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Summary.—Reasons for Enquiry.—To determine the underlying cause of the collapse of a parachute, known as 'squidding.'

Range of Investigation.—Measurements of pressure were made in a wind tunnel at a number of positions over the surfaces of rigid models representing (*a*) a fully inflated canopy (*b*) a semi-squidded shape, and also at points over the surface of a small parachute. Each rigid model was uniformly perforated with holes representing a degree of porosity which was varied in some of the tests by covering different areas of the surface. Tests on the parachute were made with it tethered, (1) with rigging lines to a fixed point, (2) by wires to the sides of the tunnel. Directional measurements of flow required for tracing streamlines were made in the neighbourhood of the parachute both before and after the fabric had been rendered non-porous.

Conclusions.—It was found that, through the lack of deformable areas near each mouth, the rigid models did not reproduce adequately the prerequisite conditions of flow which normally lead to squidding. Radial outward forces tending to prevent collapse were shown to depend not only on the pressure inside the canopy but also on the strength and direction of the local flow. Any change which brings the direction nearer to that of the axis of the parachute decreases the incidence of the lip of each gore, and hence reduces the outward radial force. Such a change results from an increase in porosity of the fabric, and since an increase in porosity usually occurs with rise of speed, the process of squidding starts at a speed when the lips of the gores become deformed inwards. Similar changes of flow were not observed with a non-porous parachute, which remained fully inflated at the highest speeds attainable in the tests.

Introduction.—Most of the experimental evidence on the squidding of parachutes given in previous reports[1 2 3 4] relates to factors influencing the higher critical speed. This speed is known to be lowered by an increase in porosity of the canopy or by an enlargement of the vent hole in the crown. On the other hand an increase either in the length of the rigging lines, or of the hem, has the reverse effect in raising the squidding speed. Size of the parachute also enters into the problem as a factor, as canopies made from the same fabric but on a larger scale exhibit a readier tendency to squid. Steadiness of the wind speed is yet another factor, as is apparent from the fact that disturbances in the airflow may promote an earlier collapse and therefore a lower critical speed.

The changes in shape of a small parachute during the processes of squidding and unsquidding in a wind tunnel are revealed in the photostatic reproductions made from a film taken with a cinematograph camera. Plate I shows:—

(1) Five views of a parachute taken at different times between stages of being fully inflated and completely collapsed.

(2) Five views taken during the latter part of the period of unsquidding.

In each set the time interval between successive views is different, as in fact is the period occupied by the two processes; for while squidding took place during the time the wind speed was increased from 70 to 72 ft/sec, the reverse process occupied the much longer period required to reduce the speed gradually from 60 to 30 ft/sec; only the latter part of this period is represented in the illustrations. Thus the bottom left-hand figure shows the condition just prior to complete collapse, and the top right-hand figure, taken at a lower wind speed, shows the shape assumed by the parachute when partially inflated at a lower speed. With shorter rigging lines the squidding speed is lowered, and the complete process extends over a wider range of speed. The first indication is given when the lip of one of the gores starts to vibrate radially. With increase of speed the amplitude of the motion increases, and a stage is reached when the lip of the gore is permanently deflected inwards. At a slightly higher speed all the gores become similarly deformed; the parachute takes the shape exhibited in the top left-hand figure, and remains unchanged until, at a higher speed, the depression in each of the gores begins to extend. Once this stage is reached a small increase of speed is usually sufficient to bring about the final collapse.

It became apparent that the causation of squidding is associated with the change from an outward to an inward pressure over the canopy in the region of the mouth, since the instability cannot arise so long as there exists an excess outward pressure at all points. Professor Duncan suggests that the internal pressure will exceed the external pressure for a canopy of almost any shape provided that it is impervious; and for a porous canopy, or when a vent is fitted, there will be a diminution of internal pressure owing to the increased inward flow. In any circumstances, if the pressure difference vanishes the lip of the parachute will, by turning inwards, increase the external pressure in this neighbourhood, and so favour the development of conditions leading to the collapse of the parachute.

Experiments conducted with models in a wind tunnel, which form the subject of the present report, provide additional information from which certain conclusions are drawn regarding the cause of squidding. These experiments include an examination of the aerodynamic pressure over the inner and outer surface of two metal models representing, approximately, the general shape assumed in flight by an unsquidded and a squidded parachute. Measurements made with the models drilled uniformly with holes, and also when partly covered so as to render different areas of the surface impervious, furnish data on the effect of porosity on the distribution of pressure; others disclose the effects produced by an obstacle held at various positions ahead of a model, as well as the changes ensuing from a yaw of the relative wind. A second series of tests include pressure measurements over the surface of a small fabric parachute tethered (*a*) by the rigging lines to a fixed point; (*b*) by additional cords from a number of points round the hem to the tunnel walls, so that the size and position of the mouth could be adjusted to suit the shape appropriate to any given length of rigging lines. Observations of speed and direction with the model thus constrained provide a basis for the construction of stream lines in regions near the parachute where the flow is reasonably steady.

From an analysis of the results it is concluded that squidding is an instability of the canopy caused by a change in direction of flow in the neighbourhood of the lip. At low speeds, when the parachute is fully inflated, there is an excess outward pressure over all parts of the surface. As the speed increases the direction of the streams near the lip becomes less inclined to the axis of symmetry. Hence when the effective incidence of the curved area near the mouth is reduced to zero, under reversed pressure, the lips of the gores turn inward and the process of squidding starts. External pressure acting on the new shape tends to extend the area already deformed, and in consequence of the increased radial forces developed, including the component due to tension in the rigging lines, collapse usually follows a small increase in speed. An exception occurs if the rigging lines are unduly short—that is, well beyond the limit found useful in practice—for the parachute can then remain distended with the lips bent inward over a wide range of speed.

It is found that the porosity of the fabric has a marked influence on the direction of the streams on which the stability of the canopy depends. An increase of porosity which normally accompanies a rise of speed augments the flow through the mouth, and so reduces the inclination of those streams to the axis. But though the variable porosity of the fabric appears to be a contributory factor in determining the speed at which squidding occurs, the alteration of shape which the parachute undergoes in the vicinity of the mouth by influencing the speed and direction of the flow past the lip must also play a part. Inside the canopy the flow is confined to a relatively thin layer near the surface; the streams unite at the vertex and produce a return flow along the axis, the whole region of flow being very unsteady. If the canopy is made impervious this vortex-ring type of motion leads to a radial flow directed against the inside surface near the lip, and the parachute does not close even at the highest speed reached in the experiments.

Some of the observations previously mentioned may now be explained—at least qualitatively. It is evident, for example, that because of directional changes of flow, an increase of porosity lowers the critical squidding speed; for the same reason, and also because of the diminution of pressure on the inner surface, similar effects are produced when a bluff obstacle is supported in front of the parachute. A reduction of porosity conversely raises the critical speed, but at the same time increases any tendency towards lateral instability in flight. In the extreme case of a non-porous fabric, a change of flow takes place in the boundary layer at high speeds, somewhat analogous to that observed in the critical speed range of a sphere; this increases the internal pressure near the mouth and therefore assists in maintaining the canopy inflated. Observations further show that, other factors remaining unchanged, an increase in length of the rigging lines or of the hem cords reduces the effective incidence at the lip and thus raises the squidding speed.

Photographs taken of the opening of an already squidded parachute as the speed is reduced to a critical value show that the crown is always partly inflated. During the process, which extends over a large range of speed, the shape changes progressively and increases in size as the speed decreases. Eventually the mouth begins to open, and soon afterwards the parachute becomes completely inflated. It is possible, that, as in the reverse process of squidding, the variation of permeability of the fabric with speed influences the direction of the flow into the mouth, and produces the requisite pressure distribution required to maintain a stable shape appropriate to any particular speed. Qualitatively, by disclosing the effects produced by a change in porosity, such pressure measurements as were made on a rigid model lend support to this view. The results, however, cannot be applied quantitatively, since the model represented only approximately the general shape of a squidded parachute and could not be readily adapted to reproduce such details as folds in the fabric around the mouth, which may conceivably modify the distribution of pressure in this region.

Description of Models.—Since the processes involved in squidding and unsquidding depend on the aerodynamic forces brought into play, measurements of the pressure distribution over the surface were likely to throw light on the underlying causes. Such experiments, it was evident, could most conveniently be made with the aid of models in a wind tunnel, where the flow conditions are easily controlled. As at this stage the action of the flexible lips in modifying the flow into the mouth of the canopy was unknown, it seemed that the choice of rigid models instead of small parachutes for the experiments would be advantageous in facilitating measurements of pressure over the surfaces. Accordingly, two models were made, one to represent a parachute fully inflated, the other a typical semi-squidded shape (Plates II and III). Both were spun from copper plate 0·015 in. thick; each being symmetrical about an axis; such details as the flutings of the gores were omitted. The generator for the exterior surface of the first (for particulars, *see* Fig. 1 and Table 1) was constructed to correspond with the measured mean of the shapes taken by the median lines and sides of the gores of a basic parachute fitted with unduly short rigging lines*, when fully inflated in an airstream; the shape agreed approximately with the form of a canopy having a hoop tension inversely proportional to the radius (*cf.* curve for $\lambda = 0$, Fig. 6, R. & M. 862[5]). The shape of the second model was derived from a photograph of the same parachute when partly open. Each model was drilled with holes of 0·11 in. diameter spaced as uniformly as possible 0·25 in. apart, in order that the porosity† might be higher than that of the fabric at the squidding speed, namely, 130 ft/sec. For some of the tests the holes in the unsquidded model were enlarged to 0·15 in. diameter. Finally, provision was made for the

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* These were made shorter than the designed lengths in order to reduce the squidding speed to about 130 ft/sec.

† *See* Appendix for measurements of porosity and reasons for the choice of the value used.

attachment of rubber tubes to connect with an inclined multi-tube manometer, so that the pressures, in excess or defect of the static pressure of the free stream, might be recorded at ten equally spaced points on the outer surface, and also at corresponding points on the inner surface situated on the opposite side of the model.

Experimental Procedure.—At the start it was anticipated that the internal would exceed the external pressure, and when the critical speed was reached the difference on the two sides at the lip would vanish. As no appreciable scale effect was found at speeds between 30 and 200 ft/sec a number of expedients was tried in an attempt to discover factors likely to influence the distribution of pressure. These involved a series of tests with:—

(1) a circular disc held coaxially at different positions upstream,

(2) enlarged holes to give an effective increase of porosity,

(3) the axis of the parachute inclined at 5 deg. to the main stream,

(4) parts of the surface covered as an alternative means of varying porosity.

Experimental Results.—(*a*) *Model of Unsquidded Parachute.*—Values of the normal pressure p, at any point distant S along the generator from the lip, expressed as ratios of $\frac{1}{2}\rho U^2$, are exhibited graphically in Figs. 3 to 7 for $U = 120$ ft/sec.

Reference to the results show that every part of the unsquidded model perforated with the smaller holes is always subject to an outward pressure. Near the lip the excess is $0 \cdot 375\rho U^2$, while over the greater part of the surface it reaches about $0 \cdot 68\rho U^2$. The presence of a disc, even as small as 1 in. diameter, held 22·5 in. from the mouth causes a general reduction of the internal pressure and lowers the difference at the lip from $0 \cdot 375\rho U^2$ to $0 \cdot 25\rho U^2$: a similar result is also produced by a disc 4 in. diameter placed at a distance of 20 in. Changes resulting from an increase in the size of the holes from 0·11 to 0·15 in. diameter are shown to be confined mainly to pressures over the lower part of the model; these give rise to inward forces near the mouth. Similar remarks apply when the model is yawed, but in this case it is to be noted that the forces are augmented on the windward side*.

Values given in the Appendix indicate the porosities tried in the experiments are approximately proportional to the square of the diameter of the holes. Thus from Figs. 3 and 5 it is clear that, for the particular shape of model employed, a change of the order of 1 : 1·86 (that is, corresponding with an increase in diameter of holes from 0·11 to 0·15 in.) is needed to bring about conditions likely to promote squidding, within the range of the tests. On the other hand, if the porosity is initially high, the blocking of a comparatively small area at the crown (*see* Fig. 7) alters entirely the distribution of pressure at the mouth tending to prevent squidding. Again, there is no evidence of scale effect in the measurements except when the perforated model is completely covered to render the surface impervious; then at speeds between 120 and 130 ft/sec, in addition to an audible change of sound emanating from the disturbed wake, the suction over the lower part of the outer surface suddenly increases in a manner suggestive of a change in the type of flow around the model, such as occurs in the neighbourhood of a sphere, within the critical region of velocity.

(*b*) *Model of Semi-squidded Parachute.*—Fig. 8 exhibits graphically the results obtained with a model of the squidded shape, and shows the pressures over the inner and outer surfaces when the model is uniformly perforated with holes of 0·11 in. diameter, and also when different areas from the vertex downwards are covered. In all cases the net force acting on the surface near the lip is directed inwards, and not until 58 per cent. of the total area is covered is the direction reversed.

Though the results of both the squidded and unsquidded shapes are consistent with the tendency of porosity to favour squidding and to reduce the upper and lower critical speeds, they indicate

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* It has often been observed that, if a lateral oscillation exists during the descent of a man-carrying parachute, at the extreme end of each swing the gores on the windward side are temporarily forced inwards. The results of the present experiments suggest this is caused by the canopy becoming yawed at an angle where a local area is subjected to a resultant inward force. Recovery follows when the yaw is sufficiently reduced by the velocity of the sideways motion.

that a parachute having the same degree of porosity as the model with 0·11 in. holes should remain inflated, whereas, in point of fact, a canopy with a lower porosity is known to be unstable in shape. Moreover, the results suggest that the porosity must be increased to a value almost equivalent to the permeability of a surface perforated with 0·15 in. holes before collapse occurs. As figures in the Appendix show, the porosity of the fabric increases with speed; but over the range 60 to 140 ft/sec the change is from 5·2 to 8·0 per cent., that is, the same as would result from an increase in the size of the holes from 0·11 to 0·135 in. It must be concluded, therefore, that the experiments, while providing useful data, fail to represent adequately the conditions of flow around a fabric parachute. This failure may be due to:—

(1) The omission of fluted gores, and hence a lack of essential detail in the model*.

(2) The use of a perforated surface whose porosity characteristics, unlike those of fabric, decrease slightly with increase of speed.

(3) The use of a rigid model instead of a surface capable of deforming under the action of wind forces.

Further tests were accordingly made with a fabric parachute; this was tethered by a single cord and, for some experiments, cross-braced to the sides of the wind tunnel, in order to restrict the lateral freedom of motion. The tests are described in the following section.

Description of Basic Fabric Parachute.—The parachute was designed in conformity with the shape given in Fig. 5, R. & M. 862[4] for $\lambda = 0$. The canopy, made of cotton fabric, consisted of twelve equal gores sewn together with a hem between each to accommodate a shroud line. These lines were attached to the canopy at only twelve points on the lip; they passed over the crown and crossed at the vertex, around which there was a small vent.

The principal dimensions of a gore are as follows:

Length of median line measured form vertex	25 in.
Maximum width	9 in.
Width at lip	9 in.,

the last two dimensions being measured at right angles to the median line. Pressure points were arranged at six positions along the median line of a gore and another six similarly along a gore situated on the opposite side of the parachute. At each place a small metal tube with a thin plate attached, flush with the end of the tube, was inserted through the fabric. A second plate was screwed on to the tube against the other side of the fabric, both being fixed by a suitable adhesive solution. For pressure determinations the tubes were connected to an inclined manometer by light rubber tubing, which, for measurements over the outer surface, was led through the vent at the vertex to the appropriate tubes inside the canopy.

Pressure Measurements.—During the first series of observations, which were taken with the parachute free to oscillate laterally, except for the slight restriction imposed by the connecting tubes, different lengths of rigging lines were used; and for each length the pressures were measured at a number of wind speeds. The values obtained are plotted in Figs. 9 to 12.

In contrast to the measurements made with rigid models, these disclose pressure changes with speed which ultimately lead to squidding. Fig. 9 in particular gives the pressure distribution between 30 and 45 ft/sec for the shortest length of rigging. Inspection shows that at the lowest speed there is a resultant outward force acting on the canopy near the lip which decreases progressively in magnitude with increase of speed and vanishes at 45 ft/sec; collapse follows later when the speed reaches about 48 ft/sec. Fig. 10 shows similar indications for a rigging length of 12·5 in.; the changes, however, are noticeably smaller than before, being influenced possibly by the sideways motion of the parachute, which becomes more unstable as the squidding stage is approached (at 70 ft/sec). A further extension of the rigging lines to 33·5 in. is found to raise

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*Apart from the constructional difficulty of representing fluted gores, tests show the fullness of the gores may be modified to some extent without affecting the squidding speed.

the squidding speed beyond the maximum obtainable in the wind tunnel. Lastly, Fig. 12 affords a comparison of pressure measured at 40 ft/sec with different lengths of rigging.

Since many of the previous observations were taken with the parachute oscillating about the point of attachment, it was necessary to determine whether the motion modified the pressure acting on the surface. A second series of tests was accordingly made with the parachute secured to prevent this lateral movement. For the purpose, a number of points around the lip were fixed to wires radiating from the centre of the mouth to the walls of the tunnel, to which they were fastened. The rear part was also constrained by other wires stretching from the vertex to the walls. Thus it was possible to set the aperture at the mouth to correspond with any prescribed length of rigging; also, by preventing collapse, to maintain the inflated shape even at the highest speeds.

The results plotted in Figs. 13 to 16 confirm the existence of collapsing forces which would have caused the parachute to take the squid shape had it been unrestrained. Measured values of the pressures are in fair agreement with those previously obtained with the appropriate length of rigging lines to give a similar shape of canopy. Moreover, they are consistent in indicating an increase in squidding speed with increased aperture; for the changes of shape so produced can also be simulated by a lengthening of the rigging lines. It is important, however, to recognise that change of shape is accompanied by a change in the effective incidence of the surface in the neighbourhood of the mouth, in consequence of which a redistribution of pressure takes place.

To illustrate this point, a few observations were taken of the pressures acting on the upper and lower surfaces of a flat plate, measuring some 10 by 40 in. The plate was mounted spanwise across the tunnel with a fabric sheet attached along the trailing edge and anchored to the floor in order to restrict the flow past the undersurface (*see* Fig. 17). With the plate set at a negative incidence, flow conditions near the centre section, where measurements were made, thus bore some resemblence to those obtaining near the lip of the parachute. Reference to Fig. 18, where the results for 80 ft/sec are plotted, show there was an excess difference between the pressures on the two surfaces, producing upward forces over the part explored for angles as high as 40 deg; beyond this range the direction is reversed and the forces become larger as the inclination is increased. At higher speeds the reversal takes place at a lower angle: this is due to the reduction of pressure on the undersurface, in consequence of a proportionately faster rate of flow through the fabric. The conditions of stalling of the plate thus exhibit certain features in common with those on which the stability of the canopy depends.

Flow Patterns.—An examination of the flow near the lip throws more light on the changes of incidence which are responsible for the ultimate collapse of the canopy; but before this is considered in detail it may be helpful to refer to some of the main characteristics of the general flow.

These were determined in the first instance by visual observations of the behaviour of a silk thread when held in different parts of the field. Later this rough survey was supplemented by measurements of local direction made with a light metal vane pivoted so as to be capable of rotation about a transverse axis. Readings were taken at a number of positions along vertical traverses* in the neighbourhood of the basic parachute and also near the smaller non-porous parachute. In reasonably steady flow the mean direction of the vane could be measured with a telescope and angle scale to within ± 0·2 deg; but, owing to the continuous oscillations set up in other parts of the field, the accuracy was less. Over a frontal region and also within each parachute, the flow was found to be too unsteady to permit of readings being taken; there were, however, definite indications in each case of an axial return flow extending from the vertex to the mouth.

Streamlines plotted from the measurements are reproduced in Figs. 19 and 20. Included also are hypothetical representations of the flow within the canopies, each bearing a marked

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* These were in the central plane of the wind tunnel, which also coincided with one of the planes of symmetry of a parachute passing through the axis and through the medians of opposite pairs of gores.

resemblence to the cross-section through a vortex ring. Each diagram is intended only to illustrate the existence of a reversed axial flow, and to portray the manner in which this returns with the inflowing streams around the inner surface. Owing to unsteadiness the circulatory currents are variable and at times extend forward of the mouth; their positions are perhaps more permanent and better defined inside the non-porous parachute. Streams entering the parachute are seen to be concentrated near the inner surface and inclined to the lips of the gores; the angle is larger for the non-porous than for the porous parachute, corresponding with the greater tendency to preserve the unsquidded shape.

Details of Flow at the Lip.—Measurements of speed and direction made at a number of points along a vertical line some 3 in. in front of the porous parachute and along another line situated 2 in. in front of the non-porous parachute, reveal some interesting and important features of the flow. As before, the parachutes were, in turn, attached to wires which fixed the size of the opening at the mouth. For the one, the minimum distance across the mouth was 15 in.; for the other, 11 in. When fully inflated the shapes corresponded with those of free parachutes having rigging lines of 12·5 and 9·2 in. respectively: the gores had the usual fluted appearance. At the top of each gore the surface was parallel to the axis, but in the hollows between the flutings tangents to the surface were inclined at 30 deg approximately to the axis.

(*a*) *Porous Canopy.*—The directions of the local flow to the main stream, θ, along the line explored are given in Fig. 21, and the corresponding measurements of speed in Fig. 24. From the first figure it will be seen that, at low speeds, the stream is more or less uniformly inclined at about 35 deg to the axis, then, when the wind speed is increased to a certain value (not the same for all positions), the inclination starts to decrease and continues to become smaller with further increase of speed. Air entering the under side of the canopy is subject to greater changes than that in the stream passing over the top. Just prior to squidding at 130 ft/sec the directions in the two cases are 17 deg and 23 deg respectively. If the local direction is taken as 20 deg —the mean of the two measured values at this stage—the surface surrounding the shroud lines is inclined at 10 deg negative incidence to the local flow.

The sequence of changes in local speed may be traced from Fig. 24 and described as follows. At the lowest wind speed the flow entering the parachute is confined to a layer in contact with the inner surface. This layer has a thickness of about 0·13 of the minimum distance across the mouth, and has a steep velocity gradient across it. Ahead of the parachute, where the observations were taken, the mean speed is about $0 \cdot 4U_0$, U_0 being the speed in the free stream. Now as U_0 increases the layer becomes thicker and the speed relatively greater; at 130 ft/sec a further and significant increase of speed takes place as the lips of the gores are forced inwards to new positions. Corresponding changes also occur in the stream passing over the parachute, the rate of which, compared with that of the free stream, is seen to be reduced as U_0 increases. Whether this reduction compensates the proportionately greater rate of flow into the parachute at the higher speeds, or whether, on balance, there is difference made up by an increased circulation within the canopy, cannot be determined from the data available. The evidence of an increased flow is, however, clear and consistent with the change likely to result from increased porosity of the fabric.

(*b*) *Non-porous Canopy.*—Near the lip of the impervious canopy the conditions differ from those described above inasmuch as the direction of flow at any point is, within the limits explored, independent of the wind speed (*see* Fig. 22). Air enters the canopy inclined at about 40 deg. to the axis, and, as in the case of the porous parachute, remains mostly concentrated in a relatively thin layer near the surface. Increase of wind speed appears to decrease the thickness and to retard the flow in this layer. Apart from these small changes, the flow pattern remains the same at all wind speeds, and is such as to keep the parachute always inflated.

Stream Lines.—Further evidence of the change in direction occurring near the lip of a parachute fitted with a porous canopy is afforded by diagrams of stream lines in the neighbourhood of the model.

To obtain these the parachute employed in the previous tests was secured to cross-bracing wires at the mouth, the width of which was adjusted to conform with the shape having a critical squidding speed of about 130 ft/sec. As a more convenient alternative to a detailed exploration with a vane, photographs were taken of silk threads indicating directions at numerous points in the field of flow. The threads were attached to vertical wires equally spaced, in the central plane of the tunnel, over a distance extending both forward and to the rear of the parachute. A camera mounted outside the tunnel with its axis inclined at 12 deg enabled photographs of $0 \cdot 01$ sec exposure to be taken of the complete field, when this was illuminated with an arc lamp. The directions of the threads in the steady region of flow were afterwards traced from the photographs and tangential curves drawn to give the stream lines reproduced in Fig. 26.

A comparison of the diagrams reveals a progressive decrease in the slope, β, of the streamlines near the lip, as the wind speed is varied from 50 to 100 and then to 130 ft/sec. These changes of direction have already been shown to depend on the porosity of the fabric; furthermore for squidding to occur within the speed range attained in the experiments, the porosity must increase as the speed is raised. If the canopy assumes the shape represented by the rigid models used in the earlier tests, then very considerable changes of porosity would be needed to bring about squidding. Figures given in the Appendix, however, show that the porosity of the fabric over the range 60 to 140 ft/sec varies from $6 \cdot 2$ to $9 \cdot 4$ per cent. Therefore it must be concluded that the rigid model used in the earlier experiments failed to incorporate some important feature of a parachute which conduces to squidding. Apart from other reasons, in view of the fact that small changes in the size of the mouth have a pronounced effect on the pressure in this region (*see* Figs. 13 to 16), it is probable that the model was deficient in being of a fixed shape and unable to contract slightly at the mouth as the speed increases, in conformity with the redistribution of pressure. Changes of this kind, in fact, were recorded by an electrical extensometer. Hence, though the increased porosity at the higher speeds allows a greater proportion of the air to pass into the parachute, secondary effects due to change of shape, it is concluded, must also influence the speed and direction of the flow around the lip.

APPENDIX

The size of holes used at first for the rigid models was based on comparative measurements of flow through fabric, and uniformly perforated plates. Each specimen area, in turn, was clamped by a metal ring to the end of a long pipe 1·5 in. diameter, connected at the far end to the pressure side of a rotary fan. The mean speed of flow, v, was estimated from the pressure drop across a sharp-edged orifice plate inserted in the pipe, and the pressure, p, across the specimen measured by a U-tube manometer, one limb of which was open to atmosphere. Values of v obtained for differences of head ranging from 0·25 to 6 in. of water are tabulated below. Those for the fabric include a series of measurements supplied by the Royal Aircraft Establishment, as well as figures obtained at the beginning and end of a test of one hour duration. Included also in the same table are values of b, a quantity denoting the measure of percentage porosity, expressed as

$$b = \frac{100v}{V},$$

where

$$V = \frac{2p}{\rho}$$

and ρ is the air density, p and v are respectively the pressure difference and mean speed, as defined above.

The figures from the R.A.E. tests were accepted as being most representative of the average conditions of flow through the basic parachute. By the use of holes of 0·11 in. instead of 0·09 in. diameter, the porosity of the metal model in the first instance was deliberately made greater than that of the fabric, in the expectation that squidding conditions would be brought well within the range of working speed of the tunnel. As will have been seen, these conditions were only realized when the porosity was increased in the ratio 1 : 1·86.

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Measurements of Porosity

Difference of Pressure p lb/ft^2	Perforated Plate								Fabric					
	Diameter=0·08 in.		0·10		0·12		0·15		At start		After 1 hour		R.A.E.	
	v ft./sec.	*b*	*v*	*b*	*v*	*b*	*v*	*b*	*v*	*b*	*v*	*b*	*v*	*b*
1·30	2·95	8·93	4·02	12·17	5·55	16·82	9·10	27·6					1·10	3·33
2·59	3·66	7·83	5·46	11·68	7·43	15·89	12·12	25·95	2·94	6·31	2·74	5·87	2·10	4·52
5·18	4·73	7·16	7·60	11·48	10·04	15·18			4·71	7·12	4·25	6·33	3·65	5·52
10·40	6·24	6·69	10·73	11·51	14·45	15·42			7·07	7·57	6·20	6·64	6·25	6·68
15·60	7·45	6·52	12·72	11·12					9·08	7·94	7·88	6·89	8·55	7·50
20·8	8·58	6·49	14·57	11·00					10·81	8·18	9·52	7·19	10·60	8·00
26·0	9·68	6·55							12·42	8·41	11·16	7·55	12·43	8·42
31·2	10·77	6·64							13·98	8·63	12·76	7·87	14·40	8·88

TABLE 1

Details of Models representing Unsquidded and Squidded Parachutes

Unsquidded shape					Squidded shape				
Generator			Pressure holes		Generator			Pressure holes	
Z in.	r in.	No.	Z in.	r in.	Z in.	r in.	No.	Z in.	r in.
	0	1	0·04	1·45	0	0	1	0·02	1·22
0·05	1·81	2	0·07	1·94	0·07	1·51	2	0·30	2·26
0·14	2·40	3	0·29	3·09	0·71	3·02	3	0·76	3·09
0·27	3·01	4	0·66	4·09	1·33	3·62	4	1·48	3·72
0·54	3·61	5	1·30	5·01	1·96	3·90	5	2·34	3·96
0·72	4·21	6	2·26	5·70	2·60	3·97	6	3·90	$3{\cdot}76_5$
1·12	4·82	7	3·54	$6{\cdot}01_5$	3·22	3·94	7	4·92	3·44
1·75	5·42	8	4·75	5·80	3·85	3·80	8	5·89	2·60
2·29	5·71	9	5·42	5·42	4·48	3·51	9	6·96	$2{\cdot}05_5$
2·64	5·86	10	5·97	4·99	5·11	3·12	10	8·02	$1{\cdot}64_5$
3·58	6·01				5·74	2·71			
4·88	5·71				6·37	2·36			
5·44	5·42				7·00	2·06			
6·12	4·85				8·26	1·55			

In the table above, Z co-ordinate is measured from vertex along axis and r at right angles to axis.

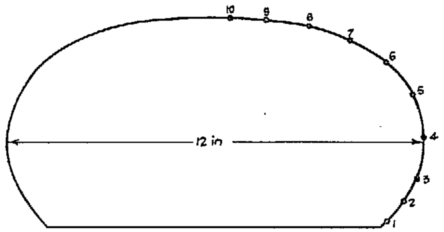


FIG. 1. Unsquidded Shape.

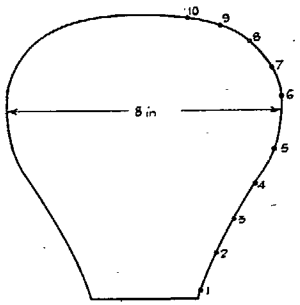
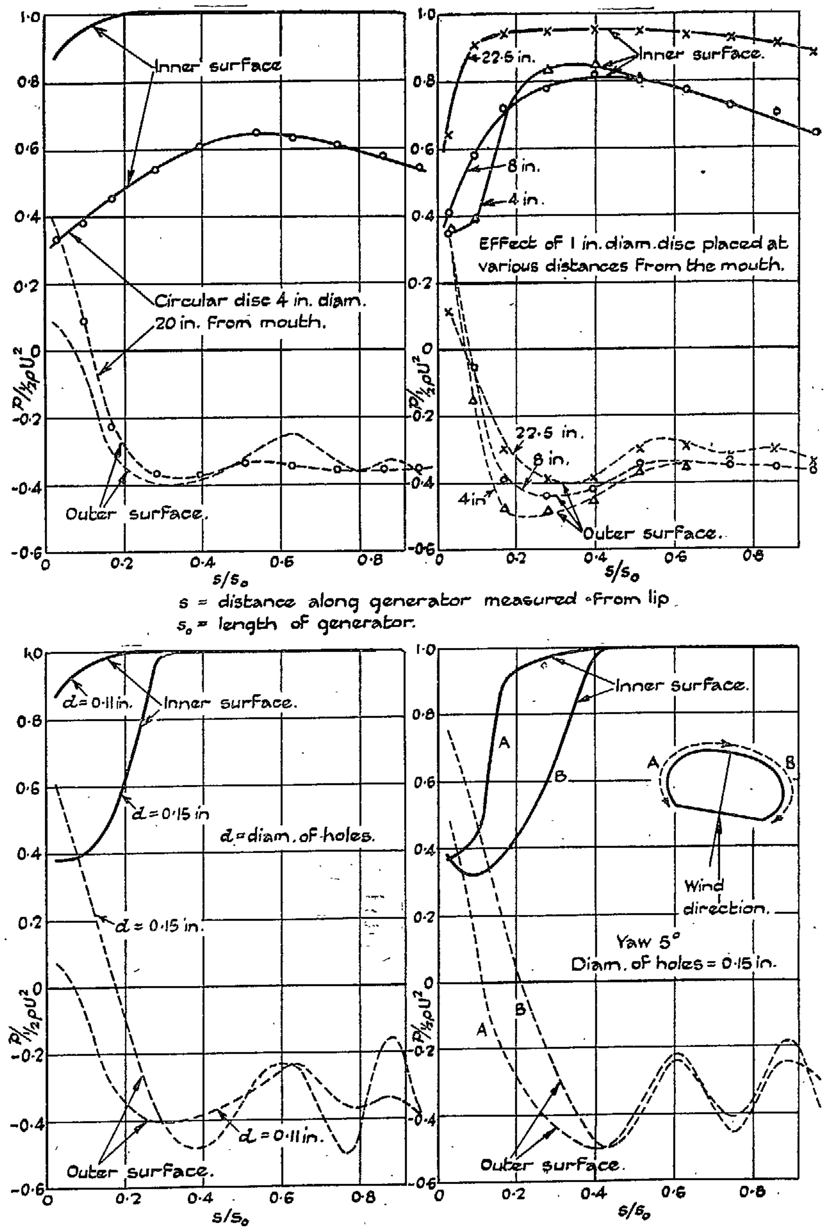


FIG. 2. Semi-squidded Shape.

Sections of Models showing positions of pressure holes.



FIGS. 3–6. Distribution of Pressure over Inner and Outer Surfaces of a Metal-Parachute Model, Perforated, unless otherwise stated, with Holes of 0·11 in. diameter—Unsquidded Shape.

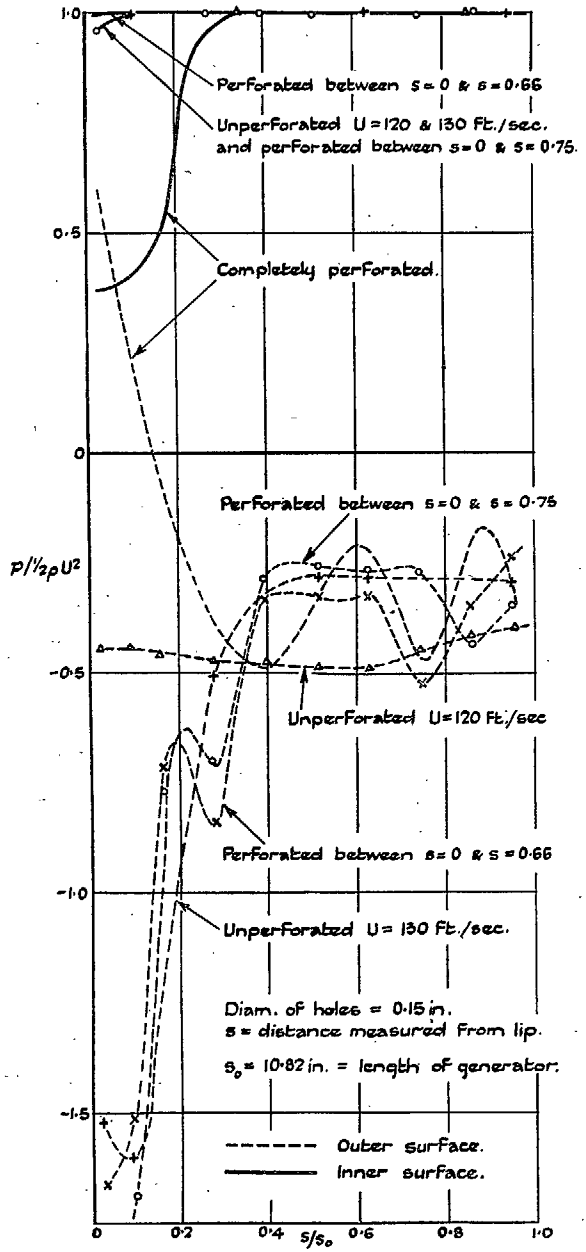


FIG. 7. Pressure Distribution over Metal Parachute Model, showing Effects of Different Degrees of Porosity—Unsquidded Shape.

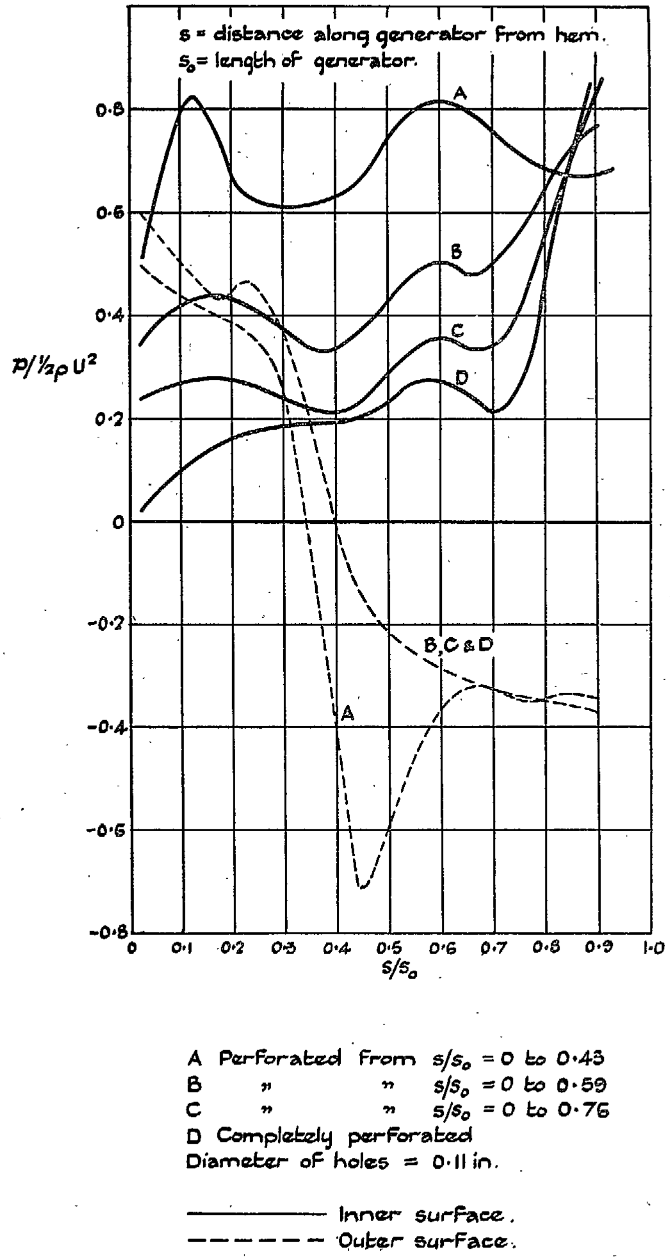
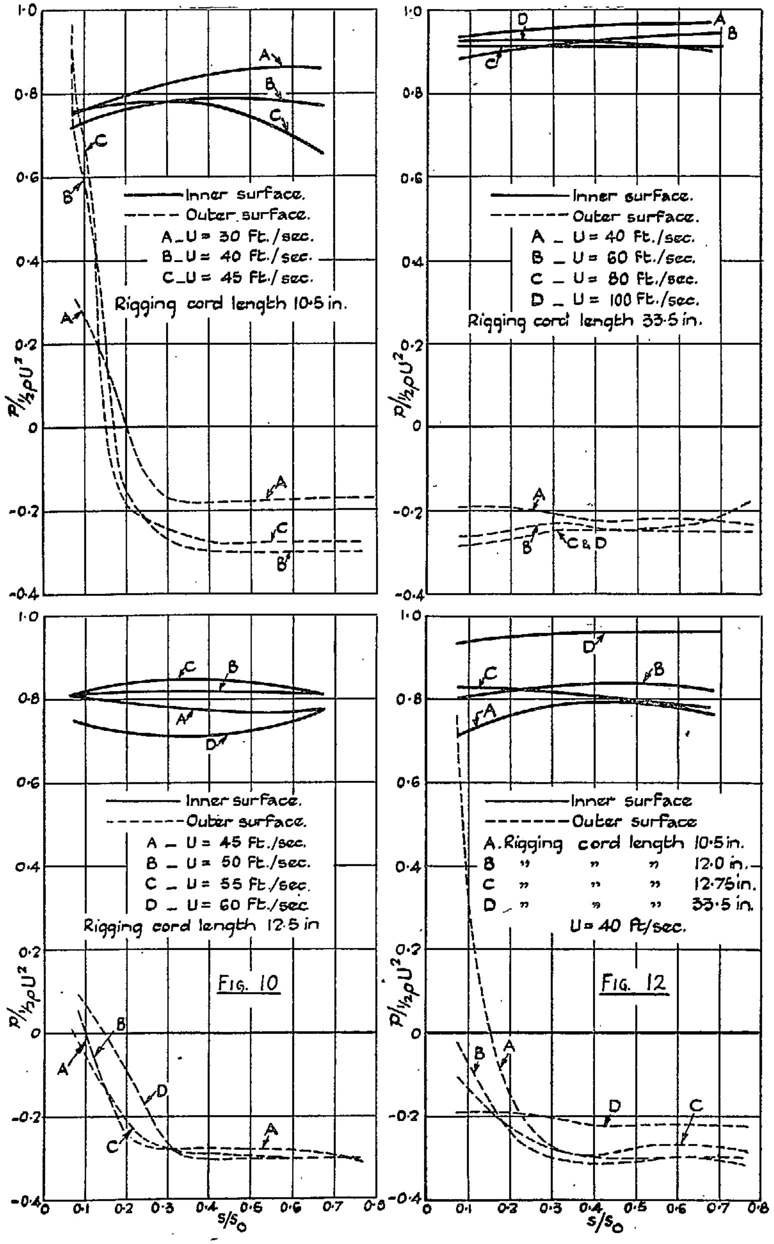
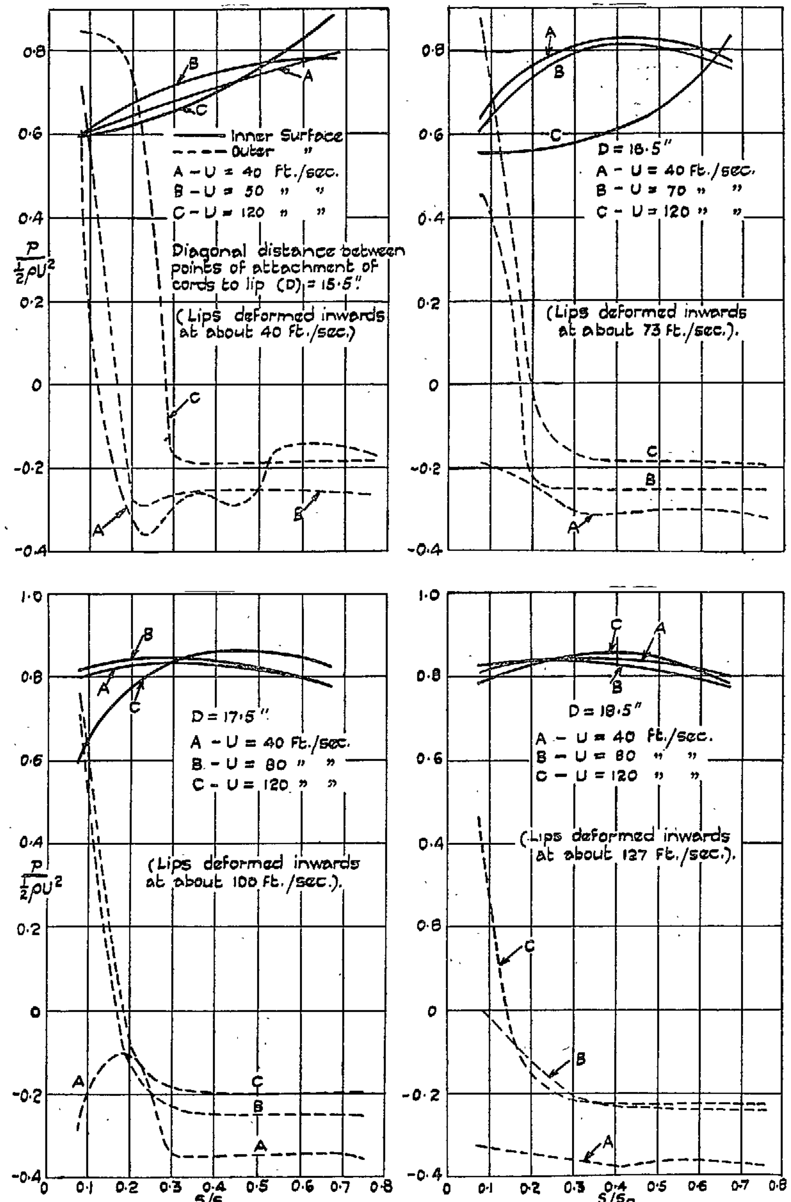


FIG. 8. Pressure Distribution over Model representing Squidded Parachute.



FIGS. 9–12. Pressure Distribution over Surface of Free, Fabric Model Parachute.



FIGS. 13–16. Pressure Distribution over Fabric Model Rigidly Secured to the Sides of the Wind Tunnel.

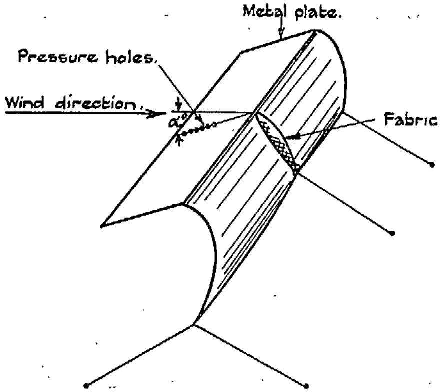


FIG. 17. Flat Plate inclined at a Negative Incidence, with Fabric Screen attached to Trailing Edge. $U = 80$ ft./sec.

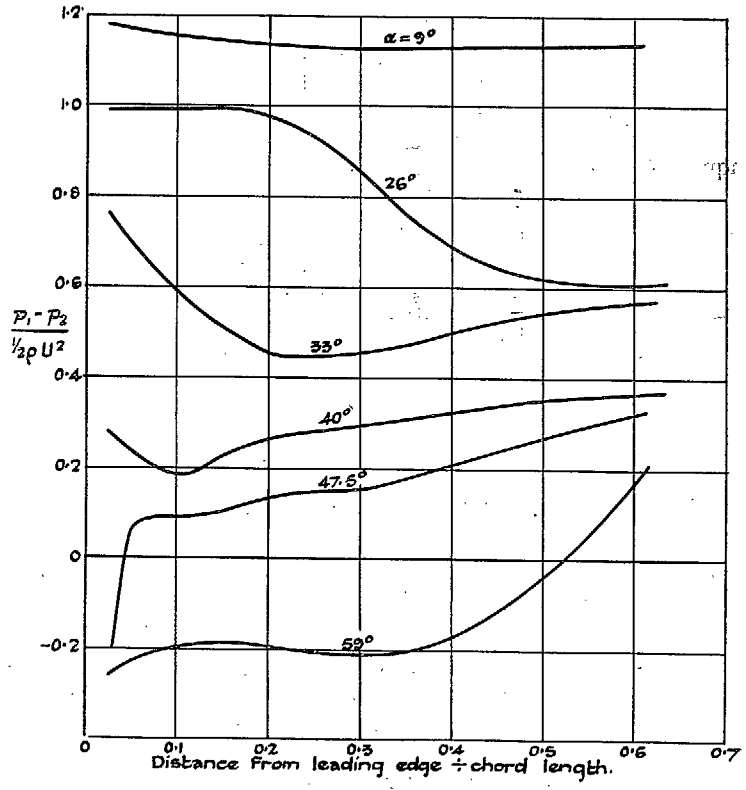


FIG. 18.

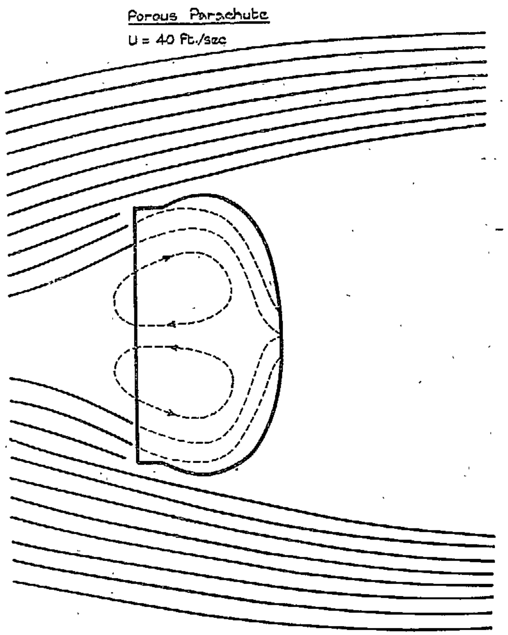


FIG. 19.

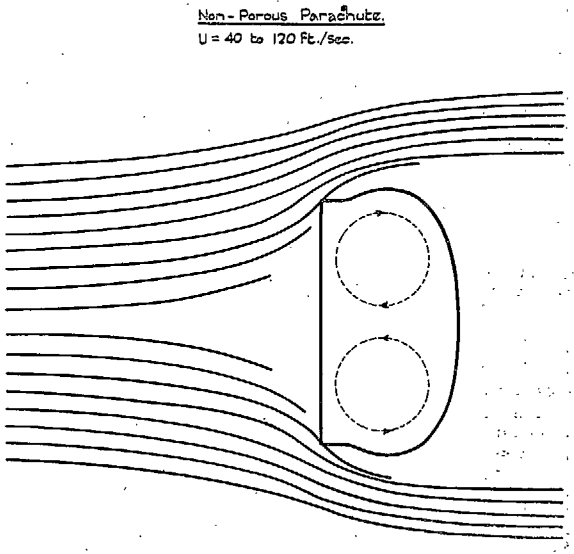


FIG. 20.

Streamlines in the Vicinity of Two Fabric Parachutes.

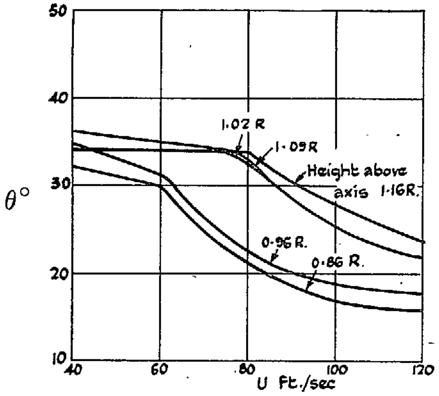


FIG. 21. Porous Fabric Parachute, $R = 9{\cdot}5$ in.

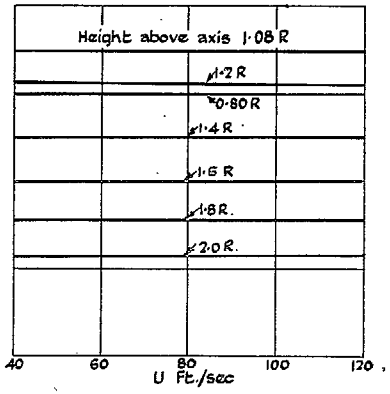


FIG. 22. Non-porous Fabric Parachute, $R = 6{\cdot}5$ in.

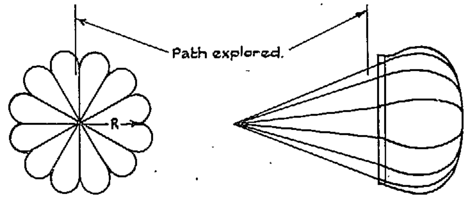


FIG. 23.

Porous Fabric Parachute, $R = 9{\cdot}5$ in.

Non-porous Fabric Parachute, $R = 6{\cdot}5$ in.

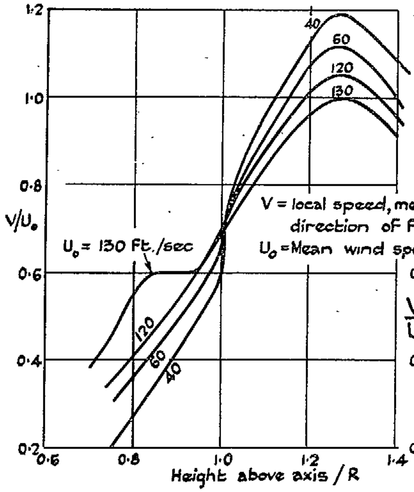


FIG. 24. Porous Fabric Parachute, $R = 9{\cdot}5$ in.

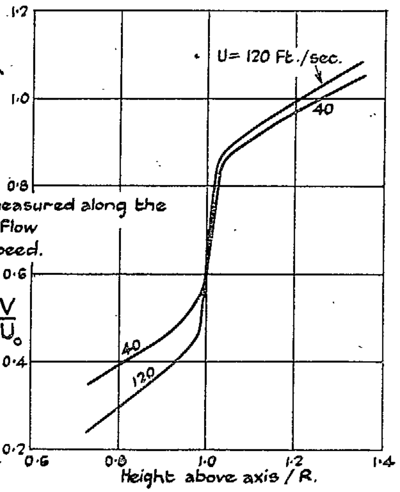


FIG. 25. Non-porous Fabric Parachute, $R = 6{\cdot}5$ in.

Direction and speed of Flow near Porous and Non-porous Parachutes.

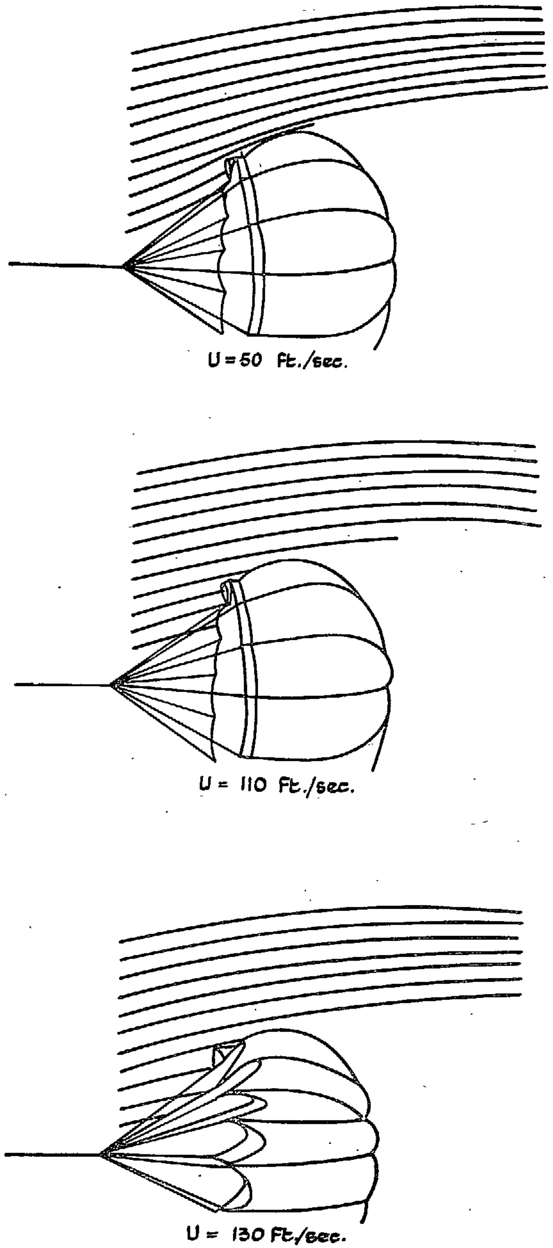


FIG. 26. Streamlines at Various Wind Speeds in the Neighbourhood of a Fabric Parachute, illustrating the Reduced Inclination in the Neighbourhood of the Lips as the Speed Increases.

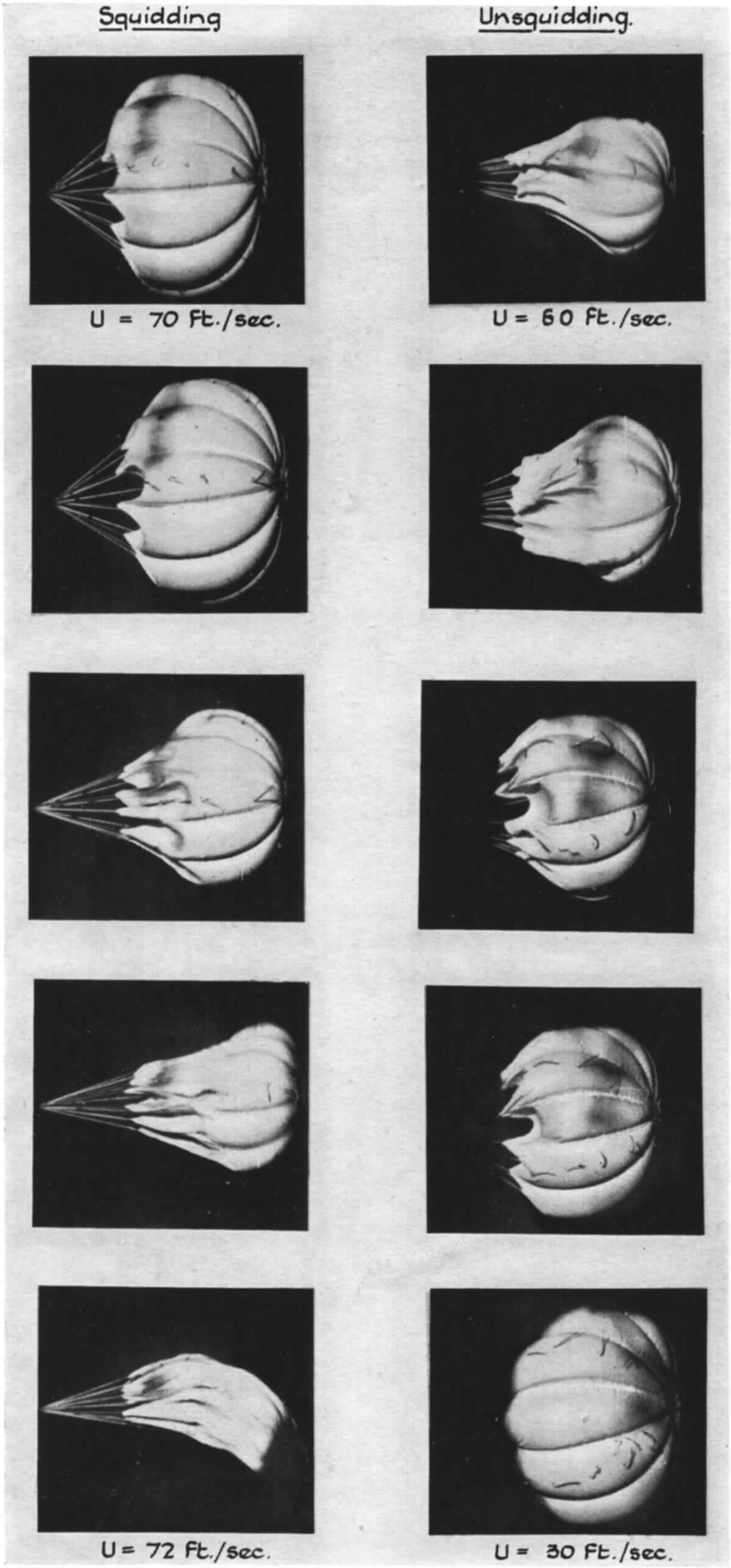


Plate I. Reproductions made from Photographs of a Parachute illustrating various Phases of Squidding and Unsquidding.

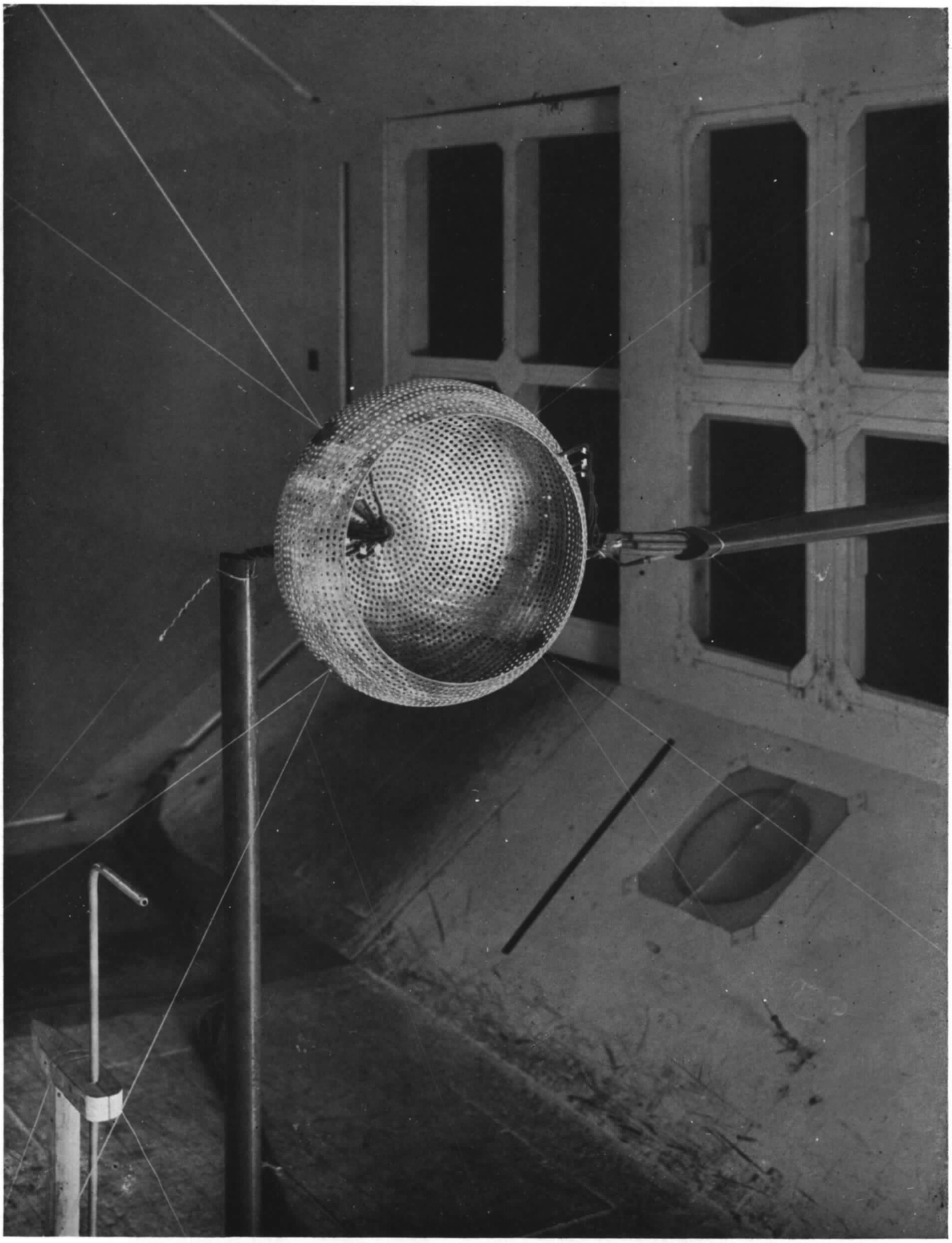


Plate II. Model of Unsquidded Shape supported in Wind Tunnel.

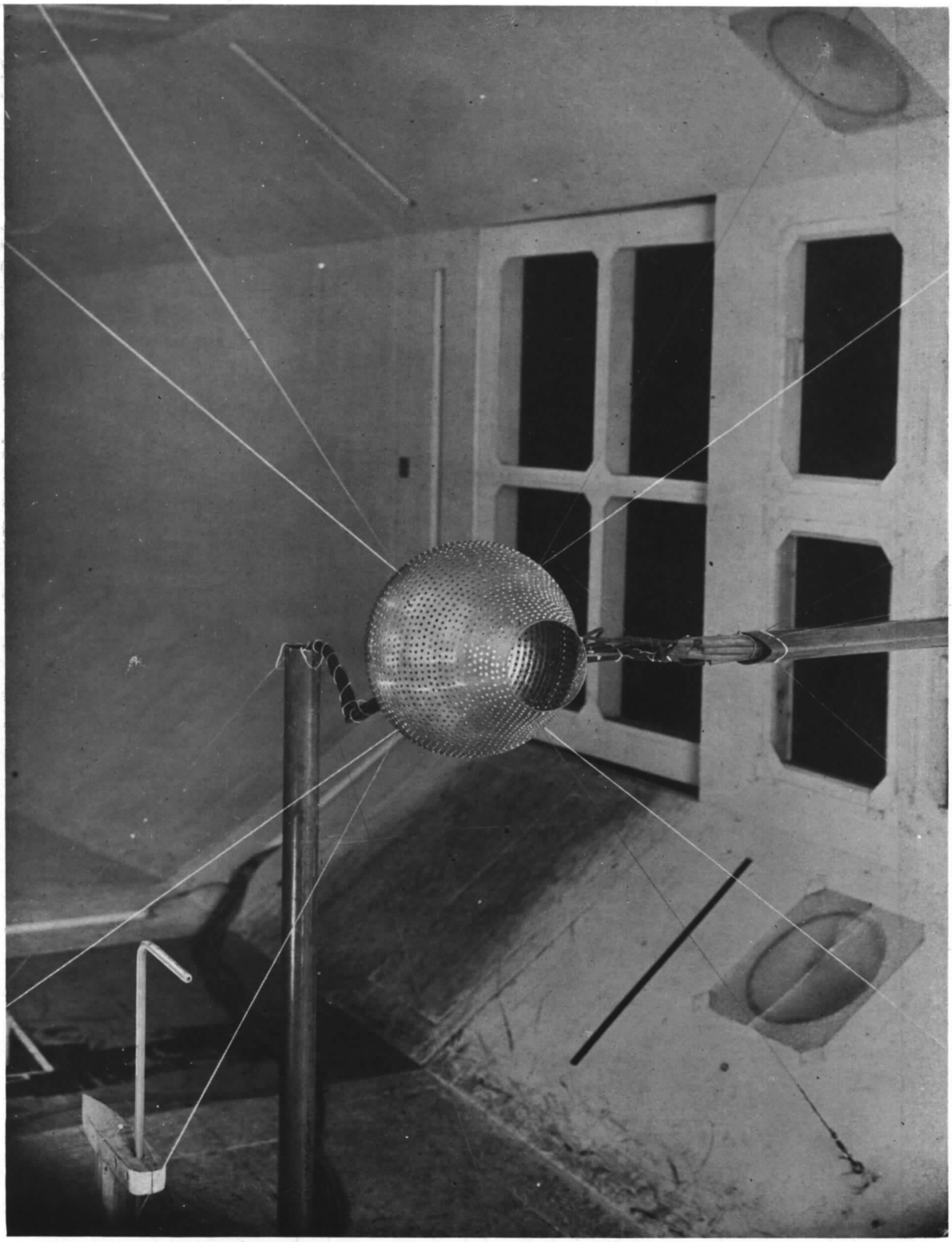


Plate III. Model of Semi-squidded Shape supported in Wind-Tunnel.

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