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Flight Experiments on Boundary-Layer Control for Low Drag

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Summary.—Tests have been made with distributed suction applied to a short-span sleeve fitted to the upper surface of the wing of a single-seat *Vampire* aircraft. Full-chord laminar flow was maintained up to Reynolds numbers in the region of 29 million and Mach numbers up to 0·70, which was very nearly the critical Mach number of the sleeve section. The suction quantities required were sufficiently small to result in overall reductions in profile drag of between 70 and 80 per cent, account being taken of the power required for suction. Difficulties were experienced due to surface roughness, and although these are believed to have resulted largely from the particular type of porous covering used in the tests, the problem of maintaining a sufficiently smooth and clean surface is evidently of crucial importance to full-scale application.

1. *Introduction.*—This report describes the first phase of a series of flight experiments on maintaining laminar boundary layers by means of suction. The experiments were performed on a *Vampire* aircraft to which a suction sleeve had been fitted over part of the upper surface of the wing. The results presented were obtained in the period August, 1953, to March, 1954.

Earlier experiments in wind tunnels and small-scale experiments in flight had demonstrated that, in favourable circumstances, suction might be used to maintain extensive laminar flow and thus to obtain corresponding reductions in profile drag; but between the promising results of such experiments and full-scale application there remained a very considerable gap, which the present series of flight experiments was designed, in part, to close. The constructional difficulties of applying suction, particularly distributed suction, at full scale are considerable. Moreover, if impressive drag reductions are to be obtained, other desirable performance characteristics must be to a greater or less extent compromised. In these circumstances it is obviously of great importance, if boundary-layer control for low drag is to find practical application, not only to establish the extent of the drag reductions which are ideally possible at the Reynolds numbers and Mach numbers of present-day flight, but to show further that these gains may be regularly achieved in the actual conditions of operation.

In the present series of experiments, which are limited to suction applied through a porous surface, drag reductions of between 70 per cent and 80 per cent have been achieved and full-chord laminar flow maintained up to chord Reynolds numbers as high as 29 million,

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the critical Mach number of the section being closely approached. Thus it has been demonstrated for the first time that full-chord laminar flow can be achieved under conditions of full-scale operation. Later experiments conducted at Cambridge University included tests of suction applied through perforated surfaces which, in practice, may be more convenient than porous surfaces and it is hoped that the results obtained will establish the reliability, as well as the feasibility, of drag reduction in full-scale conditions.

The report is divided into two parts: the first describes the design and construction of the sleeve, the suction system, and instrumentation; the second analyses the results of the flight experiments. The first part of the report is given in some detail, since it is felt that the application of suction for low drag is as much a problem of engineering as of aerodynamics and that due attention should be paid at this stage to the practical aspects of the design.

PART I

Description of the Vampire Scheme

2. *General Considerations Affecting the Design.*—2.1. *Methods of Applying Suction for Low Drag.*—Numerous experiments have been performed with suction applied at slots, and full-chord laminar flow has been obtained in wind-tunnel tests on a model designed by Pfenninger at Reynolds numbers up to 17 million. The reports show the extreme importance of surface finish and of precise slot shaping, and a very high standard of constructional accuracy is evidently required. There is no very satisfactory theoretical guide either to the maximum permissible slot spacing or the minimum suction requirements for laminar flow, though semi-empirical methods have been used to obtain such estimates. Flight experiments on slot suction carried out by the National Advisory Committee for Aeronautics (U.S.A)[1] in 1944 and by Lockheeds[2] in 1947 proved unsuccessful*.

To avoid some of the constructional difficulties associated with the use of slots, it had been suggested that suction might be applied at isolated strips of porous material incorporated in the wing surface. A wind-tunnel model utilising this principle was subsequently constructed by Handley Page and tested by the National Physical Laboratory[3] and the Royal Aircraft Establishment[4]. Considerable difficulty was initially experienced in obtaining adequately smooth joints between the porous strips and the solid surface but when, by careful filling and smoothing, these had been sufficiently improved, full-chord laminar flow was obtained up to a Reynolds number of approximately 16 million. Tests were later carried out with the porous strips replaced by strips of solid Dural in which closely spaced rows of holes had been drilled. These proved satisfactory and allowed a smooth surface to be obtained with much less difficulty. Flight experiments on strip suction are currently being carried out by Handley Page in a scheme which resembles the one described in this report. Strip suction suffers from the same disadvantage as suction applied at slots, in that there is no satisfactory theoretical basis for design; moreover, uniform stability of the boundary layer cannot be secured and the skin friction immediately downstream of any strip will be high due to the removal of the lower part of the boundary layer, and increased sensitivity to surface roughness will result in these regions.

As compared with suction applied at isolated slots or strips, suction applied through a continuously porous surface offers considerable advantages; the boundary layer develops in a substantially uniform manner with the thickness increasing, and the skin friction decreasing, continuously along the chord. The development of the boundary layer can be calculated with acceptable accuracy, and for any given chord Reynolds number and pressure distribution, a distribution of suction velocity can be determined which will maintain formal stability of the laminar boundary layer over the entire chord. Past experiments on distributed suction, in flight by Head at Cambridge[5], and in wind tunnels by Braslow, Tetervin, Burrows and Visconti[6,7,8]

* Since the writing of this report successful flight experiments on slot suction have been carried out by Pfenninger at Northrop Aircraft Inc. *Aero. Eng. Rev.*, March, 1957.

in America, have shown very close agreement between such theoretical estimates and the suction quantities actually found necessary to maintain laminar flow. In the American tests full-chord laminar flow was maintained up to a Reynolds number of 22 million and there was no reason to suspect that similar results could not have been obtained at even higher Reynolds numbers.

Because distributed suction appeared to offer the best prospect of achieving full-chord laminar flow in flight, and because results obtained in this way could be directly compared with theory, it was decided to begin the flight experiments with suction applied through a continuously porous surface. It was realised, however, that such a surface might prove unsuitable for embodiment in the design of a full-scale aircraft and it was intended that the initial tests, if successful, should be followed by a second series of experiments to establish a more acceptable scheme, which might consist of suction applied through closely spaced rows of perforations in a continuous metal skin. Flight tests of a similar arrangement had been carried out in America by Raspet[9] on a glider and the results obtained were entirely satisfactory; nevertheless, in view of the much higher Reynolds numbers of the present experiments and the absence of any rational basis for determining suitable hole sizes and spacing it was decided, as stated previously, to perform the initial tests using distributed suction. The results obtained would provide a datum with which subsequent results with perforations could be compared. The form of construction adopted, which is described below, was equally suitable for both methods of applying suction and the experimental arrangement could be readily modified for the second series of tests.

2.2. *Milled Skin Construction.*—On a wing in flight the external pressure varies considerably, particularly along the chord. With uniform internal pressure it would therefore be necessary, in order to obtain the required distribution of inflow velocity, to vary the porosity along the chord and to keep the internal pressures well below the lowest external pressure so as to avoid any danger of local outflow. The required inflow velocities are normally of the order of inches or fractions of an inch per second, and to obtain an adequate pressure drop through the surface, with much small velocities, it would be necessary either to make the surface of low porosity or to use very small widely spaced perforations. The latter conflicts with the ideal of distributed suction whilst with the former there is the problem of blockage by dust and fine material present in the atmosphere.

To overcome these difficulties the type of construction shown in Fig. 1 (the two forms of construction are identical in principle) has been evolved, which closely approaches the ideal solution. The scheme employs thin sheets of porous or perforated material, overlying a main stress-bearing skin which has a series of recesses, each communicating with the ducts or compartments of the wing *via* a small hole. The outer porous or perforated skin, which may be very light in weight and of low resistance to flow, is bonded to the lands between the recesses in the main skin. The holes connecting the recesses to the duct or compartment beneath, are small, so that most of the pressure drop to the interior takes place through them; thus the sole function of the outer, low-resistance skin is to distribute the suction over the area of each recess, which may be made of any convenient size. The diameters of the holes in the main skin may be chosen to obtain any desired distribution of inflow, and in this way a surface of effectively graded porosity may be obtained.

It will be seen that the suggested method of construction allows the main skin to be joined to ribs and other members without the necessity for blanking off corresponding areas of the porous surface. The recesses need not be deep, nor need they be milled into the surface; any other method of forming isolated recesses or cells would presumably be equally satisfactory. The principle might be applied to sweat or transpiration cooling, and is certainly applicable to boundary-layer control for high lift, where the suction velocities are very much greater than in the present case, but the local pressure gradients correspondingly more severe.

The type of construction adopted in the present scheme is similar to that shown in Fig. 1b, 2.3. *Porous Materials Available.*—The most suitable porous material which may be envisaged for use with the type of construction described in the previous section is a light plastic sheet of high porosity, rather more rigid than a normal fabric, and with a high standard of surface smoothness. No such material was found to be available, and the tests to be described were performed with an outer covering of rolled Monel-metal cloth of 320×20 mesh. An enlarged photograph of a sample of this material is shown in Fig. 2a. The wire cloth was chosen because it could be obtained in sheets of sufficient size to cover the full area of the sleeve without the necessity for making joints. A more suitable material would probably have been Perflec (a type of electro-deposited mesh), but at that time this could be obtained only in strips two feet wide. Electroplated wire gauze might have proved satisfactory, but this again was not commercially obtainable. Anticipating the results described in later sections, it may be stated here that difficulty was found to arise with the Monel-metal cloth due to its picking up very small hairs which, at the higher Reynolds numbers, were sufficient to cause transition. This property arises from its structure, and is certainly not common to all types of porous material; it substantially disappears if the cloth is more heavily rolled. As an expedient, the Monel-metal surface was covered, during a number of the tests, with tightly stretched calendered Nylon fabric; for reasons discussed later, this also could not be considered entirely satisfactory, though quite consistent and repeatable results were obtained at the lower range of Reynolds numbers. An enlarged photograph of the Nylon fabric is shown in Fig. 2b.

2.4. *Outline of Scheme Adopted.*—When flight experiments on distributed suction were first proposed, a sleeve fitted to the wing of a single-seat *Vampire* aircraft was suggested as the most economical means of carrying out tests at acceptable values of Mach number and Reynolds number. Initially, it was intended to fit a parallel-chord sleeve which would eliminate adverse effects due to sweep. Because of the considerable chordwise overhang of such a sleeve on the sharply tapered *Vampire* wing, it would have been necessary to fit the sleeve with end plates, to ensure approximately two-dimensional flow, and to install a dummy sleeve on the opposite wing. To allow the work to be completed in reasonable time the greatly simplified arrangement shown in Fig. 3 was finally adopted.

From Fig. 3 it will be seen that the sleeve fits closely over the existing wing surface and follows the taper of the wing. The surface of the sleeve is porous from approximately 6 per cent to 98 per cent chord and over this region suction is applied by a turbo-pump unit driven by air bled from the compressor of the aircraft engine. The porous surface, of rolled Monel-metal cloth, is bonded to the Dural skin in which recesses have been milled, and this Dural skin is supported on a series of spanwise bars which divide the space between the wing and the surface of the sleeve into nineteen ducts. The inboard end of the sleeve is separately compartmented to form two collectors, into which the ducts discharge. The air then passes, *via* two venturis, to the pump which is mounted in the wing root.

3. *Details of the Aircraft.*—The *Vampire* III is a single-seat fighter aircraft powered by a Goblin II jet engine. Its maximum speed in level flight is approximately 460 knot at all heights, and the critical Mach number of the wing section will be exceeded at this speed above 10,000 feet. The wing section is a modified E.C. 1240; at the mid-span of the sleeve its thickness/chord ratio (which varies along the span) is 13·3 per cent and the camber is 0·9 per cent. The wing has a taper ratio of approximately 0·33, the leading edge being swept-back at 11·5 degrees and the trailing edge swept-forward about 13 degrees. The all-up weight at take-off is 9,500 lb. giving a wing loading of 37 lb/sq ft.

4. *Design and Construction of Sleeve and Suction System.*—4.1. *Design of Section.*—To retain the utmost simplicity of construction and to keep the depth of the sleeve at a minimum, it was decided to forego any attempt at theoretical design of the sleeve section. Instead, aft of approximately 5 per cent chord, a constant thickness (different for inboard and outboard sections) was added normal to the surface of the existing wing. The chord-line of the sleeve was fixed

parallel to the chord-line of the existing wing and a nose radius chosen which was similar, in terms of percentage chord, to that of the basic section. The leading edge of the sleeve section was arbitrarily fixed a short distance ahead of the existing leading edge, and nose shapes determined by fitting polynomials to the nose circle at the leading edge and to two points on the upper and two points on the lower surface. Calculated velocity distributions for both inboard and outboard sections obtained in this way are shown in Fig. 4. It will be seen that the distributions differ noticeably near the trailing edge ; this is due to differences in the existing wing sections at the two positions, the inboard section being of extended chord with tangential straight lines joining the modified trailing-edge position to the basic section. Ordinates of the inboard and outboard sections of the sleeve are given in Table 1.

4.2. *Calculations of Optimum Distributions of Suction Velocity.*—On the assumption of incompressible flow and a chord Reynolds number of 20 millions for both inboard and outboard sections, calculations were performed using the pressure distributions at $C_L = 0 \cdot 2$ shown in Fig. 4, to find the corresponding distributions of suction velocity which would ensure neutral stability of the laminar boundary layer at all points along the chord. The method used for the calculations is given in Ref. 10 and the calculated distributions of suction velocity are shown in Fig. 5.

4.3. *Design of Sleeve to Obtain an Approximation to the Calculated Distributions of Suction Velocity.*—It was considered that the calculated distributions of suction velocity could be used only as a rough guide to the actual optimum, since the pressure distribution over the sleeve would be influenced by Mach number and by inaccuracies of construction. Moreover, sweepback of the leading edge and sweepforward of the trailing edge would combine to produce the type of boundary-layer instability normally associated with wings of appreciable sweep. It seemed likely, however, that the calculated suction quantities would represent the absolute minimum which would suffice to maintain laminar flow, and a distribution of suction velocity, which was approximately the mean between those calculated for inboard and outboard sections, was used as a basis for design. The problem was to obtain the desired distributions of suction velocity with the given distribution of external pressure and a uniform pressure in each collector somewhat below the minimum pressure on the surface of the sleeve. Brief calculations showed that the velocities of flow in the ducts and in the collectors were sufficiently low for losses due to this cause to be neglected. Two methods were available for controlling the distribution of inflow : either the small holes in the milled skin could be graded in size, or these holes could be made of uniform diameter and the flow controlled at the inboard ends of the nineteen ducts. In fact a combination of these methods was used. For each duct, the small holes were made of such a size that, under minimum suction conditions, the pressure drop through the milled skin was several times greater than the external pressure variation over the width of the duct ; the flow from each duct was then finally controlled by fixing the number of $\frac{3}{16}$-in.–diameter holes drilled in thin orifice plates fitted at the inboard ends of the ducts. The state of affairs was then as shown in Fig. 6 which represents the design condition of flight at 300 kt at 15,000 ft ($C_L = 0 \cdot 2$, $R = 20 \times 10^6$).

The total pressure drop to the collectors, from that external to the surface, is seen to take place in three stages. First there is the very small pressure drop through the porous surface which is just sufficient to ensure more or less uniform inflow over the area of a single cell, then there is the much larger pressure drop through the milled skin, and finally the pressure drop through the orifice plates at the inboard ends of the ducts. Fig. 6 also shows the effect of doubling the theoretical minimum inflow. It will be seen that the pressure in the collectors is then greatly reduced and the suction distribution made more nearly uniform. For design purposes the pressure drop through the rolled Monel-metal cloth was taken at 6 lb/sq ft for a mean normal velocity of 1 ft/sec. This represents a material of high porosity.

Table 2 shows the sizes of holes drilled in the milled skin and the numbers of $\frac{3}{16}$-in.–diameter holes in the orifice plates fitted at the inboard ends of the ducts.

4.4. *Adverse Effects Arising from Suction Failure.*—With the suction pump inoperative it would be possible, unless some form of non-return valves were fitted, for reverse flow to take place through the pump and out through the surface of the sleeve, thus causing considerable thickening of the boundary layer and possibly premature separation at high lift coefficients. Local outflow could similarly occur due to circulation within the sleeve itself, inflow over the rear part of the porous surface being accompanied by local outflow in regions of low pressure near the leading edge. To eliminate the possibility of such outflow occurring, simple flap valves of light-gauge aluminium were fitted to small rectangular cast boxes which were used to clamp the orifice plates to the ends of the ducts. The arrangement is shown in Fig. 7.

4.5. *Details of Sleeve Construction and Installation.*—Figs. 8 and 9 show the general arrangement and constructional details of the sleeve. It will be seen that it is virtually a sandwich of approximately one-inch depth attached to the upper surface of the existing wing. The lower skin is bolted through the wing surface to pick up on the flanges of the existing wing ribs. To this skin are attached inboard and outboard ribs and the diagonal member separating the collectors from the remainder of the sleeve. Between the diagonal member and the outboard rib are fitted the spanwise Dural bars which divide the interior into nineteen ducts. These ducts communicate with the collectors *via* rectangular holes in the built-up diagonal member (*see* Fig. 7). The outer plate over the ducts has recesses milled in the top surface, as shown in Figs. 7 and 10. To obtain this pattern, continuous spanwise grooves were first cut, then single narrower grooves of the same depth were milled at an angle of approximately 50 deg to the first set and at intervals of $2\frac{1}{2}$ inches. Lengths of aluminium wire were forced into these latter grooves and secured by hot-setting Araldite. The surface was thus divided into a series of separate recesses. Each set of the three grooves was then interconnected by end-milling a circular recess, so that the surface was divided effectively into separate cells each approximately $2\frac{1}{2}$ in. $\times$ $\frac{1}{2}$ in. in size. After attaching the milled plates to the sleeve each of these cells was connected to the interior by drilling a small hole, the diameter of which corresponded to the data given in Table 2. The leading-edge section of the sleeve was constructed of 10 s.w.g. aluminium alloy bolted to small solid ribs fitting over the existing leading edge. Wooden fairings were fitted along the edges of the sleeve.

Before the porous covering was applied, measurements were made of surface waviness. This was found to be rather severe, but was subsequently improved to an acceptable standard by filing the milled plate. The final records obtained are shown in Fig. 11. The maximum waviness, except near the trailing edge, is seen to be approximately plus or minus 0·005 in. on a 3 in.-gauge length and represents a very good surface by production standards, but such high standards of accuracy were probably unnecessary in the regions where suction was to be applied. To attach the porous covering the surface was coated with a rubber-based adhesive, which was allowed to dry. The sheet of metal cloth was secured under the leading edge, and stretched chordwise over the upper surface of the sleeve. A hot domestic iron was then applied to all parts of the surface ; this melted the glue to form a bond between the Dural and the metal-cloth covering.

4.6. *Pump Installation.*—The pump unit, together with pipes and ducting is shown in Figs. 8 and 9. It consists of a centrifugal pump coupled directly to an inward-flow turbine, the latter being driven by air bled from a number of points around the main compressor of the aircraft engine.

At the outset, it was apparent that the pump was not ideally suited to the proposed experiments, being capable of considerably larger mass flows but rather lower pressure ratios than might conceivably be required. However, a similar unit had already been fitted in the Handley Page scheme, and considerable time and effort was saved by duplicating this installation. To allow the pump to operate out of surge it was necessary to incorporate several bleed holes to allow additional air to pass through the pump, the final number of bleeds left open being determined by ground tests of the complete installation.

Because the performance of the pump was likely to be limited by pressure ratio, every effort was made to keep the losses in the ducting as low as possible ; the pipes were made large (3 inches in diameter), turning vanes were fitted in all corners and streamline entries fitted where the flow left the collectors. For the same reason venturis were fitted to measure the total flow in preference to orifice plates.

5. *Instrumentation.*—As well as the normal flight data, the following information was recorded for each set of observations :

(*a*) the boundary-layer velocity profile at the trailing edge
(*b*) the chordwise pressure distribution around the sleeve surface and leading edge
(*c*) the total suction flow from each collector
(*d*) the pressure inside each duct
(*e*) the pressure just outside the end of each duct.

From the differences between measurements (*d*) and (*e*), the chordwise distribution of suction flow could be obtained.

Normally these would be the only measurements recorded in flight, but it was also considered advisable to make provision for recording data on the losses in the suction ducting and the pressure rise across the pump.

The pilot was provided with information as to the state of the boundary layer at the trailing edge, the total suction flow and the pump operating conditions. He could also control the suction flow.

5.1. *Pressure Tappings.*—Approximately 90 copper tubes $\frac{1}{8}$-in. in external diameter were run from a corresponding number of pressure points in the sleeve and suction system to the automatic-observer position. Three lengths of tubing were run from the interior of the wing to each of the nineteen ducts to measure external surface pressures, pressures inside the ducts and pressures immediately downstream of the orifice plates, the ends of these tubes terminating as shown in Fig. 7. A further eight static-pressure holes were fitted in the solid nose in line with the others. Ten tubes were run through the lower part of the wing to connect with the pitot comb fitted at the centre-line of the sleeve at the trailing edge. The comb, which consisted of nine pitot and a single static tube made of 0·04-in. diameter hypodermic tubing is shown in Fig. 12.

Pressure tappings were also made to the throat and inlet of each venturi, to the two down-pipes from the collector ducts and to inlet and exhaust of the suction pump.

5.2. *Pressure Scanners.*—The number of pressure measurements required made some form of pressure switch or scanner essential. Four small scanners of the type shown in Fig. 13 were used. The operation of a single scanner may be described as follows. Twenty tubes, connected to the same number of pressure points, lead *via* short lengths of rubber tubing to a common collector ring ; this communicates directly with the pressure-measuring instrument. At any one time, only one of the tubes is in communication with the collector, the remainder being sealed by the rockers which are held down on the rubber tubes by leaf springs. In the case of the tube which is open, the rocker is held raised against the spring by a small roller attached to a disc which is intermittently rotated. At suitable intervals, this disc is turned through 1/20 of a revolution so that the roller passes on to the next rocker, raising it and allowing the original rocker to resume the clamped position. Thus, each pressure point in turn is connected to the recording pressure gauge. The intermittent motion of the disc carrying the roller is secured by means of a pawl mounted on the continuously rotating worm wheel. Once in each revolution the pawl passes over a fixed cam-plate which raises it to engage one of the twenty pegs fitted on the disc carrying the roller. The pawl carries the disc through 1/20 of a revolution before leaving the cam-plate and passing out of engagement with the peg. The continuously rotating worm wheel is arranged to operate the camera just before the change-over from one pressure point to the next. A small knob on the front of the instrument is used to raise all the rockers so that the rubber tubes are not compressed when the instrument is not in use.

In the present arrangement four scanners were coupled together so that they changed over simultaneously from one set of pressure points to the next. One of the scanners was fitted with a microswitch to operate the camera in the automatic observer, and a second microswitch to stop the recording sequence when the scan was complete. The arrangement of the four scanners, mounted in the gun bay of the aircraft is shown in Fig. 14.

5.3. *Recording of Results.*—By the use of pressure scanners, it was possible to present all the desired readings on only nine instruments, including an air-speed indicator and an altimeter. The instruments were mounted in a small automatic observer and photographed by an F.73 camera. Twenty frames were necessary to record a single set of observations. Because of the short time-interval between exposures and the considerable lengths of small-bore pressure tubing, it was necessary to connect the pressures to the capsules of the instruments, in order to avoid errors due to lag. A datum pressure, lower than any pressure in the suction system, was therefore necessary to obtain positive readings, and for this purpose a small suction pump was used.

5.4. *Cockpit Instrumentation.*—A sensitive differential pressure gauge was provided to indicate to the pilot the state of the boundary layer at the trailing edge of the sleeve. This instrument was connected to the comb so as to indicate the difference in pressure between the pitots at 3 in. and 0·22 in. from the surface. When the gauge indicated a zero reading the boundary layer was evidently less than 0·22 in. thick and full-chord laminar flow could be assumed. A second instrument was connected to the rear venturi, to give an approximate measure of the total suction flow. A three-position switch was provided to operate a valve in the high-pressure pipe to the turbine of suction-pump unit, and so control the pump speed. To take a complete set of records for one flight condition, the pilot operated a push button which initiated the recording sequence.

PART II

Flight Experiments

6. *Initial Experiments with Rolled Monel-Metal–Cloth Surface.* 6.1. *Brief Description of Tests.*—Ten flights were carried out at indicated airspeeds between 200 and 280 kt and at altitudes ranging from 3,000 to 30,000 ft. Records were obtained of boundary-layer velocity profiles at 98·4 per cent chord and of the corresponding pressure distributions and suction flows; in addition, visual records of transition were obtained on the last two flights. During take-off and climb the sleeve was protected against flies by means of a strip of tracing paper which was wrapped around the leading edge, and secured lightly by short strips of adhesive tape. On the upper surface the paper extended back to approximately 10 per cent chord, while on the lower the edge was positioned just ahead of the stagnation line corresponding to an indicated speed of 90 kt. Take-off was delayed until a speed of 100 kt had been reached, and during the climb the speed was not allowed to fall below this value. When sufficient altitude had been reached the paper covering was shed by reducing speed to approximately 90 kt.

6.2. *Results*.—The results of the initial experiments are shown in Figs. 16 to 18. Fig. 15 is included (*see* also section 4.3) to assist in interpreting the later figures and to show the information obtained from a single scan. A detailed discussion of the results is given in the following paragraphs.

6.2.1. *Pressure distributions and flow measurement*.—Measured pressure distributions obtained on the first flight of the series are shown in Fig. 16. The measurements with zero nominal suction flow show very satisfactory agreement between the pressures recorded for the surface static holes, and the pressure inside the ducts, and the boxes carrying the non-return valves. The satisfactory functioning of the valves is also demonstrated by this close agreement. It is apparent that inflow is taking place over the last few per cent of the chord, where the pressure over the sleeve surface is presumably higher than at pump exhaust or at the position in the wing where the bleed orifices of the suction system are situated.

The pressure holes around the nose show an irregularity in the pressure distribution at about 5 per cent chord. The reason for this discrepancy, which persisted throughout the experiments, could not be found.

Fig. 17 shows a comparison between the external stream velocities corresponding to the pressure measurements of Fig. 16 and the design velocity distributions for inboard and outboard sections of the sleeve. The measured pressure distribution was reduced to incompressible-flow conditions by applying the Prandtl-Glauert rule. The mean wing lift coefficient for which the pressure measurements were carried out was $0 \cdot 17$, whereas the design data correspond to $C_L = 0 \cdot 2$. In view of the uncertainty as to the lift coefficient on the sleeve itself the agreement must be considered entirely satisfactory.

From the pressure drop across the orifice plates fitted at the inboard ends of the ducts it was possible to calculate the flow from each duct and to obtain a check on the flow as measured by the two venturis. In fact there was a discrepancy of 6 per cent in the flow measurements from the front collector, and 15 per cent in those from the rear, the venturi readings in each case giving the higher mass flows. Because extensive precautions had been taken to ensure the air-tightness of the system, it was assumed at this stage that the calibration of the orifice plates was in error. The values of C_Q given correspond, therefore, to the venturi measurements, the pressure differences across the orifice plates being used only to obtain the chordwise distribution of suction velocity where this is required. In view of the uncertainties as to the precise flow quantities and the approximations involved in obtaining C_Q, values of the coefficient are given only to the nearest $0 \cdot 00005$.

6.2.2. *Transition*.—Boundary-layer velocity profiles measured at $98 \cdot 4$ per cent chord are shown in Fig. 18. From those obtained on the first flight (Fig. 18a) it appeared that transition was occurring very near the leading edge, both with and without suction. The second flight produced very similar results, and, as a check on the transition position, a wire was taped to the surface at 5 per cent chord. From the results obtained with transition fixed in this way (Fig. 18b) it was concluded that free transition was occurring on the solid nose. When the Monel-metal cloth over the solid nose had been filled with paint, back to 6 per cent chord, to provide a smoother finish, a small improvement was noted and flights at reduced Reynolds numbers showed more marked improvements (*see* Figs. 18c and 18d), though it was evident that the extent of laminar flow was still extremely limited. To determine the possible cause of this early transition and, in particular, to find out whether the flow was breaking down at a front or as a result of roughness, it was decided to obtain visual records of transition by the sublimation technique. The surface of the sleeve was sprayed with a solution of azobenzene ($2 \cdot 5$ per cent by weight) in petroleum ether, which was found to produce no noticeable effect on the porosity of the surface, and three flights were carried out with maximum suction at altitudes in the neighbourhood of 5,000 ft. The last two flights produced visual records which showed numerous wedges of turbulence originating at between 5 per cent and 20 per cent chord and intersecting no further back than 30 per cent chord. In the case of some of the wedges the cause of transition was clearly seen as a piece of grit or a small hair which had become lodged in the interstices of the metal-cloth surface. In many cases, however, the closest scrutiny failed to reveal the cause of transition.

At this stage it appeared likely that premature transition was being caused by roughness, probably roughness picked up in flight, and that the type of surface used was largely responsible for this difficulty. A smoother surface appeared necessary if full-chord laminar flow was to be achieved under design conditions.

7. *Tests with Nylon Covering over Monel-metal Surface.*—It would have been possible to replace the surface (Fig. 2a) with a more heavily rolled piece of Monel-metal cloth but even so the quality of the surface might not have been sufficiently improved. Instead, the simple expedient was adopted of covering the existing surface with a $1\cdot6$-ounce heavily calendered Nylon parachute fabric (Fig. 2b). This could be obtained only in widths of less than three feet, so that it was necessary to joint three widths together. These were stretched over the surface so that the two seams were disposed at approximately equal distances on either side of the centre-line of the sleeve, and secured along both edges of the sleeve, under the solid leading edge and the trailing edge by means of dope. After covering the sleeve it was found that there were several serious flaws in the weave of the fabric which seemed likely to prejudice the maintenance of laminar flow. Attempts were made to smooth these over both before the tests commenced, and at later stages in the experiments.

7.1. *Description of Tests and Results.*—From the previous series of experiments it appeared that the most favourable results might be obtained at lower Reynolds numbers than had yet been tried, although this would necessitate flying at greater lift coefficients, with consequently more extensive and more severe adverse pressure gradients over the surface. Accordingly, on Flight 12 scans were made at 30,000 ft ($C_L = 0\cdot38$, $R_C = 9\cdot9$ million) and at 35,000 ft ($C_L = 0\cdot31$, $R_C = 10\cdot3$ million). The measured profile for the first case was definitely laminar as may be seen from Fig. 19, in which the turbulent profiles obtained from Flight 1 are shown for comparison. In subsequent flights, with the surface somewhat improved, the results shown in Figs. 20 and 21 were obtained. Other records have had to be rejected owing to irregular comb readings which were subsequently found to be due to the presence of water in the connecting tubes.

During the tests the sensitive pressure gauge in the pilot's cockpit was reconnected to indicate the pressure difference between the pitots at 3 in. and $0\cdot12$ in. from the surface. A gauge reading less than $0\cdot03$ lb/sq in. was taken to indicate that the boundary layer was laminar at the comb. It was not found necessary to define this value precisely, as transition, when it did occur due either to reduced suction or to increased Reynolds number, was sufficiently far forward to give a gauge reading of at least $0\cdot3$ lb/sq in. By the use of this instrument the pilot could immediately see whether the boundary layer was laminar or turbulent at the comb, and pilots' reports were used to supplement the information obtained from the automatic observer.

At this stage, full-chord laminar flow could be achieved regularly at Reynolds numbers in the region of 10 million and to verify that surface roughness was in fact the cause of transition at higher Reynolds numbers the apparatus shown in Fig. 22 was constructed and fitted. It consisted of a small surface pitot traversed across the sleeve by means of an electric motor which was housed in a streamlined fairing on the inboard end of the sleeve. To the pitot were brazed two short lengths of hypodermic tubing which enabled it to slide along two parallel piano wires tensioned across the surface. The camera in the automatic observer was arranged to operate independently of the scanners and to record the pressure at the mouth of the pitot at half-inch intervals across the surface. It was hoped that the results would enable the positions of the offending roughness to be located ; the surface could then be progressively improved and the Reynolds number for full-chord laminar flow correspondingly extended. However, although the results showed clearly that transition was taken place due to surface roughness and although in almost every case the cause of transition could be traced to a fault in the Nylon surface (*see* for example Fig. 23), it was not found possible to produce a progressive improvement in surface smoothness, partly because new flaws developed, and partly because no satisfactory technique was devised for permanently repairing the surface defects.

7.2. *Calculations*.—It was thought of interest to compare the first record of full-chord laminar flow (Fig. 19) with the velocity profile calculated by the method used earlier to estimate the suction-flow requirements. The data used for the calculations is given in Fig. 24, and Fig. 25 shows the comparison obtained between the measured and calculated profiles. It will be seen that the agreement is not particularly close, and it appears likely that the suction flow through the surface was in fact rather less than that measured by the venturis, on which the calculations were based. Other explanations of the discrepancy are, of course, possible.

7.3. *Drag Estimates*.—From the theory of the laminar boundary layer it may be simply shown that for a given pressure distribution and a given distribution of suction velocity, the quantity $(\theta/C)\sqrt{R_C}$ at any point is uniquely determined by $C_Q\sqrt{R_C}$. From the laminar profiles measured in the present series of experiments values of $(\theta/G)\sqrt{R_C}$ were determined and when plotted against the corresponding values of $C_Q\sqrt{R_C}$, the points were found to be very close to a single curve, as shown in Fig. 26, in spite of variations in lift coefficient and Mach number. From this curve the variation of (θ/C) with C_Q could readily be obtained for any given chord Reynolds number, and hence, assuming that the velocity profiles were measured at the trailing edge, the method of Squire and Young could be used to determine the wake drag coefficient (C_{Dw}) of the surface as a function of C_Q.

The effective, or equivalent, drag is the sum of the wake drag and the drag equivalent of the power required for suction. The latter will in general depend on the suction mass flow, the pressure coefficient in the collectors and the relative efficiencies of the pump and propulsive system. The various assumptions which may be made regarding these quantities and the effect of these assumptions on the equivalent drag are considered for incompressible flow in Refs. 5 and 12. For the present purpose the equivalent drag coefficient was assumed to be given simply by $C_{De} = C_{Dw} + 2C_Q$.

If the effects of compressibility are neglected this corresponds to the case where the pump and propulsive systems have equal overall efficiencies and where the pressure coefficient in the collectors is $-1\cdot 0$.

By the use of this expression and the known variation of C_{Dw} with C_Q the variation of equivalent drag coefficient with C_Q was determined for a chord Reynolds number of 11·5 million. The results are shown in Fig. 27, which also includes for comparison the drag coefficient later obtained with the surface smooth and sealed at the same Reynolds number (*see* section 8.3).

The results are shown in Fig. 27. It will be observed that the drag savings obtained by suction are very substantial, of the order of 80 per cent, and one reason for the magnitude of the drag reduction in this case is of course the very far forward position of transition with the surface sealed ; this results naturally from the pressure distribution shown in Fig. 24.

7.4. *Summary of Results Obtained with Nylon Covering*.—The tests had shown that full-chord laminar flow could be achieved with the surface sufficiently improved at chord Reynolds numbers up to 16·4 million (Fig. 21), and it appeared extremely likely that only the remaining surface imperfections prevented a similar result being obtained at higher Reynolds numbers. The suction quantities required to maintain laminar flow were sufficiently small to result in very large reductions in overall drag, and both the instrumentation of the sleeve and the method of construction had proved satisfactory. However, before proceeding to tests of perforated surfaces, which might solve the problem of surface smoothness and at the same time prove acceptable for practical application, it was considered of interest to carry out further tests with the original Monel-metal–cloth surface exposed. These tests are described in the following sections.

8. *Final Tests with Rolled Monel-metal–Cloth Surface.*—8.1. *Description of Tests.*—It will be remembered that the initial tests with Monel-metal–cloth surface exposed were confined to indicated speeds above 200 kt. It was now decided to carry out further tests at the lower speeds and conditions which had given consistently satisfactory results with the Nylon covering. First flights showed that full-chord laminar flow could in fact be maintained at $C_L = 0 \cdot 38$ ($R_C = 11$ million) and thereabout (*see* Fig. 28), though once again the flow broke down at higher Reynolds numbers.

It had been noted from the visual transition records obtained earlier that only roughness over the first 20 per cent chord was apparently responsible for transition, and that this roughness was of a type which would not normally be encountered on an aerofoil with a smooth polished surface. It was considered, therefore, that if the surface was filled and smoothed in this region it might be possible to increase the maximum Reynolds number at which full-chord laminar flow could be consistently achieved. To begin with, only the first 15 per cent of the chord was filled. With this modification it was found possible to obtain laminar flow up to $R_C = 16 \cdot 4$ million ($C_L = 0 \cdot 17$). A measured profile for this condition is shown in Fig. 29. It now became impossible to achieve laminar flow at above $C_L = 0 \cdot 25$, because at these higher lift coefficients the pressure minimum now occurred some 10 per cent chord ahead of the commencement of suction. To extend further the upper limit of the Reynolds-number range, the surface was now filled back to 25 per cent chord. Initial tests with this condition were unsuccessful. To increase the suction flow obtainable the orifice plates in the ends of the ducts were removed, but without producing any favourable result. It therefore seemed likely that transition was occurring before the commencement of suction, and to check this conclusion a visual transition record was obtained at a lift coefficient of $0 \cdot 17$. This record showed that transition was occurring along a front at approximately 15 per cent chord on the inboard end of the sleeve. This represented the chordwise extent to which the surface had previously been filled, and careful examination showed a slight ridge at this position where the more recently applied filler had not been sufficiently well rubbed down. When this ridge had been removed it was found possible to obtain full-chord laminar flow at considerably greater Reynolds numbers than had previously been achieved. On the first flight of this particular series the pilot reported full-chord laminar flow at indicated speeds between 320 kt and 380 kt at 10,000 ft. This corresponds to a maximum chord Reynolds number in the region of 29 million, a figure which was appreciably higher than any for which full-chord laminar flow had previously been achieved. No useful film records were however obtained on this flight, as the datum pressure for the instruments had not been set in anticipation of the large pressure differences corresponding to the higher indicated speeds. On subsequent flights for which records of full-chord laminar flow were obtained (*see* Fig. 30) the maximum chord Reynolds number achieved was in the region of 26 million. It seems likely that this reduction was due to some slight deterioration in the standard of surface waviness over the first 25 per cent of the chord, which the earlier unsuccessful results in this series of experiments had shown to be critical. This conclusion is supported by the fact that at a later stage, it again became impossible to obtain full-chord laminar flow until the standard of surface waviness was improved. In these tests full-chord laminar flow was maintained up to a Mach number of $0 \cdot 70$ which is approximately the critical speed for the sleeve section.

8.2. *Suction Flows.*—It will be noted that on Fig. 30 two values of C_Q are given. The first represents in each case the value obtained from the venturi readings while the second, in brackets, represents a value which is believed to be more nearly correct. The possibility of appreciable leakage flows was suggested in the first place by the fact that the minimum values of C_Q required for full-chord laminar flow were apparently considerably higher in the present series of tests than in the earlier tests at lower Reynolds numbers. Moreover, the measured laminar-boundary-layer velocity profiles were in many cases considerably thicker than might be expected for the higher Reynolds numbers and apparently increased C_Q values of the present tests. When the surface was sealed in preparation for the tests described in the next section the opportunity was therefore taken to measure the leakage flow both on the ground and in flight. The ground tests indicated appreciable mass flows and showed that the greater part of the leakage was taking place around the collector covers. It should be remarked here, however, that these covers had been removed and replaced before these tests were carried out, and the leakage may consequently have been somewhat affected. The flight tests indicated a C_Q due to leakage of approximately $0 \cdot 0002$ for conditions of pump operation and collector pressures similar to those for the tests with the surface porous, and the appropriate value has been subtracted from the earlier measured values of C_Q to obtain the values given in brackets. In the earlier series of tests with the Nylon surface the fabric was doped over the collector covers, effectively sealing them, so that the leakage flows were probably then relatively small, though possibly sufficient to account for the observed discrepancy between the suction flow as measured by the venturis and the orifice plates in the ends of the ducts.

8.3. *Boundary-Layer Measurements with Surface Sealed.*—To obtain a measure of the drag reductions brought about by suction, the surface was sealed and two sets of measurements made of boundary-layer velocity profiles at the comb. The first measurements were made with transition fixed at 5 per cent chord and the second with transition free. The measured profiles are shown in Fig. 31. Comparison of the results indicate an appreciable extent of laminar flow at the higher speed with transition free, so that the drag figures given below evidently correspond to this condition.

Drag estimates taking into account the effects of compressibility, were made for the transition-free case by applying the method given by Thompson[13] to the pressure measurements at the comb. The drag coefficients for the single surface were found to be $0 \cdot 0051$ at $C_L = 0 \cdot 38$, and $0 \cdot 0034$ at $C_L = 0 \cdot 10$. These drag values are some 20 per cent higher than would be obtained from the appropriate Royal Aeronautical Society Data Sheets on the basis of the probable transition positions at the two speeds (say 8 per cent and 28 per cent chord). It will be noted however, that the measured results refer to the upper surface only of a lifting section and this may contribute appreciably more than half the total drag of the section. It is also possible that the measured results are somewhat in error through neglect of the static-pressure variation through the boundary layer.

8.4. *Estimates of Drag Reduction.*—When the corrected values of C_Q are used it is found that values of $(\theta/C)\sqrt{R_C}$ obtained from the measured profiles of Fig. 30 lie close to the curve given in Fig. 26. This curve has, therefore, been used, as in section 8.3, to estimate the variation in equivalent drag coefficient with C_Q, in this case for a chord Reynolds number of 23 million. The comparison between the measured drag with surface sealed and the estimated drag with suction is shown in Fig. 32. It will be seen from the figure that, for a C_Q value of $0 \cdot 0003$, a drag reduction of 75 per cent is indicated. Because of uncertainties in the experimental data and in the method used to assess the drag equivalent of the power required for suction, this precise value is of course open to question, but there can be no doubt that drag reduction of a similar order has in fact been achieved.

9. *Discussion.*—The present investigation has demonstrated that by means of suction applied through a continuously porous surface it is possible to achieve full-chord laminar flow in the conditions of full-scale operation, and the way has thus been cleared for tests of methods of applying suction which may be more acceptable in practice. Roughness of a particular type has been seen to give rise to appreciable difficulties in the present series of tests, but because this type of roughness does not appear to cause trouble on conventional wings it is possible that this problem would not arise with more suitable porous materials, or with a perforated surface. It will still, of course, be necessary to prevent or remove gross contamination of the leading edge due to flies, but methods such as that used in the present experiments are evidently satisfactory and more elegant solutions to the problem may be developed. It has not been found possible to deal with the effects of varying the chordwise distribution of suction nor,

on the basis of the present results, can any useful assessment be made of the reliability of suction as a method of ensuring low drag, though within the limits stated in the text it was generally possible to obtain repeatable results. A shortcoming of the present results is the uncertainty, owing to leaks, regarding the minimum suction quantities required to maintain laminar flow. This is probably of no great practical importance, since the equivalent drag is seen to be relatively insensitive to changes in suction quantity, but an accurate knowledge of these minima would indicate the adequacy of methods of design based on two-dimensional calculations of the laminar boundary layer. The measured suction flows, with account taken of probable leakage, are in reasonable agreement both with the original estimates and with calculations made for the measured pressure distributions at the lower Reynolds numbers.

In earlier flight experiments performed at Cambridge[14] it was observed that, in certain circumstances, it was impossible to maintain laminar flow by suction at altitudes between 5,000 ft and 10,000 ft, though it was possible to do so near the ground. This phenomenon, which was quite repeatable in the original tests, has not been encountered at any stage in the present series of experiments.

10. *Future Research.*—As already stated, the next phase of the experiments in flight will deal with suction applied through perforations, and these tests are already in progress at Cambridge University. It is hoped that in these experiments it will be possible to obtain accurate measurements of the suction flow through the surface, and to assess accurately the power requirements for suction with the effects of compressibility taken into account. Different hole arrangements will be tested and an attempt made to determine the optimum configuration, *i.e.*, the configuration which is both aerodynamically acceptable and likely to involve least difficulties in production.

11. *Conclusions.*—The following are the main conclusions drawn from the present experiments:

(*a*) By means of distributed suction it is possible to maintain laminar flow in flight on the wing of an aircraft at least up to Reynolds numbers in the region of 29 million and Mach numbers up to 0·70.

(*b*) The required suction quantities are sufficiently small to result in very considerable reductions in overall drag. In the present case, the drag reduction is estimated at between 70 per cent and 80 per cent.

(*c*) Altitude of operation, *per se*, has not been found in the present experiments to introduce any additional problems, and the effects of compressibility are evidently of minor importance at least up to the critical Mach number of the section.

(*d*) Difficulties encountered due to surface roughness in the present tests are believed to have resulted largely from the particular type of porous covering used; nevertheless the necessity for preserving a clean and smooth surface is likely to present the greatest difficulty in the way of practical application.

12. *Acknowledgements.*—The authors wish to acknowledge the assistance given by Dr. G. V. Lachmann of Messrs. Handley Page in the manufacture of ducting and the pump installation; and the very valuable advice and encouragement given by Sir Melvill Jones both during the course of the experiment and in the preparation of this report. The authors also wish to acknowledge the contribution to this work made by J. Spillman during the early stages of the flight tests.

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13	J. S. Thompson	A simple method of computing C_D from wake traverses at high speeds. R. & M. 2914. December, 1944.
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TABLE 1

Ordinates of Sleeve Section

(Stations and ordinates as a percentage of wing chord)

Inboard Section

Station	Upper Surface	Lower Surface
0	0	0
0·50	1·21	1·06
0·75	1·48	1·28
1·25	1·92	1·63
2·50	2·73	2·26
5·0	3·81	3·16
7·5	4·60	3·78
10	5·22	4·26
15	6·18	4·95
20	6·84	5·42
25	7·30	5·76
30	7·61	5·93
35	7·76	6·03
40	7·74	6·04
45	7·61	5·96
50	7·34	5·78
55	6·94	5·52
60	6·43	5·18
65	5·82	4·73
70	5·09	4·19
75	4·27	3·56
80	3·42	2·86
85	2·57	2·15
90	1·71	1·43
95	0·86	0·70
100	0	0
Leading edge radius 1·31. Slope of radius through leading edge : zero		

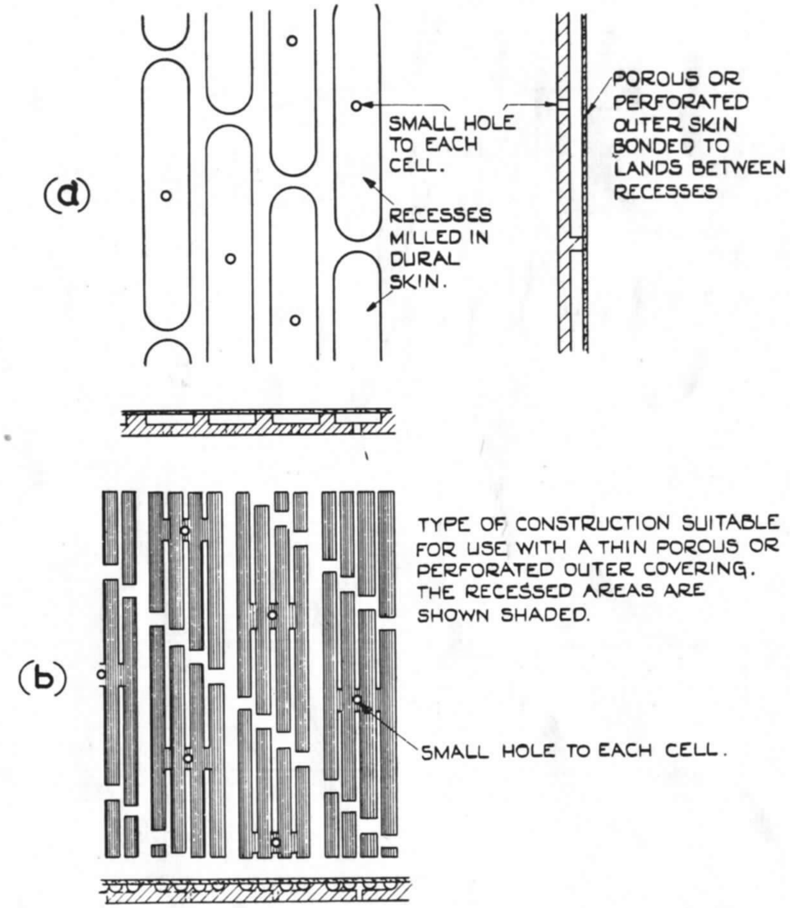
Outboard Section

Station	Upper Surface	Lower Surface
0	0	0
0·50	1·24	1·14
0·75	1·50	1·37
1·25	1·91	1·73
2·50	2·68	2·35
5·0	3·74	3·19
7·5	4·51	3·78
10	5·12	4·25
15	6·06	4·92
20	6·74	5·36
25	7·30	5·68
30	7·56	5·90
35	7·75	6·00
40	7·78	6·02
45	7·70	6·00
50	7·49	5·87
55	7·15	5·69
60	6·73	5·41
65	6·19	5·04
70	5·56	4·58
75	4·85	4·04
80	4·04	3·42
85	3·13	2·71
90	2·16	1·91
95	1·09	0·98
100	0	0
Leading edge radius 1·28. Slope of radius through leading edge : zero		

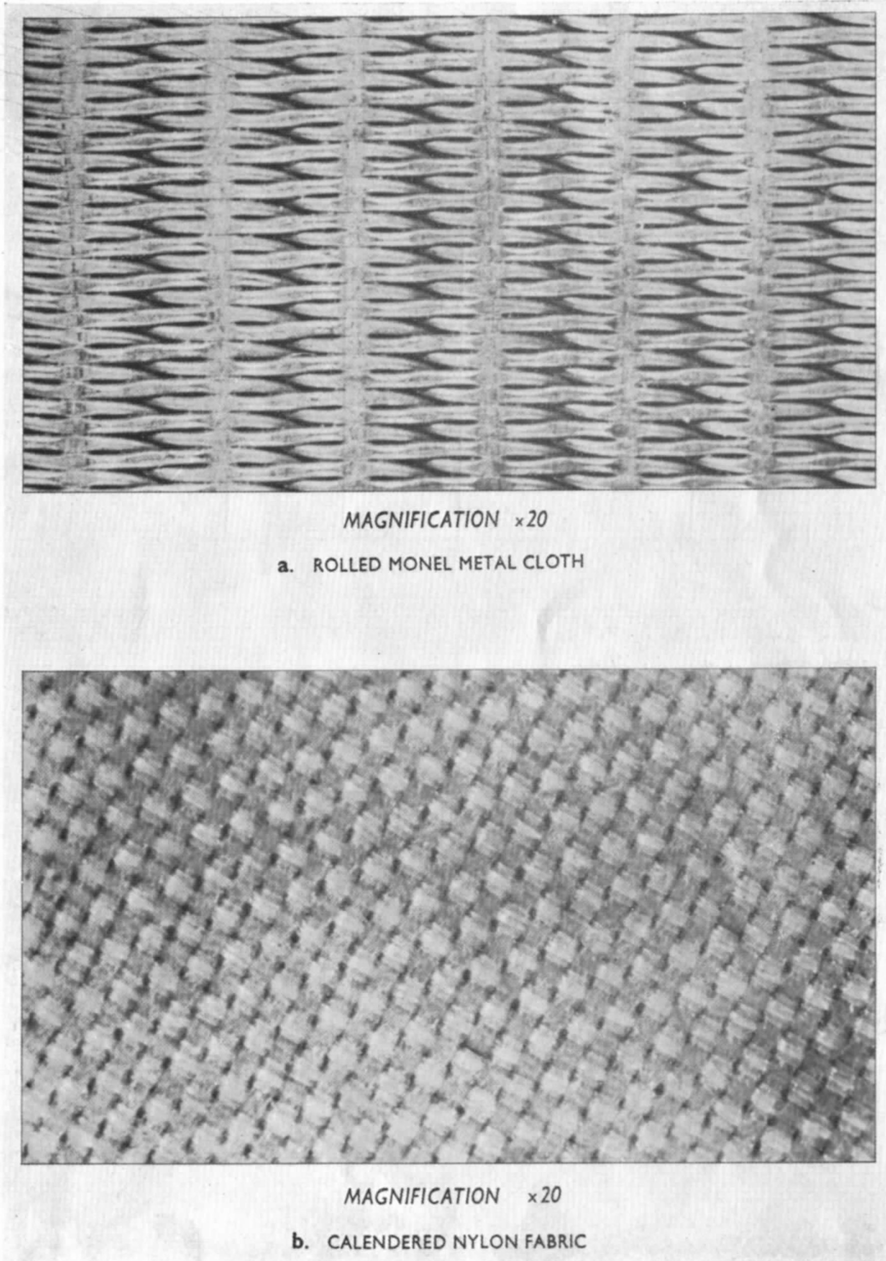
TABLE 2

Particulars of Small Holes Drilled Through the Milled Skin

Duct	Drill number	Drill diameter (in.)	Effective hole diameter	Number of $\frac{3}{16}$ in.-diameter holes in ends of ducts
1 to 11	65	0·035	0·036	5
12 to 16	61	0·039	0·041	5
17	56	0·046	0·049	5
18	54	0·055	0·057	5
19	51	0·067	0·069	6



FIGS. 1a and 1b. Suggested methods of construction for use with distributed suction.



FIGS. 2a and 2b. Porous materials.

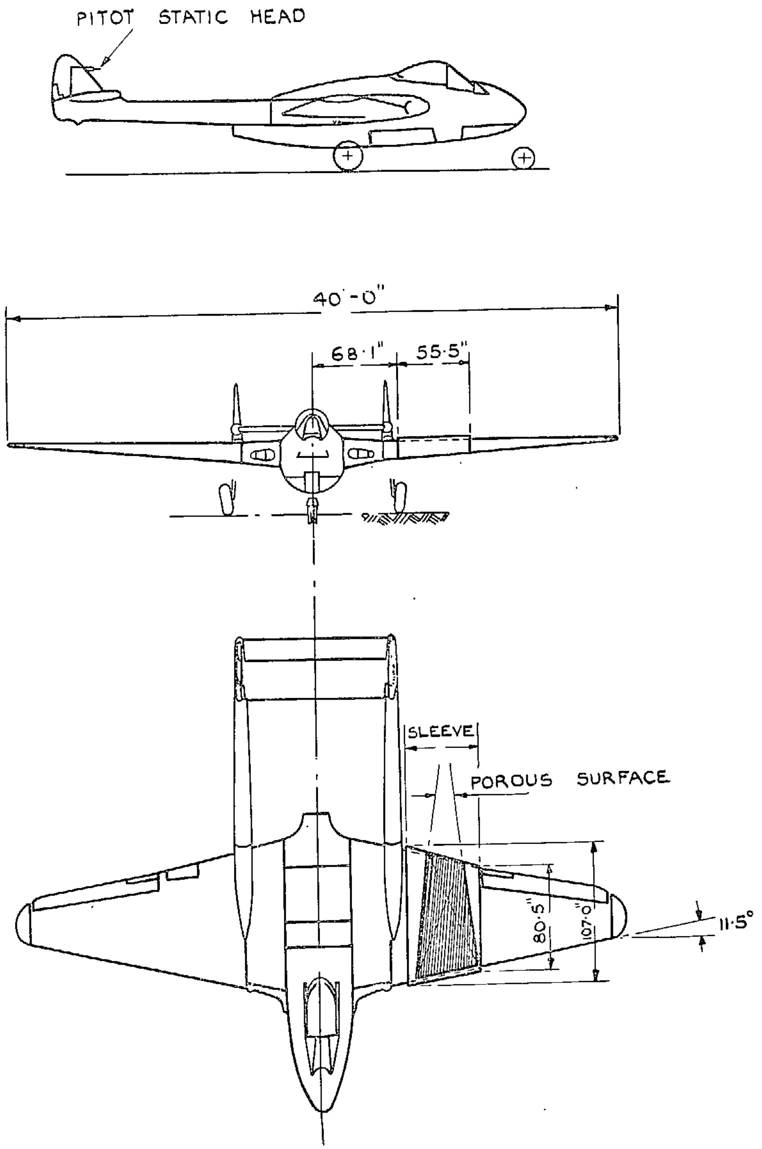


Fig. 3. G.A. of *Vampire* showing sleeve.

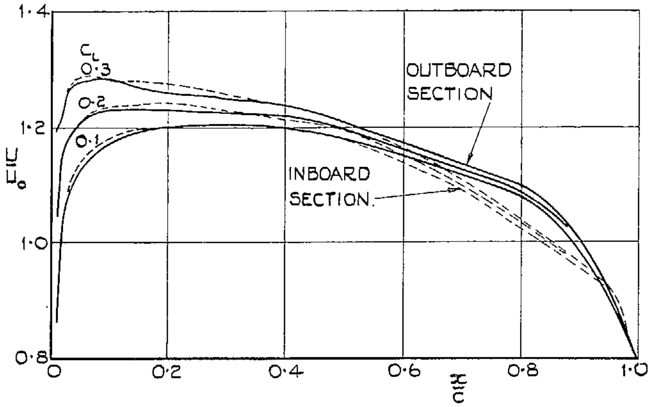


Fig. 4. Calculated velocity distributions over upper surface of sleeve.

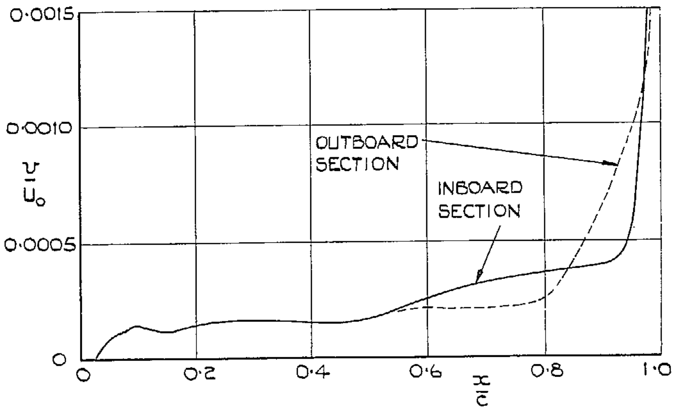


Fig. 5. Calculated distribution of suction velocity.

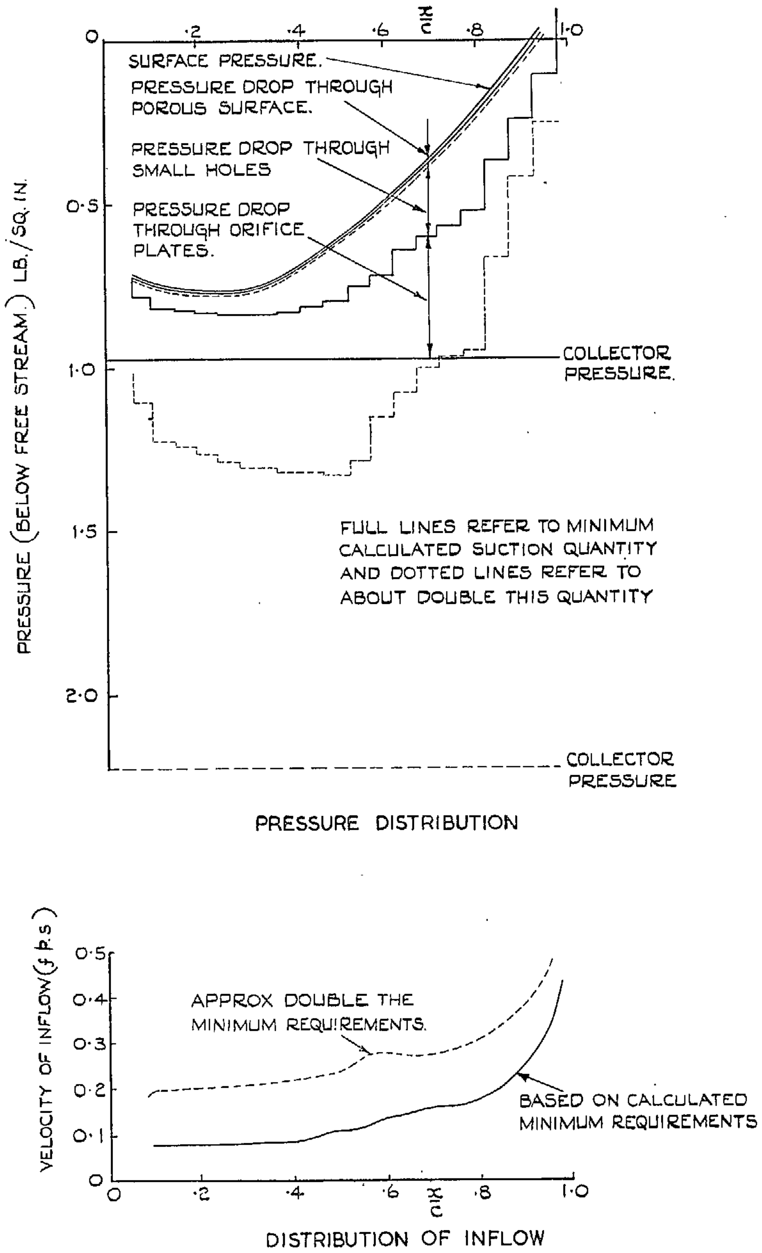


FIG. 6. Approximate distribution of pressure and inflow expected at $C_L = 0{\cdot}2$ (15,000 ft).

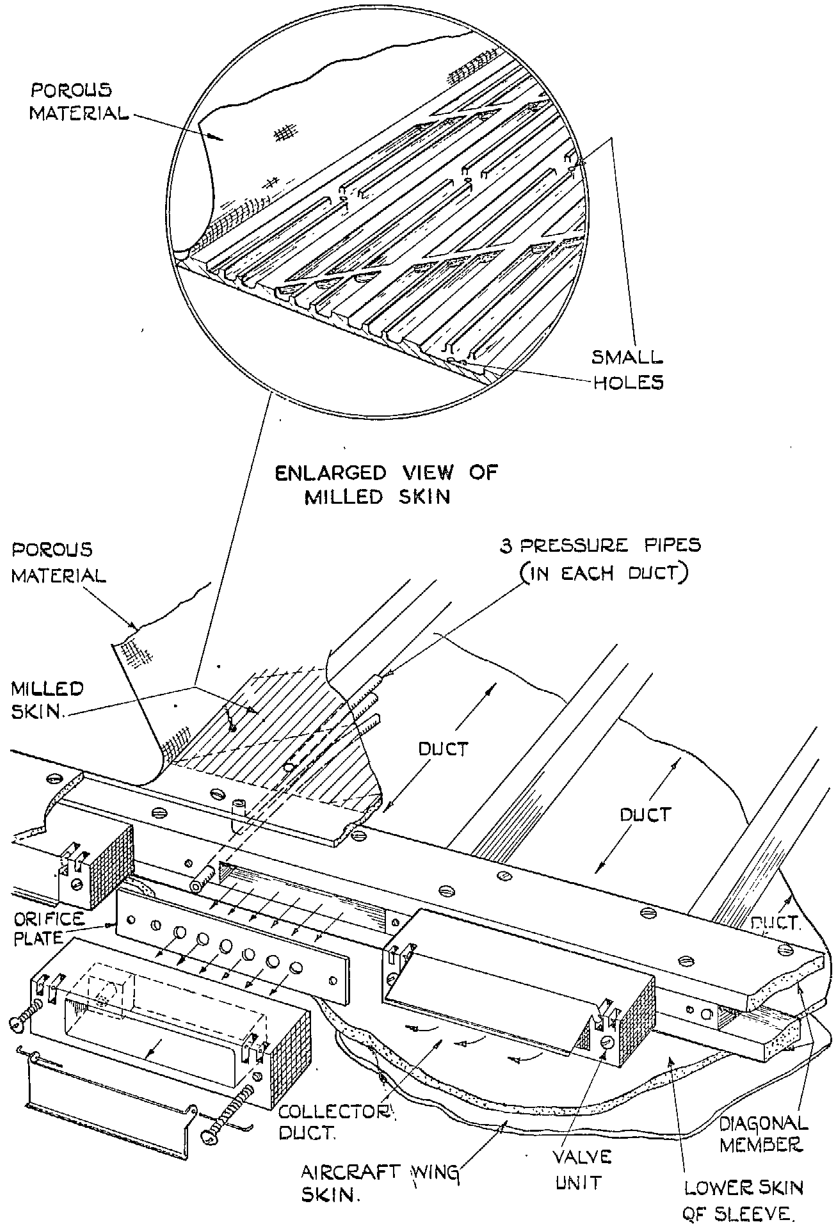


FIG. 7. Illustration of sleeve construction and non-return valves.

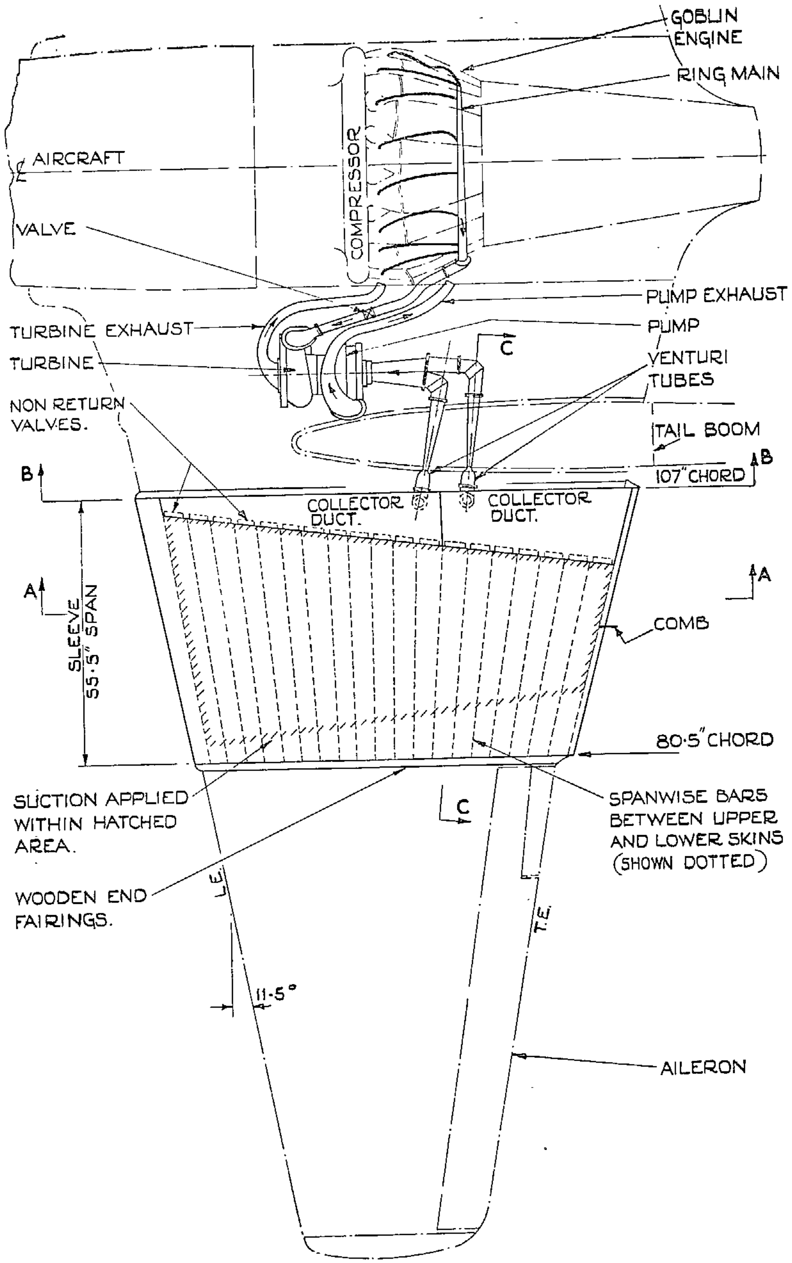


FIG. 8. General arrangement of sleeve and suction system.

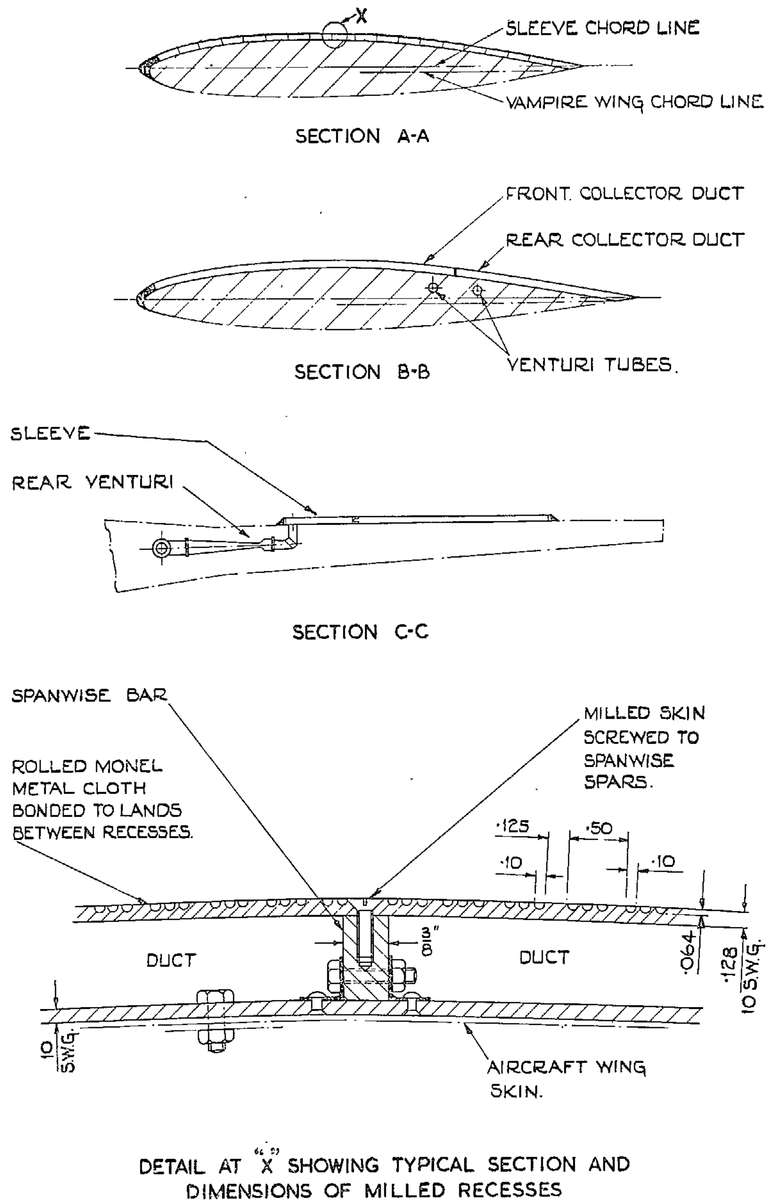


FIG. 9. Sections through sleeve.

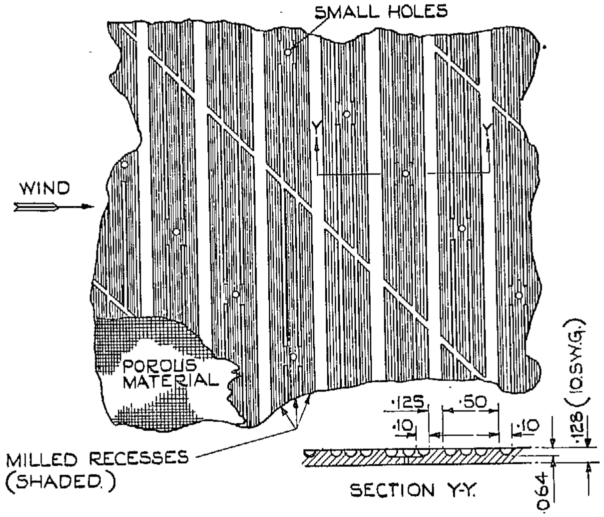


FIG. 10. Construction of the milled skin.

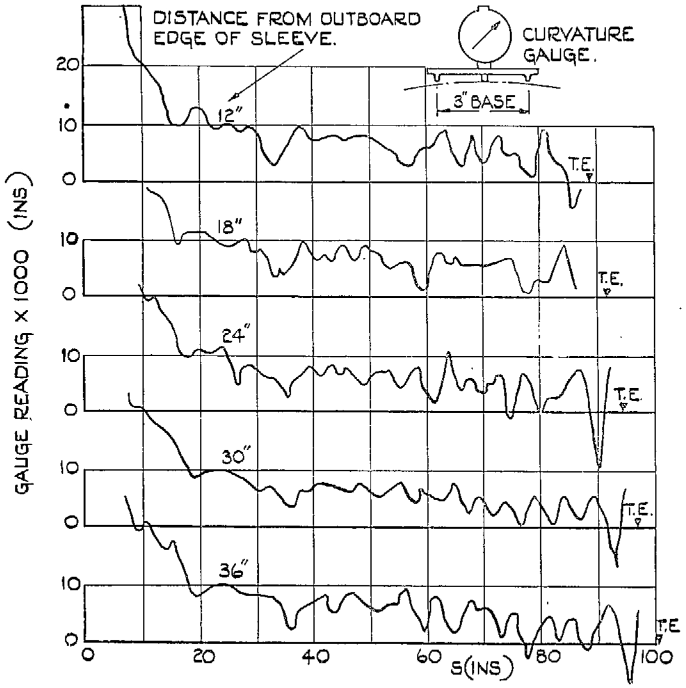


FIG. 11. Chordwise surface waviness as indicated by curvature gauge (3 in. base length).

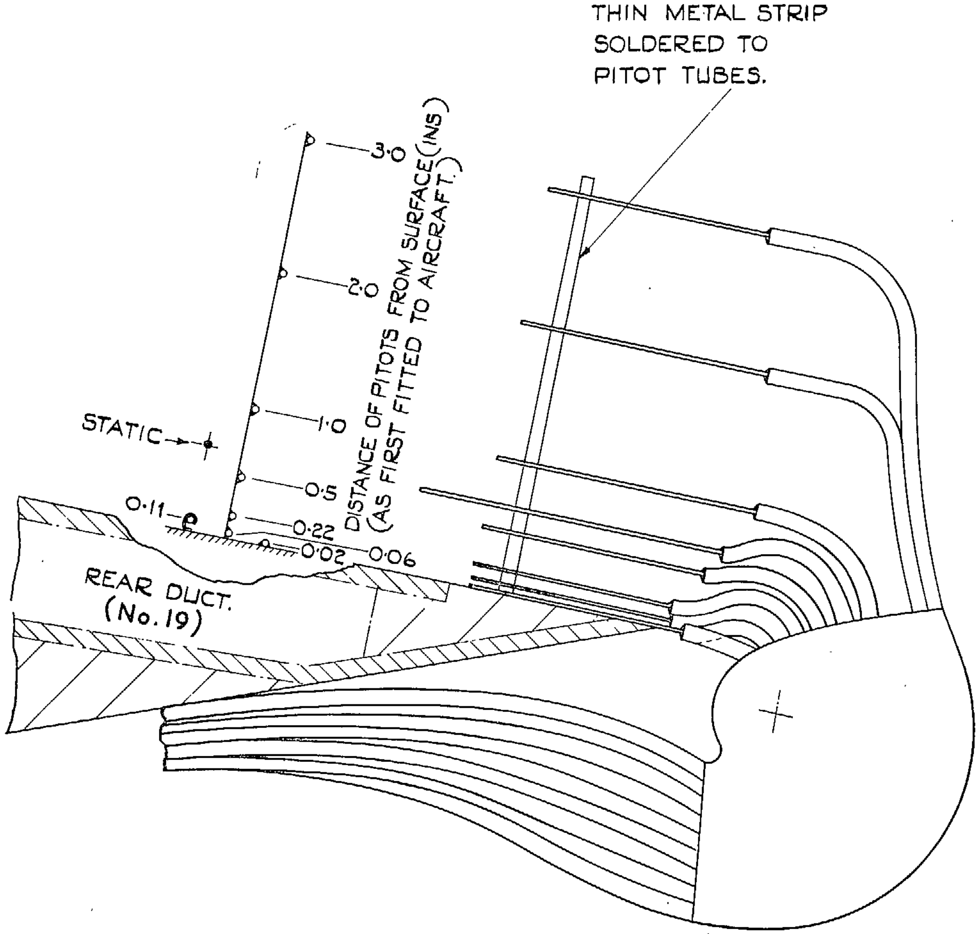


FIG. 12. Trailing-edge comb.

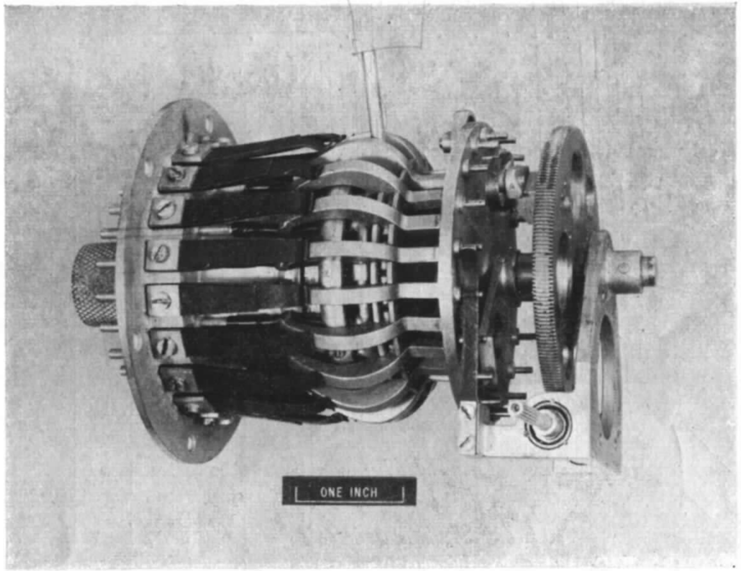


FIG. 13. Pressure-scanner unit.

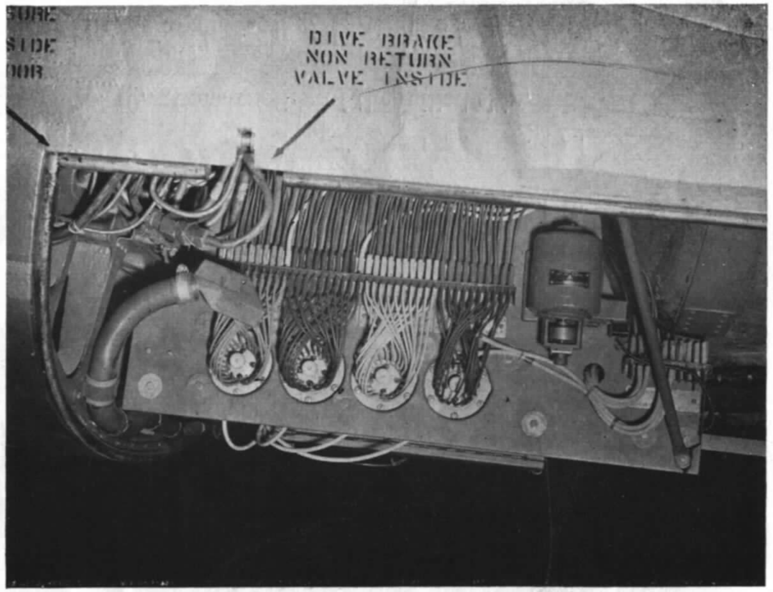


FIG. 14. Four pressure-scanner units mounted in aircraft.

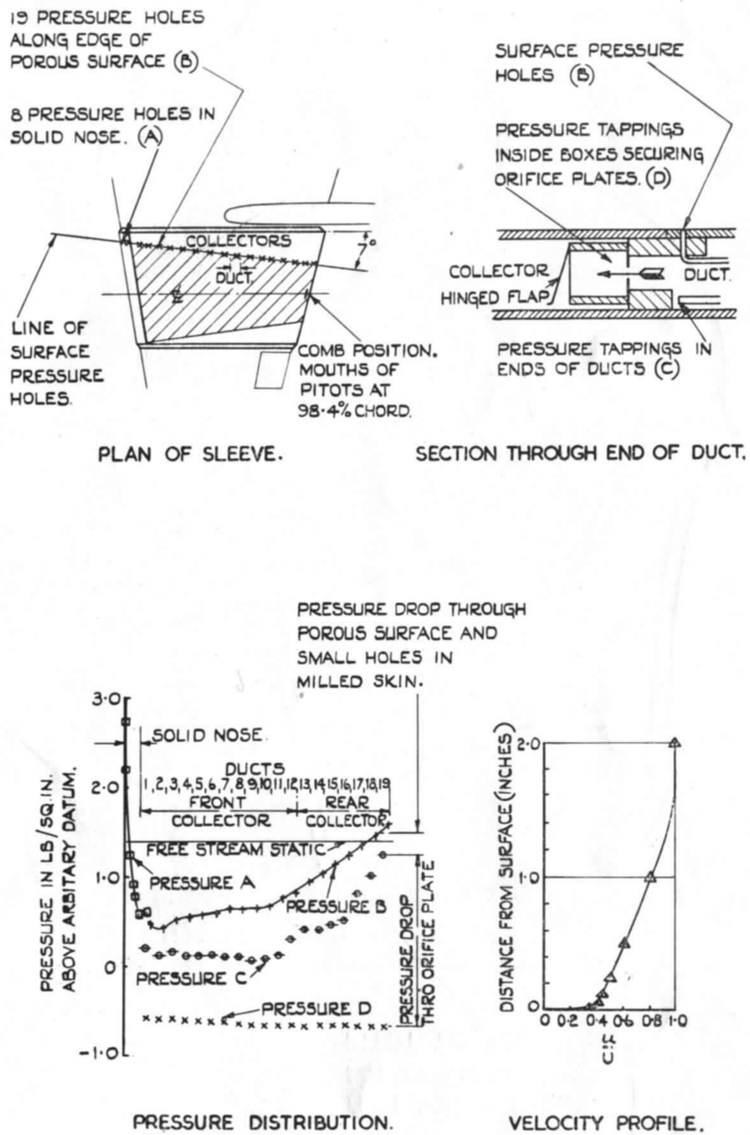


FIG. 15. Arrangement of pressure tappings and typical set of observations.

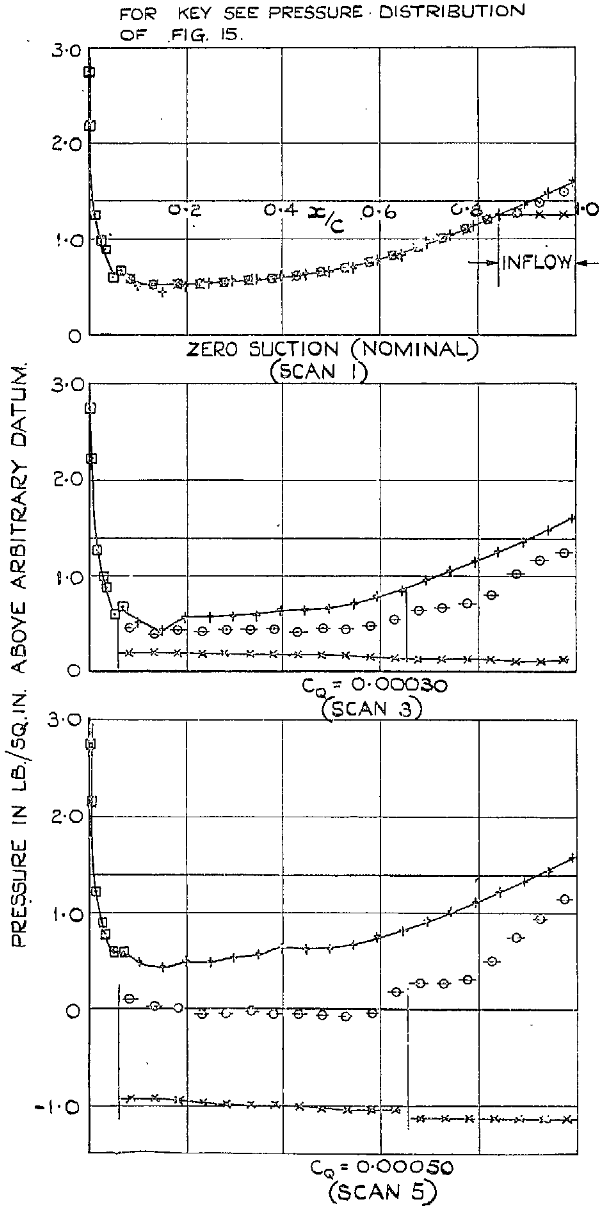


FIG. 16. Measured pressure distributions at three different rates of suction (Flight 1. C_L = 0·17. Altitude 15,000 ft).

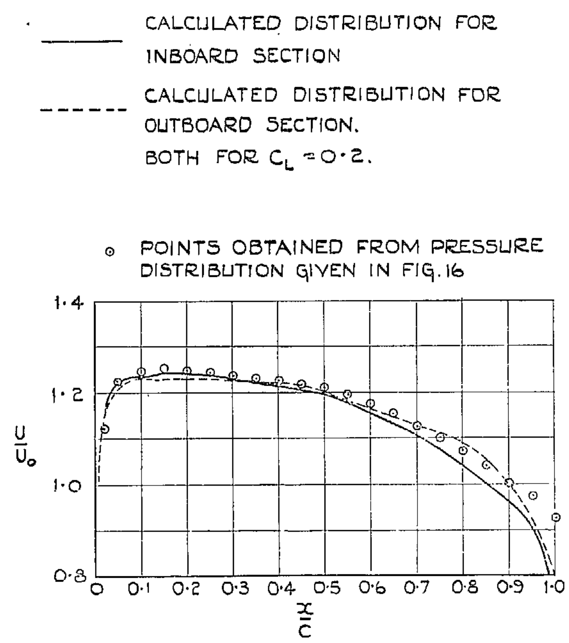
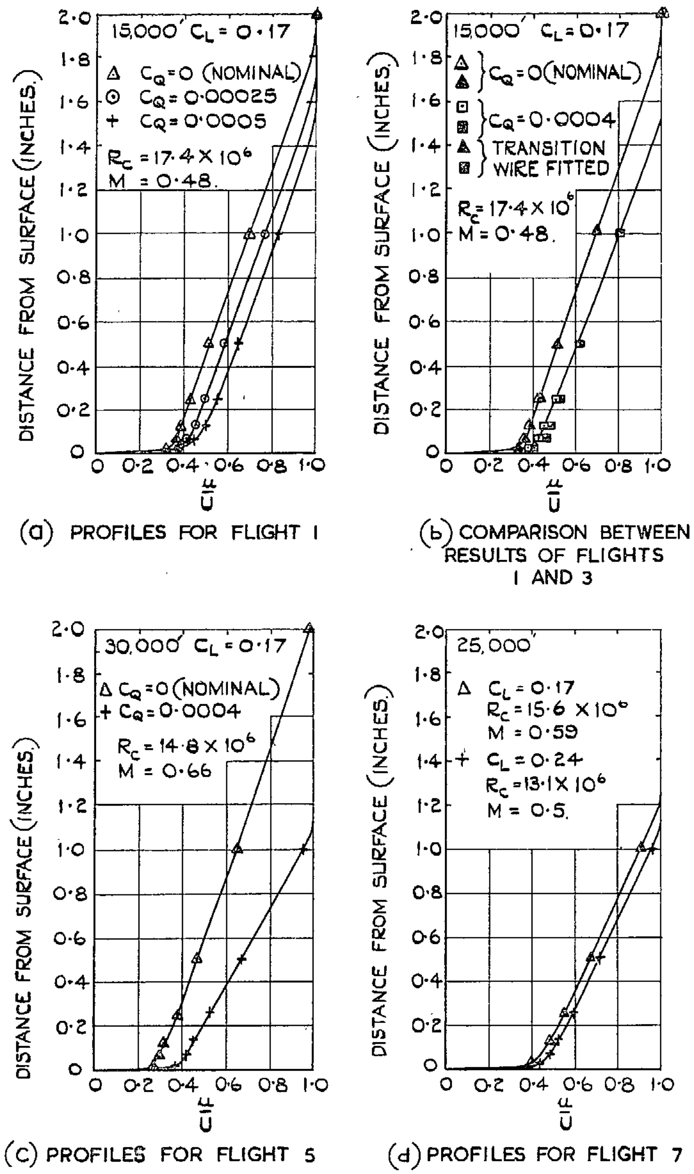


FIG. 17. Comparison between measured and calculated distributions of velocity over sleeve.



FIGS. 18a to 18d. Measured velocity profiles at 98·4-per-cent-chord initial tests with Monel-metal-cloth surface.

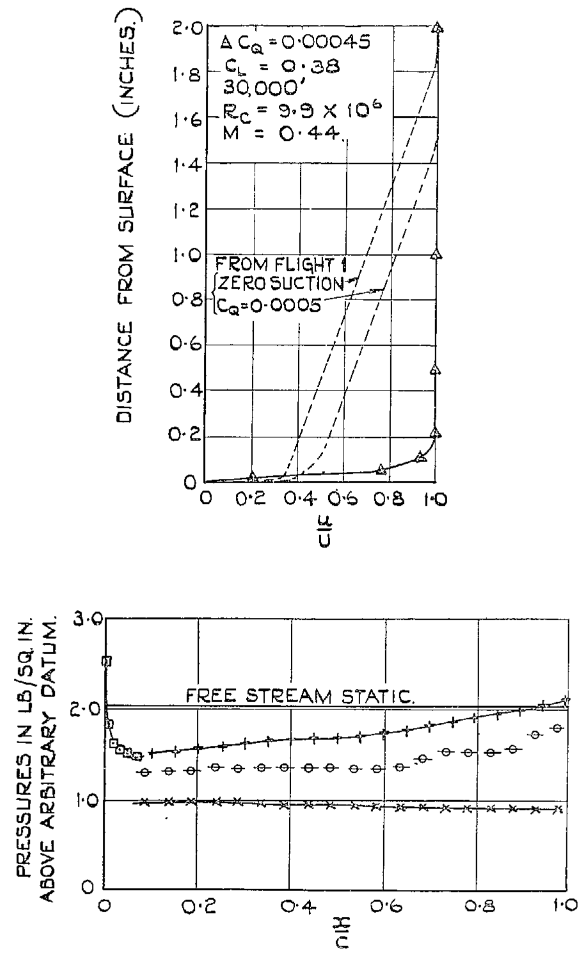


FIG. 19. Measured laminar velocity profile and pressure distribution. Nylon surface.

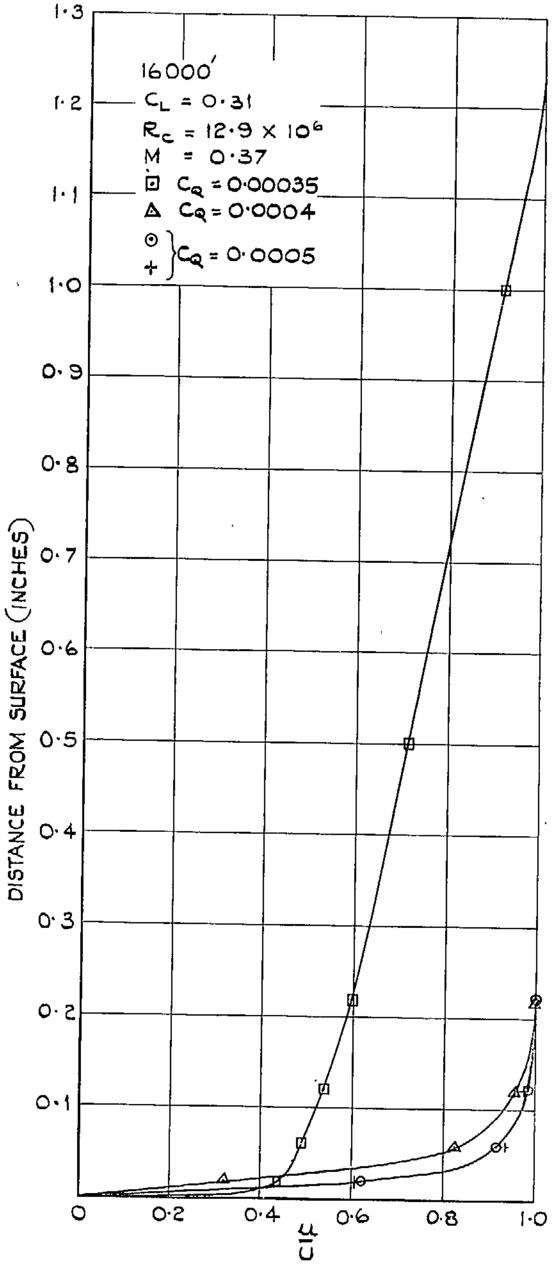


FIG. 20. Measured velocity profiles at 98·4 per cent chord. Nylon surface.

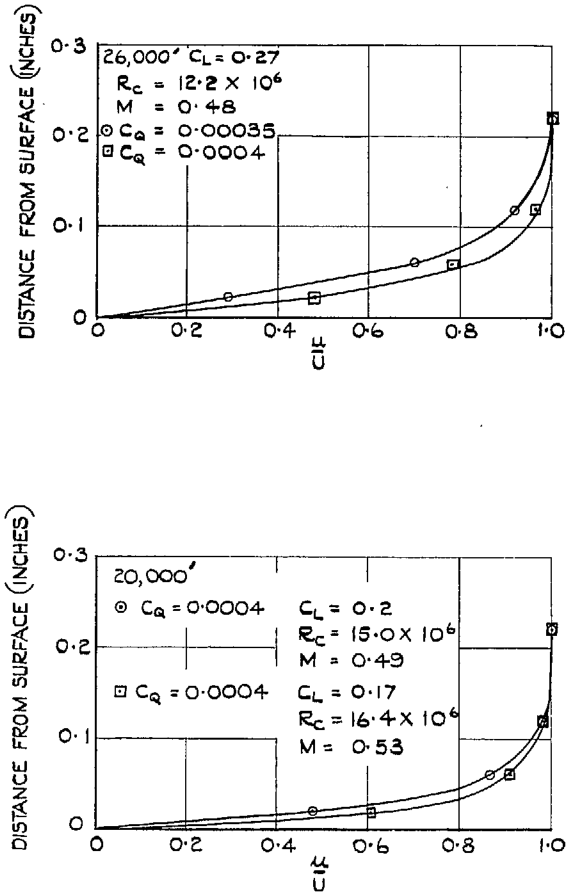


FIG. 21. Measured velocity profiles at 98·4 per cent chord. Nylon surface.

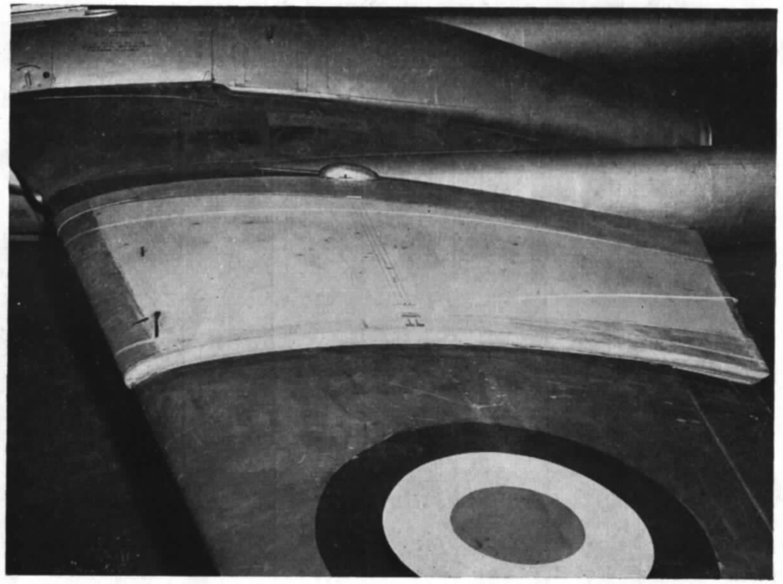


FIG. 22. Spanwise traversing surface pitot shown fitted to sleeve.

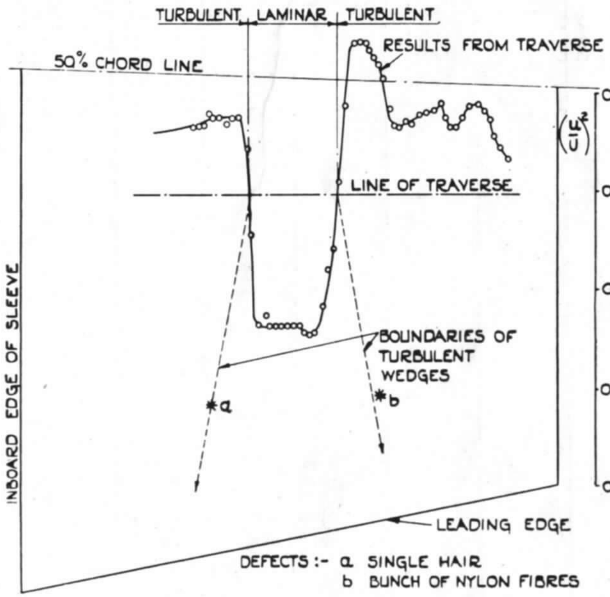


FIG. 23. Example of spanwise surface pitot record.

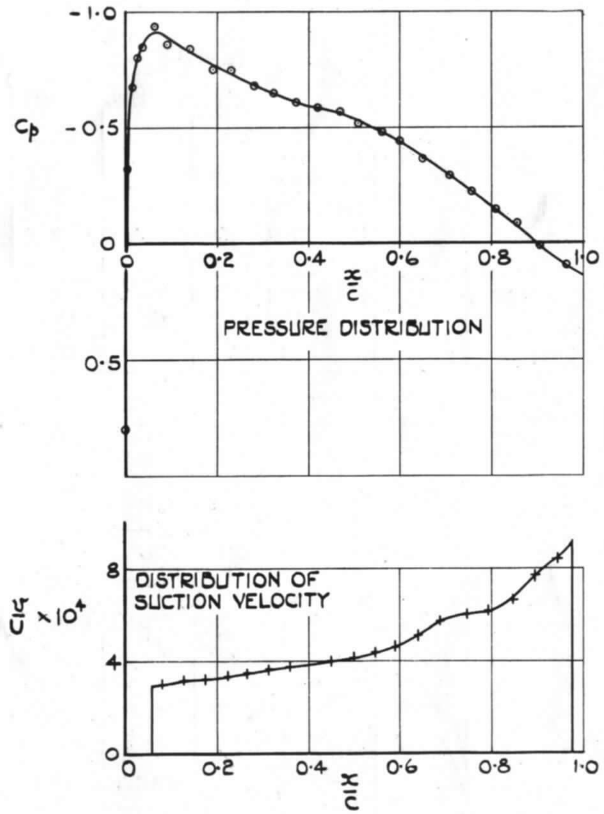


FIG. 24. Chordwise distributions of pressure and suction velocity used in calculations.

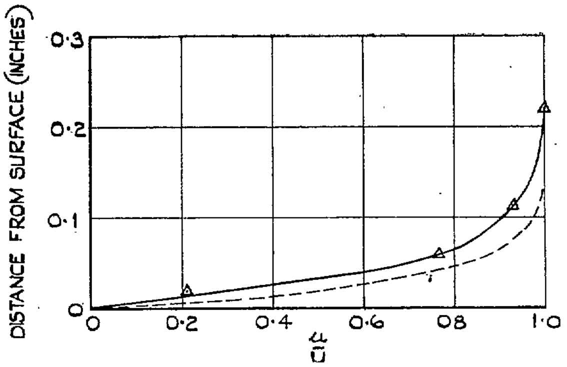


FIG. 25. Comparison between measured and calculated profiles.

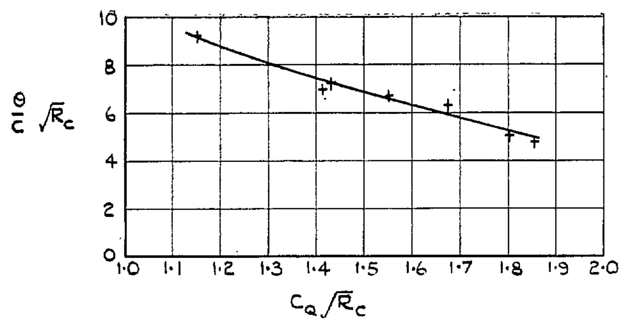


FIG. 26. Variation of momentum thickness with suction quantity coefficient.

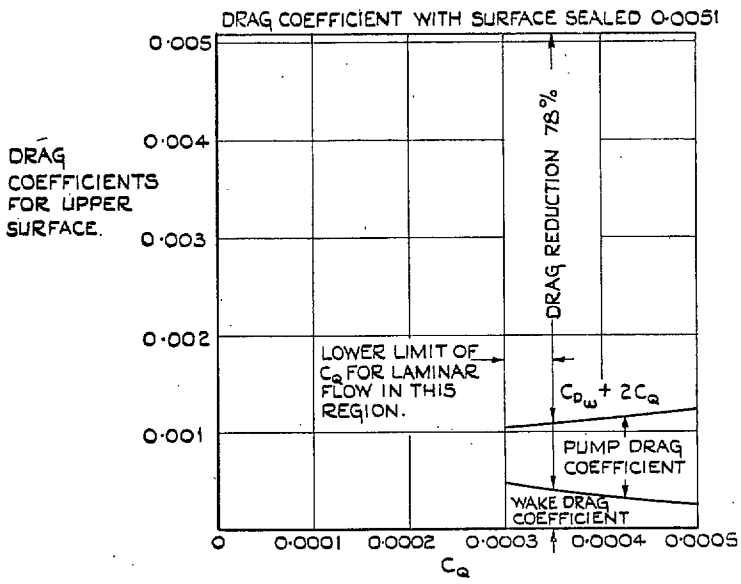


FIG. 27. Analysis of drag with suction.

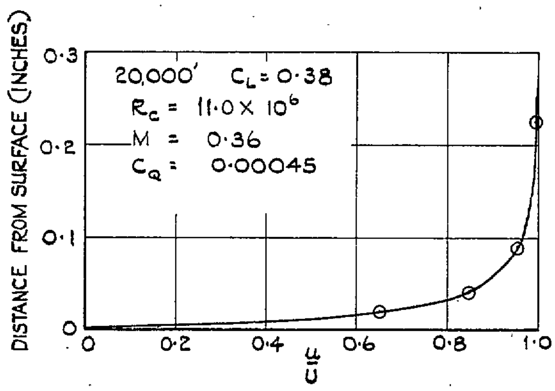


FIG. 28. Measured profile at 98·4 per cent chord (Monel-metal–cloth surface porous from 6 per cent chord).

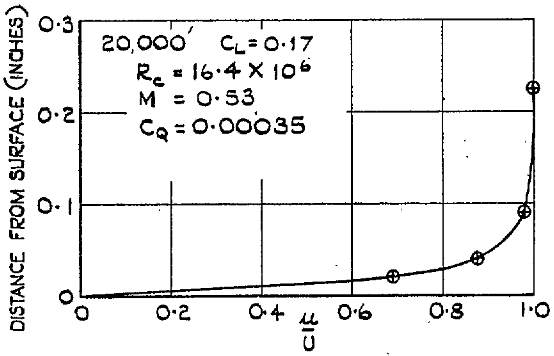


FIG. 29. Measured profile at 98·4 per cent chord (Monel-metal–cloth surface porous from 15 per cent chord).

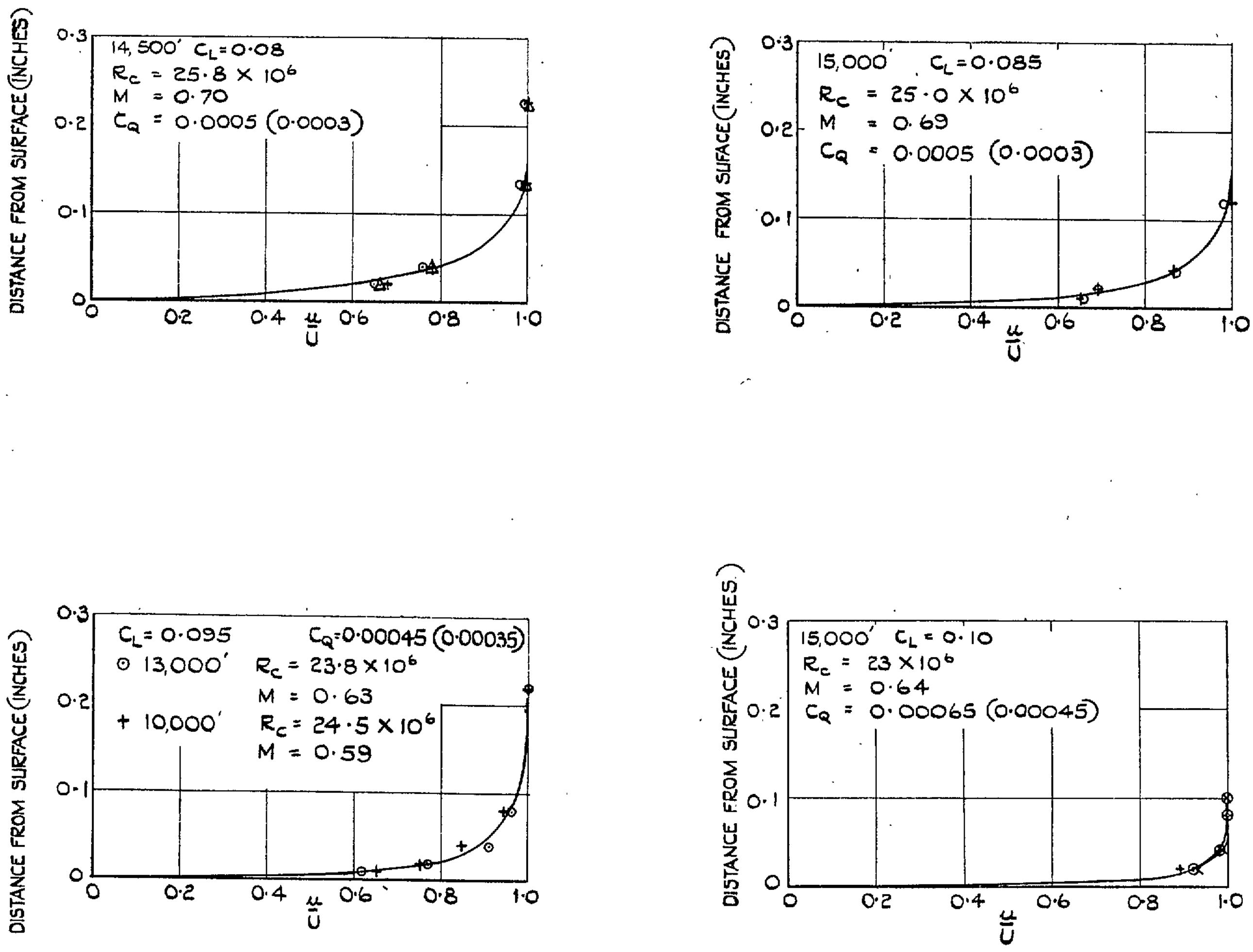


FIG. 30. Measured velocity profiles at 98·4 per cent chord (Monel-metal–cloth surface porous from 25 per cent chord).

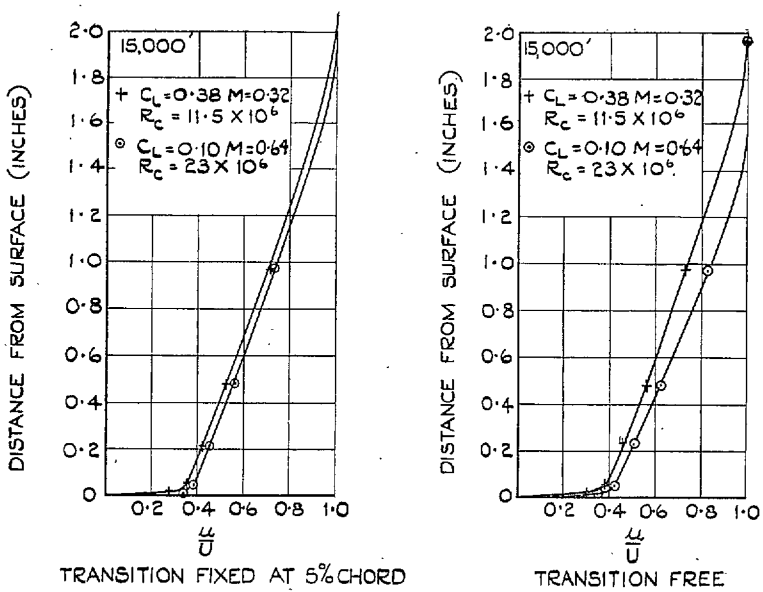


FIG. 31. Measured velocity profiles at 98·4 per cent chord (surface sealed and smooth).

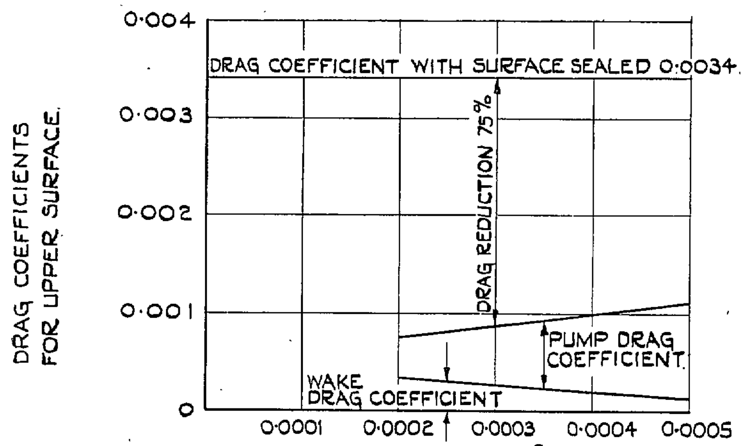


FIG. 32. Tentative drag analyses on data in Fig. 30 and assumption that $C_{De} = C_{Dw} + 2C_Q$.

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