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The Indication of Boundary-Layer Transition On Aerofoils in the N.P.L. 20 in. x 8 in. High Speed Wind Tunnel

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CORRIGENDUM

Last two sentences on Page 3, continued on the top of Page 4, should read:-

"It has been noticed that when the boundary layer is laminar this bright line is separated from the dark shadow by a space where the illumination is of normal intensity. Comparisons between photographs and liquid film transition measurements have shown that this line converges on to the shadow very near the transition position, somewhat as sketched in Fig.1."

ADDENDUM

Arising from information which has become available since the original issue of this report in the A.R.C. Series it is now possible to make the following comments on statements in the last two paragraphs of the text on Page 7. The bright line separated from the dark shadow which occurs in the presence of laminar boundary layers, has been noticed in direct shadow photographs of flow over two-dimensional aerofoils in other high speed wind tunnels. It has also been realised that it is sometimes present on Schlieren photographs if these are slightly out of focus or if the depth of focus is not sufficient to permit a sharp focus over the whole span of the model. The indication on these is not, however, as clear or as reliable as on direct shadow photographs and, moreover, it is not possible to cover both surfaces with one position of the knife-edge or the whole Mach number range with a single setting of the focussing lens.

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The Indication of Boundary-layer Transition on Aerofoils in the N.P.L. 20 in. × 8 in. High Speed Wind Tunnel.

- By -
H. H. Pearcey, B.Sc.
of the Aerodynamics Division, N.P.L.

14th December, 1948.

Summary

The "liquid film" evaporation method developed by Gray[1] for indicating the position of boundary-layer transition on models in low speed wind tunnels has proved satisfactory in the N.P.L. 20 in. × 8 in. high speed tunnel. Observation of transition over the complete span of the model can be simultaneous with that of surface pressures, profile drag and flow pattern.

Direct shadow photographs taken in this tunnel also give an approximate indication of the transition point in certain cases, due to the change in density profile accompanying the change from laminar to turbulent flow. Thus, except when transition occurs near the leading edge, a laminar layer is indicated by a bright line parallel to, but separated from, the dark shadow of the aerofoil and converging on to this shadow to meet it just downstream of the transition point.

1. Introduction

The state of its boundary layers can have an important influence on the aerodynamic characteristics of an aerofoil at high subsonic speeds. The profile drag is of course largely dependent on the position of the transition from laminar to turbulent flow and, in addition, it is now known that laminar and turbulent layers often interact differently with the shock waves, so that the other forces are likely to be affected also. It is therefore desirable that force measurements at high speeds and shock-wave photographs should be accompanied by observations of the transition position.

These observations should, if possible, be simultaneous with the other measurements in order to avoid discrepancies in tunnel or model conditions and to check that regimes of laminar boundary-layer flow are not contaminated by the wedge-shaped turbulent regions caused by dust particles, leaky pressure holes, etc.

Holder[2] (1945) successfully applied the "china clay" technique to aerofoils in the 20 in. × 8 in. tunnel. This method is not, however, easy to use simultaneously with other measurements since access to the model in the tunnel is difficult, necessitating its removal for the coating and spraying operations. Moreover Rogers[3] (1948) suspected an increase in drag due to the presence of the indicator in a rather critical case. Special care is also needed to free the small pressure holes. The "liquid film" evaporation method developed by Gray[1] (1946) is much simpler to use, a film of oily liquid being rubbed on to the surface of the aerofoil in position. The above objections do not arise for this method which has been used with success. The results obtained have been used to confirm that direct shadow photographs also give an indication of the transition position in certain cases.

2./

2. The Liquid Film Evaporation Method

Gray[1] lists the requirements for a good method of indicating transition and describes how these are fulfilled by his liquid film method in a typical low speed tunnel. These requirements apply equally for the 20 in. × 8 in. tunnel with the addition that simultaneous pressure plotting should be possible.

The present observations were made when trying the method in this tunnel, during other experiments with the Goldstein 1442/1547 "roof-top" section, under the normal test conditions for which a suitable indicator is required. The model, typical of those normally used, was of polished brass and liquids were tried which were recommended by Gray[1] to give the surface a dulled appearance when wet which becomes fully reflective again on evaporation in the turbulent regions. Of these, glycerol alpha-monochlorhydrin, usually known simply as alpha-monochlorhydrin, gave good indications at all Mach numbers up to the top speed of the tunnel, i.e. about 0.87, the time taken varying from about two minutes at $M = 0.4$ to about a half-minute at top speed*; this has therefore been adopted for general use. ≠

Since the size of the model is only 5 in. chord by 8 in. span no great difficulty was experienced in obtaining a uniform, very thin film. When cloth or chamois leather was used to apply the liquid, the specks of material left on the surface caused some trouble and good quality tissue paper was more satisfactory. It was found better to use circular or chordwise rather than spanwise strokes since a discontinuity in thickness of film from one spanwise stroke to the next can lead to misinterpretation of the transition pattern.

It is not easy to photograph the polished metal surface of the aerofoil in position between the glass walls and for routine tests the transition "point", which is usually at a well defined chordwise position and uniform across the span, is observed visually at the end of the run. To illustrate the results obtained a few photographs were taken and examples are reproduced in Figs. 1-3. Although, no great pains were taken with the

lighting/

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*Acceleration and deceleration occupy only a very few seconds so that even for these very short runs the tunnel is steady for most of the run.

≠Very little information is available on the toxicity of this compound, but it is known to be dangerous if swallowed. There is no spray of any kind involved in the liquid film technique and the liquid is used only in minute quantities in the 20 in. × 8 in. tunnel, being applied from outside of the tunnel. Moreover there is no discharge from the tunnel into the operating room and, since it is of the injector type an accumulation of vapour is prevented by a continual exchange of the air in the circuit. Further, the boiling point of the compound is high and its vapour pressure low. As used in this experiment, therefore, the substance would appear to be harmless provided that reasonable care is taken in handling to preclude, also, any possibility of skin absorption. For a tunnel where conditions are less favourable and there is any danger of operators being exposed to the vapour, an alternative compound should be used, e.g. one of the distilled fractions of paraffin suggested by Gray[1] which are non-toxic but are, however, difficult to observe on a polished metal surface.

lighting, the transition position is clearly defined, the dull laminar regions being easily distinguished from the clear turbulent regions where evaporation has occurred. The apparent scratches are merely polishing marks accentuated by the grazing light. The simultaneous surface pressure measurements and direct shadow photographs are also shown in Figs. 1-3. Figs. 1(a) and 2(a) show transition well back on the upper surface at 0.5° incidence, for M = 0.46 and M = 0.8 respectively; apart from wedge-shaped regions of turbulence which were traced to small particles of dust the transition is reasonably uniform across the span. At M = 0.8 (Fig.2) there is a region of local supersonic flow and transition occurs at about 0.06 chord ahead of the normal shock wave on this surface.* Fig. 3(a) shows transition near the leading edge on the upper surface at 6.5° incidence, M = 0.5.

Readings of surface pressures and profile drag were taken with and without the film on the surface and no adverse effect could be detected except in one case where excess liquid had been applied and actual droplets were formed.

In a special experiment for which the model was mounted in perspex instead of the usual glass windows, the polished perspex surface deteriorated when alpha-monochlorhydrin was rubbed against it.

For some runs fine dust and oil particles formed a light deposit in the turbulent regions, similar to those mentioned by Thom and Douglas[5] (1945) in their account of some German high speed tunnels, and the transition positions deduced from these agreed very well with those indicated by the liquid film.

3. Direct Shadow Photographs

Direct shadow photographs sometimes yield information on the state of the boundary layer and in many cases give an approximate indication of the transition position. Although it is not suggested that these can replace other methods, such as that described above, which give a more positive indication and cover the whole span, some examples together with a probable explanation are briefly described as a matter of interest, and may be of use for interpreting photographs taken without other transition observations.

Parallel light entering the boundary layer along the span of the aerofoil is deflected outwards due to the positive density gradient. This leads to an apparent increase in the size of the shadow of the aerofoil and the appearance of bright lines along the eges of this shadow. It has been noticed that when the boundary layer is laminar this bright line is separated from the dark shadow by a space where the illumination is of normal intensity Comparisons between photographs and liquid film transition measurements have shown that this line converges on to the shadow very near the transition

position /

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*The rapid thickening of the boundary layer ahead of the shock wave tends to compress the flow and to soften the shock wave near the surface. This effect has been discussed by Donaldson[4] (1944) and others, and further examples will be described in a report to be issued shortly on the types of shock wave observed in the 20 in. × 8 in. tunnel.

position, somewhat as sketched in Fig. (i).

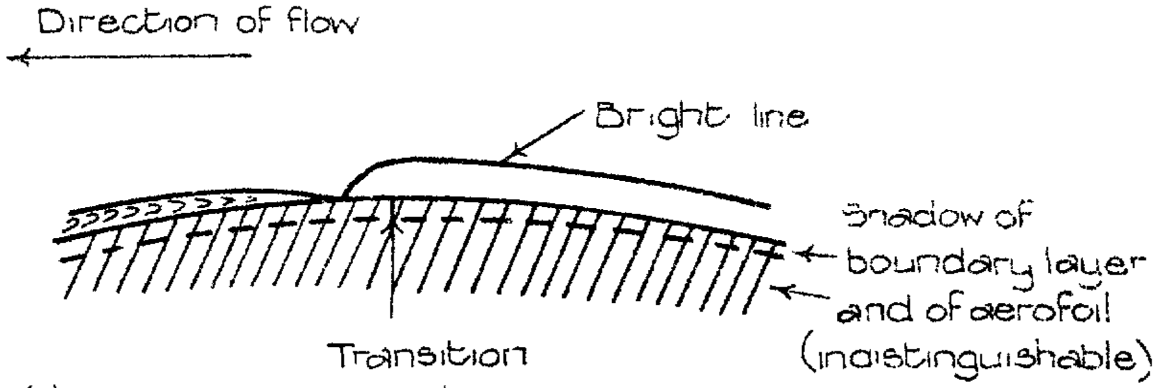

Fig (i)

This is illustrated by the photographs in Figs. 1(c), 2(c) and 3(c) and more clearly by those in Figs. 4 and 5 which are enlargements of the rear part of the aerofoil; the arrows have been drawn to indicate the transition position measured by the liquid film method. In Fig. 4(a), which shows a typical low Mach number case, $\alpha = 0.5°$, $M = 0.57$, with transition far back on both surfaces, the bright lines separated from the dark shadow are clearly visible, but are not present in Fig. 4(b) which was taken at the same incidence and Mach number with both boundary layers turbulent from about 0.1 chord back from the leading edge.* The example in Fig. 5, for $\alpha = 6.5°$, $M = 0.78$, shows the bright line very distinctly on the lower surface; the flow over that part of the upper surface shown is very turbulent behind a shock wave. A control photograph with no airflow is shown in Fig. 6 to enable external obstructions, scratches on the glass, etc. to be recognised in the direct shadow photographs of Figs. 1-5.

Since the displacement of the light entering the boundary layer is large compared with the thickness of the boundary layer, the density and density gradient will vary considerably along the path of a ray through the whole span and the photographs do not lend themselves to quantitative analysis by existing theories which depend on the assumption of infinitesimally small deviation. They can, however, be considered qualitatively. Thus, assuming the flow to be two-dimensional and ignoring the density gradient in the chordwise direction, which is very small compared with the positive gradient, $\partial\rho/\partial y$, normal to the surface, a ray of light entering the boundary layer and originally parallel to the spanwise axis of the aerofoil is deflected outwards in a plane normal to the surface, its curvature being at any point proportional to $\partial\rho/\partial y$ (see ref. 6, page 98, for example). The image produced by the strip of light entering the boundary layer will thus depend on the distribution of $\partial\rho/\partial y$ along the normal.

The /

*This photograph was taken during measurements, to be reported elsewhere, of shock-wave patterns and pressure distributions to compare with those previously obtained with laminar layers, the boundary layers being rendered turbulent by stretching a wire across the tunnel parallel to and 1.5 chords ahead of the leading edge.

The theoretical temperature distribution in a laminar boundary layer for a flat plate with no heat transfer from the plate, given in ref. 7, §268, may be regarded as typical for laminar boundary-layers and is sketched in Fig.(ii). Since the pressure

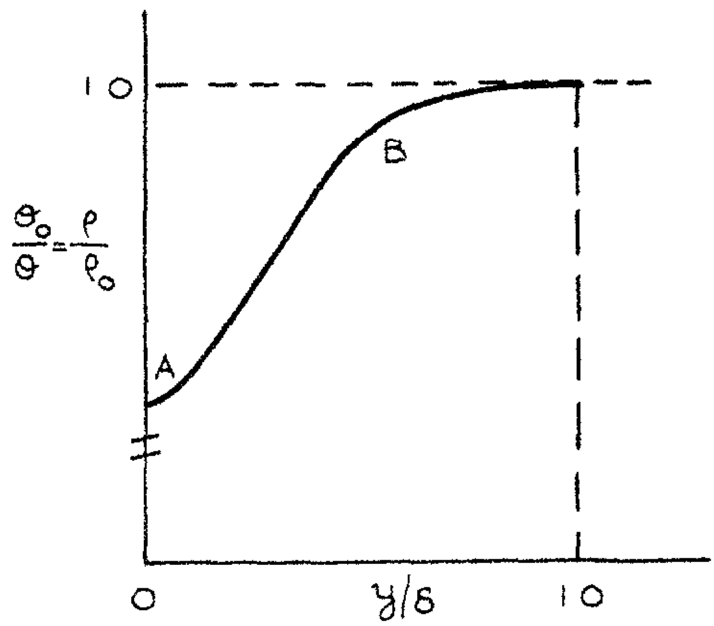

FIG (ii)

is constant along a normal, this also gives the density distribution. The interesting characteristics are (a) an increase in density gradient at A, near the surface, which must cause a divergence of light, successive rays suffering greater deflection and (b) a rapid decrease in gradient at B, near the edge of the boundary layer, which must cause a convergence of light, successive rays suffering smaller deflection. The bright line observed in the photographs could be caused by this convergence, the rays focusing some way out from the dark shadow.

Measurements by Éliás (see ref. 7, §165) have shown that for the flow in a turbulent boundary-layer along a heated plate, the temperature distribution is of the same form as the velocity distribution. Assuming this to apply also for an unheated aerofoil in compressible flow, the temperature and density distribution along a normal

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for a fully developed turbulent layer will be of the form shown in Fig.(iii). There is

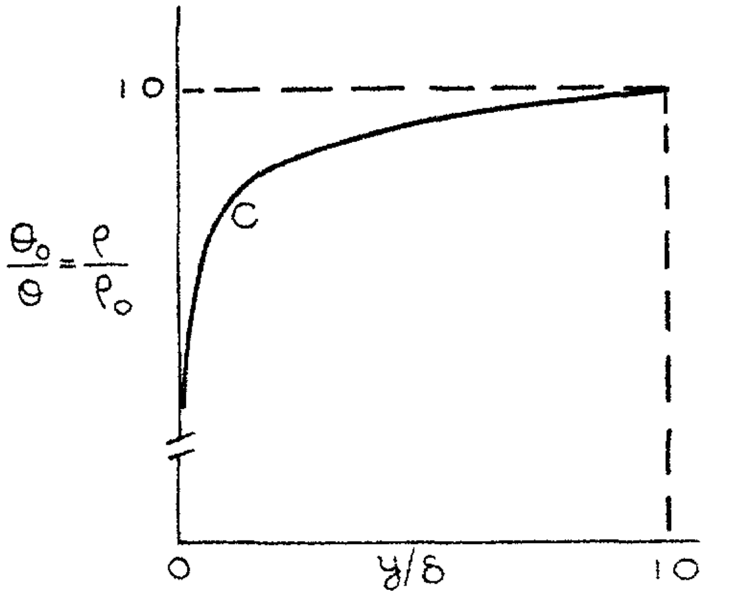

FIG (iii)

no rapid change in density gradient near the edge of the boundary layer as at B in Fig.(ii), but the gradient is much steeper near the surface, the rapid decrease occurring quite near the surface at C.

Since it is this rapid decrease in gradient which causes the focusing of light, it seems very probable that its shift from the edge of the layer to near the surface is responsible for the observed convergence of the bright line on to the dark shadow when transition from laminar to turbulent flow occurs.

Explorations of the velocity profiles near the transition point on an airship model, made by Simmons and Brown[8] (1934) and some of which are reproduced in Fig.7, show that although the slope at the surface steepens suddenly on transition, the rapid change in gradient near the edge of the layer disappears more gradually. If the velocity and density distributions change in a similar manner when transition occurs on an aerofoil, this would explain the present observations that the bright line begins to converge on to the dark shadow at the measured transition point and meets it slightly downstream of this position.

For the lower surface in Fig.2(c) the convergence is delayed slightly, presumably due to delay in the establishment of the typical "turbulent" distribution, which may be caused by the interaction of the shock wave.

The /

The bright line is not present in some cases when transition occurs near the leading edge where the boundary layer is comparatively thin, as in Fig.3(c), for example, for which transition is at 0.1 chord back on the upper surface. Faint lines are, however, visible on photographs obtained at this same incidence at an earlier date. For these the light was slightly out of alignment with the axis, more light entering the boundary layer on the upper surface and less on the lower surface, and it is noticeable that the bright lines on the lower surface are not so clear as in Fig.3(c).

The absence of this bright line does not, therefore, necessarily imply that there is no region in which the boundary layer is laminar, but if it is present it seems reasonable to assume that transition occurs just upstream, within about 0.03 chord, of the point where the line meets the dark shadow remembering that it may be slightly further upstream for cases such as that shown in Fig.2(c), where the line persists through a shock wave in the presence of an obvious boundary layer thickening.

It is not known whether this phenomenon has been observed in other wind tunnels, but it will depend to some extent on the Reynolds number, aerofoil span and distance between the tunnel and the photographic plate. The images produced are sensitive to the accuracy with which the light is aligned to the aerofoil axis, and care must be taken not to confuse the bright lines due to the laminar boundary-layer with those caused by the reflections from the surface of imperfectly aligned light, which do not converge on to the shadow at any point and which would be present on the control photograph.

The bright lines separated from the dark shadow would not of course be present on a true Toepler schlieren photograph since the deflected light escaping the cut-off is re-focused, there being no displacement in the final image.

Acknowledgements

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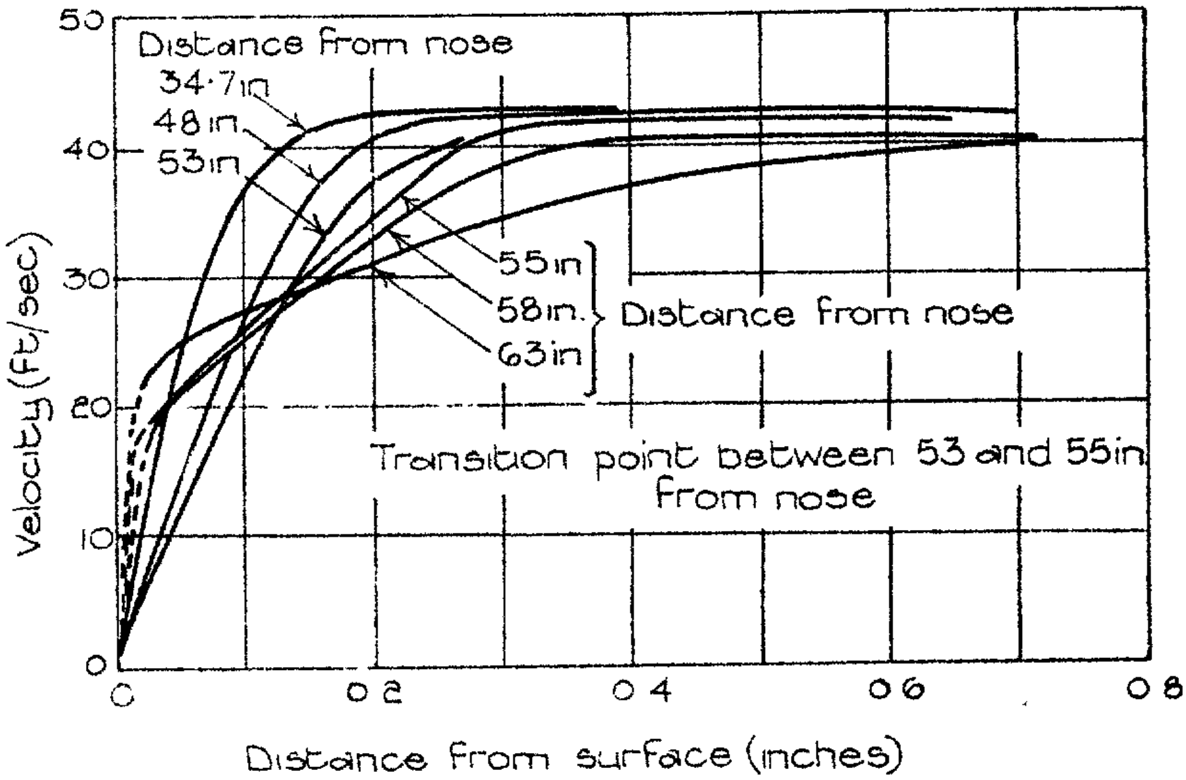

Velocity distribution normal to the surface at sections near the transition point of an airship model

(Simmons and Brown, R & M 1547)

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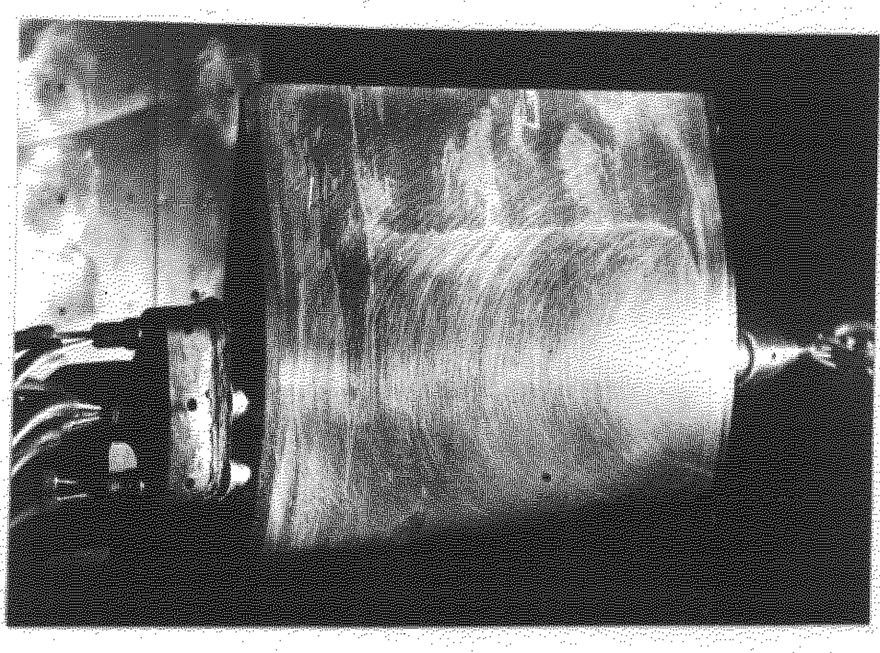
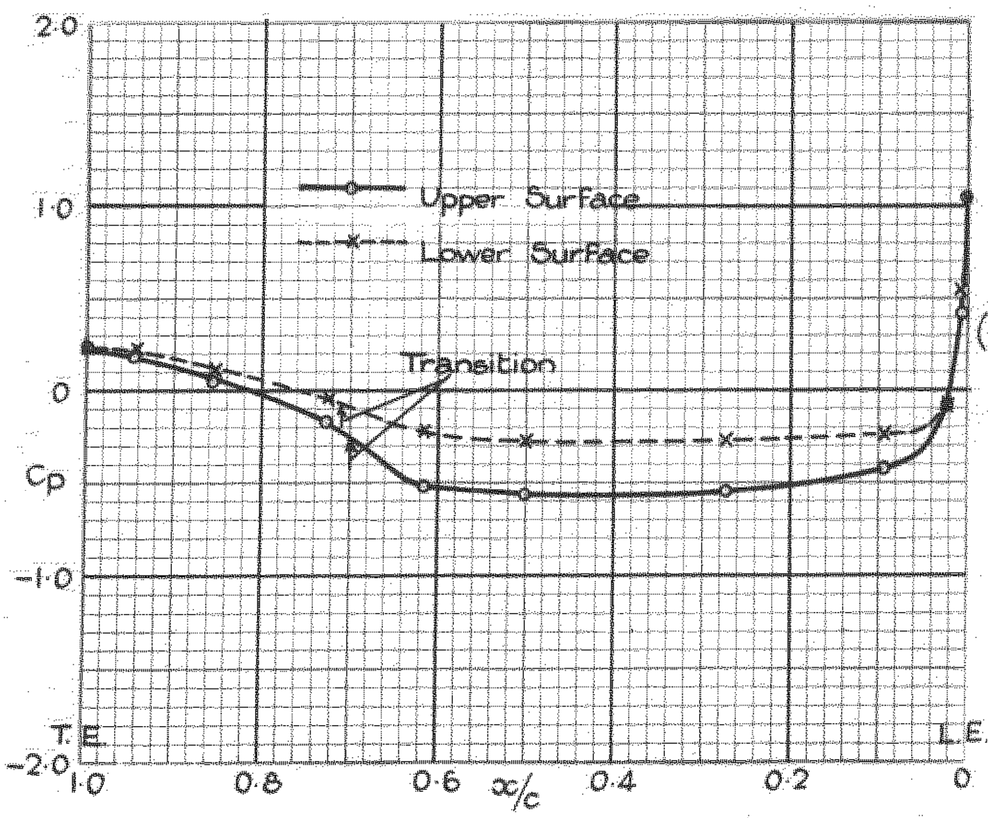
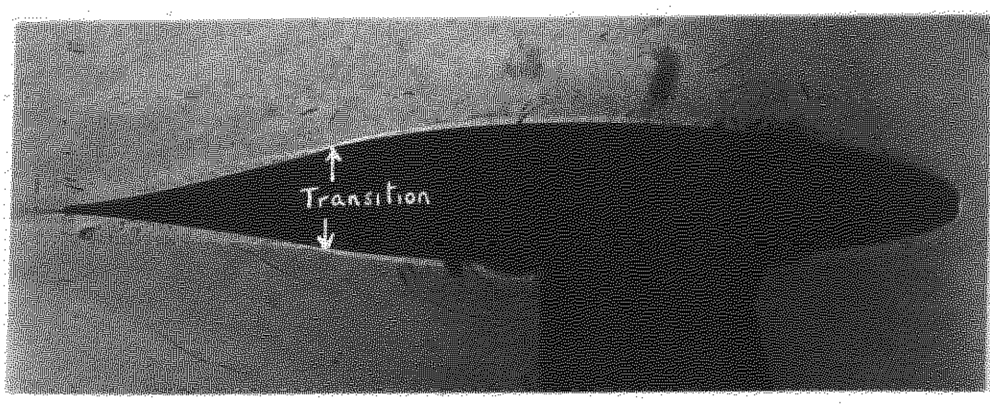
FIG. 1.



(a) Transition Indication on the Upper Surface



(b) Chordwise Pressure Distributions



(c) Direct Shadow Photograph

Observations at M=0·46; 0·5° Incidence

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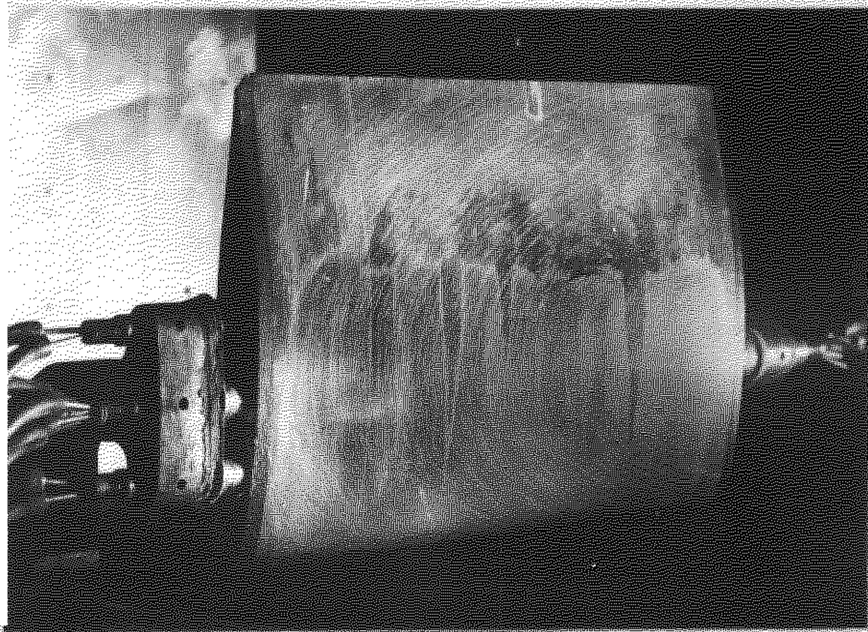
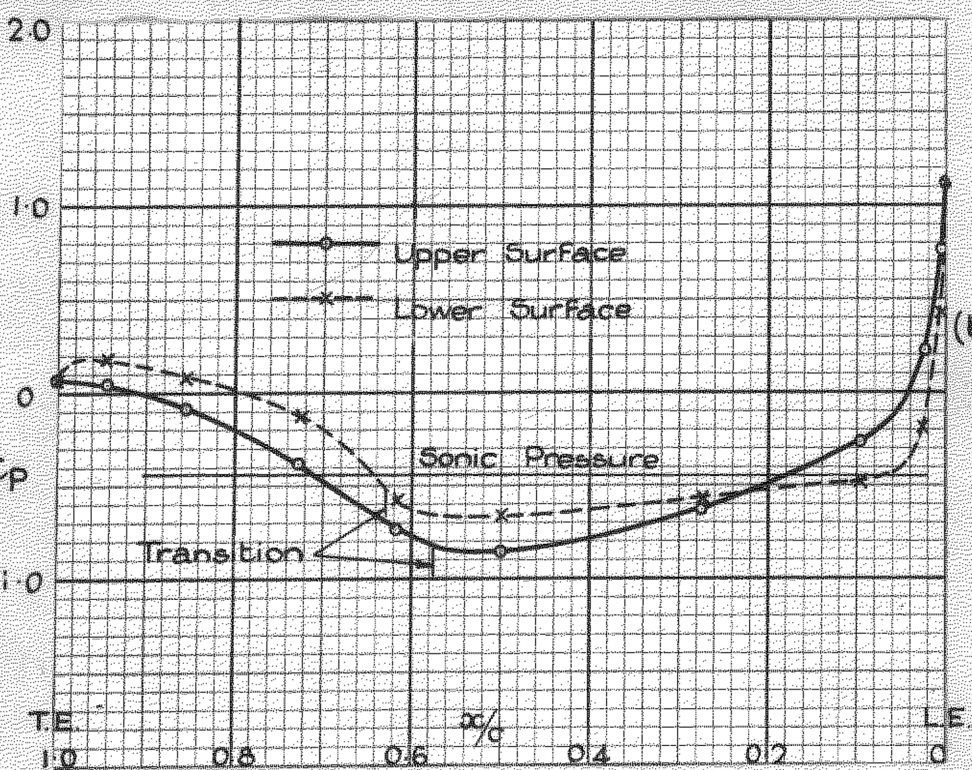
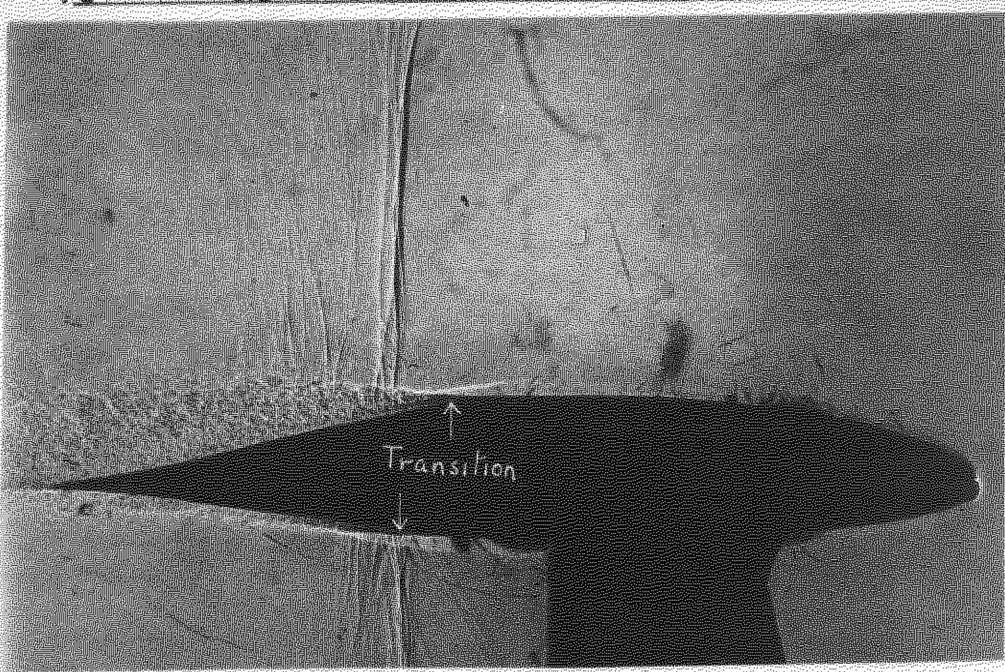
Fig. 2.



(a) Transition Indication on the Upper Surface



(b) Chordwise Pressure Distributions



(c) Direct Shadow Photograph

Observations at M = 0.8; 0.5° Incidence

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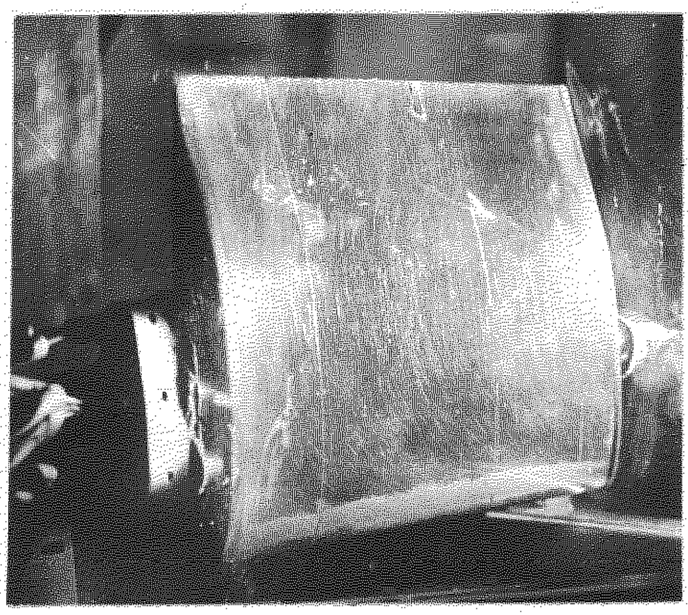
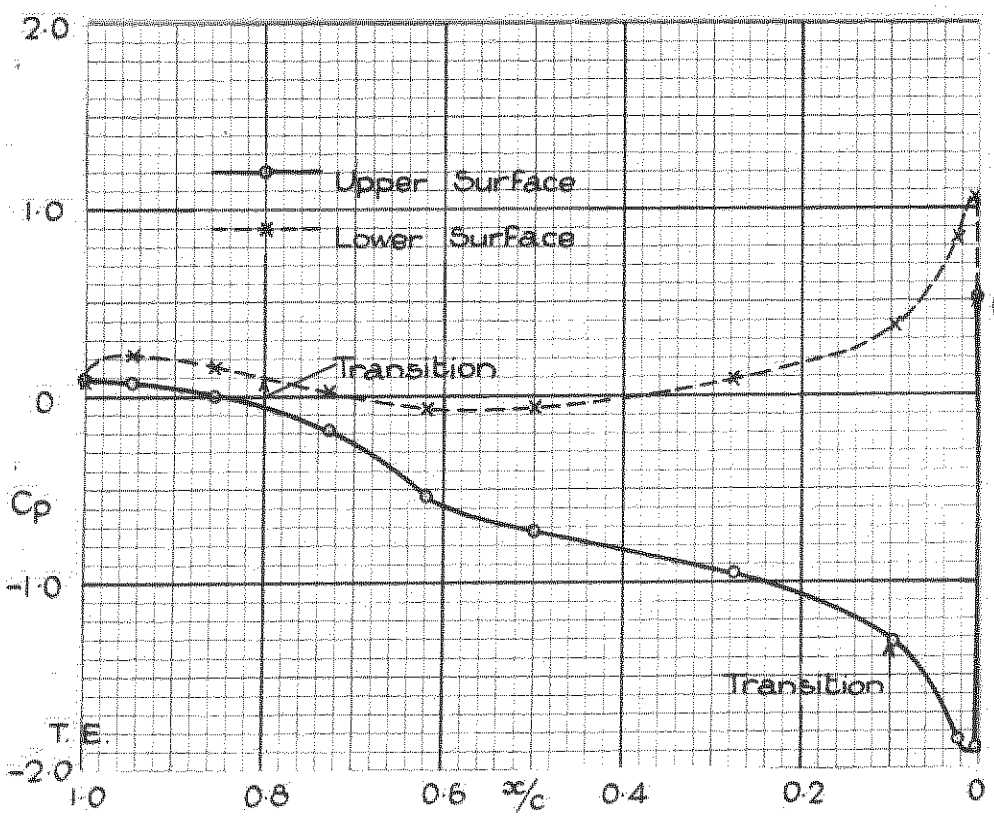
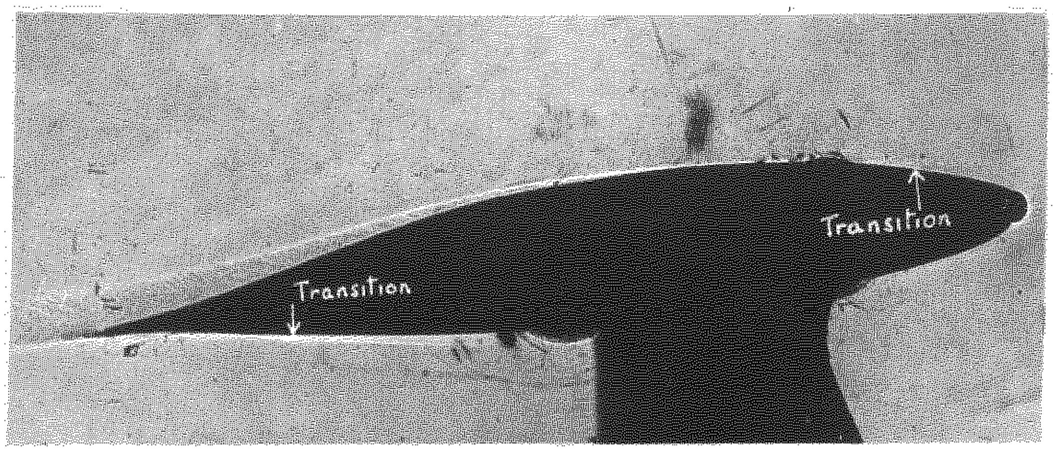
FIG. 3.



(a) Transition Indication on the Upper Surface



(b) Chordwise Pressure Distributions



(c) Direct Shadow Photograph.

Observations at M=0·5; 6·5° Incidence

FIG. 4.

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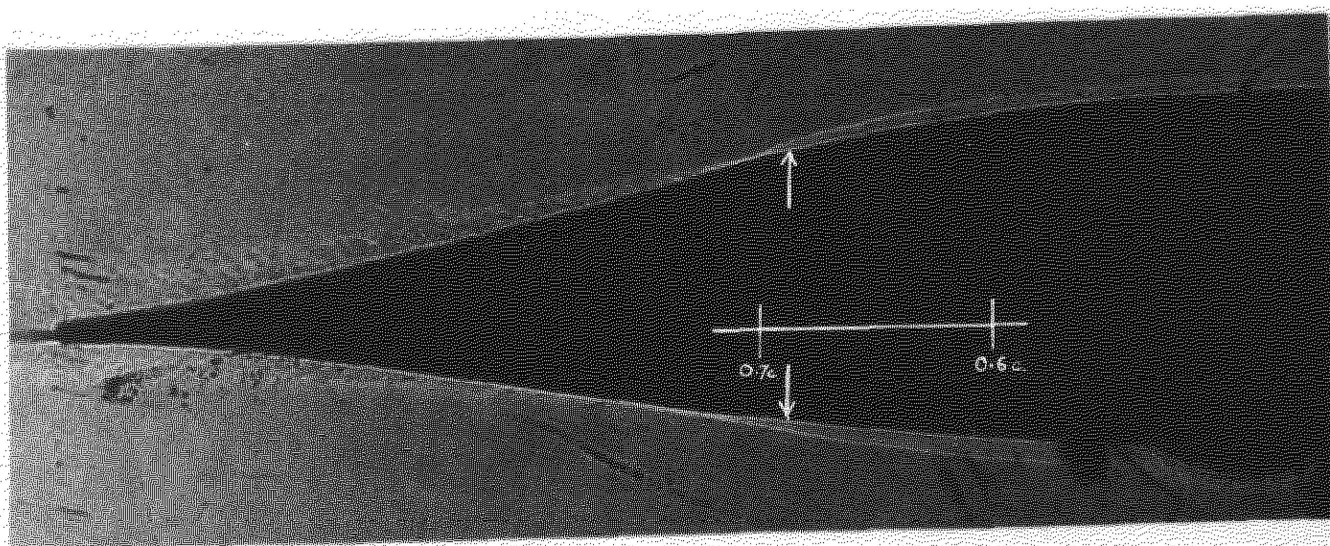
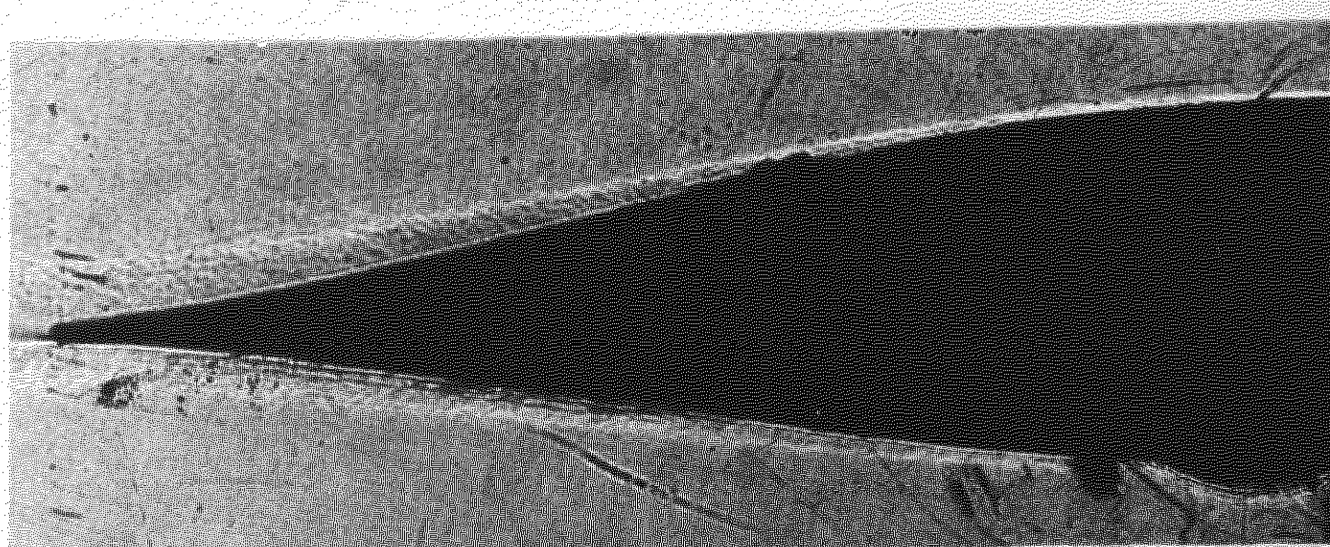


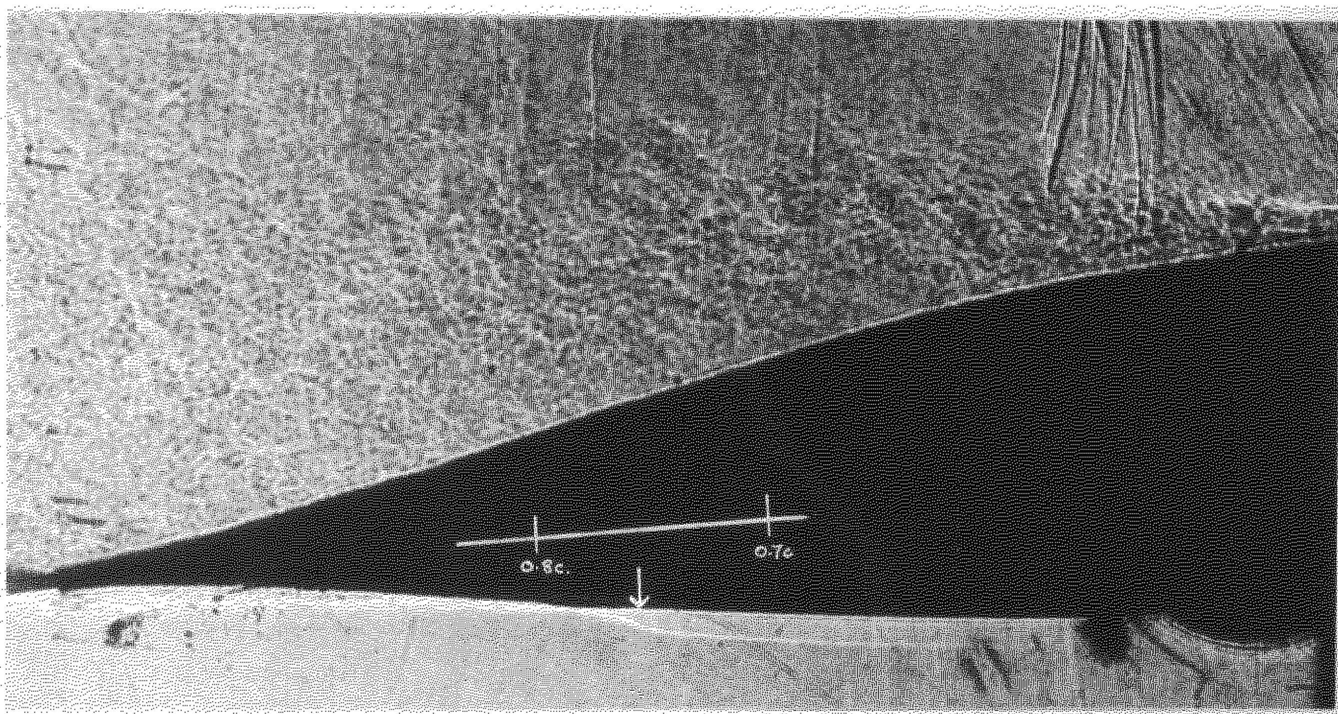
(a) With boundary layers laminar back to 0·69 chord
(White arrows show transition positions as indicated by liquid film)



(b) With boundary layers turbulent from 0·1 chord

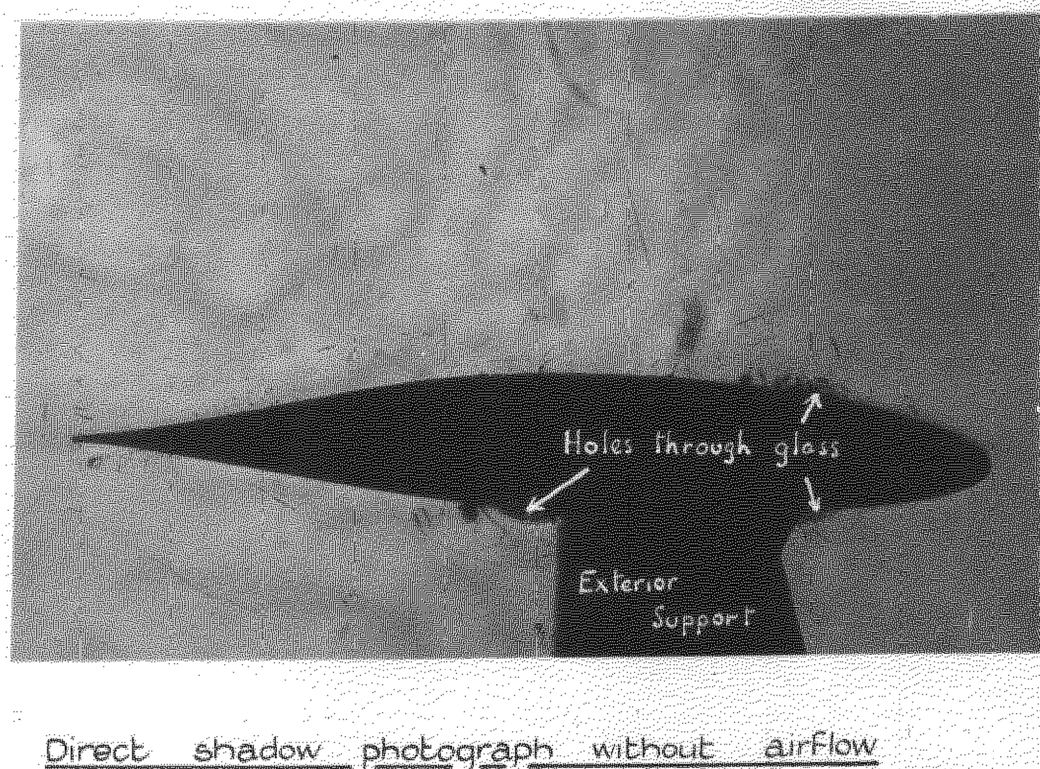
Direct Shadow Photographs (enlarged) for M=0·57; 0·5° Incidence

Fig. 5.



Direct shadow photograph (enlarged) for M = 0·8, 6·5° incidence
(White arrow shows transition as indicated by liquid film)

Fig. 6.



Direct shadow photograph without airflow

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