangements was measured. It was found that when the suction quantities were the minimum required to maintain laminar flow, the additional losses in total head of the sucked air due to the resistance of the throttle holes could be made small compared with the loss in total head of the sucked boundary layer.

1. *Introduction.*—Several carefully controlled research experiments have now shown that the boundary layer on an aerofoil may be maintained laminar over the whole chord, up to high values of the chord Reynolds number, by means of boundary-layer suction. The ideal aerodynamic solution is the use of suction distributed over the entire wetted surface, which is porous. This converts the velocity profile to the asymptotic suction form, which is stable against infinitesimal two-dimensional disturbances up to larger boundary-layer Reynolds numbers than the unsucked velocity profiles, and also thins the boundary layer so that its Reynolds number may be kept within the stable range. A smooth porous surface, however, is difficult to construct, and has the practical disadvantage that its small pore size may clog too quickly with dust or rain.

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However, experiment has shown that it is sufficient to remove a portion of the boundary layer at discrete intervals along the chord of the aerofoil. The effect in this case is mostly one of thinning the layer and keeping its Reynolds number below the somewhat smaller critical value which applies just in front of the suction points, where the profile shape has partially reverted from the asymptotic suction profile towards the unsucked profile shapes. Aerofoils have been constructed with numbers of very fine slits in the surface for suction, but Burrows and Schwartzberg[1], for example, have found that the boundary layer becomes increasingly sensitive at the higher Reynolds numbers to the precise state of the slot-entry contour. This difficulty has partly been avoided by Lachmann[2,3], who has developed a large-chord aerofoil of realistic stressed-skin construction with narrow porous strips in lieu of slots. There remain, however, the breaks in skin continuity at the edges of the porous strips, and the wind-tunnel tests at the National Physical Laboratory[2] showed that very careful assembly was required. In addition, the porous strips suffer from the same practical drawbacks of the wholly porous surface.

The present investigation examines the idea that a finely porous strip could be replaced by a number of rows of regular closely spaced perforations whose diameter, though small, is much greater than the previously accepted upper limit for the pores of a uniformly porous surface. The advantages of such a scheme are that the holes are less likely to be clogged with rain and dust than a porous surface, and no breaks in the skin are necessary, as the holes can be drilled through a continuous surface.

It must be emphasised that the purpose of the tests is to replace porous strips by strips of multiple perforations. With suction applied at discrete intervals over the surface, the mean inflow rates over the strip areas are inevitably much greater than the inflow rates over a wholly porous surface. A parallel investigation at the Royal Aircraft Establishment[9] aims at the replacement of a wholly porous surface by an array of perforations distributed over the entire wetted surface.

The present paper describes the tests of a variety of perforation sizes and arrangements which have been drilled in strips on a laminar-flow surface. From an analysis of the results, tentative design criteria are suggested. A more detailed investigation of the flow into perforations has been started by Hooper and Soley[4,5], and this is being followed up by an experiment at the N.P.L. in which it is hoped to observe the streamlines of the flow into a series of large-scale perforations with the aid of smoke-visualization techniques. Assuming that the unsuccessful perforation patterns fail because of the instability of the secondary flow induced by the discontinuous spanwise distributions of suction, these experiments should suggest a less empirical basis for perforation design to confirm or supersede the approximate design criteria presented here.

2. *Suction Parameters.*—In order to make the most of the measurements of the suction flow, it is necessary to express the flow in more than one non-dimensional form. The three parameters used in the present report are as follows :

$$\frac{Q}{U_1\theta}, \frac{Q}{U_0 c} (\equiv C_Q), \frac{v_0}{U_1},$$

when Q = volume flow rate into the strip per unit span

U_0 = free-stream velocity

U_1 = local velocity outside the boundary layer

c = aerofoil chord

θ = momentum thickness of boundary layer just ahead of strip

v_0 = mean velocity of flow through perforation

$$= \frac{4p_s Q}{\pi n d^2},$$

where d = hole diameter

n = number of rows of holes to the strip

p_s = pitch of holes in spanwise direction ;

also, p_c = pitch of holes in chordwise direction.

The fundamental parameter $Q/U_1\theta$ relates the suction quantity directly to the boundary layer and may be used as a measure of the proportion of the boundary layer sucked. This is illustrated in Figs. 6 and 7. The parameter is not always easily written down as it requires a knowledge of θ, the momentum thickness of the layer, to be obtained either by experimental traverse or by calculation. The parameter is not a practical one for use on a multi-strip aerofoil, as variation in the suction quantity at one strip will alter the value of θ and hence of the parameter $Q/U_1\theta$ at all subsequent strips.

The suction quantity coefficient C_Q relates the suction flow at a strip to the wing area, and is the most convenient and frequently used parameter. If the attempt is made to maintain laminar flow over the whole surface, the suction economy of different wings (at the same chord Reynolds number) may be compared in terms of the total suction quantity-coefficient summed over all the strips. But the values of C_Q per strip should not be compared between models with different strip spacings. It must also be remembered that once asymptotic conditions have been established, and the flow is the same at all strips, laminar flow can be extended, in theory, to any chord Reynolds numbers merely by adding to the chord and to the number of strips. Manipulations of this kind will alter the value of C_Q required per strip.

The remaining parameter v_0/U_1 expresses the ratio of the velocity through the holes to the local streamwise velocity at the edge of the boundary layer. It is in part a measure of the effectiveness of the discontinuous distribution of suction in producing the secondary flow whose ultimate breakdown, when suction is excessive, leads to wedges of turbulent boundary layer. The parameter is therefore of value as a variable when the suction-quantity coefficient has a constant value and changes are made in the hole diameter, pitch or pitch/diameter ratio, and in the number of rows of perforations per strip. Alternatively, if the hole pattern is fixed, the ratio may be used as a measure of the suction quantity.

3. *Preliminary Experiments with Isolated Holes and Single Rows of Holes.*—Initial experiments were carried out in a small return-flow-type wind tunnel whose working-section was approximately 1 ft square. An aluminium plate of 40-in. chord, with a sharp leading edge obtained by chamfering the lower surface, was installed in the centre of the working-section. In order to obtain (at the low Reynolds number of the test) any turbulent boundary layer on the plate at all, and with a transition position which was not sensitive to the condition of the leading edge, the plate was given $1\frac{1}{2}$-in. camber at the one-third chord position and set at about zero incidence (Fig. 1). At 83 ft/sec wind speed, transition was observed by means of the china-clay technique and was found to occur 28 in. from the leading edge and to be due to an incipient laminar separation, as the boundary-layer velocity profile measured just in front of transition had a value of H of 3·07 (Fig. 1). The perforations were drilled 6 in. forward of the transition position.

An isolated hole 1/32-in. diameter was drilled first, and successively enlarged to 1/16-in. 1/10-in. and 1/8-in. diameter. Without suction it was found that the 1/16-in. and 1/32-in. holes did not affect transition, whilst the larger holes left a very faint trace of streaks in the china clay with transition spreading forward locally by about $1\frac{3}{4}$ in. The pattern in the china clay is similar to that encountered in the flow round small excrescences[6]. Application of a small amount of suction produced signs of twin streaks in the china clay, with the normal transition position. More suction produced firmer streaks, which broke down to a wedge of turbulent flow, whose apex moved up to the hole with increasing suction.

Chamfering the edges of the holes had little effect on the critical suction quantities. It ensured, however, that no spurious wedges occurred because of ragged edges, so all holes were imperceptibly chamfered. The flow rate just causing a wedge of turbulence was found to be independent of hole size and was 0·00058 ft^3/sec under the conditions of the experiments. Thus the velocity ratio v_0/U_1 varied between 1·4 for the 1/32-in. diameter hole and 0·1 for the 1/8-in. diameter hole.

Single rows of holes of several different diameters and spacings were next investigated. The results are summarised graphically in Fig. 2 which shows the effect of suction on transition position. For the sake of clarity, the individual observations are not shown. Transition without suction was 5 per cent chord further forward than on the clean unperforated plate, but a very small amount of suction sufficed to restore transition to its original position. Faint signs of streaks were observed in the china clay, and with increasing suction, either the streaks broke down to wedges of turbulent flow or the boundary layer was stabilised and transition moved much further back.

In the cases where wedges of turbulent flow occurred, no obvious correlation was discovered between the critical values of either C_Q or v_0/U_1 for the various hole sizes and spacings tested.

The tentative conclusions are that with a single row of perforations under the conditions of the tests the hole diameter must not exceed 0·0625 in. or d/δ^* must not exceed 1·5 in order to avoid excess suction causing wedges of turbulent flow; in addition, the pitch/diameter ratio (p/d) must not exceed 1·33. Provided these requirements are satisfied, the tests showed that the hole diameter used has no appreciable effect on the relation between suction quantity and transition position. Additional and less restrictive criteria are given later (Section 6) as the result of tests with several rows of perforations. These tests, which are described below, were carried out on a model in a larger wing tunnel, which allowed an appreciable variation of the Reynolds number to be made.

4. *Scope of the Main Tests.*—The remaining tests were concerned with porous strips consisting of several rows of perforations, for which, as had been expected, the design requirements proved to be less stringent than those for single rows of perforations.

The experiments were performed in the N.P.L. 13 ft × 9 ft Wind Tunnel on an aerofoil which was conveniently available, and which enabled the perforation patterns under test to be changed without undue difficulty. A description of the structural and aerodynamic features of the model is given below (Section 5), together with an account of the methods which were adopted to ensure uniform flow into the several rows of perforations. The securing of uniform flow was found to be an essential preliminary to the testing of the various patterns. The patterns were tested at different wind speeds at the one strip positions (Section 6) and from these results, two successful patterns were selected for further study. This consisted of tests of an arrangement of three perforated strips which simulated a portion of a laminar-flow wing on which full-chord laminar flow would be obtained by means of a succession of strips as on the Handley-Page wing with porous strips[2]. In these tests (Section 7), the main emphasis was on the relations between transition position, wake drag, pump drag and suction quantity.

In conjunction with these latter tests, three three-strip panels supplied by Dr. G. V. Lachmann, Director of Research at Messrs. Handley Page, Ltd., were also tested. These panels had been manufactured by aircraft engineering methods in a form more suitable for full-scale application than the panels constructed at N.P.L. for research purposes. These panels and the results are described in Section 8.

5. *The Aerofoil and Perforations.*—The aerofoil model had a 5-ft chord and had been previously tested by Cumming, Gregory and Walker[7] when it was fitted with an auxiliary slot through which the turbulent boundary layer had been sucked and a laminar layer re-established. The portion of the aerofoil containing the slot was removed and the gap bridged by a number of wooden ribs onto which were screwed the 14 S.W.G. skin panels on which the present tests were

conducted (Fig. 3). The ribs were cut away in four positions to allow for the perforation of the panel and the fixing of the suction ducts. The single perforated strip was located at 0·25 chord. For the three-strip tests it was thought desirable to separate the strips as much as possible, within the limitations of the panel, so the strips were centered at the 20, 32·5 and 42·5 per cent chord positions.

The aerofoil section was originally calculated as a design exercise. It is not a very practical section owing to the small radius of curvature at the nose. This results in a pronounced peak in the velocity distribution on the aerofoil at the limits of its C_L range, and consequently, large movements in transition position occur for small changes in incidence. Although use was made of this feature, it proved rather a mixed blessing. For it was necessary to test the aerofoil at an incidence where the transition position was sensitive to small changes in the state of the boundary layer at the strips, as it was by the movement of transition position that the effect of suction was judged. This meant working at an incidence at the top of the C_L range where the movement of transition position with change of incidence was large, and it also meant that the transition position was sensitive to changes in wind speed.

The experimental observations of transition position taken before the panels were perforated are plotted in Fig. 3. With perforations, the aerofoil was tested at 120 ft/sec or 130 ft/sec at $2\frac{1}{2}$-deg incidence. Under these conditions, the boundary layer at the strip position was in a sensitive state by reason of the premature velocity peak at the nose, but at the higher wind speed of 180 ft/sec, the transition position indicated by the china-clay technique had moved forward so that it was very close behind the first perforated strip and suction was in many cases unable to effect any improvement. This suggests that spots of turbulence were intermittently occurring ahead of the strip. In these circumstances, it was found in the course of the tests that reducing the incidence to 2 deg at 180 ft/sec wind speed removed the velocity peak at the nose and enabled the stabilising effect of suction to be restored. In addition to the deterioration with increasing wind speed of the performance of perforation patterns tested at $2\frac{1}{2}$-deg incidence for the reasons outlined above, there were also patterns that failed with increasing wind speed because the parameter d/δ^* became too large. It was sometimes difficult to distinguish between these two effects.

The perforation patterns investigated throughout were of the type in which adjacent holes formed equilateral triangles. The spacings and hole diameters used are listed in Table 1, and the pattern is illustrated in Fig. 4 which also sketches one of the ducts, which were stuck underneath the perforated skin with Bostik sealing compound. The air sucked into each duct was removed *via* twin lengths of 7/8-in. bore rubber hose. Outside the wing, the pipes reunited, and the flow from each strip was measured by means of the pressure drop across an 0·5-in. orifice in a 1-in. diameter pipe. These pipes led *via* control valves to the main suction plant.

The first attempts to stabilize laminar flow with suction through several rows of holes failed completely. This was because there was so little resistance to the flow that it was not evenly distributed. An attempt to overcome the lack of uniformity was made by backing the holes with rolled Monel-metal cloth, which was dry-mounted to the underside of the perforated skin. This provided appreciable resistance and considerable increases in the extent of laminar flow were obtained. However, it was noticed that when a strip failed to work owing to excessive suction, the first wedges always appeared from the same holes. This was due to large ' pinhole ' variations in porosity of the metal cloth, giving a poor distribution of flow.

The alternative scheme originally suggested by Head[8,3] and more suited to full-scale application was therefore tried. It proved completely successful. In this scheme (the cellular type of construction illustrated in Fig. 5), the flow through a number of perforations is admitted to a cell with one outlet into the spanwise suction duct. The number of perforations per cell varied from 1 to 14 according to the perforation diameters and spacings, but in each case the area of the outlet ' throttle ' hole was designed so that the velocity of the air through this hole was sufficient for the resulting pressure drop to ensure uniform distribution of the flow through the cells along the whole area of the strip†. No further effort was made to secure uniform suction distribution amongst the several perforations in each cell nor were any measurements of the detailed flow distribution made. The details of the cells are given in Table 1 which shows that the ratio of area of perforations to area of throttle holes varied between 6 : 1 and 9 : 1. The uniformity of areas of suction 1 in. × 0·3 in. was checked, with the wind off, by holding a vane-type flowmeter against the perforations. In use, the overall uniformity was demonstrated by the fact that when laminar flow broke down owing to excessive suction, only a small increase in suction was required to spread the region of failure over the whole spanwise extent of the strip. A hexagonal cell and half-cell arrangement was tried first (*see* Table 1), but it was found that sealing one or two rows of perforations externally with tape upset the spanwise uniformity of suction along the remaining rows and led to regular wedges of turbulent flow along the span. This difficulty did not occur with the later cell patterns of rhomboid form.

6. *Experiments with the Single Strip of Multiple Rows of Perforations*.—In order to be able to present the suction quantities in the parametric form $Q/U_1\theta$, a few traverses of the boundary-layer velocity profile in front of the strip position were first made. Fig. 6 shows a typical profile whilst Fig. 7 gives the relation between $Q/U_1\theta$ (for a profile with $H = 2\cdot4$) and the velocity at the edge of the sucked layer. This shows at a glance how much of the boundary layer is sucked away with a given value of $Q/U_1\theta$. The boundary-layer displacement thickness also was obtained from the measured profiles, and the values at other speeds estimated by interpolation. Table 2 shows the variation of δ^* with wind speed and the ratios of the three hole diameters to δ^* at all the speeds of test.

The experimental observations made on the five hole patterns listed in Table 1 are presented in graphical form in Figs. 8a to 12b, where the transition position as a percentage chord behind the perforations is plotted against the suction-quantity parameters for the various test wind speeds.

The effect of suction is similar to that noted for the single row of holes. As suction is increased from zero, the transition position at first moves rapidly back, becoming more definite, and then reaches a limit beyond which no amount of suction applied at the strip will effect any improvement. With large amounts of suction producing a thin layer, a regular pattern of streaks trailing from the suction holes is marked in the china-clay diagram. Under certain conditions of hole sizes and spacings, however, wedges of turbulent boundary layer originate at the holes themselves at some value of the suction quantity ; turbulence of this nature cannot be removed by any increase in the amount of suction. At any wind speed, a perforation pattern can be described as useless, possible, or safe, according to whether extraneous wedges of turbulent flow appear, before the laminar boundary layer has been extended, after the laminar layer has been extended, or do not appear at all up to the maximum flow rates used. It is considered that there is a real distinction between these last two categories and that the arrangements which are safe and have been tested with practically the whole boundary layer removed, would allow the suction flow rate to be increased without limit.

The variation of the performance of the perforation patterns with wind speed, and hence with the ratio of hole diameter to boundary-layer displacement thickness, is shown in Table 3. In compiling this table from the experimental observations of Figs. 8a to 13b, it was realised that the deterioration in performance of the strips at a wind speed of 180 ft/sec was due to the incipient transition which occurred ahead of the strips, referred to in Section 5. A few patterns were therefore tested at the reduced incidence of 2¼ deg at both 180 ft/sec and 210 ft/sec, and these results, shown in Figs. 13a, 13b and Fig. 14, were used in compiling Table 3. It is noteworthy that although suction is more effective in extending laminar flow at the lower incidence, the critical values of suction quantity which just produce wedges of turbulent flow are not greatly affected by the change.

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† The resistance of the throttle holes in relation to the ideal pump drag is considered in Sections 7 and 8.

It appears from Figs. 8 to 14 and from Table 3, that provided wedges of turbulent flow do not occur, the rate of increase in extent of laminar flow with suction quantity is not greatly affected by variations in the perforation geometry of the strip.

Of the arrangements tested, the safest is that with 0·031-in. diameter holes spaced at a p/d of 2·67. The ratio d/δ^* is less than 2 for these holes up to 180 ft/sec. There also appears to be no point in using more than 3 or 4 rows of this pattern. Increasing either the p/d ratio or the hole diameter from the values just quoted results in a big reduction in the range of safe working conditions. But the patterns with 0·031-in. diameter holes at a p/d of 3·56 and with 0·063-in. diameter holes at a p/d of 2·67 are possible up to 180 ft/sec wind speed provided that a minimum of 6 rows is used.

One of the possible arrangements was tested at an incidence of − 8 deg. This was intended to check the cellular arrangements for obtaining uniform suction in the presence of an appreciable pressure gradient over the surface. Although the positions of transition, both with and without suction, were much further back than at 2½ deg incidence, there was no change in the values of the excess suction quantities at which wedges of turbulence occurred. This suggested that the chordwise pressure gradients across the width of the strips had no adverse effect, although the test was inconclusive as the boundary layer at the strip was sufficiently stable owing to the favourable pressure gradient not to be upset by any automatic inflow and outflow through the holes without any suction being applied.

The measurements at the R.A.E.[9] were made over a sufficiently wide range of tunnel wind speeds for some estimate of scale effect to be formed. For a single row of holes, it was suggested that the critical value of C_Q, or v_0/U_0, at which wedges of turbulence first appear, was approximately inversely proportional to the wind speed. In the present tests it is not possible to derive such a simple conclusion. For most of the patterns with multiple rows there is a limiting wind speed below which no critical suction quantity exists at all. Above this wind speed, the critical suction quantity does exist, and falls with increase of wind speed until it becomes effectively zero. The critical quantity, expressed either as C_Q or v_0/U_0, varies with the number of rows

Some comparison with the R.A.E. results is possible. Fig. 15 shows the variation between the critical value of suction velocity and the pitch/diameter ratio for both single and multiple rows of holes. Especial note should be taken of the rise in value of $(v_0/U_1)_{\text{crit}}$ as the pitch/diameter ratio is reduced, and the fact that this region of high values of $(v_0/U_1)_{\text{crit}}$ extends to larger values of p/d with multiple rows than with a single row of perforations. This makes the use of a safe arrangement of holes a practical possibility. The use of high values of (v_0/U) also helps to ensure even distribution of the flow through the holes.

It is not possible to obtain any information by cross-plotting the results from Figs. 8a to 14b with wind speed as a parameter, as the data is too sparse and irregular. At a wind speed of 120 ft/sec, the variation of the critical velocity ratio with all the other parameters is shown by Figs. 16a, 16b and 16c. These graphs demonstrate clearly the conclusions of the present section. Within the range of the tunnel wind speeds at which tests were made, there is no limitation to the suction velocity which may safely be used provided p/d is less than 3, d/δ^* is less than 2 and not less than 3 rows are used.

7. *Experiments with Three Perforated Strips*.—The previous section describes tests in which the laminar boundary layer was stabilized by suction through a single strip of multiple perforations. These tests were followed by tests in which the removable panel on the aerofoil was fitted with three perforated strips and associated ducts (Fig. 3). The purpose of this was to discover to what extent the perforated patterns which were not safe with oversuction could be used. It was also hoped that there might be some alleviation of the sensitiveness of strips to oversuction owing to the different boundary layers at the second and subsequent strips. In addition, information was sought as to the possible performance of a wing in which the flow was maintained laminar by suction through perforated strips and a comparison was made with the original laminar-flow wing[2], which had suction through porous strips.

At the same time, the opportunity was taken of testing three three-strip panels supplied by Messrs. Handley Page, Ltd. with the main emphasis on the suitability of the cells, which were manufactured by aircraft engineering methods. These tests are described in Section 8.

The strips of perforations in the removable panel were centred at 20, 32·5 and 42·5 per cent chord (Fig. 3). Each strip was 2-ft span, so that two different patterns could be fitted into the 4-ft span of the panel. The first pattern chosen for test was the safest pattern of the preceding tests, an arrangement of 0·031-in. diameter holes spaced at a p/d ratio of 2·67, and 4 rows of holes were drilled for each strip. The second pattern consisted of 6 rows of 0·063-in. diameter holes at a p/d ratio of 2·67, a pattern which was safe up to 120 ft/sec, and possible at the higher speeds, remembering that the poor performance shown at 180 ft/sec (Figs. 11a and 11b) was in part due to turbulence originating ahead of the strip at this speed.

The wake drag of the aerofoil surface in which the perforations were drilled was measured by means of a pitot comb mounted at the trailing edge. The pump-drag coefficient was evaluated as the product of C_Q and C_H, where C_H is the ratio of the loss of total head of the sucked air to the free-stream dynamic head. The static pressure measured just upstream of the orifice in the calibration pipe was the same as that in a static-pressure tapping situated in the spanwise duct beneath the perforations, so it is concluded that the duct losses are negligible. The pump drag was calculated from the loss in total head up to the position of the static-pressure tapping in the calibration pipe and therefore includes the losses due to suction through the throttle holes as well as the boundary-layer losses.

The performance of the aerofoil at a wind speed of 130 ft/sec with suction applied to the 0·031-in. and 0·063-in. diameter holes is shown in Figs. 17 and 18 respectively, where the transition position, the wake-drag coefficient and the pump-drag coefficient are plotted as functions of the total suction-quantity coefficient. The effect of increasing suction on one strip at a time, with fixed suction quantities on the earlier strips, is also shown. The pump drag is plotted with the positive direction downwards, so that the total drag of the surface is represented by the length of ordinate between the curves of pump and wake drag. Minimum drag is obtained at the value of C_Q for which the two curves run parallel. At higher values of C_Q, the overall drag is greater owing to the increasing resistance of the throttle holes to the flow. This can be seen in Figs. 17 and 18 as the approximate value of the ideal pump-drag coefficient due to the boundary-layer losses alone is shown. The value of this coefficient was derived using the momentum thickness of the boundary layer at the strip position (obtained by traverse measurements) and the variation of the mean loss of head in the laminar boundary layer in terms of $Q/U_1\theta$, which was obtained from Fig. 6 of Ref. 10. It happens that over the range of small suction quantities used, the velocity in the boundary layer is approximately linear with distance from the surface so that, to a first approximation, the relation between pump-drag and suction-quantity coefficients is also linear and a single curve results from the superposition of the effects of suction at the three strips.

The variation of wake-drag coefficient with suction at 150 ft/sec and 180 ft/sec is shown in Fig. 19 and it will be noticed that the curves are similar to those of the two preceding figures. The effect of suction on the two panels is slightly different from that at lower speeds where suction is safe. The 0·031-in. diameter holes work at 150 ft/sec but are sensitive to over-suction, whilst at 180 ft/sec it proved impossible to prevent intersecting wedges of turbulence from appearing, although some laminar flow was evidently possible. The 0·063-in. diameter holes are satisfactory at 150 ft/sec, only the first strip being sensitive to oversuction, whilst only a few wedges of turbulent flow were present at 180 ft/sec for all rates of suction and it was possible to make some observations. In part, the difficulty experienced at 180 ft/sec is probably associated with spots of turbulent flow occurring ahead of the first strip as in the earlier tests on a single strip, though the difficulty should be somewhat alleviated since the first strip is 5 per cent of the chord closer to the leading edge than was the single strip. It is unfortunate that the panel was not tested at any lower incidence, but the effect of decreasing incidence is shown in Section 8 for the Handley-Page three-strip panels. This section also discusses more fully the pump-drag analysis and the effects of the diameter of the rear strip perforations.

The comparison of the performance of the present aerofoil with that of the Handley-Page porous-strip aerofoil is not easy to make in view of the somewhat different conditions. However, a rough calculation based on Fig. 18 and on Fig. 13 of Ref. 2 shows that at the same wind speed, the same increases in the extent of laminar flow give similar reductions in wake drag and total effective drag, and that on the present aerofoil these changes require about 17 per cent less suction quantity. A further comparison is given in Figs. 20a and 20b. A few traverses of the boundary layer were made just upstream and downstream of the three strips at a wind speed of 130 ft/sec. The traverses were done under conditions of minimum suction for both the 0·031 and 0·063-in. diameter hole patterns. Values of $R_{\delta*}$ and R_{θ} calculated from the traverses are shown in Fig. 20a and can be compared with the corresponding set of values shown in Fig. 20b for the porous-strip aerofoil at a closely similar wind speed (120 ft/sec). Despite the less favourable pressure gradient on the perforated strip aerofoil, and the regular variations in suction due to the perforation pattern, it is clear that the boundary layer on the perforated-strip aerofoil is attaining as large values of $R_{\delta*}$ as on the porous-strip aerofoil.

The downstream traverses were sited 1/8 in. behind, and in line with a hole in the last row of perforations. A check traverse which was aligned mid-way between adjacent rows gave practically the same profile. There was considerable scatter in the values of H, the boundary-layer shape parameter, as this requires very accurate measurements of the profile. The mean value decreased from about 2·35 upstream of the strips to 2·15 just downstream of the strips.

8. *Experiments with the Handley-Page Perforated Panels.*—The tests of the three panels of three perforated strips which were designed by Dr. G. V. Lachmann of Messrs. Handley Page, Ltd., and constructed by the firm, were essentially tests of the engineering methods used in construction of the panel, particularly the methods of obtaining uniform suction. At the same time, variations were made by Dr. Lachmann in the perforation patterns used, and interesting results were obtained from these patterns.

Details of the perforation patterns tested are given in Table 4, whilst the methods of construction are illustrated in Fig. 21. The first and third panels were of sandwich construction (Figs. 21a and 21c) consisting of a thick skin out of which circular-arc recesses were milled, and a thin skin which closed the cells and which was bonded to the thick skin with adhesive. The perforations were drilled in one skin, and the throttle holes in the other. In H.P. panel 1, the thin skin was perforated, whilst in the H.P. panel 3, the thin skin received the throttle holes. H.P. panel 2 was a single skin, with ' tapered ' holes, each perforation possessing its own throttle hole (Fig. 21b).

The tests of the first trial panel were in part spoilt as it was found that the sandwich was not airtight, air leaking from the edges of the panel between the two skins into the cells. It is thought that this leak was more serious than it appeared at the time as, judging by the behaviour of transition compared with tests on the N.P.L. panel, the flow through the perforations may have been as little as 1/3 of the total flow measured. In addition, transition was adversely affected by surface waves due to steps of 0·026 in. at both front and rear edges of the panel which were faired into the wooden aerofoil with Plasticine over a distance of 2 inches. The order of the strip-perforation diameters was also inadvertently reversed so that the largest diameter holes were in the first strip and the smallest sized holes were at the rear.

Tests with the small-hole pattern showed that safe laminar flow with full suction could be obtained at 130 ft/sec at $2\frac{1}{2}$-deg incidence and at 150 and 180 ft/sec when the incidence was reduced to 2 deg. For no obvious reason, the first 4 inches span of the leading strip caused a number of wedges of turbulent flow, and a particularly persistent wedge of turbulent flow originating in one particular perforation could not be removed by suction. Although the hole was partially blocked owing to its straddling a cell division (as did many other holes), there was no further obvious reason for the appearance of a wake at this hole, and no treatment of the surface was able to effect a cure. The large-hole pattern was disappointing. The full extent of laminar flow could only be obtained at the reduced incidence of 2 deg at 130 ft/sec. Under these conditions, the first strip alone was sensitive to oversuction ; at higher wind speeds wedges of turbulent flow originated from this strip at all rates of suction. It is clear that the choice of 0·063-in. diameter holes ($d/\delta^* = 3{\cdot}1$ at 130 ft./sec) coupled with an excessive spacing ($p/d = 4$) was unsuitable.

The second panel, designated H.P. panel 2 in Table 4, was free from leaks, and fitted satisfactorily on the aerofoil without a step ; the perforation patterns, however, were still drilled in the reverse order to that intended. These patterns varied from strip to strip and were based on conclusions drawn from the R.A.E. tests. The patterns were mainly intended for distribution over an entire surface rather than over a few rows in a strip and they were not expected to work satisfactorily with excessive suction quantities. Compared with the criteria suggested by the tests described earlier in this paper, the spanwise pitch/diameter ratios were very large, especially on the front strip.

Without suction, numerous wedges of turbulent flow originated from the perforation of the front strip in both sizes. With the small 0·047-in. diameter holes, extended laminar flow could be obtained with suction up to 150 ft/sec at $2\frac{1}{2}$ deg and at 180 ft/sec at 2 deg. With the larger holes (0·063-in. diameter), extended laminar flow was obtained up to 130 ft/sec at $2\frac{1}{2}$ deg and up to 180 ft/sec at 2 deg. But in both cases the perforations were extremely sensitive to the effects of excess suction. An increase of 50 per cent over the minimum quantity required, was sufficient to produce wedges with 0·063-in. diameter holes, whilst the 0·047-in. diameter holes produced wedges with double the minimum flow.

The third panel effectively repeated the larger-hole pattern on the first panel, but with the hole diameters increasing from strip to strip in the downstream direction. There were slight reductions in the pitch/diameter ratios which made the cell lengths exact multiples of the hole spacings, which had not applied to the first H.P. panel : in particular, no spanwise spacing exceeded a p/d value of 2·53. The duct system was tested, and the leaks were found to be negligible on two of the strips and to account for about 7 per cent of the measured flow on the third (strip 1). The panel was a good flush fit in the surface.

The test showed that at $2\frac{1}{2}$-deg incidence, full suction (C_Q about 100×10^{-6} per strip) could be applied without wedges of turbulence appearing at either 130 ft/sec or 150 ft/sec wind speed ; but at 180 ft/sec numerous wedges appeared from the first two strips, running into transition at strip 3. At the reduced incidence of 2 deg, the panel would take full suction (C_Q about 80×10^{-6} per strip) at 180 ft/sec wind speed without any wedges of turbulence. The wind speed was increased to 210 ft/sec and it was found that on occasion laminar flow was obtained with full suction without wedges of turbulence, but sometimes wedges occurred. This onset of critical conditions with excess suction may be ascribed to the hole diameter becoming too large for the boundary layer as d/δ^* at strip 1 exceeded 2, for the wedges all disappeared on reducing the suction at the first strip to the minimum necessary.

The variation of transition position, wake-drag and pump-drag coefficients with suction are shown in Fig. 22. The curves drawn on Fig. 22a for 130 ft/sec wind speed show how the transition position moves rearwards as suction is applied at successive strips ; the individual points plotted for the higher wind speeds refer, in general, to minimum and maximum suction on the three strips. The poor performance at 180 ft/sec at $2\frac{1}{2}$-deg incidence and the improvement brought about by reducing the incidence are clearly seen. The individual points of wake and pump-drag coefficients are plotted in Fig. 22b and compared with the values obtained on the previously tested N.P.L. panels. Good agreement is obtained for the wake drag, but the pump drag is seen to be slightly greater on the H.P. panel. The variation of the loss of total head of the sucked air with the suction quantity for the individual strips is shown in Fig. 23, which should be studied in conjunction with the strip details given in Table 4. The H.P. strips have greater resistance than the N.P.L. strips and would not be suitable for high suction flows, but at the optimum flow C_Q's of 20 to 40 $\times 10^{-6}$ per strip, the resistance losses are less than the boundary-layer losses and may not be considered important. The greater resistance of the H.P. strips is due to the small area of throttle holes per foot span and is not thought to depend on the contraction ratio or area of the perforations per foot span. The differences between the three curves is thought to be due to the leaks and the correct performance is probably that of strip 3. The lowest allowable strip resistance depends on the design, and is clearly related to the external pressure gradients over the area of the perforated strip.

It is concluded from the tests of the H.P. panels that the differing methods adopted for securing uniform flow into the perforations were all satisfactory. For despite the differing performance of the various perforation patterns, there was no sign that the breakdown to turbulent flow was due to non-uniformity of suction between adjacent holes. The exception to this statement was a few inches span on strip 1 of the small holes on H.P. panel 1, but this may have been due to other causes. In any case, it should be easy to ensure that the cell length is a multiple of the hole spacing and thus avoid having holes straddling the cell divisions.

The pattern of holes drilled in H.P. panel 3 worked extremely well. By keeping the diameter of holes at the first strip down to 0·031 in. (as was also tried on panel 1), the parameter d/δ^* was below 2 up to almost 210 ft/sec wind speed and wedges due to excess suction were avoided. The tests showed that the diameter of the holes in the subsequent strips could be increased successively to 0·047 and 0·063 in. without adverse effect. The boundary-layer measurements undertaken on the N.P.L. panels suggested that with minimum suction, δ^* in front of the subsequent strips was only about 20 per cent greater than its value in front of the first strip. It thus appears to be possible to allow a slight increase in the value of d/δ^* over the rear strips.

9. *Conclusions.*—Wind-tunnel experiments have shown that it is possible to construct a laminar-flow aerofoil in which the boundary layer is stabilized by suction at discrete strips of multiple rows of small perforations. This scheme possesses structural and practical advantages over the schemes previously tested in which multiple slots or strips of porous material were used. Despite the discontinuous nature of the inflow, suction is as effective as in the earlier schemes provided the hole sizes and spacings conform to certain empirical criteria summarised below.

It is essential to ensure that the suction is evenly distributed through all the perforations. Two methods have been successfully employed. The first is the ' cellular ' method in which air sucked through a small group of holes enters a cell, the only exit from which is a single throttle hole into the duct underneath. The hole sizes are arranged so that the flow through the exit hole suffers an appreciable pressure drop compared with the external static-pressure variations and thus ensures uniform flow from cell to cell. The second method uses tapered holes in which the cross-section of the holes on the outside of the skin is again determined by aerodynamic criteria, and the much smaller exit cross-sections on the duct side of the skin are arranged so as to give the required pressure drop for uniformity. In this respect, the ' cellular ' and ' tapered ' perforation arrangements worked satisfactorily on three panels constructed by Handley Page, Ltd., by aircraft engineering methods. The resistance of some of the cellular arrangements was measured during the tests. It was found that when the suction quantities were the minimum required to maintain laminar flow, the additional losses in total head of the sucked air due to the resistance of the throttle holes could be made small compared with the loss in total head of the sucked boundary layer.

Given a uniform suction distribution, a preliminary small-scale experiment showed that even at the low test wind speed of 83 ft/sec, a single row of perforations was only satisfactory if d/δ^* did not exceed 1·5 and p/d did not exceed 1·33, conditions which are impracticably restrictive.

More elaborate tests on an aerofoil model, which were carried up to a wind speed of 180 ft/sec (U_0/v of $1 \cdot 15 \times 10^6$) showed that with three or more rows of perforations, laminar flow could be extended safely by means of suction at the strip provided d/δ^* was less than 2 and p/d was less than 3. This result was obtained on the first strip of a series for values of R_{δ^*} up to 2,400. Extended laminar flow could be obtained with perforations whose diameters and pitches exceeded these values slightly, but only with the danger that increases in the suction quantity might lead to wedges of turbulent flow originating at the holes. The results of the tests of all the different perforation patterns are summarised in Table 3 where the performance has been classified as either safe, possible or useless.

The velocity with which the air is sucked through the holes is found to be much greater for the strips of perforations than for the widely distributed array of perforations tested at the R.A.E. This is an advantage as it helps to keep the suction distribution uniform.

Scale effect on suction of the type investigated is so uncertain that it is desirable that perforation patterns intended for use at Reynolds numbers greater than those reached in the present tests should be tested under the required conditions. However, it is intended to follow up the present investigation with an experiment in a low-speed smoke-tunnel in order to obtain a picture of the three-dimensional physical flow into the perforations. This should lead to a better understanding of the reasons for the breakdown of laminar flow to wedges of turbulence which can occur, and hence to a reliable basis for predicting any scale effect on the operation of the perforation patterns.

Some difficulties in extending laminar flow which were encountered in the tests were ascribed to the closeness of the incidence, 2½ deg, to that of the top of the C_L range of the aerofoil. This underlines the necessity in any practical application of avoiding at all costs any premature peak in the velocity distribution ahead of the first perforated strip.

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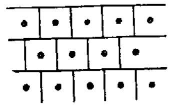
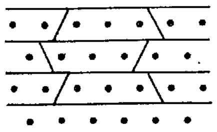
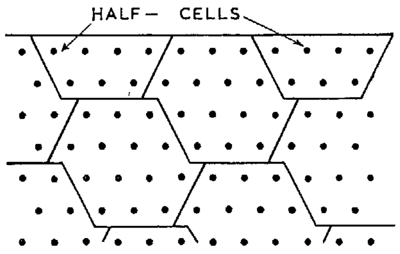
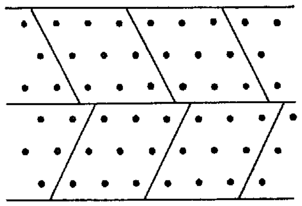
TABLE 1

Details of the Perforations and Cell Arrangements Tested on the Single Porous Strip

Perforation diameter (in.)	Spanwise p/d spacing*	Number of rows	Full area of perforations per ft span (sq ft)	Diameter of throttle holes (in.)	Full area of throttle holes per ft span (sq ft)	Contraction ratio in cells $\frac{\text{inlet area}}{\text{outlet area}}$	Number of holes per cell	Cell pattern ←→ spanwise direction
0·094	2·67	4	$9{\cdot}25 \times 10^{-3}$	0·031	$1{\cdot}03 \times 10^{-3}$	9	1	
0·063	2·67	6	$9{\cdot}2 \times 10^{-3}$	0·037	$1{\cdot}07 \times 10^{-3}$	8·6	3	
0·031	2·67	10	$7{\cdot}66 \times 10^{-3}$	0·043 0·033	$1{\cdot}08 \times 10^{-3}$	7·4 6·3	14 7	
	later	9	$6{\cdot}9 \times 10^{-3}$	0·037	$1{\cdot}07 \times 10^{-3}$	6·4	9	
0·031	3·56	9	$5{\cdot}18 \times 10^{-3}$	0·037	$8{\cdot}1 \times 10^{-4}$	6·4	9	
0·031	5·33	6	$2{\cdot}3 \times 10^{-3}$	0·037	$3{\cdot}6 \times 10^{-4}$	6·4	9	

*Chordwise spacing between rows is 0·866 × spanwise spacing.

TABLE 2

Displacement Thickness of Boundary Layer at 25 per cent Chord at 2½-deg Incidence and Ratio of Hole Diameters to Displacement Thickness

Wind speed (U_0 ft/sec)	Displacement thickness (δ^* in.)	Hole diameter (d) 0·031 in.	0·063 in.	0·094 in.	$R_{\delta^*} = U_1\delta^*/\nu$
		d/δ^*	d/δ^*	d/δ^*	
40	0·036	0·9	1·7	2·6	910
60	0·029	1·1	2·1	3·2	1120
90	0·024	1·3	2·6	3·9	1370
100	0·023	1·4	2·7	4·1	1450
120	0·021	1·5	3·0	4·5	1580
130	0·020	1·6	3·1	4·7	1650
150	0·019	1·7	3·3	5·0	1770
180	0·017	1·8	3·7	5·5	1940
210	0·016	2·0	4·0	6·0	2100

TABLE 3

Variation of Perforated-Strip Performance with Wind Speed

Location of strip : 25 per cent aerofoil chord ; aerofoil at $2\frac{1}{2}$-deg incidence

Strip performance classified as follows :

$(U_0)_A$	Maximum measured wind speed at which the perforation pattern is safe, and no extraneous wedges of turbulent flow appear up to the maximum suction quantity used
$(U_0)_B$	Maximum measured wind speed at which the perforation pattern is possible, and extended laminar flow is obtained with increasing suction before wedges of turbulent flow occur
$(U_0)_C$	Minimum measured wind speed at which the perforation pattern is useless, and wedges of turbulent flow occur without any extension of laminar flow

Note :—Tests were made only at the 'standard' speeds of 40, 60, 90 (in some cases), 120, 150, 180 and 210 ft/sec.

Hole diameter (d) (in.)	Spanwise spacing (p/d)	Number of rows	$(U_0)_A$ (ft/sec)	d/δ^*	$(U_0)_B$ (ft/sec)	d/δ^*	$(U_0)_C$ (ft/sec)	d/δ^*
0·031	2·67	10, 8	180	1·8	Not tested above 210	2·0		
		4	150	1·7	180	1·8	210	2·0
		3	150	1·7	150	1·7	180	1·8
		2	Less than 60		60	1·1	120	1·5
0·031	3·56	9	90	1·3	Not tested above 210	2·0		
		6	90	1·3	180	1·8	210	2·0
		3	60	1·1	150	1·7	180	1·8
		2	Less than 60	(<1·1)	120	1·5	150	1·7
0·031	5·33	6	Less than 60	(<1·1)	Not tested above 120 (on verge of failure)	1·5		
0·063	2·67	6	120	3·0	Not tested above 180	3·7		
		5, 4, 3	40	1·7	Not tested above 120	3·0		
		2	Less than 40	(<1·7)	40	1·7	60	2·1
0·094	2·67	4	60	3·2	150	5·0	180	5·5
		3	Less than 40	(<2·6)	90	3·9	120	4·5
		2	Less than 40		60	3·2	90	3·9

TABLE 4

Details of the Perforations and Cell Arrangements of the Three-Strip Panels

Panel	Strip number	Perforation diameter (in.)	Number of rows	p/d spacing		Area of perforations per ft span (sq ft)	Diameter of throttle holes (in.)	Area of throttle holes per ft span (sq ft)	Contraction ratio in cells $\frac{\text{inlet area}}{\text{outlet area}}$	Number of holes per cell
				Spanwise	Chordwise					
N.P.L. 3-strip panel	All strips	0·031	4	2·67	2·31	$3 \cdot 07 \times 10^{-3}$	0·035	$4 \cdot 8 \times 10^{-4}$	6·4	8
	All strips	0·063	6	2·67	2·31	$9 \cdot 2 \times 10^{-3}$	0·074	$14 \cdot 3 \times 10^{-4}$	6·4	9
H.P. panel No. 1	1	0·031	9	2·72	2·4 and 4·0†	$6 \cdot 78 \times 10^{-3}$	0·028	$2 \cdot 8 \times 10^{-4}$	24·2	19·4
	2	0·031	9	2·72	2·4 and 4·0†	$6 \cdot 78 \times 10^{-3}$	0·028	$2 \cdot 8 \times 10^{-4}$	24·2	19·4
	3	0·028	9	2·68	2·68 and 4·46†	$6 \cdot 15 \times 10^{-3}$	0·028	$2 \cdot 8 \times 10^{-4}$	22	22
	1	0·063	6	4·0	1·6 and 2·8*	$6 \cdot 15 \times 10^{-3}$	0·028	$2 \cdot 8 \times 10^{-4}$	22	6·6
	2	0·047	6	2·34	2·56 and 3·3*	$7 \cdot 85 \times 10^{-3}$	0·028	$2 \cdot 8 \times 10^{-4}$	28	15
	3	0·031	9	2·72	2·4 and 4·0†	$6 \cdot 78 \times 10^{-3}$	0·028	$2 \cdot 8 \times 10^{-4}$	24·2	19·4
H.P. panel No. 2	1	0·047	4	4·6	4·97	$2 \cdot 66 \times 10^{-3}$	0·020	$4 \cdot 85 \times 10^{-4}$	5·5	1
	2	0·047	3	3·09	7·35	$3 \cdot 22 \times 10^{-3}$	0·020	$5 \cdot 9 \times 10^{-4}$	5·5	1
	3	0·047	2	2·36	10·25	$2 \cdot 6 \times 10^{-3}$	0·020	$4 \cdot 7 \times 10^{-4}$	5·5	1
	1	0·063	4	6·36	3·73	$2 \cdot 57 \times 10^{-3}$	0·020	$2 \cdot 6 \times 10^{-4}$	9·75	1
	2	0·063	3	4·23	5·6	$2 \cdot 90 \times 10^{-3}$	0·020	$3 \cdot 0 \times 10^{-4}$	9·75	1
	3	0·063	2	2·38	9·76	$3 \cdot 43 \times 10^{-3}$	0·020	$3 \cdot 5 \times 10^{-4}$	9·75	1
H.P. panel No. 3	1	0·031	9	2·51	2·3 and 4·33†	$7 \cdot 31 \times 10^{-3}$	0·028	$2 \cdot 8 \times 10^{-4}$	26·1	21
	2	0·047	6	2·35	2·99	$7 \cdot 84 \times 10^{-3}$	0·028	$2 \cdot 8 \times 10^{-4}$	28·0	10
	3	0·063	6	2·53	2·21	$9 \cdot 71 \times 10^{-3}$	0·028	$2 \cdot 8 \times 10^{-4}$	34·7	7

† Where the larger value applies to the spaces between sets of 3 rows (*i.e.*, between rows of cells).

* Where the larger value applies to the spaces between sets of 2 rows (*i.e.*, between rows of cells).

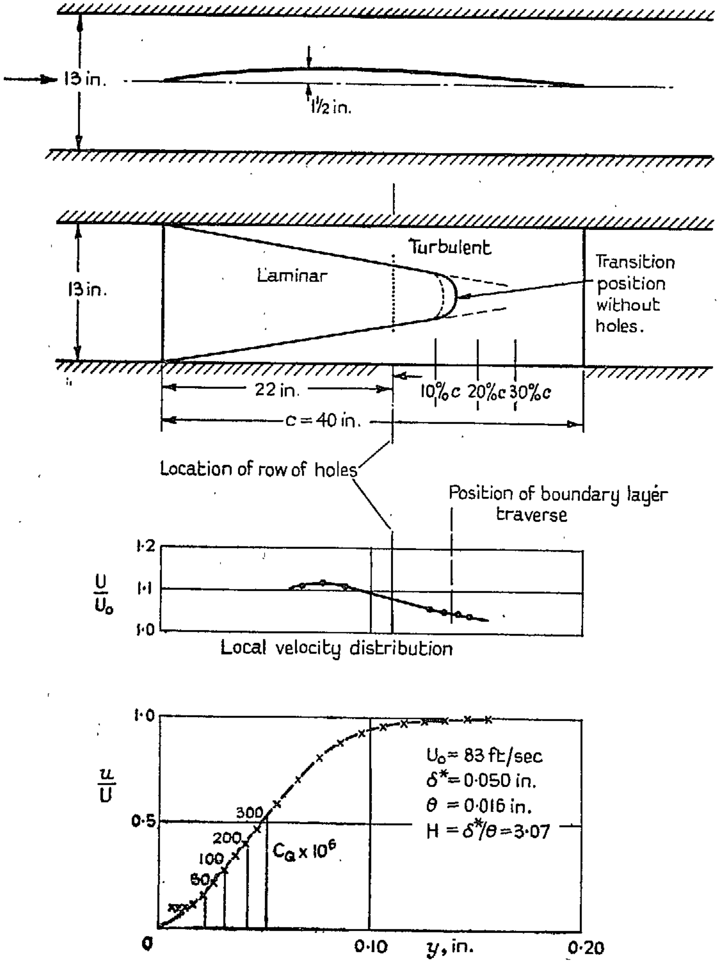
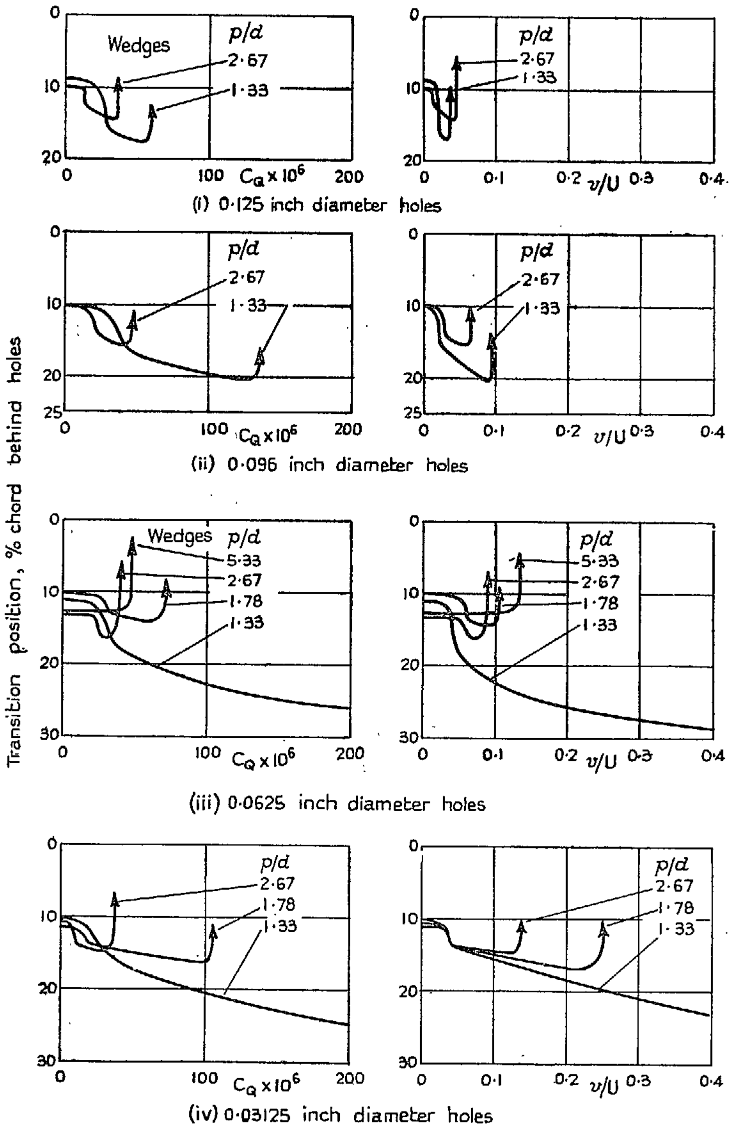


FIG. 1. Arrangement of cambered plate in small tunnel, velocity distribution and boundary-layer profile on plate.



(i) 0·125 inch diameter holes

(ii) 0·096 inch diameter holes

(iii) 0·0625 inch diameter holes

(iv) 0·03125 inch diameter holes

FIG. 2. Effect on transition of suction at a single row of holes of various sizes and spacings ($U_0 = 83$ ft/sec ; $x = 1 \cdot 83$ ft ; $c = 3 \cdot 35$ ft).

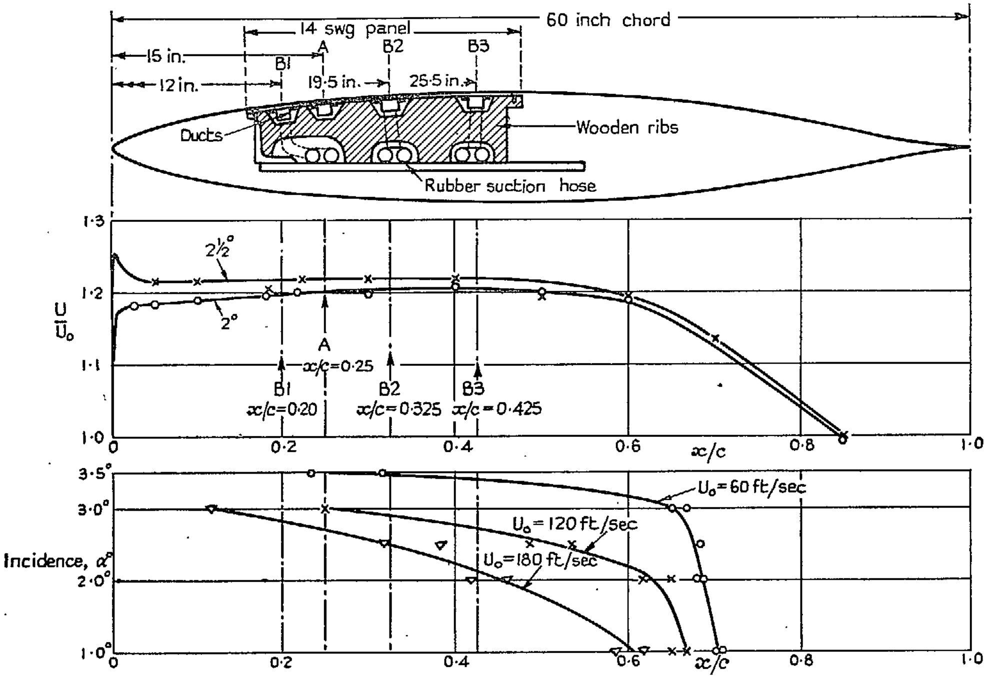


FIG. 3. 13 per cent low-drag aerofoil section ; velocity distribution and transition position.

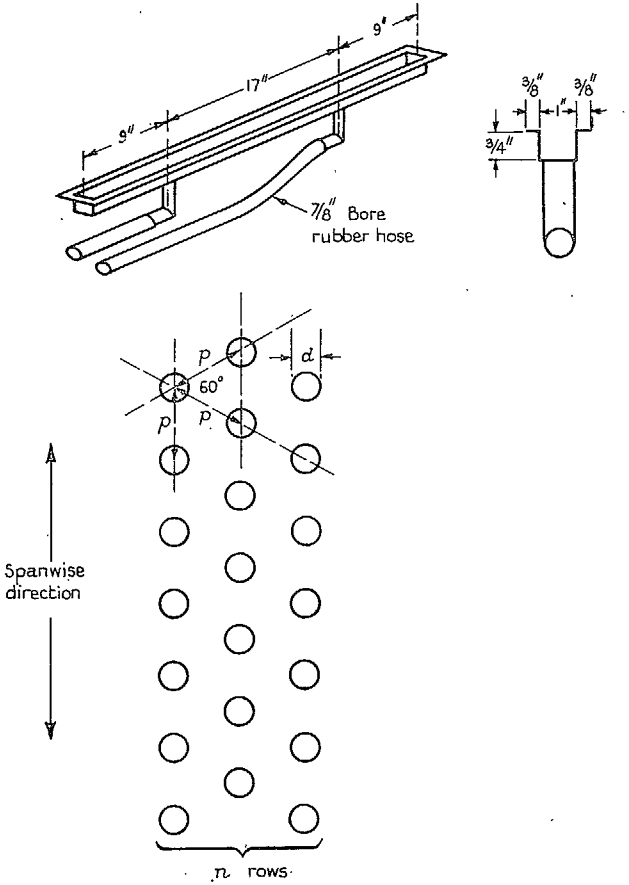


FIG. 4. Sketch of a duct and of perforation pattern.

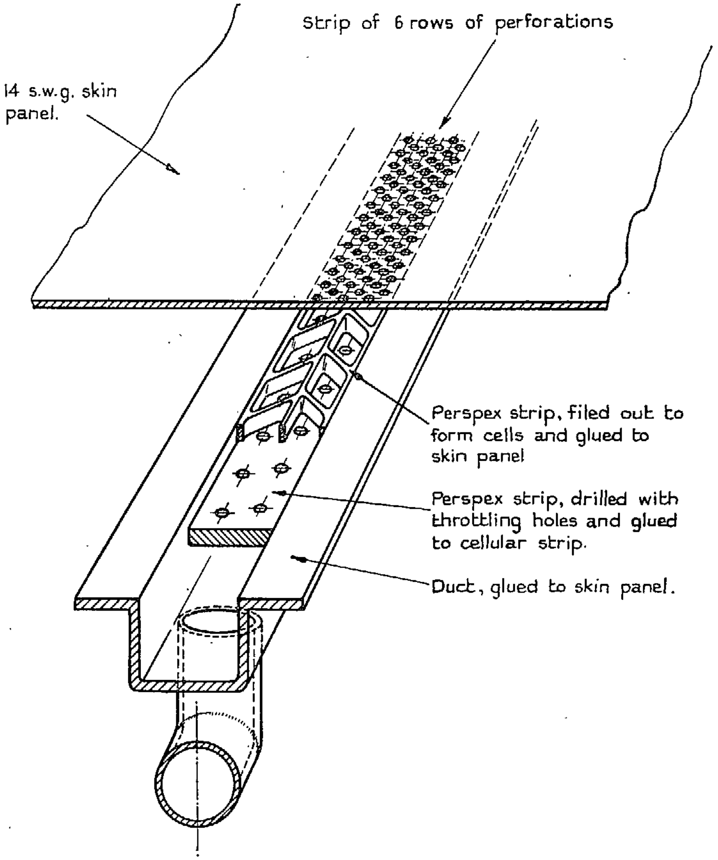


FIG. 5. Sketch showing cellular construction used to ensure uniform suction.

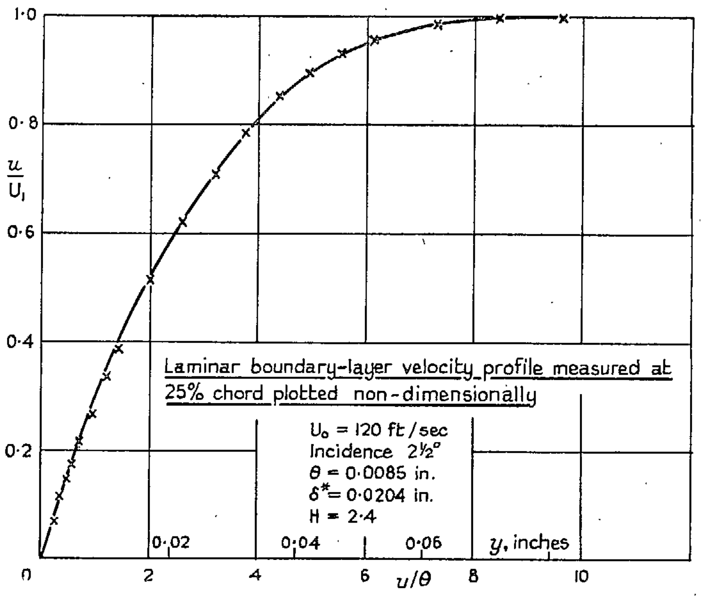


FIG. 6.

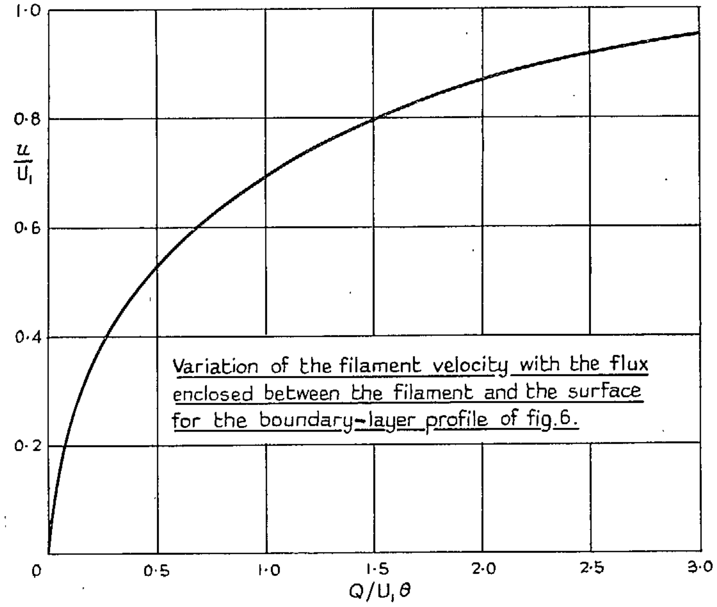


FIG. 7.

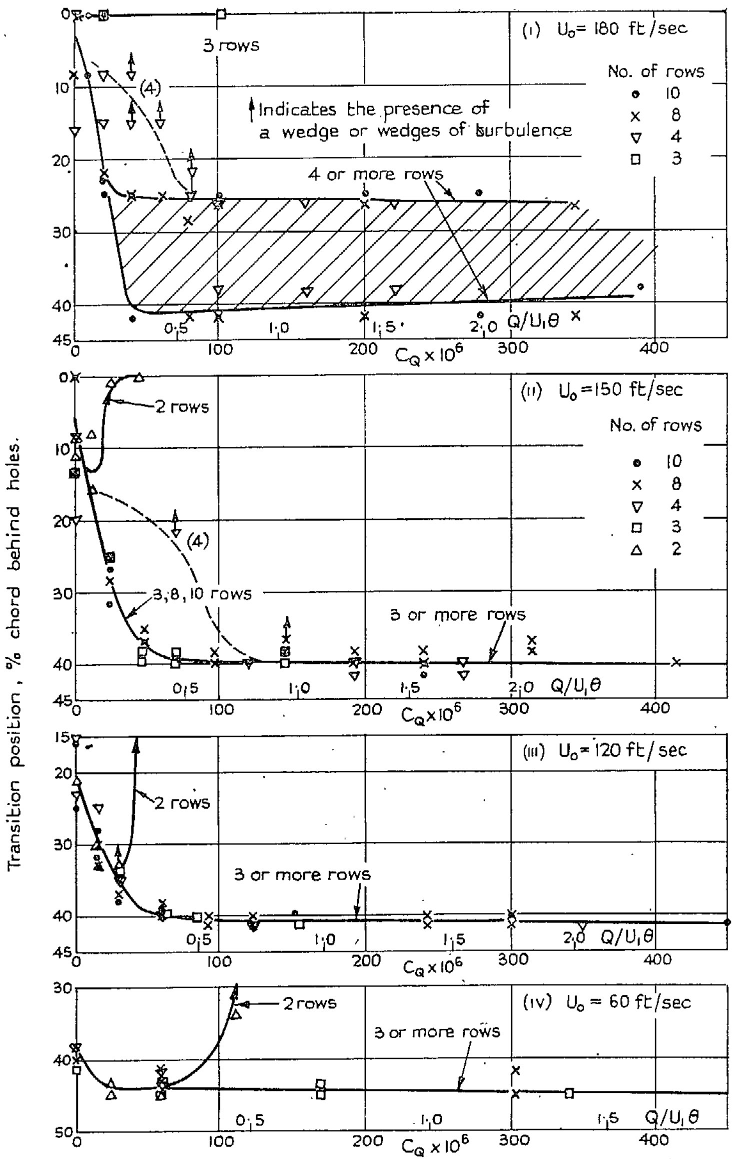


FIG. 8a. Variation of transition with suction-quantity coefficient for 0·031-in. diameter holes spaced at 2·67 pitch/diameter ratio (Incidence 2½ deg).

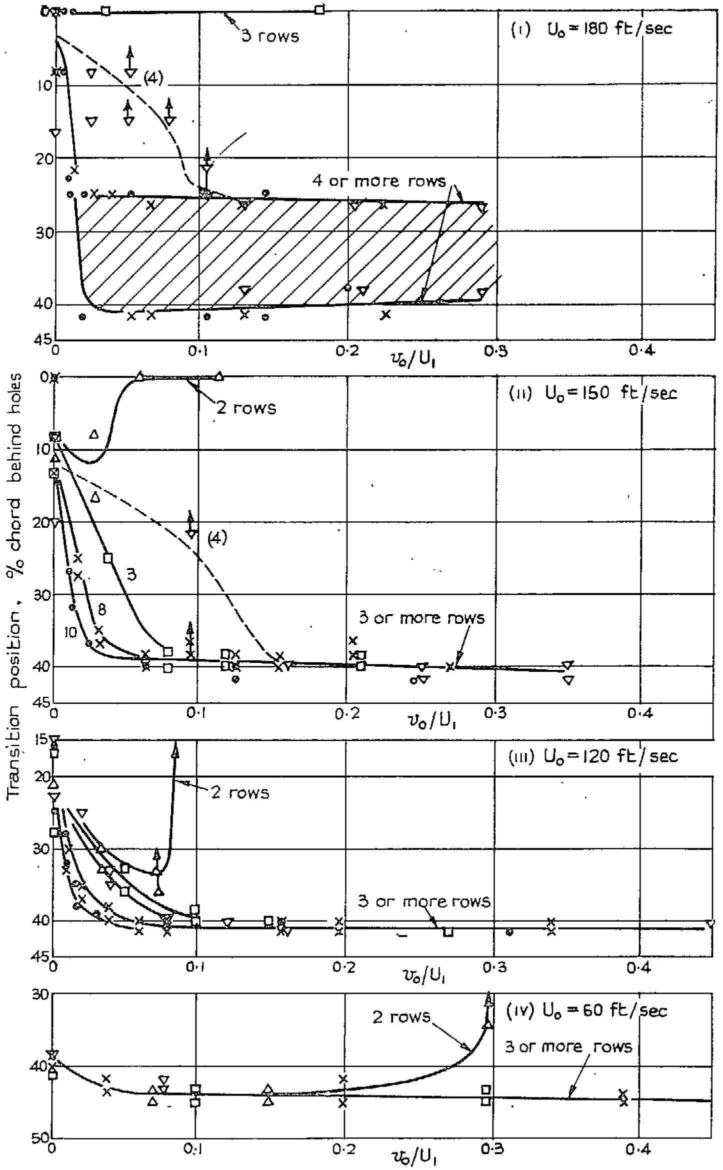


FIG. 8b. Variation of transition with suction-velocity ratio for 0·031-in. diameter holes spaced at 2·67 pitch/diameter ratio (Incidence 2½ deg).

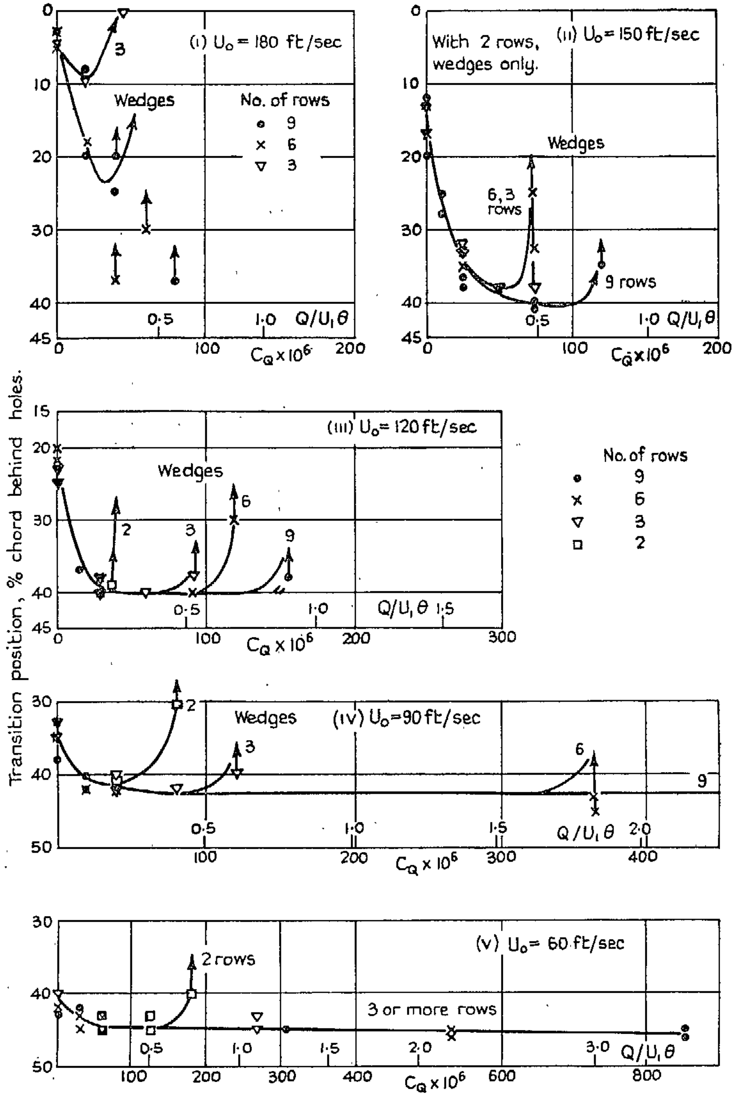


FIG. 9a. Variation of transition with suction-quantity coefficient for 0·031-in. diameter holes spaced at 3·56 pitch/diameter ratio (Incidence 2½ deg).

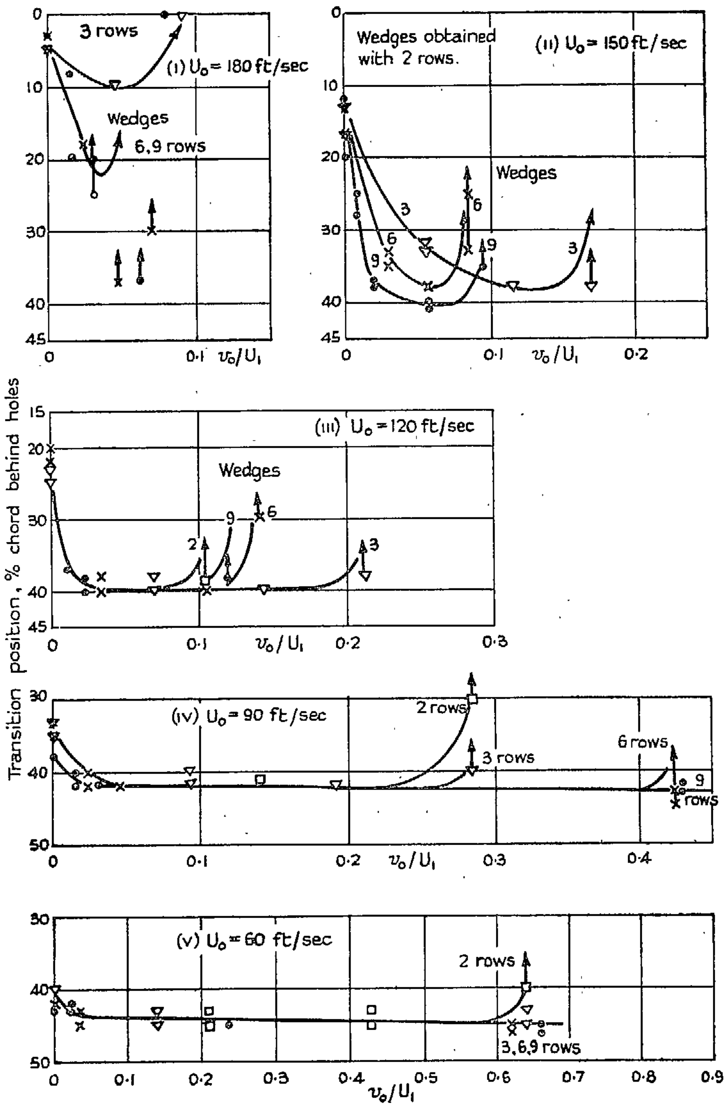
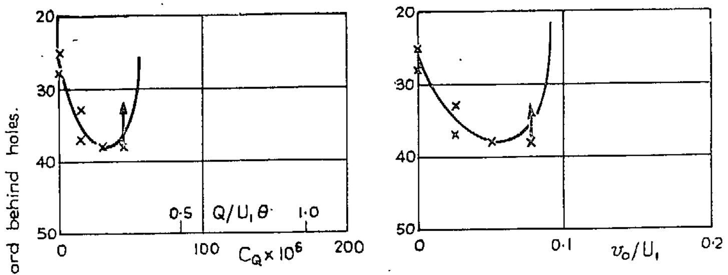
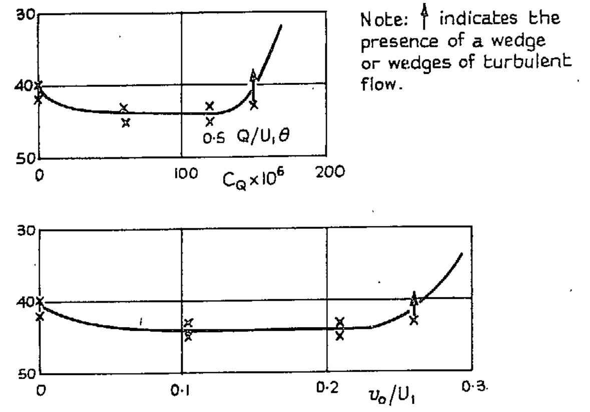


FIG. 9b. Variation of transition with suction-velocity ratio for 0·031-in. diameter holes spaced at 3·56 pitch/diameter ratio (Incidence 2½ deg).



(i) U₀ = 120 ft/sec, 6 rows



Note: ↑ indicates the presence of a wedge or wedges of turbulent flow.

(ii) U₀ = 60 ft/sec, 6 rows

FIG. 10. Variation of transition with suction for 0·031-in. diameter holes spaced at 5·33 pitch/diameter ratio (Incidence 2½ deg).

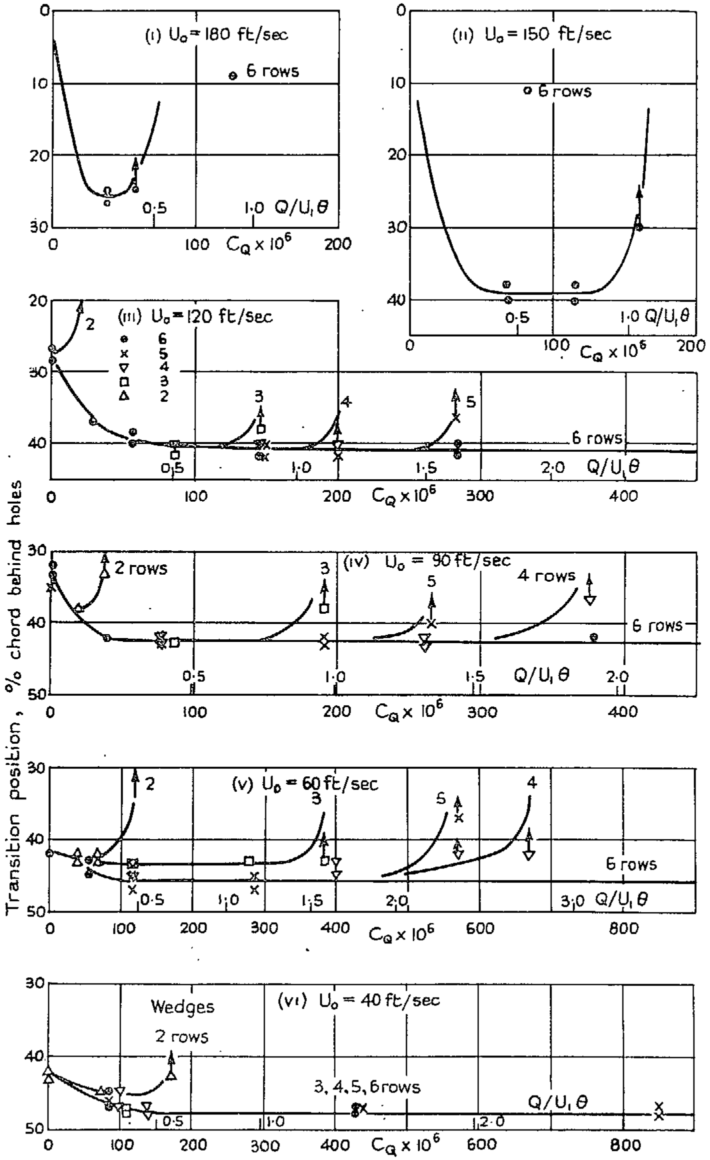


FIG. 11a. Variation of transition with suction-quantity coefficient for 0·063-in. diameter holes spaced at 2·67 pitch/diameter ratio (Incidence 2½ deg).

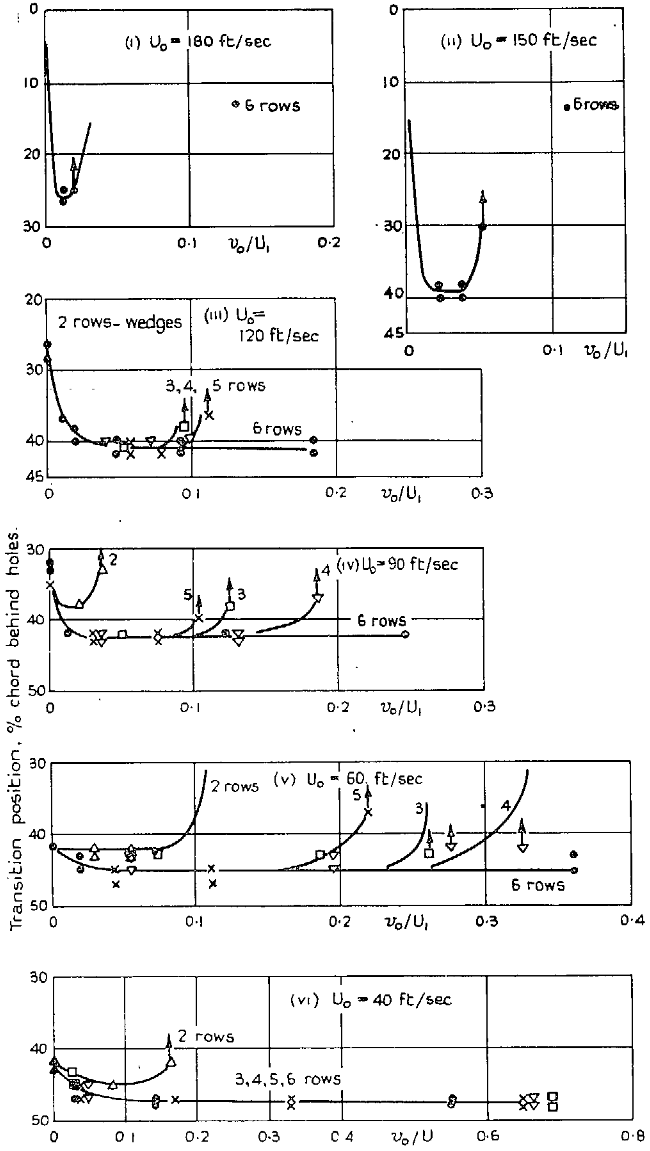


FIG. 11b. Variation of transition with suction-velocity ratio for 0·063-in. diameter holes spaced at 2·67 pitch/diameter ratio (Incidence $2\frac{1}{2}$ deg).

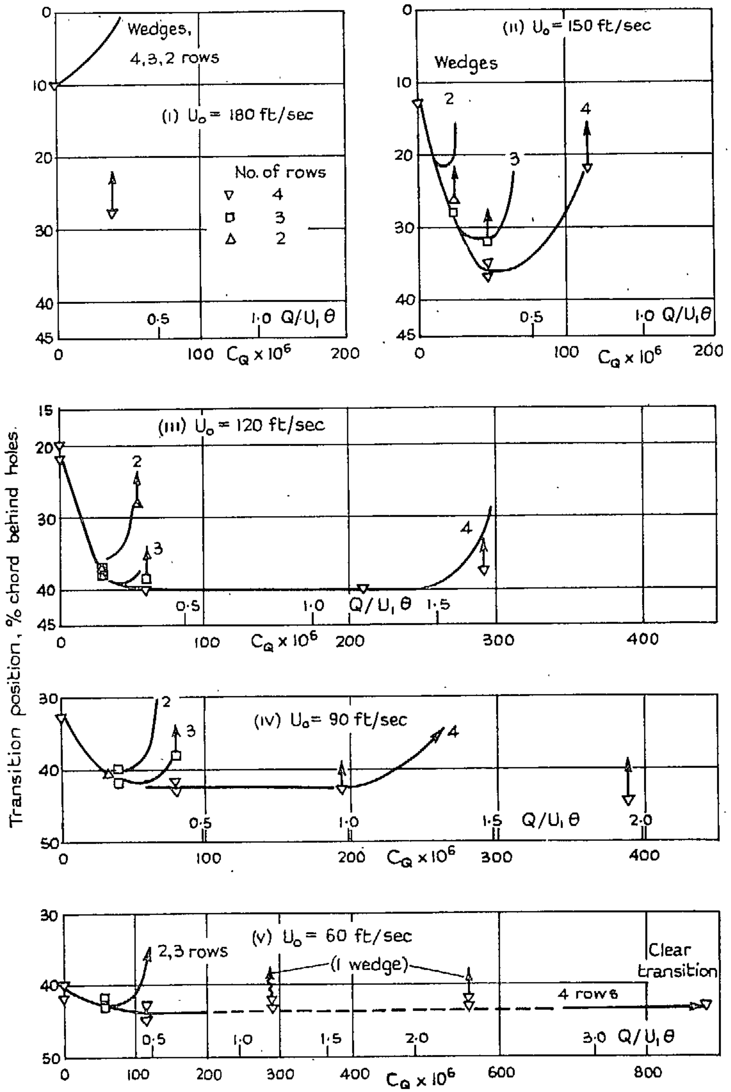


FIG. 12a. Variation of transition with suction quantity coefficient for 0·094-in. diameter holes spaced at 2·67 pitch/diameter ratio (Incidence $2\frac{1}{2}$ deg).

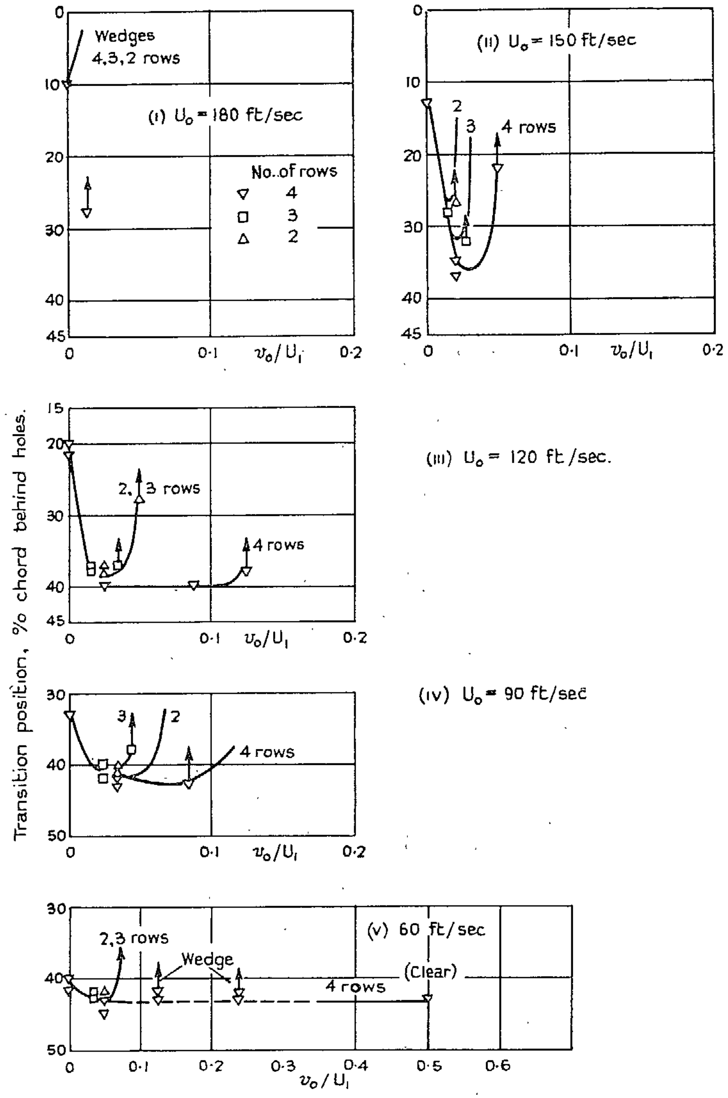


FIG. 12b. Variation of transition with suction-velocity ratio for 0·094-in. diameter holes spaced at 2·67 pitch/diameter ratio (Incidence $2\frac{1}{2}$ deg).

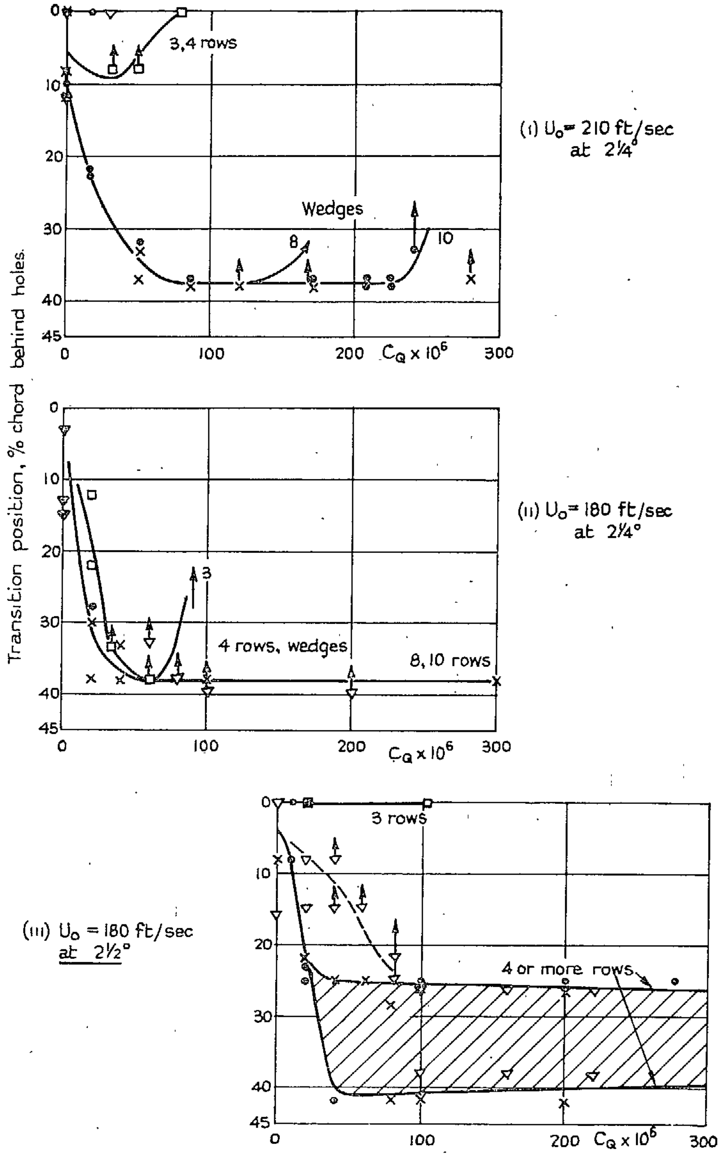


FIG. 13a. Effect of reduction of incidence on performance of 0·031-in. diameter holes spaced at 2·67 pitch/diameter ratio.

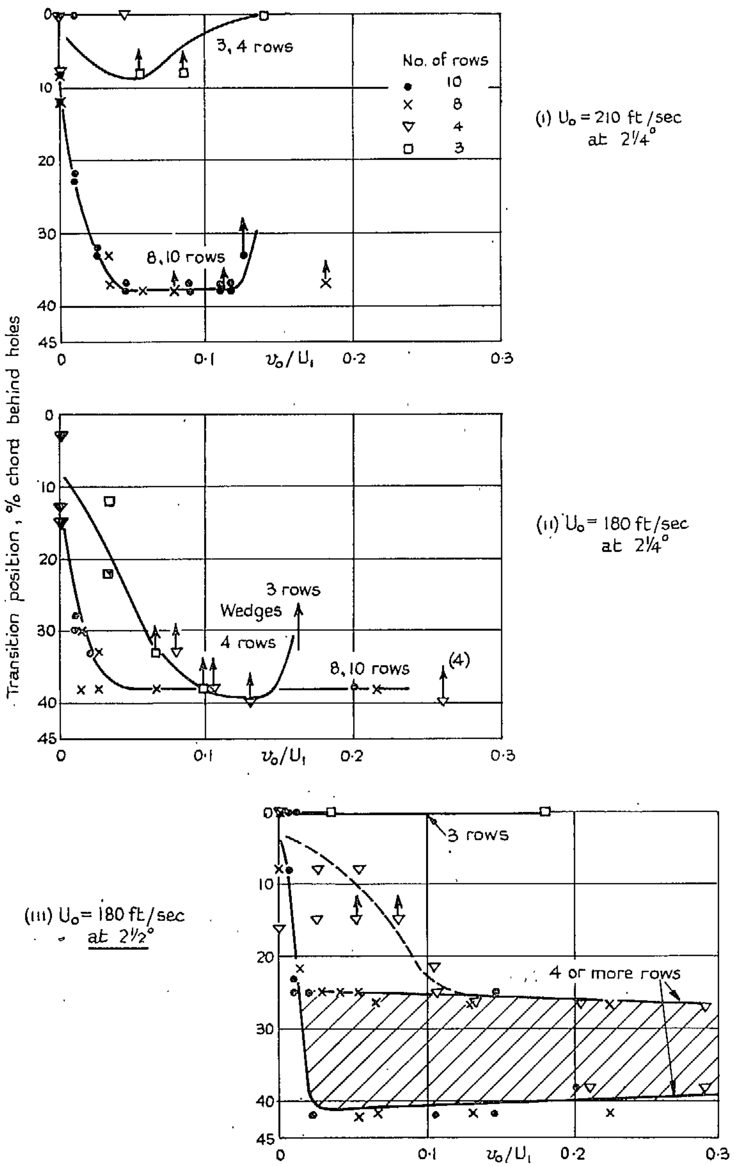


FIG. 13b. Effect of reduction of incidence on performance of 0·031-in. diameter holes spaced at 2·67 pitch/diameter ratio.

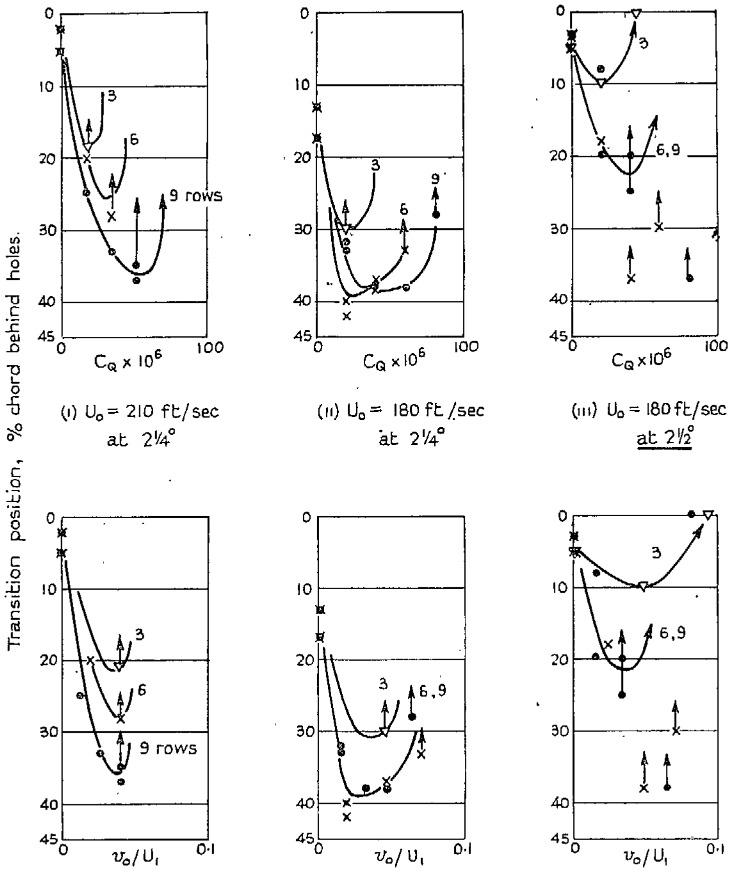
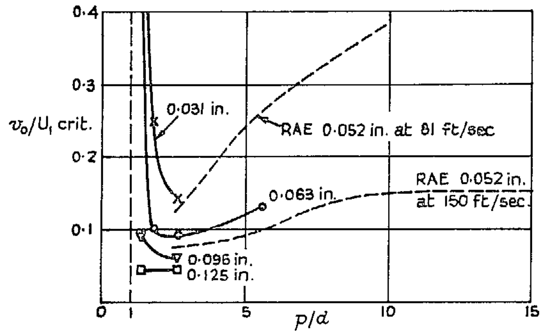
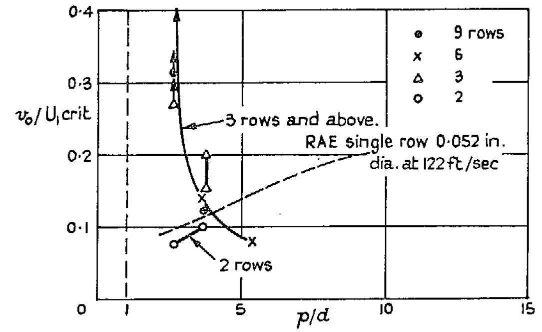


FIG. 14. Effect of reduction of incidence on performance of 0·031-in. diameter holes spaced at 3·56 pitch/diameter ratio.



Single row of holes
NPL $U_0 = 83$ ft/sec $R_x = 0{\cdot}97 \times 10^6$ (on cambered plate)
RAE $U_0 = 150$ ft/sec $R_x = 1{\cdot}85 \times 10^6$
$U_0 = 81$ ft/sec $R_x = 0{\cdot}99 \times 10^6$



Multiple rows (on aerofoil)
0·031 in. dia at
$U_0 = 120$ ft/sec $R_x = 0{\cdot}96 \times 10^6$
$d/\delta^* = 1{\cdot}54$

FIG. 15. Variation of critical velocity ratio with pitch/diameter ratio for single and multiple rows of holes.

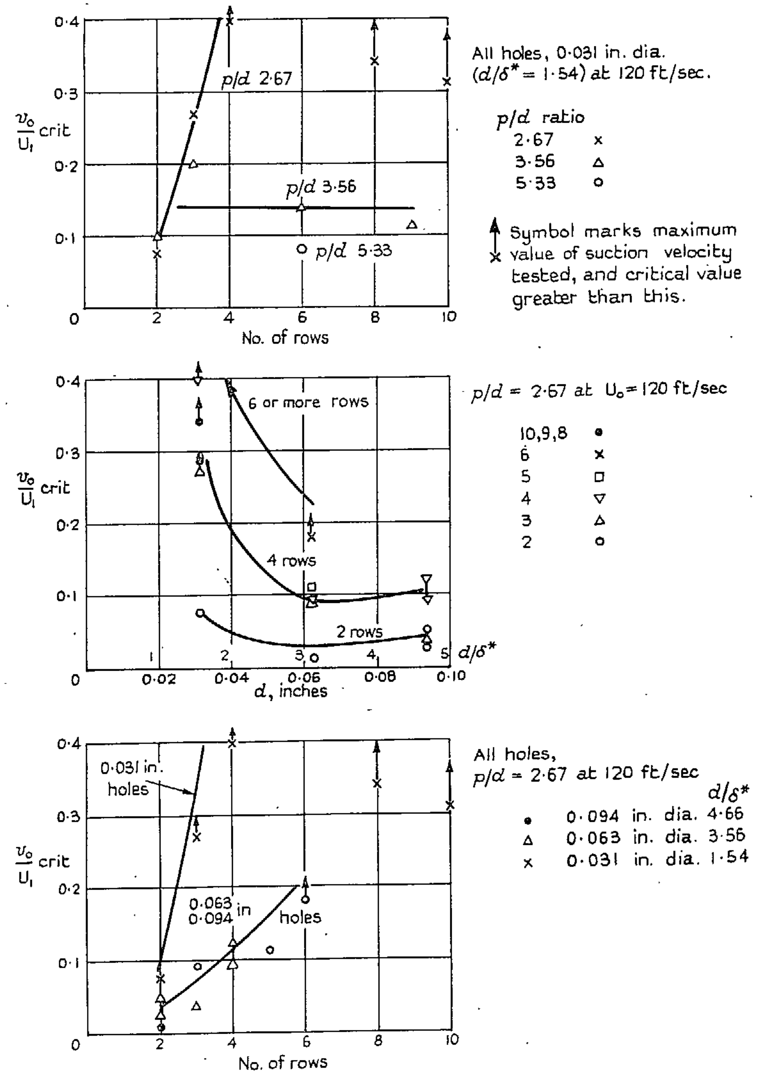


FIG. 16. Variation of critical velocity ratio with pitch/diameter ratio, hole diameter, and number of rows at 120 ft/sec.

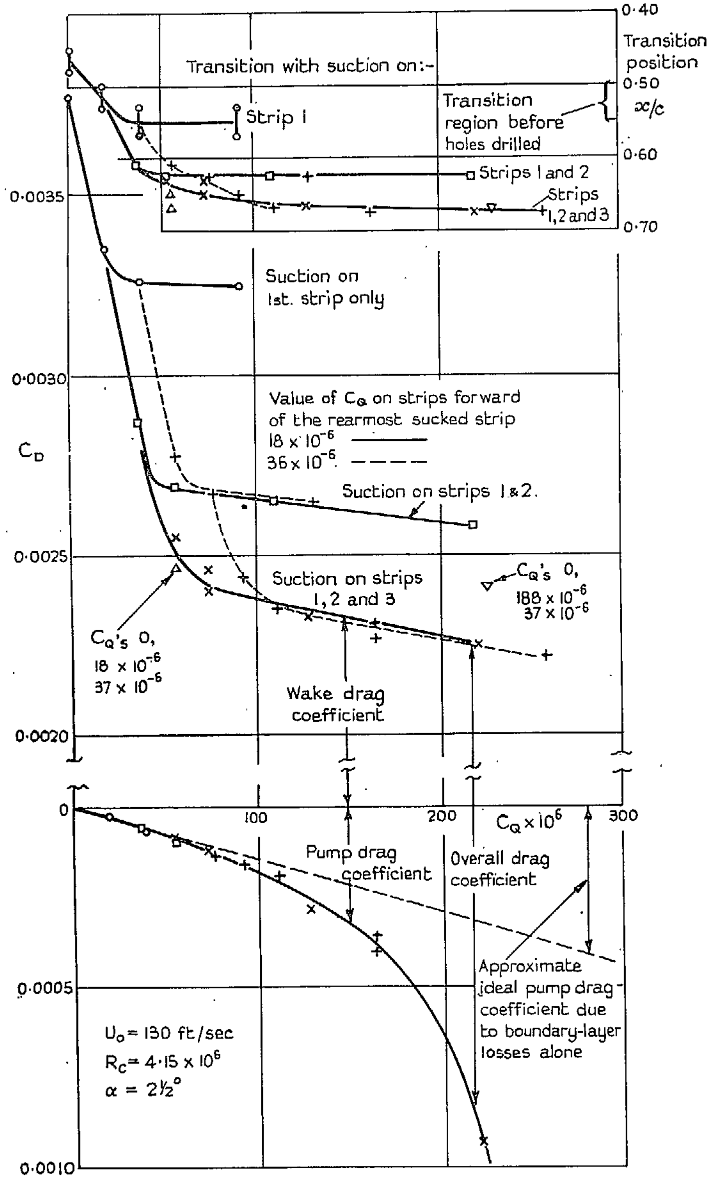


FIG. 17. Variation of transition position and drag coefficient with suction-quantity coefficient (0·031-in. diameter holes; 4 rows per strip spaced at $p/d = 2{\cdot}67$).

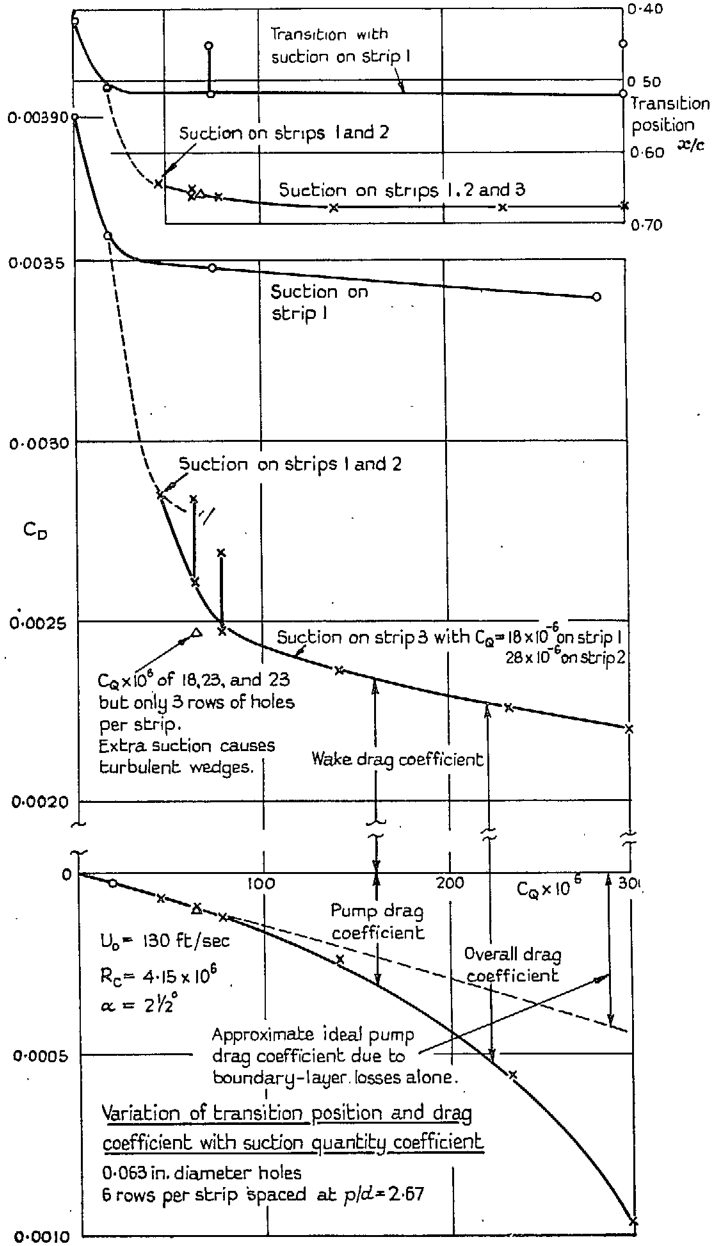


FIG. 18.

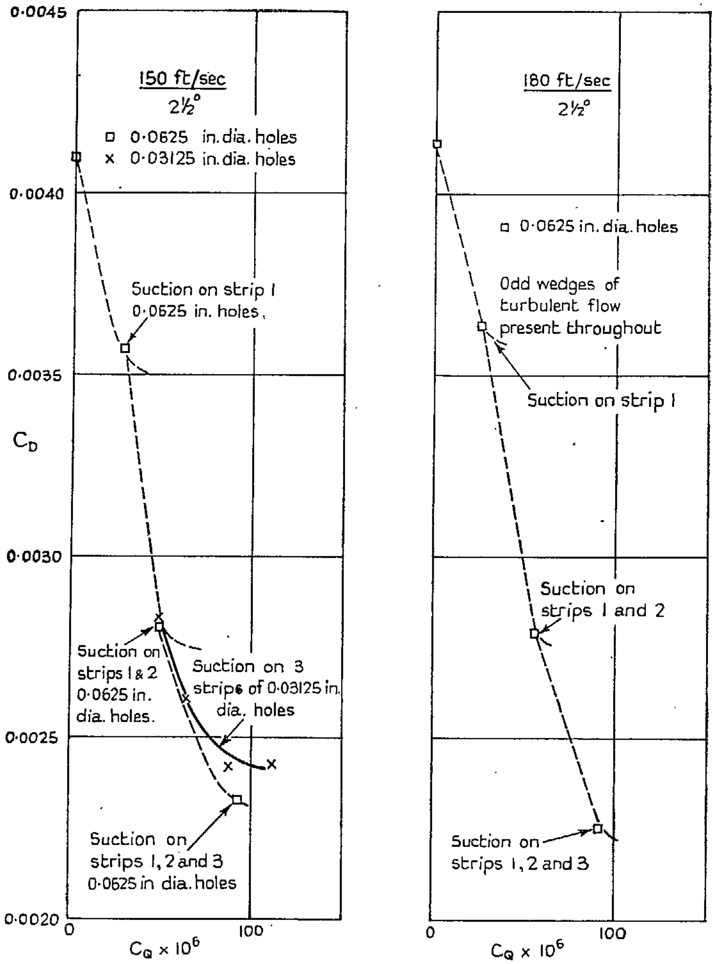


FIG. 19. Variation of wake-drag coefficient with suction-quantity coefficient at 2½-deg incidence at 150 and 180 ft/sec wind speed.

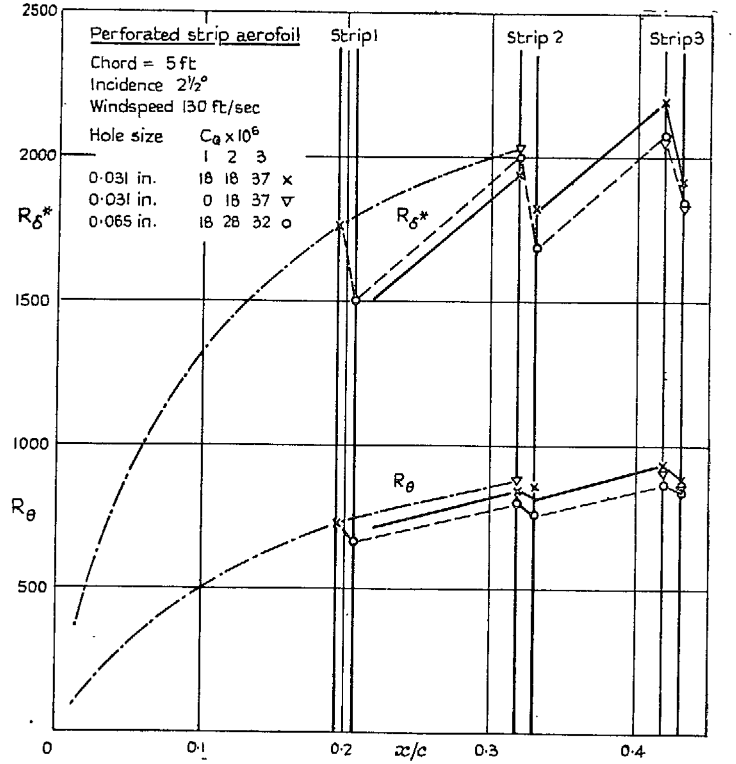


FIG. 20a. Variation of $R_{\delta*}$ and R_θ along surface with minimum suction quantities.

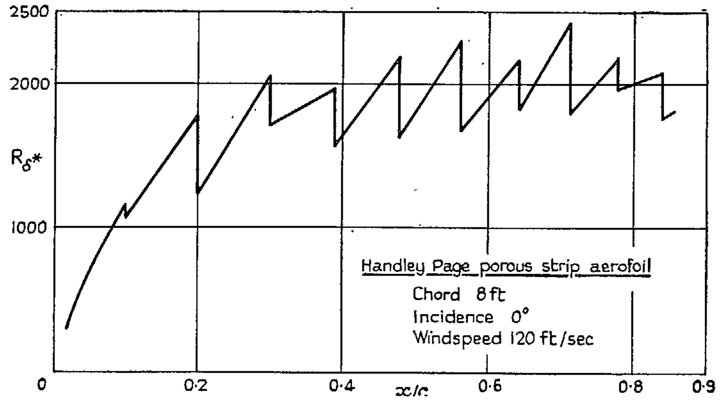


FIG. 20b. Variation of $R_{\delta*}$ along surface of Handley-Page porous-strip aerofoil.

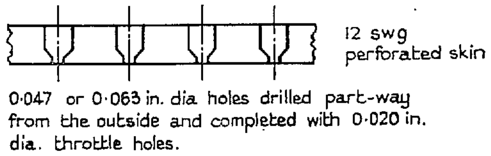


FIG. 21b. Details of perforated strip on H.P. panel 2.

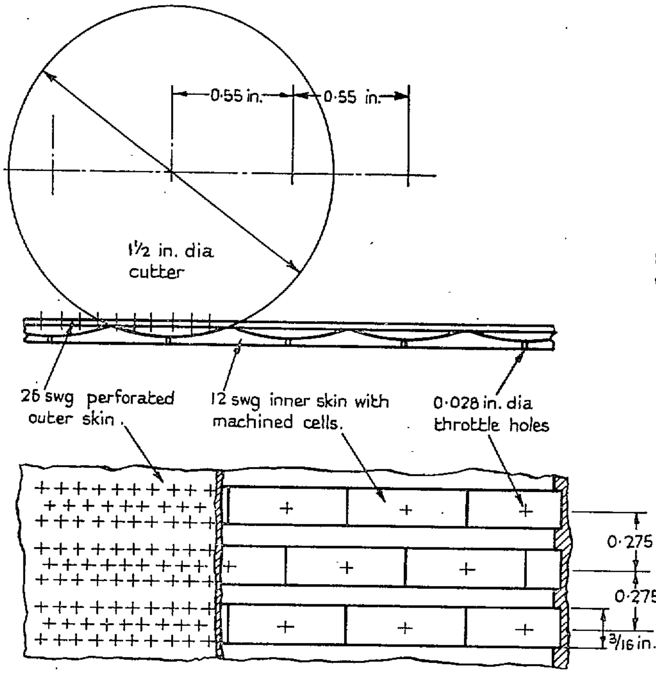


FIG. 21a. Constructional details of perforated strip on H.P. panel. 1

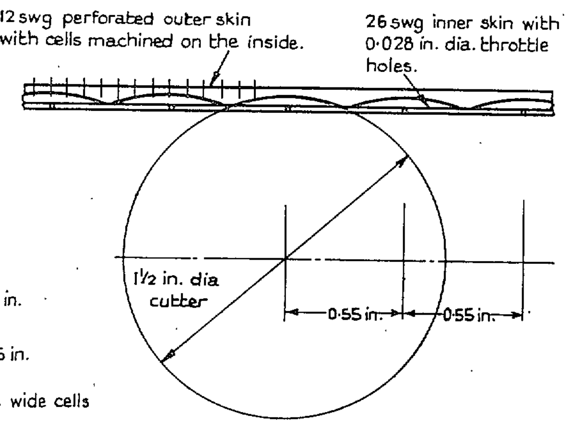


FIG. 21c. Constructional details of perforated strip on H.P. panel 3.

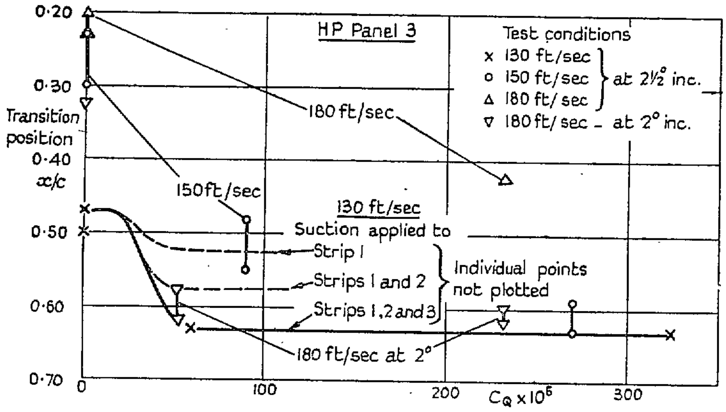


FIG. 22a. Variation of transition position with suction on H.P. panel 3.

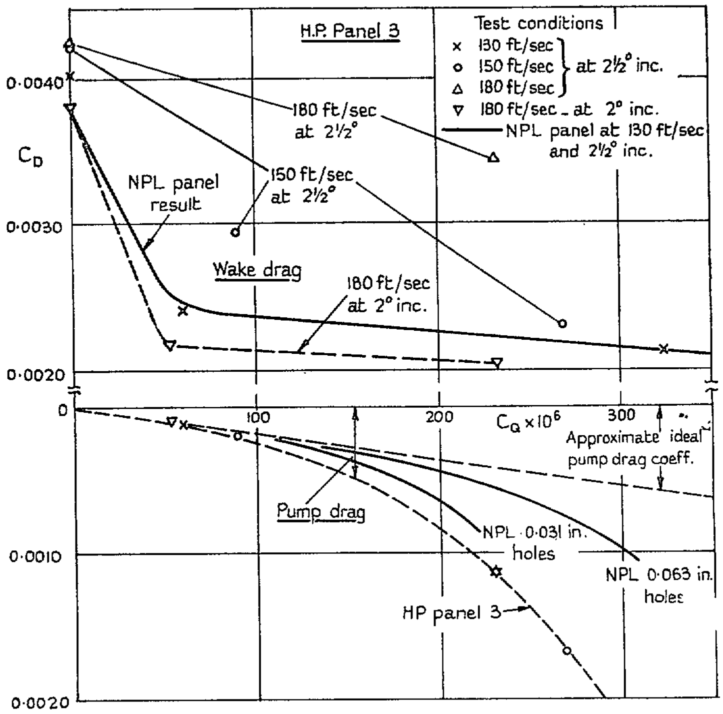


FIG. 22b. Variation of wake-drag and pump-drag coefficients with suction on H.P. panel 3.

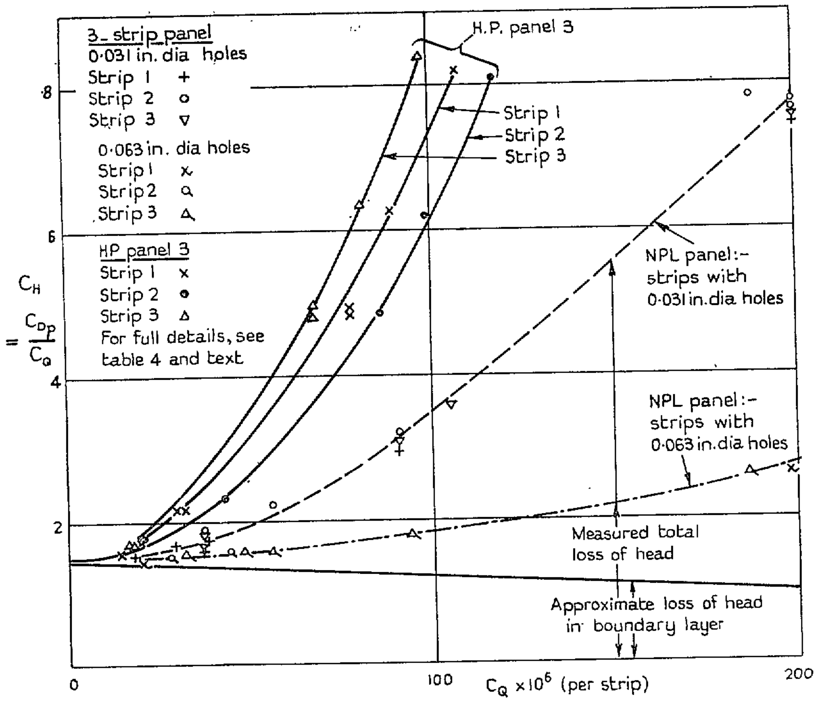


FIG. 23. Variation with suction of the losses in the pumping system for various perforation arrangements.

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