ROYAL AIRCRAFT ESTABLISHMENT
BEDFORD.

ARC

MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

Tests on the Loss of Vertical Jet Thrust due to Ground Effect on Two Simple VTOL Planforms, with Particular Reference to the Short SC1 Aircraft

By L. A. WYATT, Ph.D.

Tests on the Loss of Vertical Jet Thrust due to Ground Effect on Two Simple VTOL Planforms, with Particular Reference to the Short SC1 Aircraft

By L. A. WYATT, Ph.D.

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

Reports and Memoranda No. 3313*
May, 1958

Summary.

The net vertical thrust available to an aircraft for vertical take-off and landing falls off with proximity to the ground. Measurements have been made of this thrust loss as a function of wing height above the ground, on plane circular and delta wings, and on a 1/6th scale model of the Short SC1 aircraft. At normal undercarriage height, the Short SC1 would lose nearly 20% of its vertical thrust, but a scheme has been developed to reduce the thrust loss to negligible proportions.

---

1. *Introduction.*

Much research is currently devoted towards achieving vertical take-off and landing (VTOL) without seriously limiting aircraft performance in the normal forward-flight condition. One possible VTOL configuration, exemplified by the Short SC1 aircraft, consists of a conventional aircraft fitted with additional engines to give vertical thrust for take-off and landing only. These lifting engines, of low specific weight, may be placed centrally in the fuselage so that they exhaust vertically downwards below the wing, which is maintained essentially horizontal when the aircraft is close to the ground.

The presence of the ground affects adversely the take-off and landing characteristics of such an aircraft. The flow regime which is induced between the wing and the ground by the jet efflux includes a region whose pressure is less than that of the atmosphere above the wing. The resulting download due to suction on the wing lower surface reduces the net vertical thrust available, and an abnormally large margin of available thrust over total weight must be provided to ensure safe take-off at maximum weight. The problem is less severe when landing because the thrust/weight ratio exceeds that at take-off. However, during landing, the aircraft would experience an increasing acceleration towards the ground, and when hovering near the ground would be in an unstable equilibrium. The permissible rate of descent might be restricted by this effect and by related considerations of undercarriage strength.

---

* Replaces A.R.C. 20,369.

The Short SC1 research aircraft was designed to investigate problems associated with VTOL and with the transition to and from forward flight. Fig. 1 gives a G.A. of the aircraft and Table 1 lists the relevant data. The aircraft has a fixed delta wing of aspect ratio $2 \cdot 61$; four centrally placed Rolls-Royce RB 108 engines provide the required vertical thrust for VTOL, and a fifth engine is installed at the rear of the fuselage for forward flight.

Tests were made at Royal Aircraft Establishment, Bedford, to measure this ground effect on jet lift, first on simple planforms and later on a simplified scale model of the Short SC1. On the latter model, the suction due to ground effect at the design undercarriage height proved to be of the order of 20% of the jet thrust, and a scheme was therefore developed to reduce the downwards suction, thereby alleviating one of the problems of this version of VTOL.

2. *Flow between Wing and Ground.*

2.1. *Basic Flow Pattern.*

The physical nature of the flow pattern induced by a jet directed downwards from a wing near the ground was investigated only briefly during small-scale experiments on circular wings, but seems to be as follows. The jet spreads out radially from its point of impact with the ground. Due to entrainment of air into the jet by turbulent mixing, the jet expands and its upper boundary moves away from the ground. An additional smaller upward movement of the jet boundary arises from the growth of a boundary layer on the ground, which may even separate under the influence of the adverse pressure gradient experienced as the jet diffuses outwards. Approximately 1/6th of the jet is likely to be occupied by the boundary layer[7].

Consider a wing at such a height above the ground that it is well above the free boundary of the spreading jet. Due to the turbulent mixing at the edge of the jet, air is entrained into the jet from the regions below and outboard of the wing. A region of reduced pressure is created beneath the wing, which therefore experiences a suction towards the ground. Assuming the amount of air being entrained to remain roughly constant as the wing-ground height is reduced, the velocity imparted to the entrained flow must increase. Consequently, a greater fall in pressure occurs below the wing, and the suction force on the under surface increases correspondingly.

As the wing-ground clearance is reduced even further, the suction is found to increase more rapidly, probably because of a fundamental change in the flow pattern. The vertical growth of the jet may be such that it occupies the whole space between the wing and the ground over the outer sections of the wing. Air is then no longer entrained from the regions outboard of the wing, and a closed rotating flow with a low-pressure core is left beneath the inboard section of the wing. The boundary layer inside the jet may even separate with the formation of reversed flow over the ground.

Such flow regimes have been observed in small-scale experiments on the flow beneath circular wings (*see* Fig. 11 and Section 5.2). It may be noted that a ground effect of similar origin to that described in this report has been observed during jet-flap experiments[1].

2.2. *Scheme for Modifying Flow Regime.*

In practice, undercarriage length cannot be increased sufficiently to reduce the suction to a negligible amount, and measures such as the spanwise deflection of part of the jet efflux along the under surface of the wing are prohibited because of temperature effects on the structure. Furthermore, attempts to break up the flow pattern beneath a wing by lowering flaps did not prove encouraging. However, modification of the jet flow at the surface of the ground seemed worth investigation as a possible remedy.

Attempts were made to constrain the jet flow by allowing it to exhaust into parallel channels placed on the ground. It seemed likely that the mixing surface of the jet would be drastically reduced, together with the resulting entrainment of air and suction force on the wing. In addition, the jet would no longer be meeting an adverse pressure gradient. A little entrainment of air (and associated suction) would still occur, but it would be much smaller than in the absence of the channels and should be less dependent on the wing-ground clearance, providing that the jet were fully contained inside the channels at all wing positions.

3. Experimental Details.

The experiments were made in three distinct stages. Small circular wings, each with a single central jet, were used in exploratory tests to indicate the magnitude of the ground effect and to demonstrate the effectiveness of channels in reducing the suction. The main experiments, to determine an optimum size for the channels, were made on plane equal-area wings of circular and delta planforms. These wings were of 1/5th scale relative to the Short SC1 aircraft*, and each had a single central jet whose thrust was designed to preserve approximately the full-scale value of thrust/wing area appropriate to the SC1. Finally, tests were made on a 1/6th scale model of the Short SC1 provided by Short Bros. and Harland Ltd. This model incorporated a representation of the full-scale jet layout with four exits, and was fitted with a simple body.

3.1. Small-Scale-Model Tests.

The small models, of 1/22nd and 1/33rd scale relative to the SC1*, were plane plywood discs, with a single jet issuing from the centre. Table 2 gives details of the model and jet sizes used, and Fig. 2 shows a sketch of the model rig. Each wing could be mounted on one arm of parallel-motion scales clamped to a horizontal platform to which the jet was rigidly attached. The platform could be raised or lowered to vary the distance between the wing and a ground board supported above it. The jet and the wing were independent of one another, the balance measuring only the suction due to the presence of the ground. These principles were followed in the design of the rig for the 1/5th scale tests.

Using various wing-jet combinations, the suction due to ground effect was measured as a function of wing-ground separation H. The three available jets were used at thrusts T varying from $0 \cdot 03$ to $0 \cdot 45$ lb, and the thrust loading ($T/\bar{S}$) varied between $0 \cdot 07$ and $2 \cdot 25$ lb/sq ft; the full-scale SC1 thrust loading is of order 40 lb/sq ft. The effect of channels, formed by screwing lengths of brass angle to the ground board, was investigated with one wing-jet combination only, namely the 9 in. diameter wing and the 1/8 in. diameter jet. Channel heights and widths are included in Table 2.

3.2. Details of 1/5th Scale Wings.

The main tests used 1/5th scale circular and delta planforms of equal area (see Table 3 and Fig. 3). Each wing was made from 1 in. thick plywood, and had a central clearance hole cut to accommodate the independently mounted jet, as illustrated in Fig. 3. Three supports were positioned symmetrically about the jet centre. The delta wing did not reproduce exactly the aspect ratio appropriate to the SC1 since, although the leading-edge sweep had been preserved, the ratio of tip chord to root chord was zero as opposed to the full-scale value of 1/17. The centre of the jet was farther aft in terms of the root chord than on the SC1.

* For wings of different planform from the SC1, the relative scale is defined as the square root of the ratio of the wing areas.

3

The circular wing was chosen as a suitable shape with which to investigate the optimum channel characteristics because orientation of the channels relative to the wing fore-and-aft axis was not a variable. The delta wing was to serve as a comparison with the circular wing and to indicate the effect on the channels of orientation to the wing centre-line.

3.3. *Rig for 1/5th Scale Wings.*

In order to obtain an air supply up to 10 lb/sec for the 1/5th (and 1/6th) scale experiments, use was made of the High Speed Laboratory facilities at R.A.E., Bedford. To preserve a representative value of the thrust loading $T/\bar{S}$, the circular jet was designed to produce a thrust of order 300 lb. The jet exit area was chosen so that the jet was just choked, this being a repeatable operating condition.

A suitable contraction shape of contraction ratio 4·22:1 was chosen[2] to match the jet orifice to the main air supply pipe, a parallel settling length of 4 in. (about 1 jet diameter) being added after the contraction. Pressure tappings were inserted immediately ahead of the contraction and of the jet orifice. Although the air supply pipe included three simple right-angle bends, the last of which was immediately upstream of the contraction, the jet flow proved to be axi-symmetric. A section of the combined contraction and jet orifice is shown in Fig. 4, together with a typical velocity profile across the jet. Over the central portion of the jet, the amplitude of the variation of velocity is about 1% of the mean jet velocity. The final thrust was 270 lb ($\pm 5\%$) i.e., some 10% short of the one-dimensional-flow design value. The corresponding thrust loading on the wings was 30·9 lb/sq ft.

The mounting of the nozzle with the jet issuing vertically upwards is shown in Fig. 5 which illustrates the complete test rig. Each model was supported horizontally with its upper surface level with the jet orifice. The models were suspended from three electrically operated mechanical balances rigidly fixed to a stout wooden bridge erected over the model. A 12 ft square ground board was supported from a frame of scaffolding built around and above the model. The ground could be raised, lowered, pitched or rolled relative to the model. The model was braced horizontally by wires adjusted to maintain the small clearance between the wing and the nozzle.

Each remotely operated balance had a range of 100 lb with a sensitivity of 0·01 lb. The registered forces were usually somewhat unsteady, particularly at the smaller ground clearances, and a reading accuracy of 0·05 lb was achieved in practice. The sum of the balance readings gave the total suction on the model, and pitching and rolling moments were easily obtained by combining the readings. It should be noted that the balances always read the forces normal to the plane of the wing, but it is thought unlikely that any appreciable error could arise due to the non-measurement of any forces on the square-cut edges of the wings.

In operating the jet, the air flow was controlled by adjusting the main compressor speed to maintain an appropriate reservoir pressure to within 0·05 in. mercury. The mass-flow rate was obtained with the aid of an orifice plate in the air supply pipe, and was kept constant at 0·263 slugs/sec ($\pm 2\%$) i.e., 8·46 lb/sec. The details of the determination of the jet mass flow and thrust are given in Appendix I. The average exit velocity of the jet was 1030 ft/sec compared with the full-scale value of order 1450 ft/sec, and the mass flow was correspondingly about 35% higher than the true scaled value.

3.4. *Model Channels and Landing Platform.*

Channel heights h of $1\frac{1}{2}$, $2\frac{1}{2}$ and $3\frac{1}{2}$ in. were available, formed from lengths of iron angle, all with

a web of $\frac{1}{4}$ in. The width of the flange bolted to the ground was always $1\frac{1}{2}$ in., so that a small step was left along the ground whenever channel widths w greater than $1\frac{1}{2}$ in. were used (*see* Fig. 6).

One test was made with a grid placed above the channels to represent approximately, in shape and solid blockage, the full-scale Lionweld landing platform to be used with the SC1 (*see* Fig. 7). The model blockage of 29% compared well with the full-scale value of 31%, but the grid mesh was too large. The effect of the grid on the measured suction will strictly depend on the pressure drop associated with the drag of the platform immersed in the jet efflux, but in the absence of any evidence on the drag of the full-scale flooring, solid blockage was chosen as the main parameter. It is likely that the drag coefficient of the model platform would exceed that of the full-scale flooring, judging by the relative geometry, so that the evidence obtained on the model scale should prove somewhat pessimistic.

3.5. *Range of Tests on 1/5th Scale Models.*

With the circular wing in the horizontal position parallel to the ground, the suction due to ground effect was measured over a wide range of wing-ground separation. These tests were repeated with the wing at several angles of roll up to 15° to investigate any induced rolling moments. Extensive measurements were made at two values of the wing-ground separation with channels of varying height and width to determine the optimum arrangement for reducing the suction. Channel lengths equal to the wing diameter and to the wing radius were tried. Tests were then made with the more promising channel arrangements with the wing rolled at 5° and 10° to check the effect of channel orientation relative to the roll axis. Orientations of 0°, 45° and 90° were used.

With the delta wing, the ground effect was investigated over a smaller range of wing heights centred on the scaled SC1 undercarriage height (*a*) with the wing horizontal, (*b*) with the wing rolled 5° and 10°, and (*c*) with the wing at incidences of ± 5° and ± 10°. The optimum channel sizes determined from the circular-wing results were then tested at several wing heights for case (*a*), and at the undercarriage height only for cases (*b*) and (*c*)—in each case, the channel orientation was varied between 0° and 90°.

3.6. *Details of 1/6th Scale Short SC1 Model.*

The final series of tests were made using a simplified 1/6th scale wooden model of the Short SC1 (*see* Fig. 8) mounted on the rig described in Section 3.3. The wings were of constant thickness with a rounded leading edge and a bevelled trailing edge. The body had a rectangular aperture to accommodate freely a scaled representation of the SC1 jet arrangement with four nozzles, but its upper surface was not shaped and a fin was not represented.

3.7. *Contraction and Nozzles for SC1 Model.*

Three sets of detachable nozzles and fairings, together with a specially designed contraction, were supplied by Short Bros. to simulate various flight conditions. Fig. 9 shows the contraction cone, together with the two distinct types of nozzle-fairing combinations fitted to produce circular and annular jets: data on the nozzles are given in Table 4.

The nozzle-fairing combinations will be designated by the titles 'large annular', 'circular' and 'small annular'. The 'large annular' set was a scale representation of the SC1 annular jet exits to be used at the scaled thrusts corresponding to hovering at maximum and minimum weights. The 'circular' set had the same exit area as the large annular set and was tested in the same conditions,

so that the effect of exit geometry could be determined. The 'small annular' set had annular exits of the correct scaled outer diameter but the diameter of the fairing end was increased so that, with approximately choking conditions at the exit, the scaled mass flow corresponding to hovering at minimum weight would be reproduced. As with the single jet used in the 1/5th scale experiments, the representative thrust and mass flow could not be reproduced simultaneously. Table 5 gives the full-scale values of total engine thrust and mass flow for the Short SC1 hovering at maximum and minimum weights.

3.8. *Range of Tests on* 1/6*th Scale Short SC*1.

The range of conditions covered in the tests was extended beyond that specified by Shorts. Each of the three nozzle sets was used, as far as possible, so that the scaled thrusts were reproduced (at too high a mass flow) and also so that the scaled mass flows were reproduced (at too low a thrust). The scaled thrusts could not be reached with the small annular set, because of limitations on the operation of the main compressor. Table 6 shows the scaled values of thrust and mass flow used (corresponding to the full-scale values of Table 5), together with the respective experimental values of mass flow and thrust achieved. The table illustrates the wide range of conditions covered by the tests.

Under each set of conditions listed in Table 6, the suction and pitching moment due to ground effect were measured over a range of wing-ground separations centred on the undercarriage height, with the wing level. The channels were tested over a similar range, using two channel heights. Specimen tests were carried out to check that, with the new four-jet arrangement, the optimum channel size was of the same order as that found in the 1/5th scale experiments. Channel orientation relative to the model centre-line was varied over the range 0 to 90°. No tests were made with the model at incidence or rolled, it being considered that the 1/5th scale tests on the delta wing were adequate in these respects.

The method of measuring the thrust from the four jets of the SC1 model by allowing the jet efflux to strike a disc suspended from the test rig balances is described in Appendix II.

4. *Presentation of Results.*

The small-scale-model results on the suction due to ground effect were found to collapse best if the suction S, made non-dimensional by dividing by the thrust T, were plotted as a function of the wing height H divided by the wing diameter D. Plots of S/T as a function of H divided by the jet diameter d did not produce anything approaching a universal curve, indicating that, for the ranges of d/D and Reynolds number involved, S/T and H/D were the most important non-dimensional quantities. This form of presentation was used for the small-scale and 1/5th scale results.

The wing-ground separation H was measured from the lower surface of the wing to the ground or to the top of the channels, thereby acknowledging that the undercarriage would eventually rest on a suitable platform covering the channels. For both the circular and delta equal-area wings of 1/5th scale, the non-dimensional separation was taken as H/D so that the effect of planform variation could be seen, but, for the 1/6th scale SC1 results, H was made non-dimensional by reference to the specific undercarriage height H_u, this presentation being more useful to the designer. The two methods are of course equivalent since, for the SC1, $H/D = H_u/D \times H/H_u = 0 \cdot 28 H/H_u$. For each 1/5th scale wing, the moments were converted into coefficients by dividing by $\frac{1}{2}TD$ i.e., the coefficient gives the fraction of the thrust needed at an arm of $\frac{1}{2}D$ to correct the moment. All moments were computed about the jet centre. The moment coefficients are easily related to those using the

mean geometric chord $\bar{c}$ as the normalizing length, since, for the circular and delta wings, $\bar{c} = \pi/2 \times \frac{1}{2}D$ and $1\cdot05 \times \frac{1}{2}D$ respectively.

The moments measured on the Short SC1 model were converted to coefficients by dividing by the product $T\bar{c}$, the coefficient thus giving the thrust fraction needed at an arm of $\bar{c}$. The rolling-moment coefficients are directly usable in estimating control requirements, because the arm of the roll-control nozzles is closely equal to $\bar{c}$. The arm of the pitch-control nozzles is $1\cdot22\bar{c}$, so that the thrust fractions indicated for pitch control are correspondingly too large.

In the tests on channels, the channel width w and height h were both expressed as a fraction of the jet radius r. However, since the equivalent jet radius for the Short SC1 is not necessarily that of the single jet of equal area, the absolute channel dimensions on model scale have been quoted for that case.

5. Discussion of Small-scale Results.

5.1. Balance Measurements.

The results of the ground-suction tests on the 1/22nd and 1/33rd scale wings are presented in Fig. 10, together with a sketch defining the geometric dimensions of the system. The basic tests are indicated by two symbols, one for each wing, variations in jet size not being shown. In the tests with channels, no distinction is made between differing widths for the same channel height.

The curve of S/T against H/D confirms the satisfactory correlation of data from different wing-jet combinations. In these tests, d/D varied between $0\cdot014$ and $0\cdot083$ (see Table 2), but did not appear to be a significant parameter. The subsequent 1/5th scale models had a d/D value of $0\cdot11$ which lay only just outside the range of the small-scale tests, and the same method of presentation was therefore adopted for all later results.

Despite the small scale and the attendant experimental difficulties, these tests showed remarkably well the main features of the problem and its solution. In the absence of the channels, the S/T values exhibited what proved to be a characteristic sharp rise as H/D fell below $0\cdot3$. The suctions decreased very slowly for H/D values greater than $0\cdot5$. A typical undercarriage height would correspond to $H/D = 0\cdot28$, where the suction is between 20% and 30% of the thrust, so that Fig. 10 confirms that the suction cannot be reduced sufficiently by any practical increase of undercarriage length.

The lower curve of Fig. 10 confirms that the ground effect is significantly reduced if the jet efflux enters an array of parallel channels on the ground. At $H/D = 0\cdot28$, the channels reduced the suction by a factor of at least 5, to less than 5% of the thrust. The channels also delayed the rapid rise of the suction force at small values of H/D. The experiments suggested that the shallowest channels were least effective in reducing the suction, but it should be noted that the channel heights and widths were appreciably larger relative to the jet radius than the optimum values found in subsequent tests.

The quantitative values found in these tests were not regarded as directly applicable to the full-scale case because of the experimental difficulties and because of the possible existence of a substantial scale effect, as discussed later in Section 9.

5.2. Flow-Visualization Tests.

The flow over the wing lower surface and over the ground was visualized by the 'oil + titanium dioxide' technique, and Fig. 11 illustrates the three symmetrical flow patterns found as the parameter H/D was reduced from an initial value greater than $0\cdot3$.

For $H/D > 0.3$, pure inflow and outflow were observed on the wing and ground respectively. The pattern for $H/D = 0.194$ is of the type appropriate to the scaled SC1 undercarriage height ($H/D = 0.28$) i.e., the free boundary of the jet has just attached to the outer portion of the wing, and a closed rotating flow is developing beneath the inner portion. At the smallest H/D value of 0.083, the line on the wing separating the regions of inflow and outflow has moved inwards, and the jet boundary layer has separated from the ground. The rapid rise in ground suction as H/D is reduced below 0.3 seems to be associated with the formation of the closed flow beneath the wing.

As H/D is reduced below 0.08, the closed rotating region shrinks in size and the flow becomes no longer axi-symmetric in its outboard sections. Regions of outflow begin to predominate over both wing and ground, and the flow pattern is obviously tending to that appropriate to the very small separation of an air-lubricated thrust bearing.

6. *Discussion of Results for 1/5th Scale Circular Wing.*

6.1. *Balance Tests.*

The measurements of the suction due to ground effect, presented in Fig. 12 as a plot of S/T as a function of H/D, were made with the wing horizontal and rolled at angles of 5°, 10° and 15°. The curve for zero roll is similar to that given in Fig. 10 for the small-scale wings, especially at the smaller values of H/D. At the usual undercarriage height ($H/D = 0.28$), the suction is again about 20% of the thrust, and the rapid rise in the suction still occurs when H/D falls below 0.3. The application of roll at a fixed wing height increases the ground suction until the roll is such that a wing tip enters the jet spreading over the ground. The increased suction on the wing nearing the ground presumably outweighs the decreased suction on the wing retreating from the ground. An inflexion in the S/T curve shows where the tip of a rolled wing is nearing the jet, e.g., in the curve for $\phi = 10°$ at H/D of order 0.175.

Fig. 13 shows the rolling moments developed on the wing due to roll near the ground, the curve for $\phi = 10°$ being typical of the variation of the moment coefficient with distance from the ground. For $H/D > 0.2$, the moment is small, stable and varies slowly. For $H/D < 0.2$, the moment becomes unstable and varies more rapidly, the unstable change tallying approximately with the beginning of the sharp rise in the S/T curve of Fig. 12. At the undercarriage height, the rolling-moment coefficient is less than 0.01 in magnitude. The fore-and-aft symmetry of the model and the ground was such that no appreciable pitching moments could be detected with roll applied.

6.2. *Channel Tests.*

The ground suction was measured in the presence of channels of various heights and widths at fixed H/D values of 0.175, 0.225, 0.295 (*see* Fig. 14). For the last value, the model roll ϕ was varied from zero, and the orientation of the channels β to the fore-and-aft (i.e., rolling) axis was varied between 0° and 90°.

The efficiency of the channels was judged from four points of view—firstly, their effectiveness in reducing the suction due to ground effect: secondly, the critical nature of the channel size: thirdly, the variation of the suction with lateral position of the jet over the channels: fourthly, the magnitude of any unwanted pitching or rolling moments developed. The vertical lines through the plotted points in Fig. 14 show the scatter found by varying the lateral position of the channels relative to the jet. The scatter is negligible for the smaller widths, but becomes appreciable when the channel width w exceeds the jet diameter, $d = 2r$.

8

For the suction to be a minimum using a fixed channel height, Fig. 14 shows that the channel width should be about $1 \cdot 5 \times$ jet radius ($w/r \simeq 1 \cdot 5$). If the channel height is too small, the minimum in the suction is rather critical and the suction increases rapidly when w/r is reduced below $1 \cdot 5$. The curve for $h/r = 1 \cdot 6$ showed a broad minimum, and therefore it seems safest to specify that, for the best and least critical reduction of the suction due to ground effect, the channel height should be at least $1 \cdot 5 \times$ the jet radius and that the channel width should not exceed this value i.e.,

$$\frac{h}{r} \geqslant 1 \cdot 5, \frac{w}{r} \not> 1 \cdot 5 .$$

The shape of the S/T curves of Fig. 14 is quite logical when the problem is looked at simply as one of accommodating the jet efflux in the channel space. Pitching and rolling moments were observed only for the channel widths showing the largest variation of suction with lateral jet position over the channels, i.e., $w/r > 2$.

The most promising channel sizes (i.e., $h/r = 1 \cdot 6$ with $w/r = 0 \cdot 685$ or $1 \cdot 37$) were then tested with the wing rolled to determine any effects of channel orientation on the suction experienced—in particular, it was feared that channels arranged at right-angles to the axis of roll might prove less efficient than those parallel to the roll axis. The effect of the orientation β ($0°$, $45°$, $90°$) on the suctions measured at two angles of roll was insignificant (*see* Fig. 15). The pitching and rolling moments experienced never exceeded $0 \cdot 005$ in magnitude.

The suctions and rolling moments measured with the optimum channels are included as bands of results on Figs. 12 and 13. At the SC1 undercarriage height, the channels reduce the ground suction by a factor of 10 and, in addition, the suction then varies only slowly with the distance between the wing and the ground, even in the range where the suction normally rises rapidly. Fig. 13 shows the reduction in rolling moments due to roll achieved by the use of the optimum channels.

7. *Discussion of Results for 1/5th Scale Delta Wing.*

7.1. *Suction Forces.*

The ground suction on the delta planform was measured with the wing (*a*) in the horizontal position, (*b*) rolled up to $10°$, and (*c*) pitched up to $10°$ in either direction (*see* Fig. 16). The application of roll or pitch through the above ranges, which should cover any attitude likely to arise in practice, did not change the suction appreciably. The suction forces measured on the delta wing were slightly less than those on the equal-area circular wing: at the undercarriage height, the suction was 18% of the thrust. The small effect of planform variation suggests that the suction forces are concentrated on the unmodified portions of the wing around the jet.

The channel results were obtained using the optimum sizes found with the circular wing, and the suctions were reduced to less than 3% of the thrust (*see* Fig. 16). Fig. 17 shows in detail the variations in suction caused by changing the channel orientation at several wing heights and attitudes. The suctions tended to be somewhat larger if the channels were mounted perpendicular to the fore-and-aft axis of the model (i.e., $\beta = 90°$), particularly at the extremes of the incidence range covered. Thus, it is probably desirable to avoid whenever possible a landing in which the channels are normal to the aircraft centre-line.

9

7.2. *Rolling and Pitching Moments.*

The rolling moments generated by roll near the ground proved to vary in the same way as those measured with the circular wing, a small stable moment existing in the region of the undercarriage height (*see* Fig. 18). By using channels, the rolling-moment coefficient was reduced in magnitude from $0 \cdot 015$ to less than $0 \cdot 005$.

The existence of a positive nose-up pitching moment is the chief feature distinguishing the delta- and circular-wing results. The exact variation of the pitching-moment coefficient with wing height and its value at the undercarriage height depended on the wing attitude (*see* Fig. 19). At the undercarriage height, the coefficient varied between $0 \cdot 013$ and $0 \cdot 022$. Except when the wing was at negative incidence, the pitching-moment coefficient increased steadily as the ground was approached. Any deviation of the model from the horizontal trimmed position would be stable at the undercarriage height.

The optimum channel sizes sufficed to nullify the pitching moments completely, no coefficient exceeding $0 \cdot 003$ in magnitude being measured at the undercarriage height of $H/D = 0 \cdot 28$. With the exception of the higher S/T values recorded for $\alpha = \pm 10°$ with $\beta = 90°$ (*see* Fig. 19), no trends with model attitude or channel orientation could be detected.

The longitudinal position of the centre of suction in the absence of channels is shown in Fig. 20. As the wing height H is reduced, the centre of the suction force moves forward. At the undercarriage height, the centre of suction lies at approximately 66% of the root chord from the L.E. apex, i.e., about 4% of the root chord aft of the jet. It appears that the centre of suction tends towards the centre of area (i.e., $70 \cdot 7\%$ root chord) at large ground clearances and towards the centre of the jet when close to the ground.

7.3. *Landing Platform.*

The model landing platform shown in Fig. 7 was tested over the optimum channels mounted below the delta wing set at its undercarriage height. For the two channel widths used, the presence of the platform increased the suction only slightly from $0 \cdot 014$ to $0 \cdot 016$ ($w/r = 1 \cdot 37$) and from $0 \cdot 022$ to $0 \cdot 029$ ($w/r = 0 \cdot 685$), the suction still being less than 3% of the jet thrust.

8. *Discussion of Results on* 1/6th *Scale Short* $SC1$.

These tests covered the design conditions mentioned in Section $3 \cdot 8$ and listed in Table 6. The results are presented in Figs. 21 to 26 in terms of H/H_u rather than H/D, as used earlier. The results of the 1/5th scale delta-wing tests were considered to have contained sufficient guidance on the effect of change of model attitude, so that to save time incidence and/or roll were not applied to the SC1 model.

8.1. *Suction Forces.*

Figs. 21 to 24 show the suctions measured for the four design conditions reproducing the thrust or mass flow for hovering at maximum or minimum weight, both with and without channels in position. The S/T curve has the usual shape over the range of H/H_u or H/D covered (note that $H/D = 0 \cdot 28 H/H_u$). At the undercarriage height, the suction is some 17% of the total jet thrust (*see* Fig. 25). S/T is essentially a universal function of H/H_u, except for H/H_u less than unity, where differences appear depending on the geometry of the jet orifice. Smaller suctions result from the use of circular jets rather than annular jets for $H/H_u < 1$, even for circular and annular jets of

10

equal exit area operating at the same mass flow or thrust. In all cases, the results imply that, at a fixed wing height and with a nozzle of fixed geometry, the suction is a function of thrust rather than mass flow. The scatter of the results is greater with a circular nozzle over the range of thrust loadings covered, i.e., 12 to 34 lb/sq ft.

The tests using annular jets produce results resembling most closely those made on the 1/5th scale wings with a single circular jet; the suctions on the Short SC1 model fall only slightly below those measured on the delta wing. Although the body and the jet orifice extend well below the lower surface of the wing, the flow pattern is apparently not disturbed and no larger suctions are measured. Any effect due to the area of the bottom of the body being nearer to the ground must be offset by the smaller length of jet available to entrain air.

The channels again reduced the suction to negligible proportions. In addition to channels of the optimum depth of $3 \cdot 5$ in. ($h/r = 1 \cdot 6$ with the 1/5th scale wings), channels of $2 \cdot 5$ in. height were tried because of the reduced scale of the SC1 model. However, the graphs show that the suction was consistently greater with the shallower $2 \cdot 5$ in. channels, reaching a maximum of 4% of the thrust at $H = H_u$ as compared with 2% for the deeper $3 \cdot 5$ in. channels. At the undercarriage height, the deeper channels reduced the ground suction by a factor of at least 8.

8.2. *Pitching Moments.*

Pitching-moment coefficients about the centre of the jet are also presented in Figs. 21 to 25, the shape of the curves being approximately constant except for $H/H_u < 1$, where differences again appear between each of the three nozzle sets. The pitching-moment coefficient increases steadily as H/H_u is reduced for both 'large annular' and 'small annular' nozzles, but shows a maximum of order $0 \cdot 03$ for the circular nozzles at $H/H_u = 1 \cdot 1$. Although the trend of the annular-nozzle results is similar to that for the plane delta wing with a single circular jet, the pitching-moment coefficients are of different magnitude. At the undercarriage height, the SC1 results indicate a coefficient of $0 \cdot 030$ compared with $0 \cdot 017$ for the plane delta.

The longitudinal position of the centre of suction from the leading-edge apex is shown in Fig. 26 as a fraction of the wing root chord. The jet is situated at 53% of the root chord from the apex. At $H/H_u = 1$, the centre of suction lies at $62 \cdot 5$% of the root chord, compared with 66% for the delta wing—this difference arises from the more forward position of the jet. The centre of suction moves forward towards the jet as the wing height is reduced below the undercarriage height, but the movement of the centre of suction is not so uniform as on the plane delta wing.

8.3. *Comparison of Circular and Annular Nozzles.*

At wing heights less than the standard undercarriage height, the suction and pitching moment measured using the circular-jet nozzles were consistently lower than those measured using the annular nozzles. The differences are believed to originate in the different flow patterns set up beneath the wing.

The nozzle thrusts were measured directly, as described in Appendix II. The nozzle thrusts were determined at two distances from the disc used to measure the jet reactions, and no differences were detectable. It is known[4] that the thrust of an isolated circular jet near the ground decreases markedly only at distances less than one jet diameter and that the thrust of an annular jet near the ground is reduced noticeably only at distances less than $1 \cdot 5 \times$ the diameter of the centrebody of the nozzle. The closest approach to the ground of the SC1 nozzle orifices was about 3 in. i.e., a clearance of

11

almost twice the diameter of the circular jet and twice the diameter of the largest centrebody of the annular jets. This confirms that the ground clearance was never sufficiently small to interfere with the measured jet thrusts, and the observed differences in the tests with circular and annular nozzles must therefore be due to real features of the flow.

8.4. *Channel Modifications.*

The experiments proved conclusively the merit of the channels in reducing the ground suction on the SC1 model to less than 2% of the thrust. However, subsequent studies indicated that the full-scale array of channels of the specified dimensions would be extremely heavy, and hence extremely costly, even if the ground area covered were kept to a minimum. The weight would prove especially embarrassing if the channel array had to be portable, and, of course, any weight saving would result ideally in a proportionate cost reduction. A few tests were therefore made to see if the structure weight could be lightened by cutting away suitable sections from the channels, without incurring any increase in the ground suction.

The tests were made at a wing height at which the S/T value was $0 \cdot 137$ without the channels present. The first modification consisted of cutting a $0 \cdot 5$ in. slot at the base of all the members of the $3 \cdot 5$ in. deep channels (*see* Fig. 27a), giving a weight saving of $0 \cdot 5/3 \cdot 5$ i.e., 14%. The suction then amounted to $0 \cdot 112$ of the thrust, and the presence of the slot had obviously allowed the re-establishment of a radial outflow almost as strong as that present without any channels.

A more successful type of modification is illustrated in Fig. 27b, the base of each alternate member being cut away by an amount h'' and the height of the remaining members being reduced from $h \ (= 3 \cdot 5 \ \text{in.})$ to h'. The S/T values recorded for various combinations of h' and h'' are listed on Fig. 27b, and it can be seen that there is no consistent dependence on the percentage of the channels cut away. S/T takes mean values of $0 \cdot 023$ and $0 \cdot 032$ for $w = 1 \cdot 5$ and 3 in. respectively, and it can be seen that up to 50% of the weight of the basic channel structure ($h = 3 \cdot 5$ in., $w = 1 \cdot 5$ in.) can be saved if the suction is allowed to increase to 3% of the thrust. It is considered unlikely that modifications of the type illustrated would involve other problems, e.g., variation of the suction with lateral position of the jet relative to the channels.

With channels of unmodified height, S/T values of $0 \cdot 015$ and $0 \cdot 040$ were recorded for channel widths of $1 \cdot 5$ and 3 in. respectively. Hence, the structure weight could be halved by doubling the channel width, if suctions up to 4% of the thrust are allowable, together with any lateral position effect involved. A weight saving of 29% by reducing the channel height to $2 \cdot 5$ in. would likewise involve suctions up to 4% of the thrust (*see* Figs. 21 to 25).

The figures for weight and hence cost reduction quoted on Fig. 27b are not necessarily realistic because the structure shape illustrated would need additional support as compared with the basic channels. It is therefore clear that, although appreciable weight saving is possible at the cost of only small increases in the ground suction, any practical scheme more complicated than a simple increase of channel width (which can be objected to on other grounds) or a simple decrease of channel height, would have to take careful consideration of additional structural complications.

9. *Scale Effect.*

Data from other sources on the suction due to ground effect are compared graphically in Fig. 28 with the R.A.E. results already discussed. They include results obtained by Rolls-Royce on a 1/8th scale model of the Short SC1, the ground suction being measured at wing heights between

H_u and $2H_u$, and some results obtained at the N.P.L.* on a hexagon-planform wing with a centrally mounted fan. A few values abstracted from American tests on a deflected-jet layout[5] are also included, but the precise experimental conditions are not known. The results obtained on model wings of linear scales between 1/5th and 1/8th lie randomly in a fairly narrow band, which is quite surprising considering the different experimental conditions It is difficult to derive specific information on scale effect from the few available results but the following general arguments may be helpful.

The most important non-dimensional parameters affecting the relationship between S/T and H/D seem likely to be the ratio d/D and a jet Reynolds number, based on the mean exit velocity and diameter say. As regards the dependence of the results on the parameter d/D, it is clear that the suction effect must tend to zero as $d/D \rightarrow 1$ i.e., the wing area is reduced to zero. There is available some evidence to show that the dependence of the results on d/D is distinctly different for d/D values greater than $0 \cdot 25$, the largest quoted on Fig. 28. Preliminary analysis of further N.P.L. tests on the hexagon wing with d/D as high as $0 \cdot 5$ suggested that the suction did not increase continuously as the wing neared the ground, but was in fact reduced at small clearances. This suggests that a correlation of the results solely on an H/D basis cannot be expected to hold over the whole range of d/D from zero to unity. Assuming the above definition of jet Reynolds number and making use of a constant value of $1 \cdot 5 \times 10^{-4}$ for the kinematic viscosity since all the jets were 'cold', it is found that a jet Reynolds number of $1 \cdot 5$ to $2 \cdot 0 \times 10^5$ is typical of the R.A.E. small-scale and the N.P.L. tests, this value being an order of magnitude smaller than the value of $2 \cdot 0 \times 10^6$ which is typical of the R.A.E. 1/5th and 1/6th scale and the Rolls-Royce tests.

The difference between the R.A.E. small-scale and the N.P.L. results obtained at approximately constant jet Reynolds number is therefore attributed to the differing values of the parameter d/D. The ground effect follows the anticipated trend of a reduced suction as d/D is increased from a maximum of $0 \cdot 08$ for the R.A.E. tests to $0 \cdot 25$ for the N.P.L. tests.

The fall in suction observed between the R.A.E. small-scale tests and the R.A.E. large-scale and Rolls-Royce tests is largely due to the differing order of the respective jet Reynolds numbers: the d/D values are not coincident, but the range covered is small compared with that causing the difference between the R.A.E. small-scale and the N.P.L. results. Scale effect is therefore favourable, the suctions due to ground effect falling off as the typical jet Reynolds number is increased from 2×10^5 to 2×10^6. The suctions measured on the 1/5th scale model may therefore be taken as the upper limit of those likely to be met at full-scale.

The collected results show convincingly that a good estimate can be made of the ground suction likely to be experienced by a VTOL aircraft hovering near the ground. Until further tests are made, the results should only be applied to aircraft whose wing area is evenly distributed around the jet i.e., medium aspect ratio only.

As a point of interest, S/T is not a simple inverse function of H/D, as suggested by the shape of the curve. The results obtained on the 1/5th scale circular wing for $H/D < 0 \cdot 5$ are fitted remarkably well by a curve of the form

$$\frac{S}{T} = C_1 \exp C_2 \left(\frac{H}{D}\right)^{-1}$$

with the constants $C_1 = 0 \cdot 035$, $C_2 = 0 \cdot 46$. It will of course be unrepresentative at larger H/D where the limiting value of S/T should be zero (or nearly so).

---

* Communicated to the author by Mr. N. Gregory, National Physical Laboratory.

13

10. Conclusions.

Tests have been made to measure the suction due to ground effect acting on a VTOL aircraft operating close to the ground, the final application being to a scale model of the Short SC1 aircraft. It was shown that, at normal undercarriage height, the SC1 would probably experience a ground suction of between 15 and 20% of the gross vertical jet thrust. An array of parallel channels mounted on the ground beneath the lifting jets can reduce this suction to 2 or 3% of the thrust, thereby solving one of the problems affecting this version of VTOL. The channels contain the jet efflux, and prevent any three-dimensional spread of the jet over the ground. With a delta wing, the channels also help aircraft trim by eliminating any pitching moments caused by the asymmetric longitudinal distribution of wing area. From the limited evidence available, it seems that somewhat pessimistic values of the ground suction will be measured on a model of reduced scale and Reynolds number.

A useful condensation of the data on ground-suction tests is achieved by plotting the measured suction (expressed as a fraction of the jet thrust) as a function of the wing height above the ground (expressed as a fraction of the diameter of a circle equal in area to the wing considered) i.e., S/T against H/D, in the notation of this report.

The present experiments, particularly on the channels, were planned with practical aspects to the fore, and several fundamental problems warrant more detailed investigation e.g., the spread of the jet across the ground (with and without a wing present), the detailed changes with wing height in the pattern of the induced flow beneath a wing, and the development of the boundary layer along the ground. Some theoretical work appropriate to the flow along the ground far from the origin has been published[6], and confirmatory experiments have been made[7].

The present series of experiments is to be extended to cover wings of more varied planform shape and aspect ratio, and with more complex (and possibly helpful) jet layouts. For example, a favourable ground effect is obtained on a wing whose lifting jets are placed around the wing perimeter. Work could also be usefully undertaken towards developing a retractable and portable channel array to be carried by the aircraft—this would eliminate the risk of the emergency landing away from a prepared site.

LIST OF SYMBOLS

r		Jet radius
d	$=$	$2r$, jet diameter
D		Diameter of circular wing, or equivalent diameter of any other planform
$\bar{S}$	$=$	$\pi D^2/4$, wing area
H		Distance between ground and wing lower surface
H_u		Undercarriage height for SC1
h		Channel height
w		Channel width
d'		SC1 nozzle diameter
d''		SC1 fairing end diameter
h', h''		Lengths used to define channel modifications, *see* Fig. 27
p		Atmospheric pressure
p_0		Jet total pressure
ρ		Air density
u		Local velocity in jet
T		Jet thrust
M		Jet mass flow
S		Suction force due to ground effect
C_{RM}		Rolling-moment coefficient, defined in Section 4
C_{PM}		Pitching-moment coefficient, defined in Section 4
$\bar{c}$		Geometric mean chord, $= \dfrac{2}{b} \displaystyle\int_0^{b/2} c\,dy$
b		Wing span
α		Wing incidence
ϕ		Wing roll
β		Channel orientation relative to wing centre-line

15

REFERENCES

No.	Author	Title, etc.
1	N. A. Dimmock	Some further jet flap experiments. A.R.C. C.P.345. May, 1956.
2	B. Thwaites	On the design of contractions for wind tunnels. A.R.C. R. & M. 2278. p. 8, Table 3. March, 1946.
3	—	Flow measurement. British Standards Institution, B.S.1042. 1943.
4	U. H. v. Glahn	Exploratory study of ground proximity effects on thrust of annular and circular nozzles. N.A.C.A. Tech. Note 3982. April, 1957.
5	W. A. Newsom, Jr.	Effect of ground proximity on aerodynamic characteristics of two horizontal-attitude jet vertical-take-off-and-landing airplane models. N.A.C.A. Research Memo. L57G16. TIL 5687. September, 1957.
6	M. B. Glauert	The wall jet. *J. Fluid Mech.* Vol. 1. Part 6. p. 625. 1956.
7	P. Bakke	An experimental investigation of a wall jet. *J. Fluid Mech.* Vol. 2. Part 5. p. 467. 1957.

APPENDIX I

Measurement of Mass Flow and Thrust of Circular Jet used in 1/5th Scale Tests

The jet mass flow was calculated from the pressures indicated by a standard 6 in. diameter orifice plate inserted in the horizontal section of the air supply pipe. The mass flow m was computed from the B.S. Publication on flow measurement[3]. The jet was run at a mass flow of $0 \cdot 263$ slugs/sec ($\pm 2\%$) i.e., $8 \cdot 46$ lb/sec, this being some 35% higher than the true scaled value of the SC1 mass flow.

The jet thrust T was computed as follows. The distribution of pitot pressure across the jet was found from pitot-rake measurements. The pitot orifices were mounted slightly downstream of the jet orifice so that their presence would not induce choking of the jet. The pressure at the wall of the jet orifice was maintained atmospheric, and it was assumed that the static pressure in the plane of the pitot orifices was constant at that value. At any point in a subsonic or just sonic flow, where the static pressure is denoted by p, a small pitot tube will register a total pressure p_0 given by

$$p_0 - p = \rho u^2 (\gamma M^2)^{-1} \left[\left(1 + \frac{\gamma - 1}{2} M^2 \right)^{\gamma/(\gamma-1)} - 1 \right] = \rho u^2 f(M)$$

where ρ, u, M are the local values of air density, velocity and Mach number, and γ is the ratio of the specific heats of air.

The jet thrust T is given by

$$T = \int_0^r \frac{p_0 - p}{f(M)} 2\pi a \, da$$

where a is the local radius of a point in the jet, assuming the flow to be axi-symmetric. Over the central portion of the jet, sonic flow was assumed with $f(M) = 0 \cdot 6375$. To take account of the boundary region of the jet, a value of $f(M)$ corresponding to $M = 0 \cdot 5$ was used. The computed thrust was 270 lb ($\pm 5\%$)—a relatively large uncertainty covers any errors due to (a) variation of the static pressure in the jet from that of the atmosphere, (b) variations of the jet from the 'just choking' condition, and (c) any inadequacy of the allowance made for the boundary region of the jet. An approximate velocity profile, i.e., that of $(p_0 - p)^{1/2}/(p_0 - p)^{1/2}$ Mean, is given in Fig. 4.

APPENDIX II

Measurement of Thrust of SC1 Model Jets

In order to save time, the thrust of the model jets was determined by allowing the vertical jet efflux to impinge on and be deflected through 90° by a horizontal circular wooden disc suspended from the balances. The balances therefore measured the reaction due to the re-direction of the jet momentum by the disc.

The method was proved by using the circular jet of the 1/5th scale tests, whose thrust had been calculated as 270 lb. Measurements of the jet reaction were obtained with the disc situated approximately 1, 2 and 3 diameters above the jet orifice. Several positions were used so that, if the apparent jet thrust varied with distance from the orifice due to mixing losses, the readings of thrust could be extrapolated to yield a value in the plane of the orifice. The respective measured thrusts were 270, 275 and 272 lb, giving a mean value of 272 lb which agreed to within 1% with the value computed from the pitot measurements.

On the basis of this agreement, the method was used with the SC1 model to find the operating points for the conditions in which the thrust was specified, and to measure the thrusts for the conditions in which the mass flow was specified. Two positions of the reaction disc from the jet orifices were used, i.e., 6 in. and 11 in.—these values lay in the range of distance covered by the subsequent tests on the SC1 model. Essentially constant reservoir pressure was required to produce a given condition of thrust or mass flow in the two positions tried.

TABLE 1

Short SC1: Full-scale Data

Wing

Gross area, $\bar{S}$	211·5 sq ft
Span, b	23·5 ft
Standard mean chord, $\bar{c}$	9·0 ft
Aspect ratio, A	2·61
Taper ratio	17:1
Section	NACA 0010
Thickness/chord ratio	10%

Fin and rudder

Gross area, S_F	28·64 sq ft
Net area, S_{FN}	11·63 sq ft
Aspect ratio	1·065
Arm, l_F (c.g. to $\frac{1}{4}$ chord point)	9·152 ft
Volume coefficient, $= \dfrac{l_F}{b} \times \dfrac{S_{FN}}{\bar{S}}$	0·0214
Thickness/chord ratio	10%
Rudder area (aft of hinge line)	4·44 sq ft

Other controls

Elevator area (aft of hinge line)	15·0 sq ft
Aileron area (aft of hinge line)	8·4 sq ft
Pitch-control nozzles, mean area	3·36 sq in.
Roll-control nozzles, mean area	2·36 sq in.

TABLE 2

Small-scale-Model Data

Wing dia. D in.	Jet dia. d in.	Thrust T lb	d/D	Thrust loading $T/\bar{S}$ lb/sq ft
6·0(1/33rd scale)	$\frac{1}{8}$	0·44	0·0208	2·25
	$\frac{1}{8}$	0·36	0·0208	1·84
	$\frac{1}{8}$	0·30	0·0208	1·54
	$\frac{1}{4}$	0·13	0·0416	0·69
	$\frac{1}{2}$	0·05	0·0833	0·26
9·0(1/22nd scale)	$\frac{1}{8}$	0·37	0·0139	0·85
	$\frac{1}{2}$	0·07	0·0555	0·16
	$\frac{1}{2}$	0·05	0·0555	0·11
	$\frac{1}{2}$	0·03	0·0555	0·07

19

TABLE 2—*continued*

Channel details

Used with 9 in. diameter wing and $\frac{1}{8}$ in. diameter jet only.

Channel height h in.	Channel width w in.	h/r	w/r
$\frac{1}{4}$	$\frac{3}{8}$	4	6
	$\frac{3}{4}$	4	12
$\frac{3}{8}$	$\frac{3}{8}$	6	6
	$\frac{3}{4}$	6	12
$\frac{1}{2}$	$\frac{1}{2}$	8	8
	1	8	16

TABLE 3

1/5*th Scale Models Data*

Circular wing		Delta wing	
Wing area	8·73 sq ft	Wing area	8·75 sq ft
Aspect ratio	1·27	Aspect ratio	2·86
Diameter	3·333 ft	Wing span	5·0 ft
Thickness	1/12 ft	Mean geometric chord, $\bar{c}$	1·75 ft
		Thickness	1/12 ft
		Tip/root chord ratio	0

TABLE 4

Geometrical Data on Nozzles for SC1 Model

D = diameter of circular wing of area equal to SC1 model wing $\simeq$ 33 in.

Designation of nozzle-fairing combination	Exact design condition reproduced	Nozzle diameter d' in.	Fairing end dia. d'' in.	Exit area of 4 nozzles, sq in.	Diameter of circular jet of area equal to that of 4 nozzles, d in.	d/D
'Large annular'	Scaled exits reproducing scaled thrust	2·41	1·36	12·42	3·98	0·121
'Circular'	As above	1·975	—	12·25	3·95	0·120
'Small annular'	Reproducing scaled mass flow when hovering at min. weight	2·41	1·86	7·38	3·065	0·093

The 'large annular' and 'circular' nozzles were nominally of the same area.

20

TABLE 5

Short $SC1$: *Full-scale-Engine Data*

Flight condition	Ratio of jet total pressure to atmosphere	Total engine thrust, lb	Total engine mass flow, slugs/sec	Mean exit velocity, ft/sec
Hovering at max. weight	1·76	7240	4·65	1560
Hovering at min. weight	1·59	5700	4·225	1350

TABLE 6

1/6th Scale $SC1$: *Data on Experimental Conditions*

1. Scaled thrusts and mass flows

Flight condition	Total scaled thrust, lb	Total scaled mass flow, slugs/sec
Hovering at max. weight	200	0·129
Hovering at min. weight	160	0·117

2. Experimental values with nozzle sets

Nozzle set	Design thrust, lb	Experimental mass flow, slug/sec	Mean exit velocity, ft/sec	Thrust loading, lb/sq ft
Large annular	200	0·206	970	34·0
	160	0·183	870	27·2
Circular	200	0·200	1000	34·0
	160	0·177	900	27·2

Nozzle set	Design mass flow, slugs/sec	Experimental thrust, lb	Mean exit velocity, ft/sec	Thrust loading, lb/sq ft
Large annular	0·129	85	660	14·5
	0·117	72	615	12·3
Circular	0·129	88	680	15·0
	0·117	75	640	12·8
Small annular	0·129	122	945	20·8
	0·117	105	900	17·9

21

INTAKE FOR
4 LIFTING
ENGINES

HORIZONTAL
DATUM

GROUND · LINE

ROLL & PITCH
CONTROL NOZZLE
CENTRE- LINES

PITCH
CONTROL
NOZZLE ℄

AIRCRAFT DATUM PT.

SCALE
1/96 th FULL-SIZE
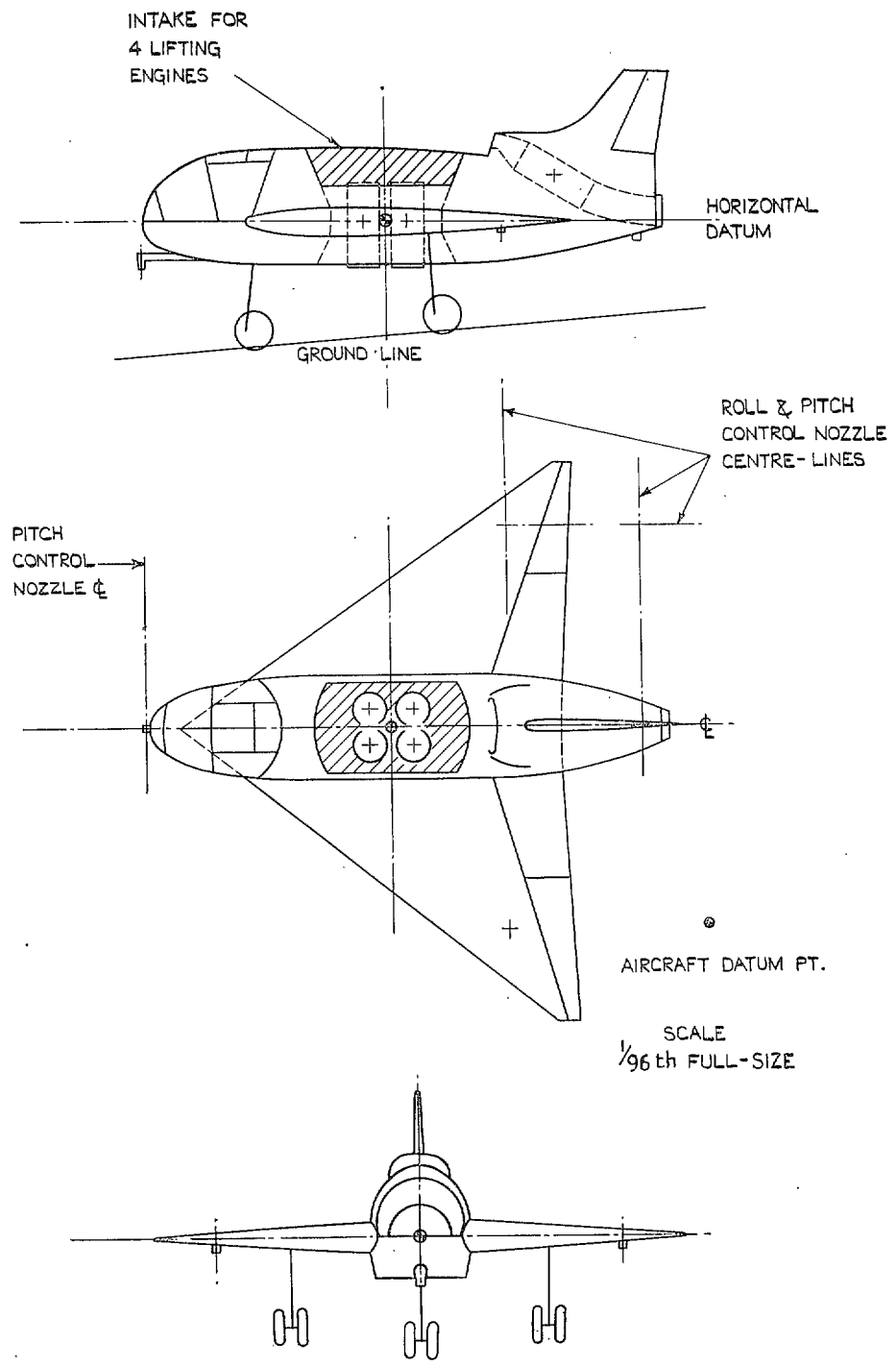
FIG. 1.   General arrangement of Short SC1.

22

23

SMALL-SCALE WINGS
MOUNTED INDEPENDENTLY
OF AIR JET

CHANNELS
CLAMPED TO
GROUND BOARD

PERSPEX
VIEWING
PANEL

GROUND
BOARD

PARALLEL-MOTION
SCALES CLAMPED
TO PLATFORM

AIR JET,
CLAMPED TO
PLATFORM

VARIABLE-
PRESSURE
AIR SUPPLY

PLATFORM CARRYING AIR-JET
BALANCE. ADJUSTABLE HEIGHT
TO VARY WING-GROUND SEPARATION

N.B. NOT TO SCALE.
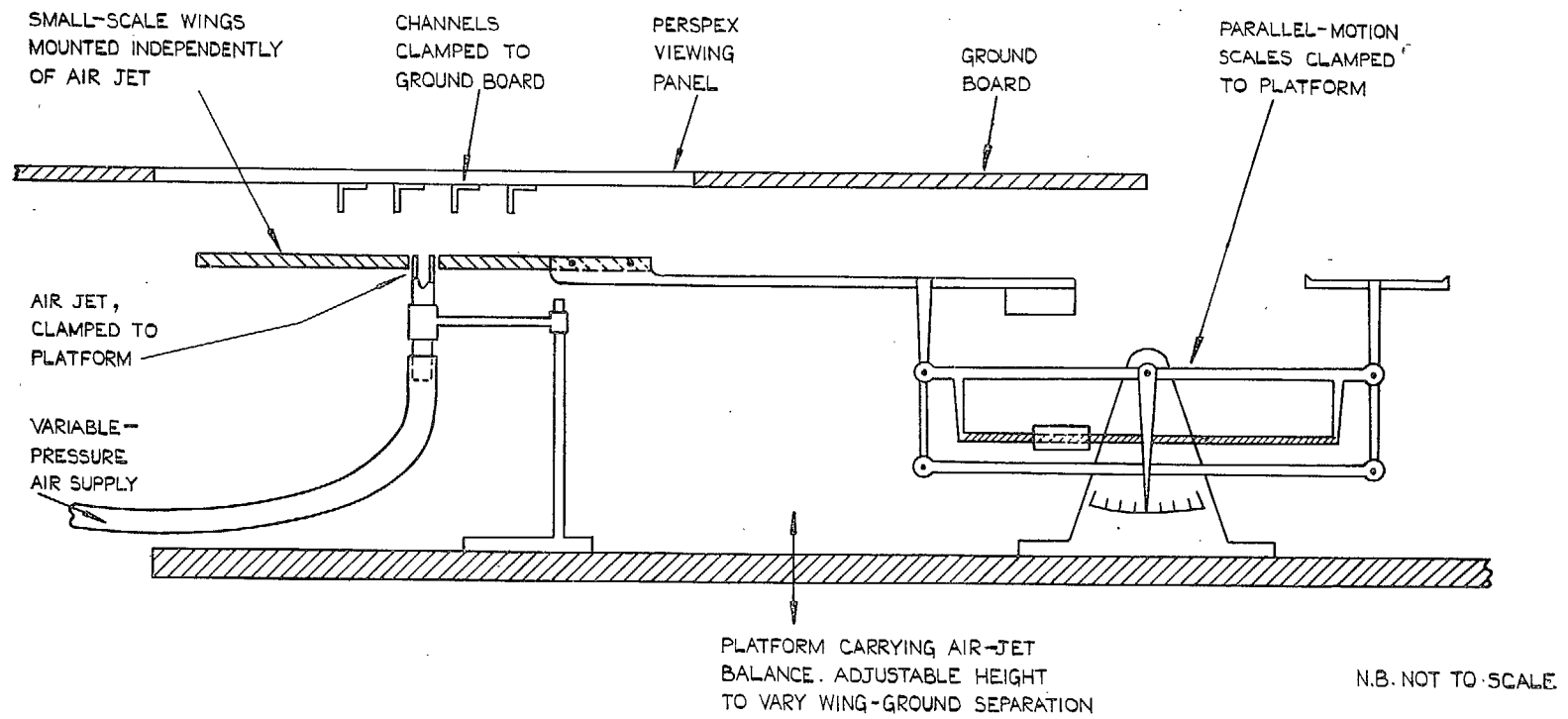
FIG. 2.   Sketch of rig used with 1/22nd and 1/33rd scale models.

⊗ POSITIONS OF THREE SUPPORTS CENTRED ON JET.

※ POSITION OF CENTRE OF JETS ON SHORT S.C.I .

SCALE
³/₄₀ th MODEL SIZE

3·0"

42·0"
ROOT CHORD

16·0"

A   A

120°

CIRCULAR WING

U.S. ON RIG.

40·0" DIA.

DELTA WING

U.S. ON RIG.

60·0" SPAN

OUTLINE OF JET
NOZZLE +
PRESSURE TAPPINGS

WING
U.S. ON RIG

SECTION A.A.
³/₈ th SCALE

APPROX ³/₁₆"
CLEARANCE

0·5"

1·0"

6·75" DIA.

10·0" DIA.
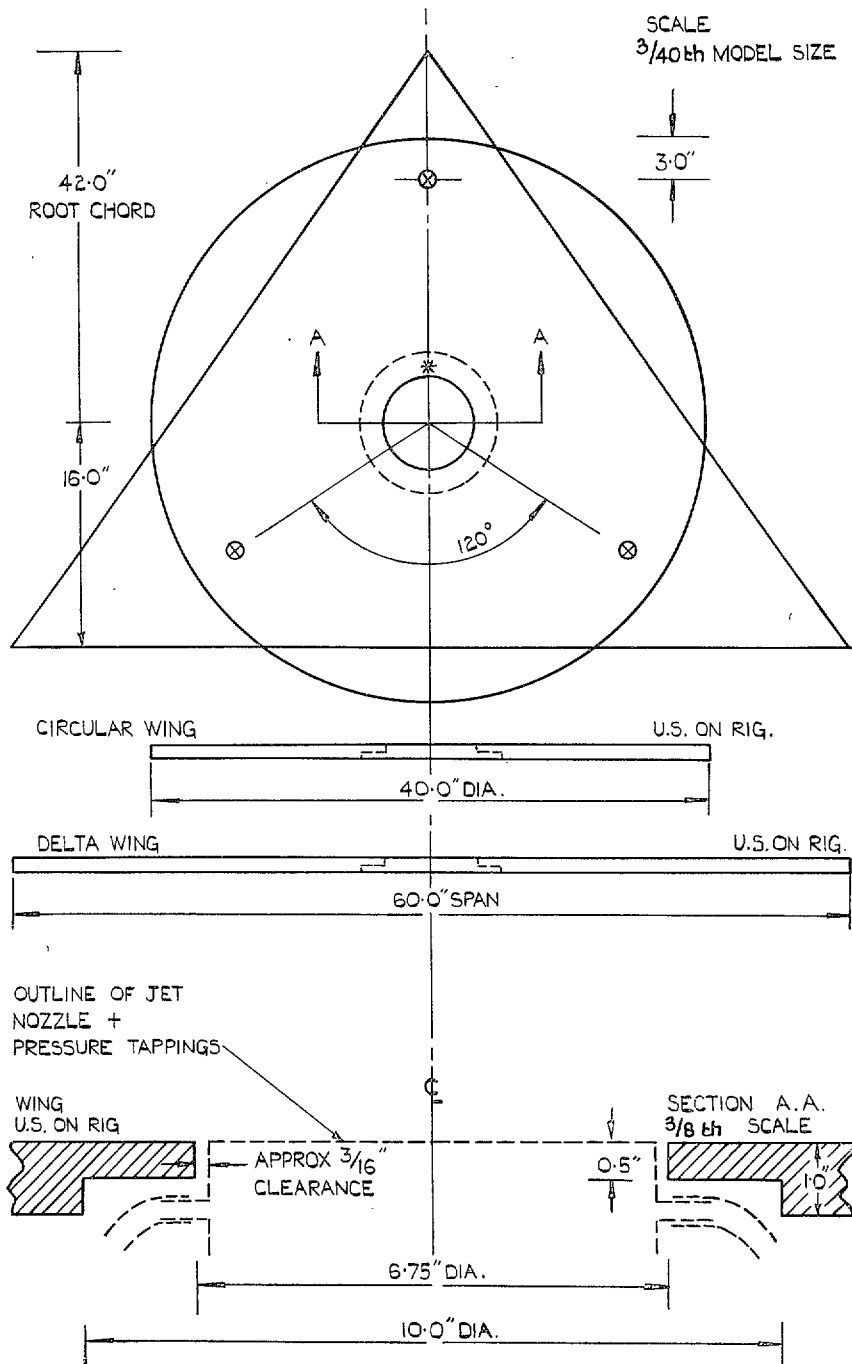
FIG. 3.   Details of 1/5th scale models—circular and delta wings of equal area.

24
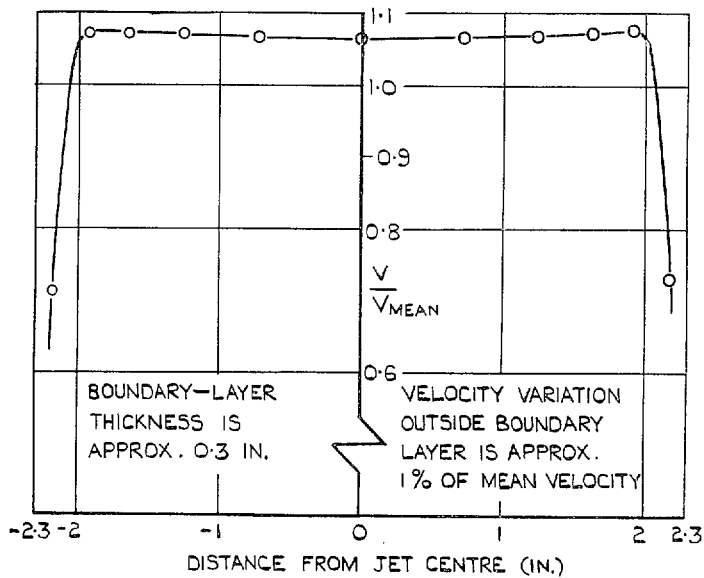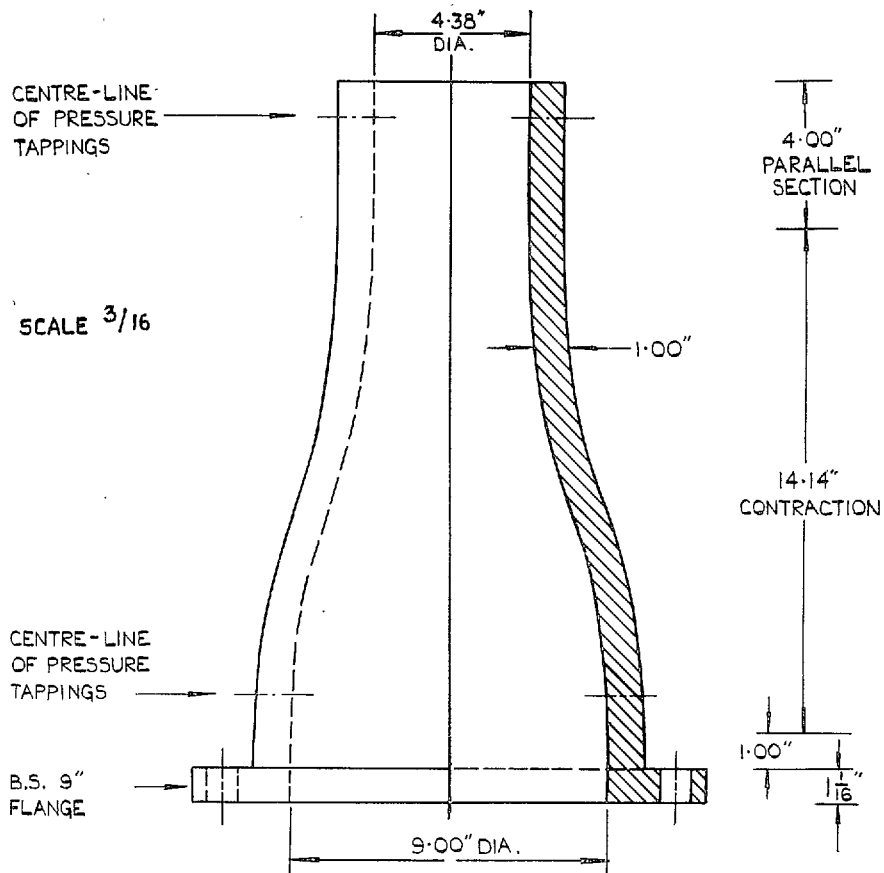
FIG. 4.   Section of nozzle used in 1/5th scale tests, with velocity profile at
0·31 × jet diameter from orifice.
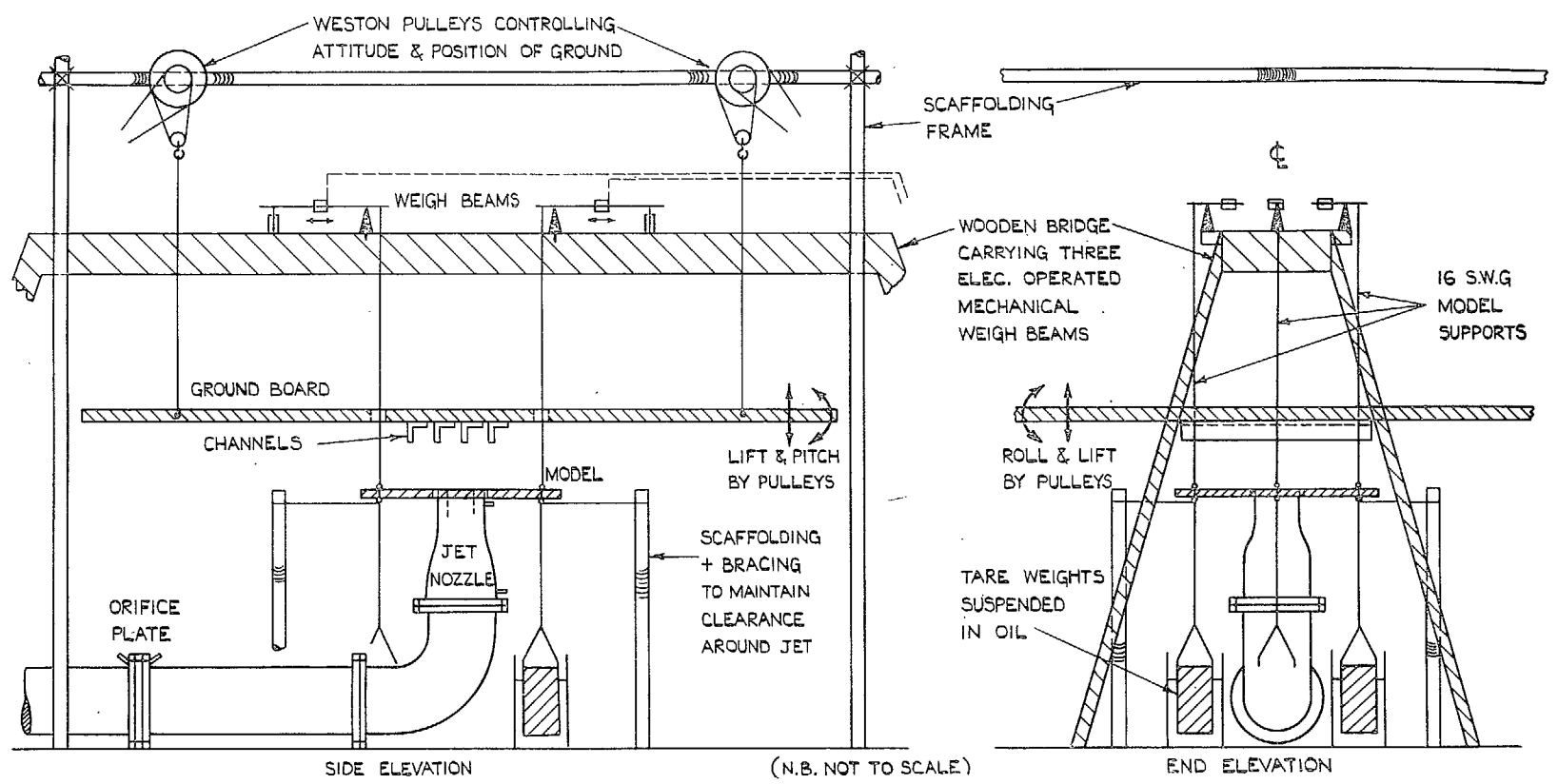
FIG. 5.   Sketch of rig used with 1/5th scale and Short SC1 models.

FIG. 6.   Channel details.

LIONWELD FLOORING PANEL.
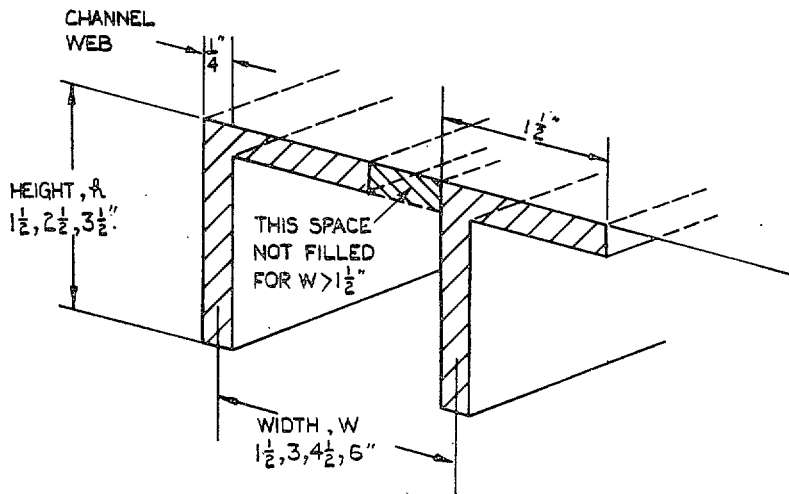
EXPANDED STEEL SHEET
USED FOR MODEL LANDING
PLATFORM IN 1/5 th SCALE TESTS.
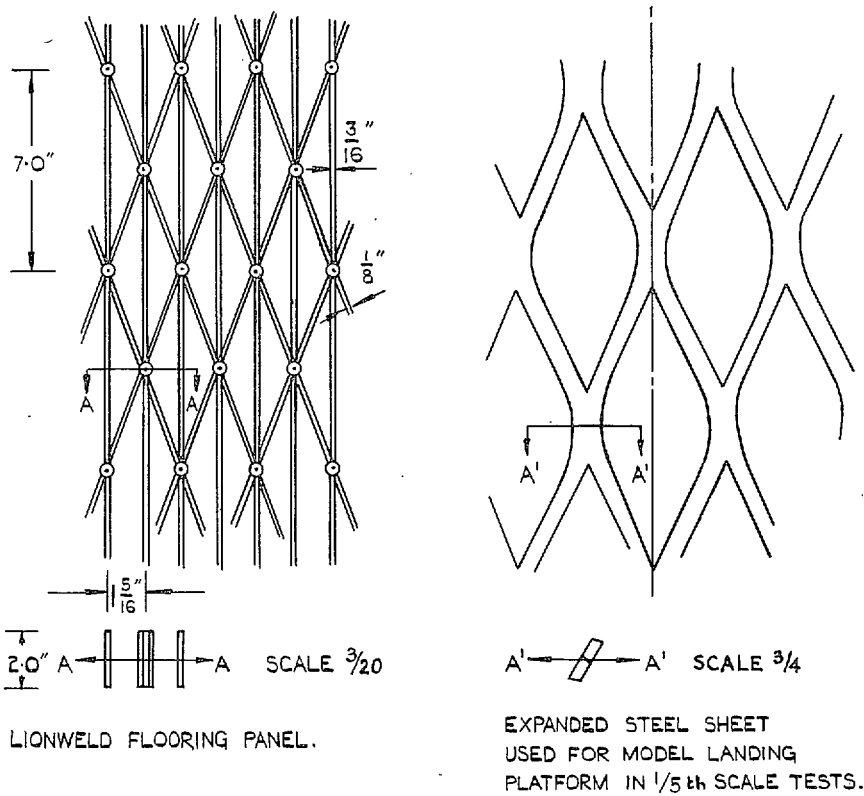
FIG. 7.   Geometry of Lionweld flooring panel and of landing platform used in
1/5th scale tests.

27
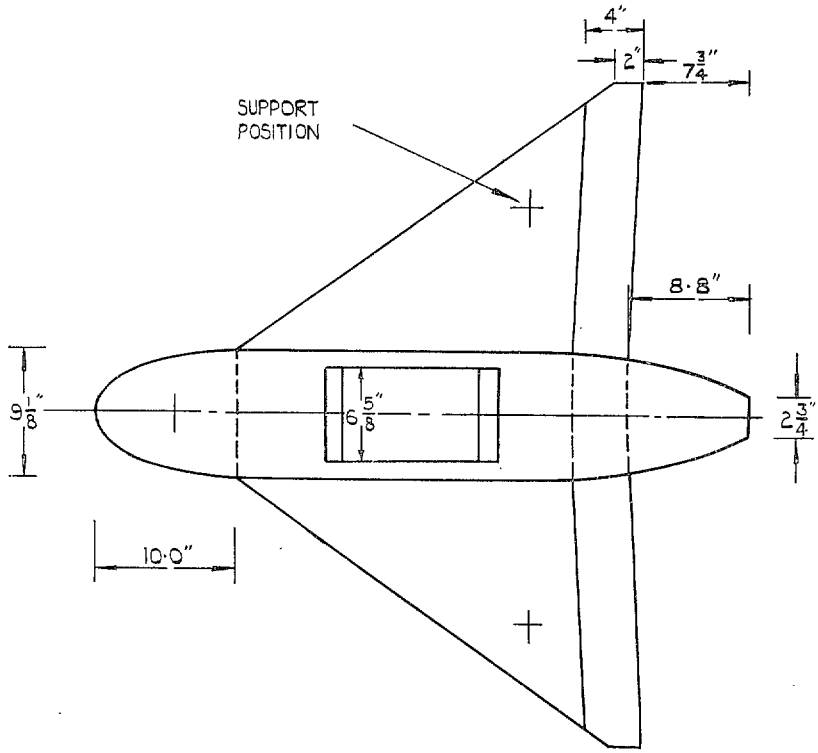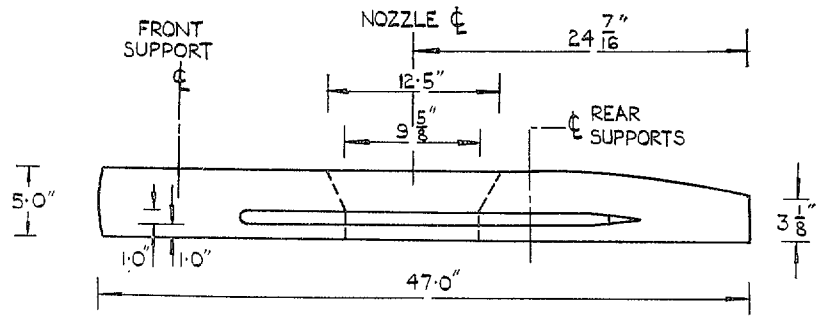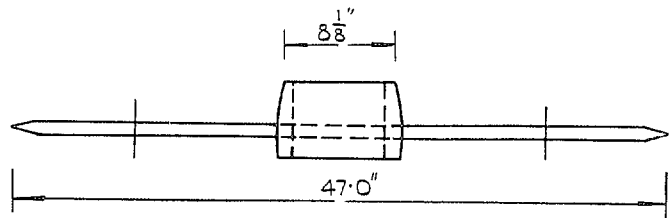
FIG. 8. 1/6th scale model of Short SC1.

FAIRING USED FOR
ANNULAR JET

NOZZLES

FAIRING USED FOR
CIRCULAR JET

FIXED FAIRINGS
ABOVE WHICH ARE
VARIABLE FAIRINGS
TO ALTER ORIFICE
SHAPE

BODY OF
SCI MODEL

PLATE TO
STOP AIR FLOW
THRO' NOZZLE
BAY

$\frac{1}{16}$" CLEARANCE
ALL ROUND PLATE

WOODEN FAIRING
TO CONTRACT
FLOW

B.S. 9" FLANGE

SECTION A A

d' = NOZZLE DIAMETER
d'' = FAIRING END DIAMETER

SCALE $^3/16$

MODEL

A

A
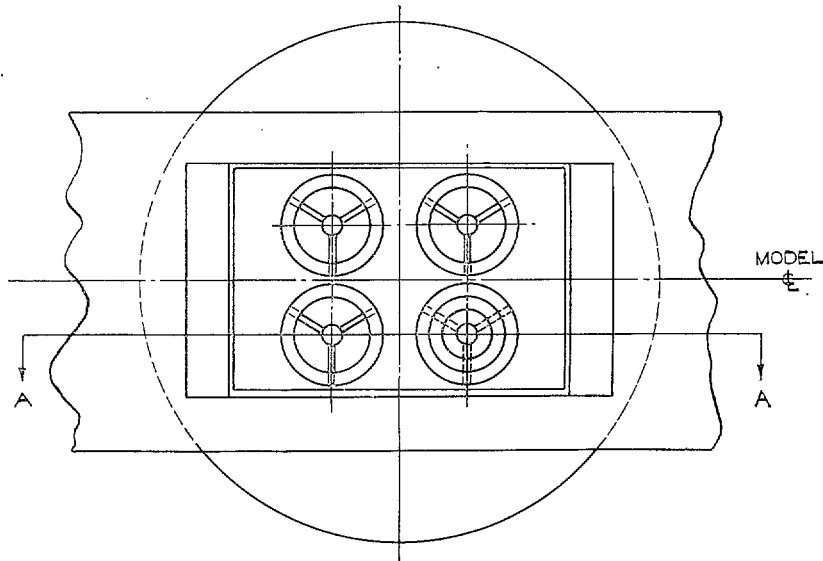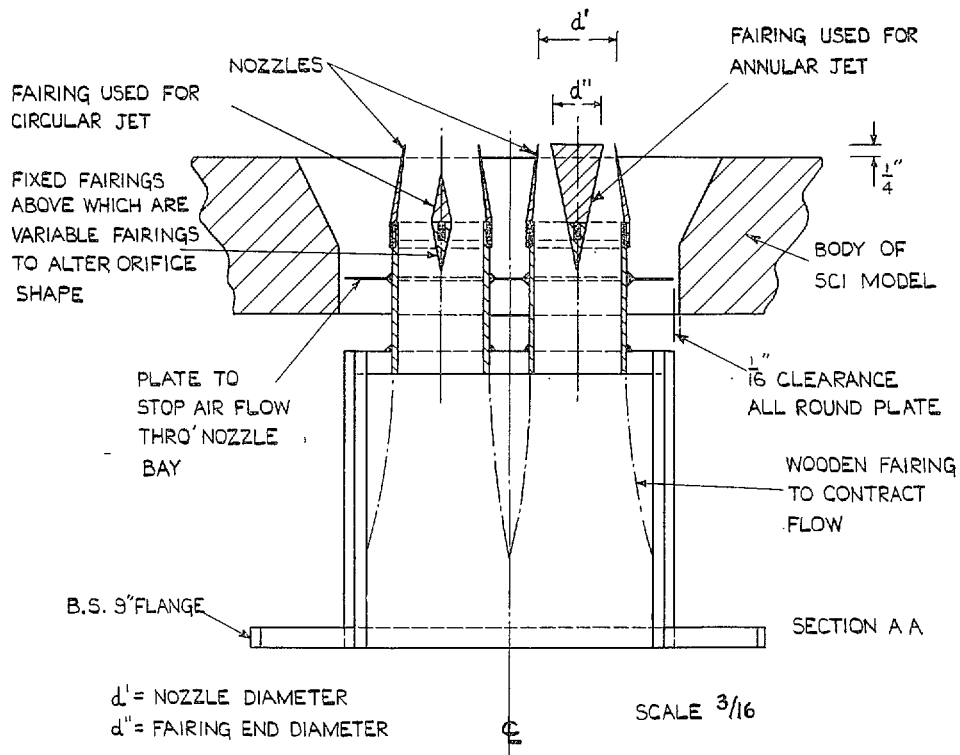
FIG. 9.   Four-jet nozzle used with 1/6th scale Short SC1, showing fairings
used to vary orifice shape.

29

30

A ≡ ATTACHMENT LINE , S ≡ SEPARATION LINE
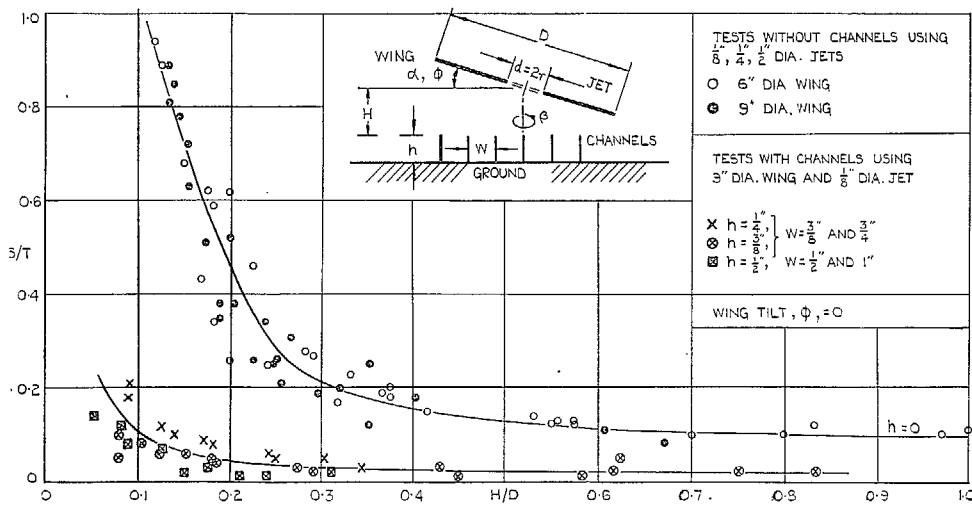
FIG. 10. Suction due to ground effect and reduction by channels—circular wings of 1/2 2nd and 1/33rd scale.
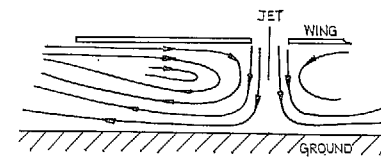
(a) H/D >0·3 PURE INFLOW ON WING LOWER SURFACE, AND PURE OUTFLOW ON GROUND.
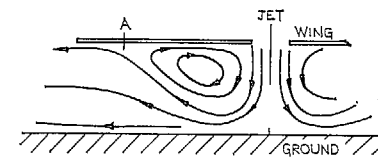
(b) H/D = 0·194 S/T = 0·5 PURE OUTFLOW ON GROUND. ON WING, INFLOW FROM 0·75 SEMI-SPAN, OUTFLOW NEAR TIP.
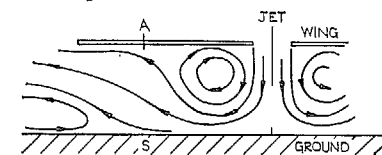
(c) H/D = 0·083 S/T = 13 ON WING, INFLOW FROM 0·67 SEMI-SPAN, OUTFLOW NEAR TIP. REVERSED FLOW DUE TO SEPARATION ON GROUND.

FIG. 11a to c. Flow patterns between wing and ground—circular wings of 1/22nd and 1/33rd scale.
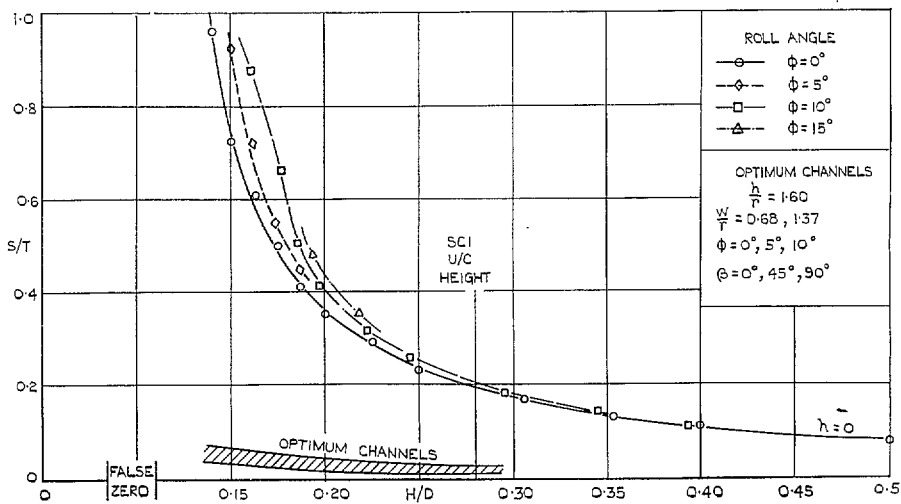
FIG. 12. Suction due to ground effect and reduction by channels—1/5th scale circular wing.
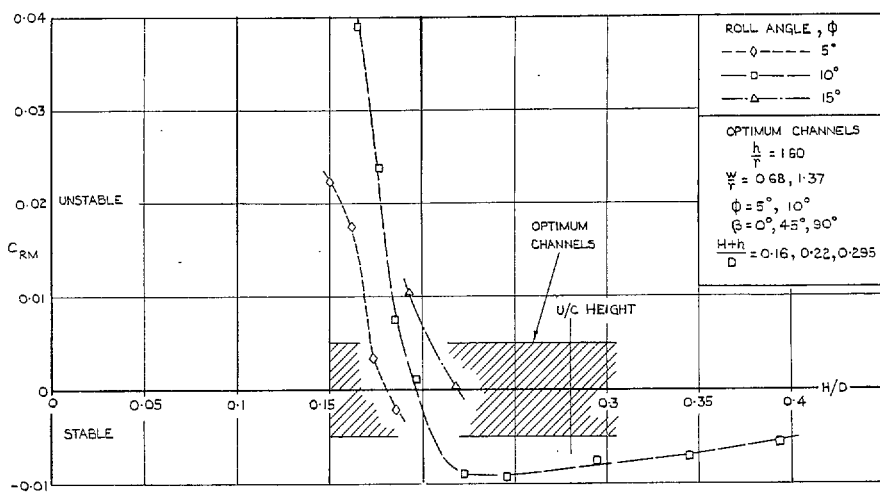
FIG. 13. Rolling moment due to ground effect and reduction by channels—1/5th scale circular wing at several angles of roll.

32
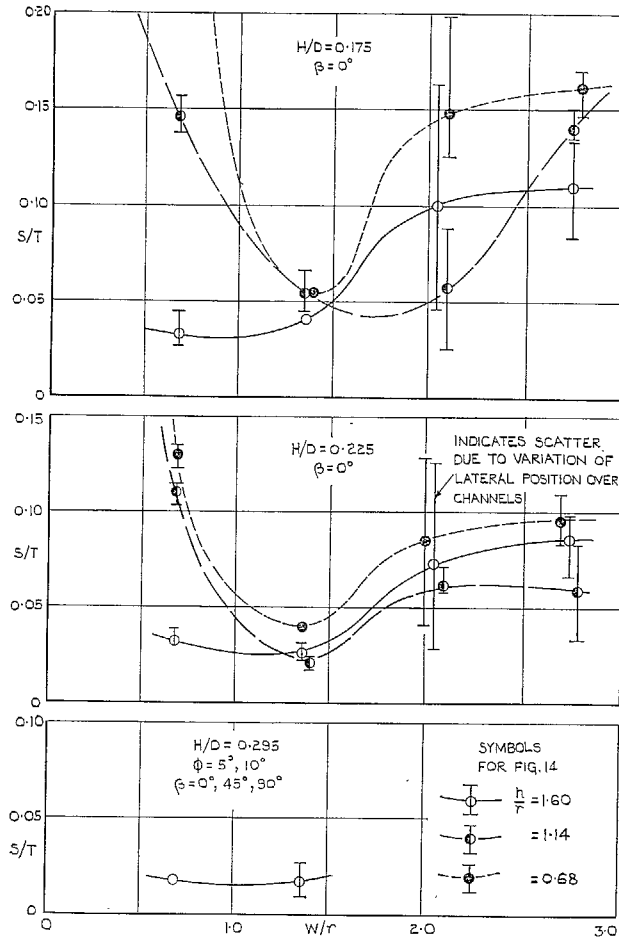
FIG. 14.   Effect of channel geometry on suction due to
ground effect—1/5th scale circular wing.
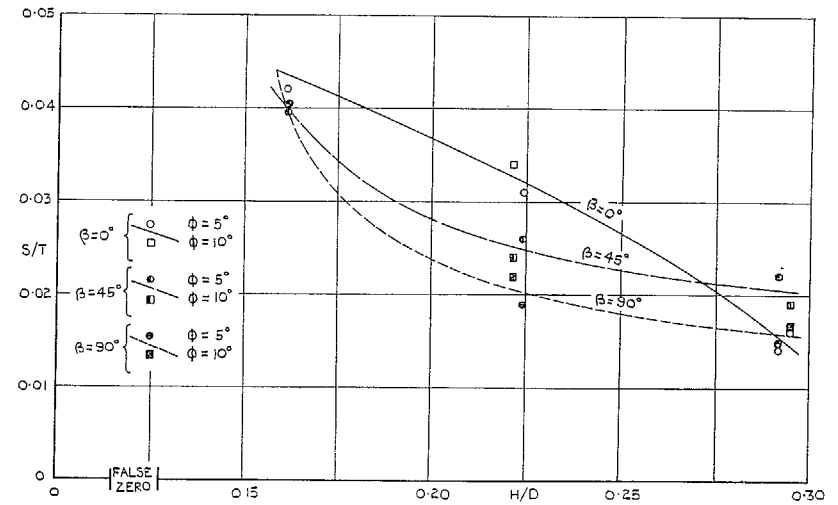
FIG. 15.   Effect of channel orientation β on suction due to ground
effect—1/5th scale circular wing at two angles of roll.
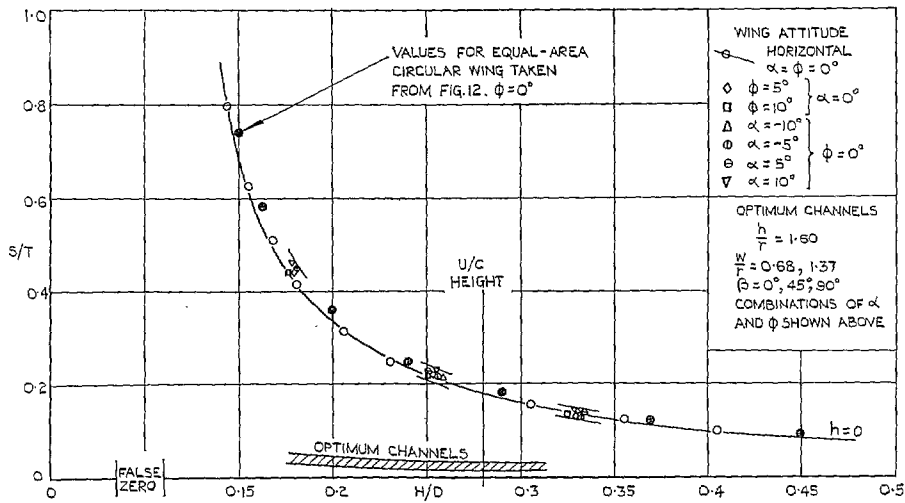
FIG. 16.   Suction due to ground effect and reduction by channels—1/5th scale
delta wing.
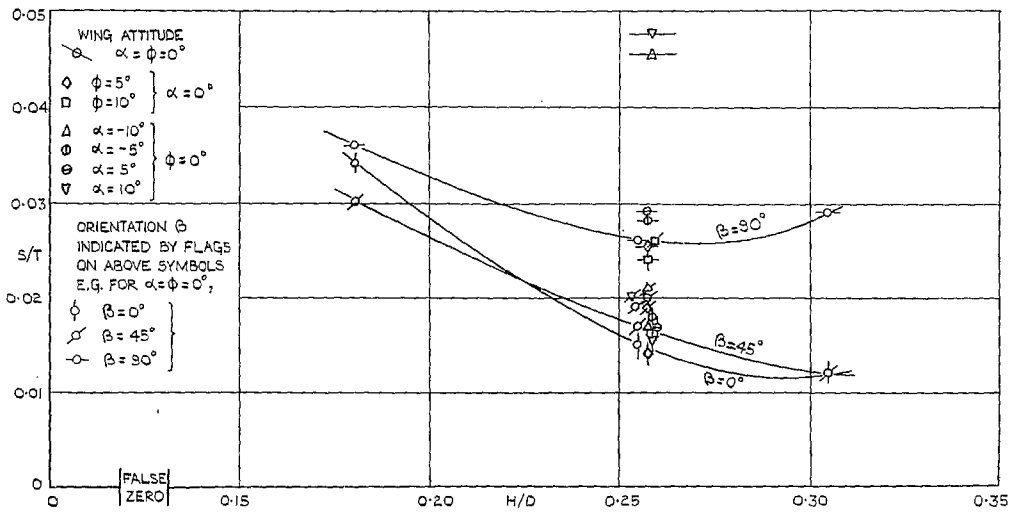
FIG. 17.   Effect of channel orientation β on suction due to ground effect—1/5th scale
delta wing in several attitudes.

33
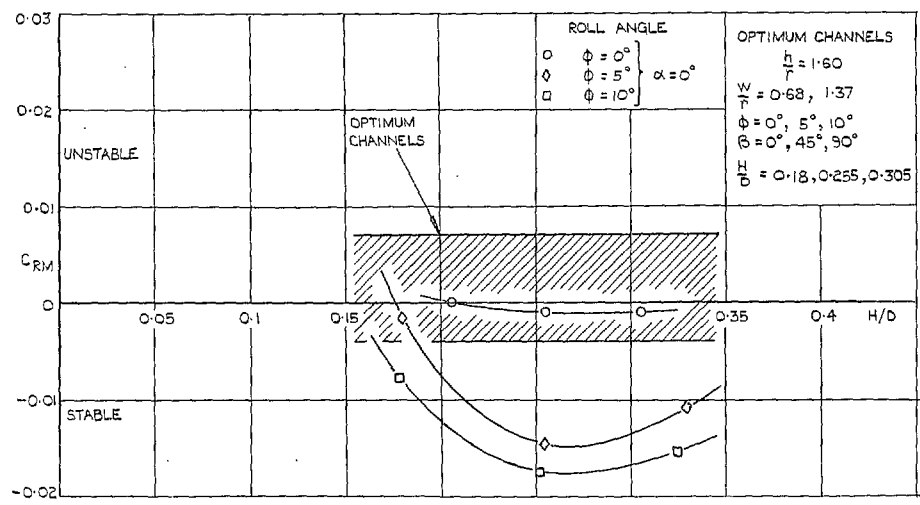
FIG. 18. Rolling moment due to ground effect and reduction by channels—
1/5th scale delta wing at several angles of roll.
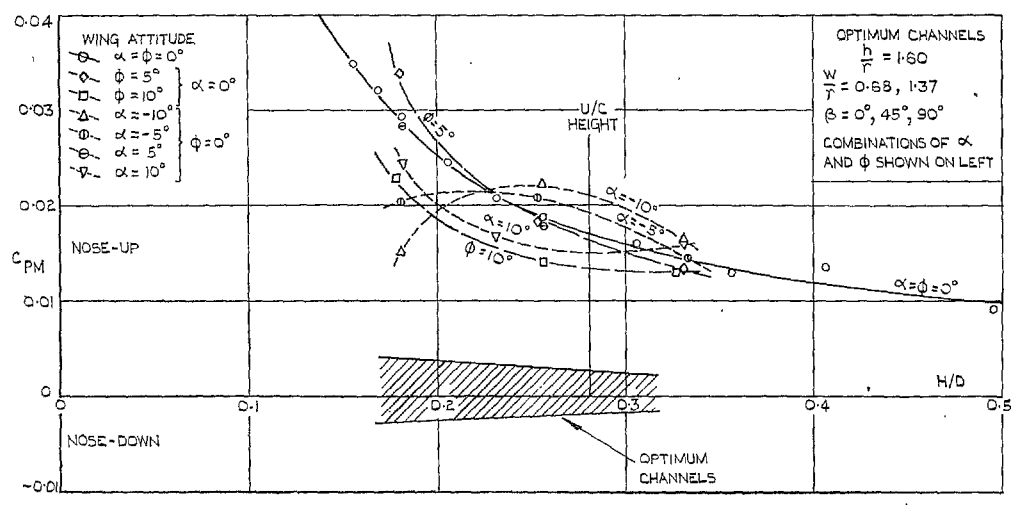
FIG. 19. Pitching moment due to ground effect and reduction by channels—1/5th scale
delta wing in several attitudes.
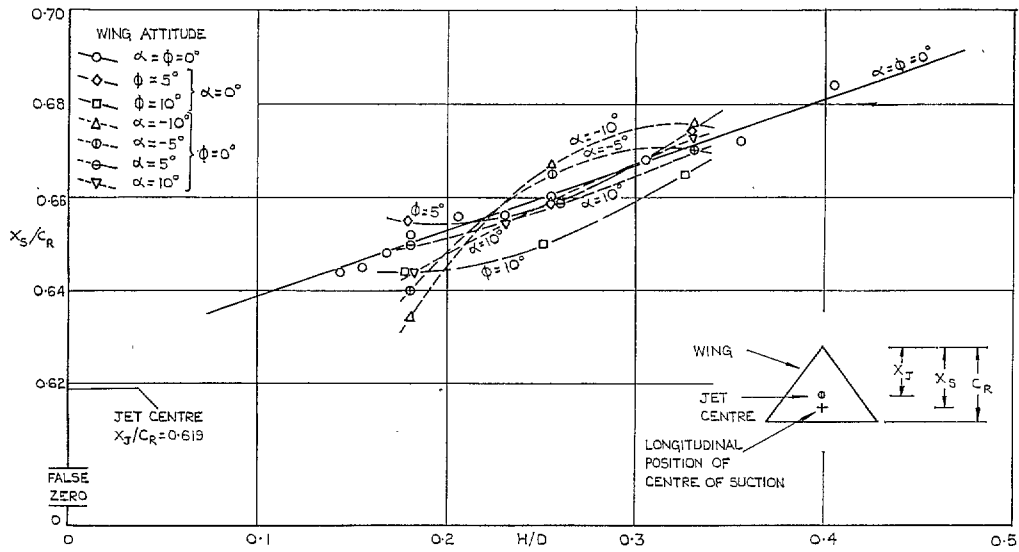
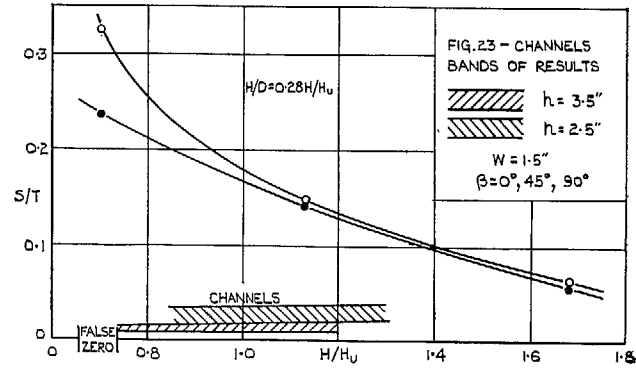FIG. 20. Longitudinal position of centre of suction due to ground effect—1/5th scale delta wing.
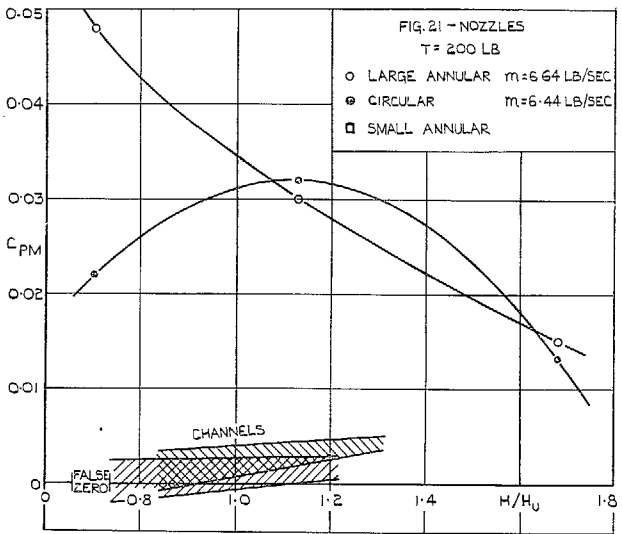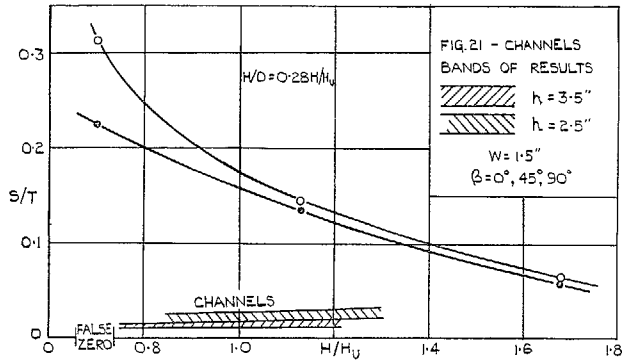
FIG. 21. Effect of channels on suction and pitching moment due to ground effect—1/6th scale Short SC1, reproducing thrust for hovering at maximum weight.
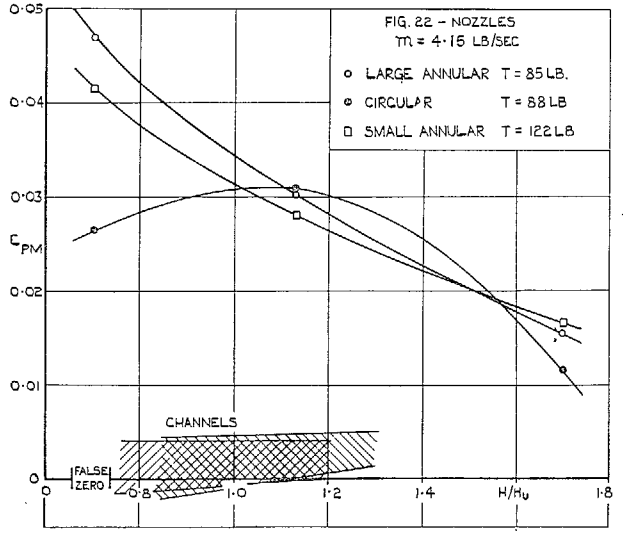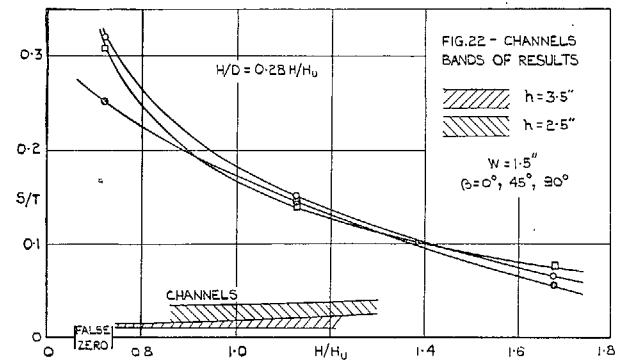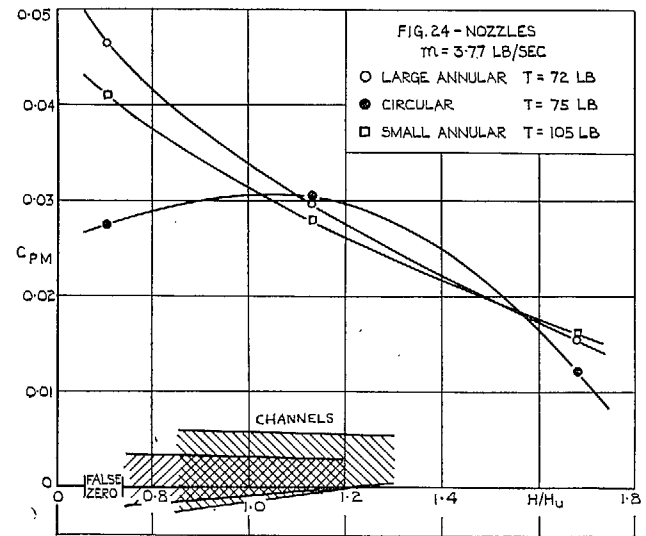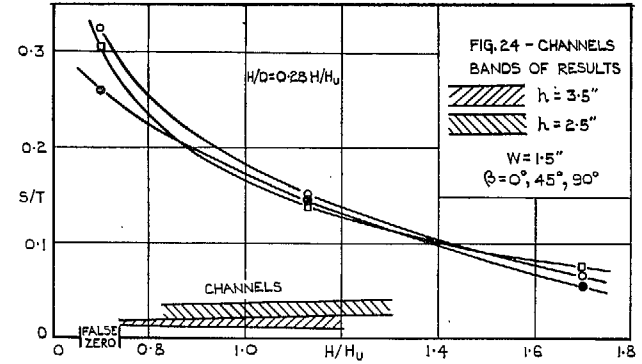
FIG. 22. Effect of channels on suction and pitching moment due to ground effect—1/6th scale Short SC1, reproducing mass flow for hovering at maximum weight.
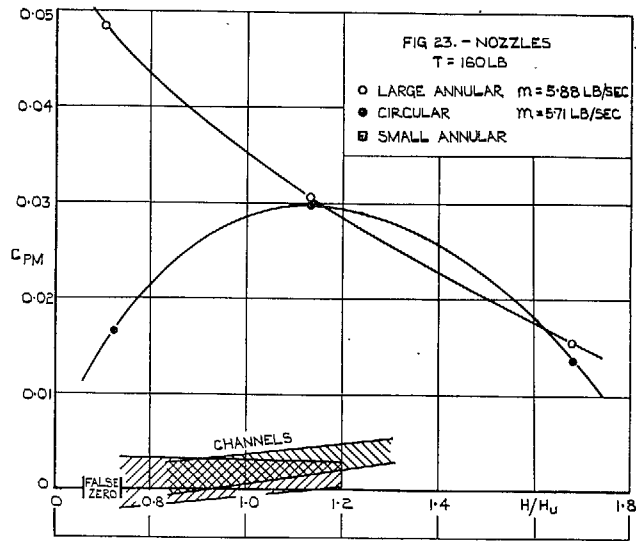
FIG. 23. Effect of channels on suction and pitching moment due to ground effect—1/6th scale Short SC1, reproducing thrust for hovering at minimum weight.

FIG. 24. Effect of channels on suction and pitching moment due to ground effect—1/6th scale Short SC1, reproducing mass flow for hovering at minimum weight.
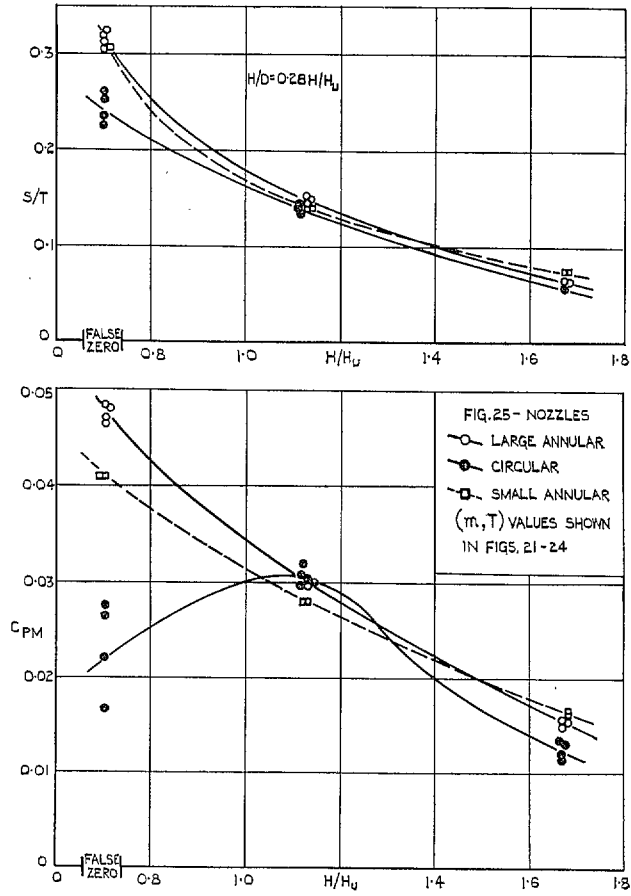
37

FIG. 25. Suction and pitching moment due to ground effect—1/6th scale Short SC1. Combined results from Figs. 21 to 24 for hovering at maximum and minimum weights.
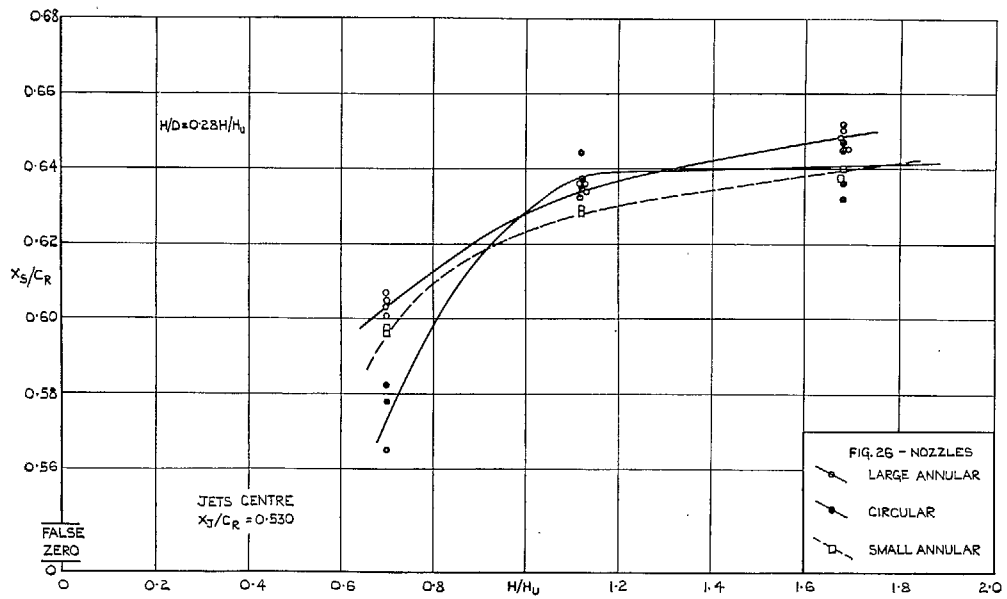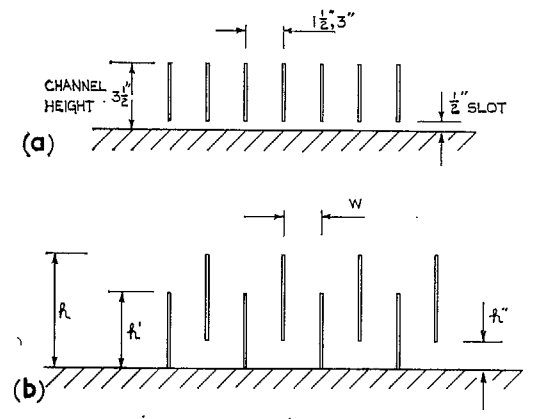
(a)

(b)

$\hbar = 3\frac{1}{2}$ IN.

SECTION	$\hbar'$ IN.	$\hbar''$ IN.	S/T		% SAVING IN WEIGHT, RELATIVE TO $\hbar'=\hbar, \hbar''=0$
			W = 1½ IN.	W = 3 IN.	
	$1\frac{1}{2}$	$\frac{1}{2}$	0.021	0.020	36
	$2\frac{1}{2}$	$\frac{1}{2}$	0.022	0.032	21
	$3\frac{1}{2}$	$\frac{1}{2}$	0.017	0.035	7
	$2\frac{1}{2}$	1	0.023	0.039	29
	$3\frac{1}{2}$	1	0.033	0.039	14
	$1\frac{1}{2}$	$1\frac{1}{2}$	0.024	0.024	50
	$2\frac{1}{2}$	$1\frac{1}{2}$	0.019	0.041	36
	$3\frac{1}{2}$	$1\frac{1}{2}$	0.024	0.035	21
	$3\frac{1}{2}$	0	0.015	0.040	0 BASIC CASES

FIG. 27a and b.   Channel modifications.

39

FIG. 26.   Longitudinal position of centre of suction due to ground effect—1/6th scale Short SC1.
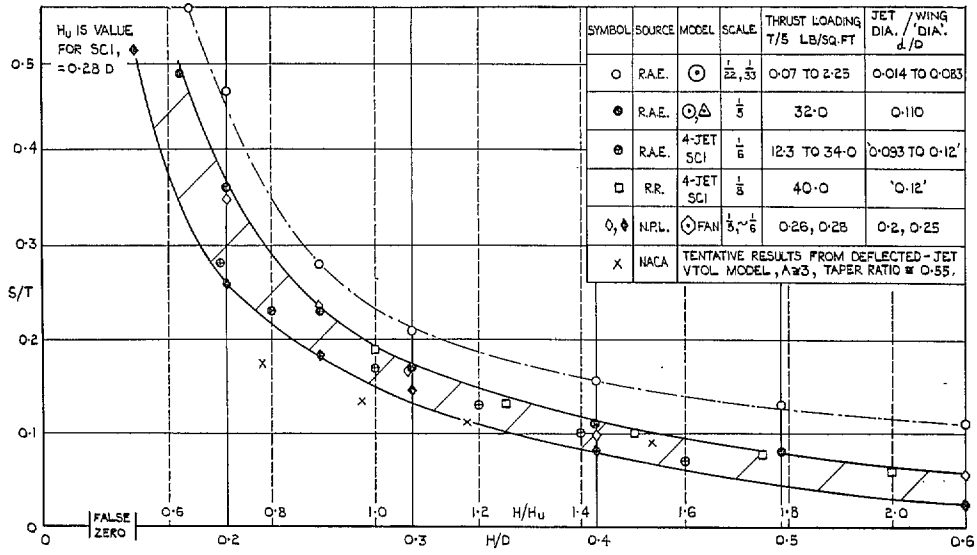
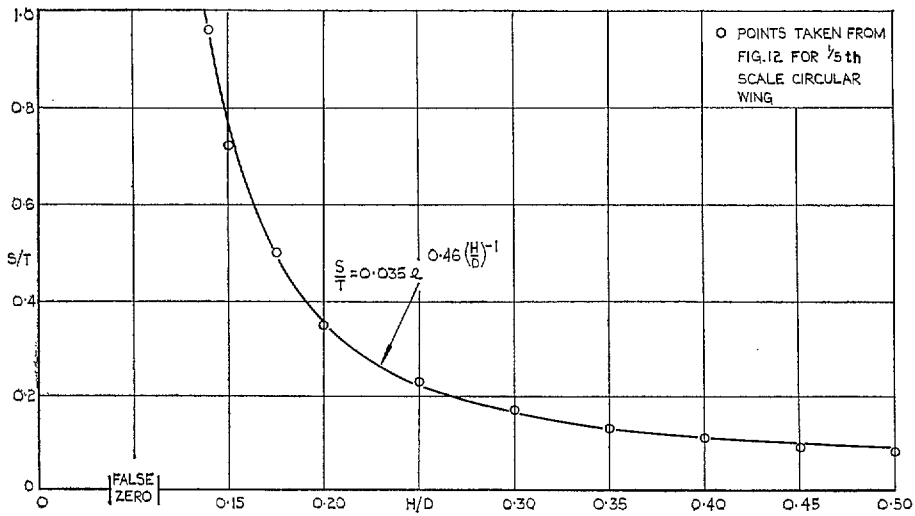FIG. 28.   Collected data on suction due to ground effect.

FIG. 29.   Fitting of empirical curve to results from 1/5th scale circular wing.

40

Publications of the
Aeronautical Research Council

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

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

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

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

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

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

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

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

Special Volumes

     Vol. I. Aero and Hydrodynamics, Aerofoils, Controls, Flutter, Kites, Parachutes, Performance, Propulsion,
               Stability. 126s. (post 3s.)
     Vol. II. Aero and Hydrodynamics, Aerofoils, Airscrews, Controls, Flutter, Materials, Miscellaneous, Parachutes,
               Propulsion, Stability, Structures. 147s. (post 3s.)
     Vol. III. Aero and Hydrodynamics, Aerofoils, Airscrews, Controls, Flutter, Kites, Miscellaneous, Parachutes,
               Propulsion, Seaplanes, Stability, Structures, Test Equipment. 189s. (post 3s. 9d.)

Reviews of the Aeronautical Research Council
          1939-48 3s. (post 6d.)   1949-54 5s. (post 5d.)

Index to all Reports and Memoranda published in the Annual Technical Reports
          1909-1947   R. & M. 2600 (out of print)

Indexes to the Reports and Memoranda of the Aeronautical Research Council
          Between Nos. 2351-2449   R. & M. No. 2450   2s. (post 3d.)
          Between Nos. 2451-2549   R. & M. No. 2550   2s. 6d. (post 3d.)
          Between Nos. 2551-2649   R. & M. No. 2650   2s. 6d. (post 3d.)
          Between Nos. 2651-2749   R. & M. No. 2750   2s. 6d. (post 3d.)
          Between Nos. 2751-2849   R. & M. No. 2850   2s. 6d. (post 3d.)
          Between Nos. 2851-2949   R. & M. No. 2950   3s. (post 3d.)
          Between Nos. 2951-3049   R. & M. No. 3050   3s. 6d. (post 3d.)
          Between Nos. 3051-3149   R. & M. No. 3150   3s. 6d. (post 3d.)

HER MAJESTY'S STATIONERY OFFICE
from the addresses overleaf