C.P. No. 484
(20,969)
A.R.C. Technical Report

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MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

Aspects of Insect Contamination in Relation to Laminar Flow Aircraft.

by

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LONDON: HER MAJESTY'S STATIONERY OFFICE
1960
Price 3s. 6d. net

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Aspects of Insect Contamination in Relation to Laminar Flow Aircraft

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April, 1959

Introduction

The great sensitivity of laminar boundary layers to any form of surface roughness has been held against the practicability of boundary-layer control for low drag.

Contamination of the wing nose by impacted flies is a typical form of accidental roughness which is experienced chiefly during take-off and initial climb during the season when flies are met (May to October in the northern hemisphere).* Since all motorists are familiar with the nuisance of fly impacts on the wind screens and other parts of their cars flies have achieved a considerable notoriety in connection with laminarisation.

There are, however, in the case of the aeroplane a number of mitigating factors.

The roughness Reynolds number for single and distributed roughness elements is defined as the product of unit Reynolds number per foot chord (U/ν) and the height of the roughness element. The kinematic viscosity ν and, correspondingly, the tolerable roughness height for a given flight Mach number increase rapidly with altitude, for example, at 50,000 ft and at a flight Mach number of 1.0, tolerable roughness is the same as for a flight Mach number of 0.17 at sea level.

The combination of deep freezing and dehydration at great heights coupled with the increased abrasive effect of high flight speeds contribute to the erosion of the remains of flies which have impacted at low altitudes. Thus the fly accretion zones contract to relatively small regions near the stagnation point; this simplifies protection against fly impacts.

Further, it has been observed that fly impacts brought back from the stratosphere had assumed the consistency of brittle deposits of much reduced adhesion compared with freshly impacted flies at low altitude. This is very helpful for all methods which aim at the removal of such deposits in flight.

Intensive studies of the fly problem have indicated a number of methods which can effectively deal with fly contamination, at least on such aircraft which climb rapidly through fly infested regions and cruise in the crystal clear stratosphere.

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* See Appendix I.

1. Wind Tunnel Experiments on Critical Insect Contamination

Very methodical experiments and extensive studies of critical insect contamination on aircraft wings have been carried out by Dr. Coleman of Blackburn and General Aircraft Ltd., (ref. 1). In these experiments a two-dimensional aerofoil of 5 ft chord and with a representative low drag section was set up between the floor and roof of the 7 x 5 ft tunnel at Brough.

At a wind speed of about 300 ft per second the Reynolds number based on chord was a little less than 10^7.

The simple device used for discharging insects into the airstream consisted of a Perspex tube 6 in. long, with an outside diameter of 1 in. and a bore of $\frac{1}{2}$ in. At each end, a brass disc was fitted. These discs were soldered eccentrically to a common spindle in the wall of the tube, so that, by rotating the discs, the openings were sealed, or exposed, simultaneously. A stand, consisting of an adjustable vertical pillar and horizontal plate, to which the tube could be clamped in a desired position, completed the instrument. (Fig. 1)

To roughen a surface, the tube was mounted in the tunnel, with its axis into wind, at some suitable distance upstream of the model. It was then charged with a number of live insects (commonly between 50 and 100) and sealed. Finally, when steady flow conditions in the tunnel were established, the insects were discharged by rapid opening of the tube, the latter operation being performed with the help of a cord running from a small lever on the upstream disc to a point outside the tunnel. Fig. 1 shows the general arrangement for the roughening of an airfoil. In this manner, any desired extent of surface could be gradually treated by successive displacements of the tube. For every setting, however, a number of discharges were normally required before the local roughness was fully established.

The fruit fly, Drosophila, was chosen for the experiments since it could be bred easily and rapidly and was considered representative of a large proportion of surface deposits under flight conditions.

The streamwise extent of roughness due to impacted flies and the variation of accretion height in streamwise direction was measured. (Fig. 2)

By cleaning the surface in successive steps at 0.5% chordwise intervals, the first step being taken at the leading edge, laminar flow was recovered appreciably before the limit of contamination was reached. Thus, the shallower, but nevertheless, sensible excrescences towards the rear of the contaminated region did not cause transition and only the larger deposits immediately adjacent to the leading edge were significant (see Table I). (Aerofoil section: N.A.C.A. 66-009. $R_c = 7 \times 10^6$)

Table I

Incidence Degrees	Average extent of total contamination per % chord (lower surface)	Average extent of significant contamination % chord
0	10.8	2.4
1	13.4	3.6
3	24.4	5.9
6	41.3	9.2

2. Observed Insect Contamination and Fly Erosion in Flight

D. Johnson (ref. 2) investigates character and distribution of insect contamination on the wings of three aircraft (Armstrong Whitworth A.W.52, a Comet airliner and a Meteor fighter); additional information was obtained on a number of other aircraft of various types.

The results suggest that the contamination which might cause transition extends between 5% chord on the upper surface of a wing and 12% chord on the lower surface. About 98% of all hits occur within these limits and the small remainder which existed further aft left only a smear on the surface, too insignificant to cause transition.

The observed limits agree very well with the results of a similar investigation made in Australia on different aircraft. (Ref. 3)

Unfortunately, one cannot distinguish, when observing fly impacts in this manner, between fly impacts which occurred at take-off and impacts which happened on landing.

It was thought that on actual wings in flight at great height and high subsonic Mach number, erosion of impacted fly remains would take place, and for this purpose fly erosion tests were conducted recently on the Handley Page "Victor". Cruising height and Mach number of this aircraft were, of course, substantially greater than those of aircraft on which fly contamination had previously been studied.

A 24 in. span aluminium glove was fitted to the outboard end of the nose flap of a "Victor" and live flies were discharged at this panel from an 18 in. long - $\frac{1}{2}$ in. tube connected to a compressed air supply.

A fly essentially consists of a bag of slightly acid blood; on impact there is a gluey splash while the body of the fly adheres to the surface.

Impact velocity was of the order of 50 to 100 feet per second and the resulting splash was thought to be representative of the impacts likely to be met with at take-off and during the initial climb.

Fruit flies (Drosophila melanogaster) and house flies were used for the impacts. The flies were bred in a special incubator which had been kindly lent to us by Messrs. Blackburn and General Aircraft Ltd. In each experiment a number of flies were anaesthetised with CO_2 so that they could be conveniently inserted into the air gun.

It was found that after flights of 2-3 hours when heights of 40,000 ft or more were reached, wings, legs and other protruberances of the fly had blown away and the body of the fly had eroded to a much smaller size. Figure 3 indicates roughly the measured height of eroded fly remains and the chordwise extension of the accretion zone.

The maximum height of eroded fly remains was about 0.01 in. measured at the leading edge, i.e. within the stagnation zone. Within a distance of 2% of the chord (actual distance 2.5 in.) the height of fly remains had decreased to less than 0.005 in. and beyond 4% of the chord, measured from the leading edge, impacted flies had been completely removed.

Complete removal of any accretion (and also, incidentally, of gelatine film which had been sprayed on part of the surface) occurred whenever the aircraft flew through a rain cloud.

It has also been observed that the zone of critical fly accretion contracted in a noticeable manner when the pilot reduced the angle of incidence by flying at a higher E.A.S. and thus shifted the stagnation zone.

It is suggested that the following effects may contribute to the more rapid erosion and subsequent contraction of the critical zone of fly accretion on actual wings with sweep compared with straight wings tested in a wind tunnel or compared with Johnson's observations.

(i) The existence of a spanwise component (or crossflow) characteristic to swept wings

(ii) Very low temperature of the order of -53° combined with low humidity in the stratosphere

(iii) Transition at the leading edge due to sweep.

The combined effect of dehydration and deep freezing makes fly remains very brittle so that they are more easily swept off the surface by the airflow than flies impacted on a wind tunnel model, especially if the boundary layer is turbulent and the air speed itself much higher than in a wind tunnel.

The boundary layer is, of course, turbulent when the wings have sufficient sweep angle and when the thickness/chord ratio and Reynolds number are supercritical so that transition occurs at the leading edge in the form of striations.

According to von Doenhoff's definition of critical roughness Reynolds number for distributed roughness of the sandpaper type, roughness of 0.010 in. height close to the leading edge, should be subcritical at heights greater than 40,000 ft at flight Mach numbers $M = 0.8$, or for heights greater than 42,000 ft at $M = 0.9$ (Fig. 4).[x] (see Appendix III)

Smaller excrescences of 0.003 in. height further aft of the leading edge should be subcritical at heights greater than 30,000 ft for Mach number $M = 0.8$ to 0.9.

Fly impacts may, possibly, be ignored on aircraft cruising at high altitude. Experimental verification is needed, especially on swept wings, where wakes emanating from roughness elements at the leading edge may have a greater disturbing effect than wakes caused by roughness elements situated at the leading edge of a straight wing.

3. Wind-Tunnel Experiments Dealing with the Prevention and Removal of Fly Contamination

A review of various proposals for the prevention of insect contamination on aircraft wings is given by W. S. Coleman in Ref. 4.

The methods which have been investigated can be broadly divided in three groups:-

(i)/

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[x] Permissible roughness height (at some distance from the leading edge) at 50,000 ft is about 40% greater for $M_\infty = 3$ than that for $M_\infty = 1$ because of the boundary-layer thickening.

(i) Mechanical devices (discardable covers, plastic films, deflector plates, scrapers)

(ii) Protective surface films taking the form of either continuously flowing liquids or resilient films removable by the application of heat or solvents

(iii) Boundary-layer control, i.e., total removal of the turbulent boundary layer behind the roughened area.

3.1 Mechanical methods
Deflector plate

A device described by Dr. Coleman (ref. 5) was tested extensively in the wind tunnel at Brough. It consists essentially of a curved plate which is projected through an opening in the leading edge of the wing during flight in the insect infested part of the atmosphere and is then retracted at insect-free altitude to leave, ideally, a smooth surface. The wind-tunnel experiments showed that a great majority of insects were trapped on the upper surface of the plate but difficulty was experienced in keeping clear the lip of the aperture through which the plate was ejected. It was also found necessary to retract the lower part of the surface of the aerofoil near the leading edge in order to give full protection. Other undesirable aerodynamic features were also observed, namely instability in pitch with the plate extended coupled with considerable increase in drag. Apart from that the mechanical complexity of such a device is considered too great.

3.2 Mechanical scraper

A mechanical type of scraper was developed by G. Beech and W. M. Nicholas of Sir W. G. Armstrong Whitworth Aircraft (ref. 6) and wind-tunnel tests with this scraper were carried out by Dr. Coleman (ref. 7).

A carrier plate is traversed along a spanwise slit (about 0.1 in. wide) by means of a piece of cable driven by an electric motor. The cable has a secondary function in that it seals the slot along the length of the wing which is not occupied by the carrier plate. Attached to the carrier plate are two spring steel arms which extend as far as 10% chord on both upper and lower wing surfaces. Tightly stretched between the two extremities of these two arms is a piece of thin 26 S.W.G. piano wire (0.018 in.) heavily spring loaded which acts as a scraper. Automatic reversing is carried out by means of a double-pole throw switch and a trip mechanism operated by the carrier plate.

When tested on a dry aluminium surface the device proved completely successful at an air temperature up to 50°C.

On dry cellulose surface it failed to remove completely the deposits even when the scraper action was prolonged unduly. Apparently, a certain amount of the contamination was flattened and compressed into the cellulose surface. Tests with a moist pad in place of the wire achieved complete removal of the contamination under the following conditions.

At a tropical temperature of about 50°C the surface can be easily and completely cleaned in four traverses of the pad for a water feed to the pad of 6 cc per minute. At lower temperatures 1-2 cc of water per minute were found sufficient.

Broadly speaking, it appears that the device has promising possibilities on a bare and dry metal skin, but would almost certainly need the added application of surface wetting on paint or relatively soft materials. (A simplified scraper is described in part 4)

3.3 Soluble films or continuous streams of liquid over the surface. (Note W.T. 131 by Coleman, Ref. 8)

The conclusion was reached that quasi-static films which rely principally on their ability to counteract the chemical processes of adhesion like silicone fluids, are unlikely to be successful.

If the film is to remain adequate for a sufficient length of time its viscosity must be relatively high and its volatility relatively low. It is then very difficult to clear the surface of all traces of the liquid, and insects adhere to the surface in increased numbers merely because of the tacky nature of the film.

On the other hand, if the liquid has a low viscosity and a high rate of evaporation it is insufficiently permanent to be of use.

Alternatively, if the protective film is temporarily solidified and subsequently carried away in a solution, full protection is afforded. Two types of films have been investigated; one consisted of 60% glycerine, 30% gelatine and 10% Teepol. The other one was soap dissolved in methanol. The first film required water at 78°C for removal, the second water at 22°C. The second film was considered inferior to the glycerine film, more water becoming necessary for its removal.

It was estimated that with the glycerine-gelatine film a total of 4 lb of water per foot span would be required to clear both surfaces of the wing.

The possibility of using ice as a protective film against contamination has also been considered and investigated in the wind tunnel. A hollow metal aerofoil was packed with lumps of solid carbon dioxide and water was then sprayed at the outside of the aerofoil until a layer of ice about 1/8 in. thick had formed. It was estimated that a maximum thickness of ice of about 3/8 in. would be required near the forward stagnation point on an aerofoil of 15 ft chord at a Reynolds number of 14×10^6 during a climb to 15,000 ft occupying a flying time of 6.5 minutes.

Continuous discharge of a liquid over the surface was found to give full protection against contamination.

Freedom from contamination can reasonably be assured for the expenditure of 0.6 lb of water per minute per foot span of the surface. This refers to moderate tropical conditions (air temperature about 35°C). For extremes of temperature, up to say 50°C, the quantity required may be nearly double. This is perhaps the simplest method of its kind that can be devised and requires no ground preparation as with the soluble film.

3.4 Total removal of the turbulent boundary layer behind the roughened area

The use of an auxiliary slot on a laminar flow aerofoil has been investigated by Cumming, Gregory and Walker of the National Physical Laboratory. (Ref. 9)

Transition was effected at 5% chord by means of wires and conical excrescences, and the auxiliary slot was situated 20% of the chord.

It was found possible, in the absence of unfavourable pressure gradients, to re-establish a laminar boundary layer by removing a little more than the whole turbulent layer reaching the slot.

4. Protection Against Fly Contamination or Removal of Impacts in Flight

The following is an appraisal of the various methods described in section 3 from the point of view of practicability, in the light of actual flight experiments with partially laminarised aircraft and also in the light of further studies in this field.

4.1 Protection

A method which has been extensively tried out in the United Kingdom and in the U.S.A., made use of discardable covers made of paper, tracing linen or light cardboard. This method has certainly given full satisfaction on partially laminarised aircraft in well over 200 flying hours.

The covers were attached so that the leading edge extended slightly beyond the stagnation point for take-off incidence. After reaching cruising height the incidence was increased and the cover jettisoned. (Fig. 5)

A more practical solution consists in protecting the critical region of the wing nose by a film sprayed on prior to take-off. Apart from being cheap such a film should have the following characteristics to ensure its being effective in all sorts of climates.

(i) It should not be affected by heat or water

(ii) It should not clog the pores of sintered material

(iii) It should not leave any deposits.

In the field of protective films (resinous or plastic) great progress has been made in recent years. In paint and plastic technology coatings come under three main headings: low adhesion coatings, brittle lacquers and resins, volatile compounds.

Low adhesion coatings

They can consist of films using organic solvents, i.e., Vinyl Copolymer resins, or films consisting of cellulose derivatives, or aqueous emulsions of low water content.

A Titanine product known as "Temprolac" comes under the first group and is being used for the protection of loft lay-out plates. The degree of adhesion of this type of film depends on the boiling point of the solvent employed.

Messrs. Titanine Ltd. have conducted laboratory experiments to assess the suitability of various materials for protective coverings. The possibility of using a sprayed-on coating having low adhesion which could subsequently be peeled off by the air flow after ripping the film at the leading edge, leaving the porous surface of the leading edge in an unclogged and uncontaminated condition, was investigated. A suitable substance was found but certain difficulties were encountered. Of these, the most serious was the need to mask the edges of the zone to be covered whilst the film was being sprayed on. This was necessary in order to ensure that the coat had sufficient thickness right up to its edge so that when stripped off it would come away completely in one operation.

In view of the drawbacks associated with sprayed-on protective coats the possibility of laying on ready manufactured sheeting was studied. Thin cellulose fibre matting with a film of a semi-adhesive, which could be

sprayed/

sprayed on to it, was found suitable. Once it had been sprayed, the mat could be made to adhere to any surface merely by the application of a gentle pressure by hand. It also maintained its adherent properties for a considerable time (several weeks). A feature of the cellulose fibre matting used was that the fibres all lay in approximately the same direction in the material. Along this direction it could be torn easily, but in the perpendicular direction it had considerable strength. This property is important in connection with arrangements for jettisoning the covering. The method of jettisoning is to slit the covering in the vicinity of the stagnation point along the full length of the leading edge and to lift the edges so formed so that the air flow can take charge and rip the covering off the wing. The mat would, therefore, be laid with its fibres parallel to the stagnation line. The device by means of which the protective sheet would be slit is shown in Figure 6.

In order to guide the cutter and enable it to slide smoothly along the leading edge without damaging it by scratching, a thin flat polythene tube would be layed on the wing surface along the stagnation line and under the semi-adhesive protective covering. A tape or cable running through the flat polythene tube would be attached to the cutter near the wing tip and to a winch at the wing root driven by an electric motor. When the protective covering is to be jettisoned the cutter would be winched to the wing root where it would be retained. This method has been tested with complete success in the Handley Page wind tunnel.

Brittle lacquers and resins
(Polystyrene and resins with similar physical characteristics)

It is considered possible to produce a lacquer of low adhesive quality which becomes increasingly brittle with temperature drop. The brittleness can be increased by incorporating pigments. This type of decomposing lacquer would seem, however, to be only possible on impervious surfaces; preliminary experiments which have been conducted by Messrs. Titanine indicate that this type of film would not be suitable on porous surfaces because of the keying action of the pores.

Volatile compounds

These can be sprayed on and their composition adjusted to enable sublimation to occur over a period of time. Sublimation can be assisted by the use of the thermal de-icing system.

Six coatings of a solution of camphor and naphthalene in petrol ether were sprayed on to the leading edge of the "Victor" prior to take-off. Flies were then fired against this film and the sublimation of the film in flight was assisted by turning on the thermal de-icing. However, it was already apparent, before take-off, that the flies could penetrate the crystalline film and that, therefore, this kind of film did not offer the necessary protection.

We have not been able yet to find a volatile compound which is not crystalline.

4.2 Removal of flies in flight

Water spray suggests itself as the most effective agent for the removal of fly deposits in flight since it has been observed on the "Victor" that fly deposits completely disappeared when the aircraft flew through a cloud leaving the surface in an immaculate condition.

Various/

Various methods have been studied which would simulate the effect of a cloud by spraying water from nozzles into the airstream ahead of the wing. The most promising method would seem to be to spray water from small nozzles (0.15 in. diameter), inserted at distances of about 1.5 to 2 ft in the leading edge. Owing to the sweep of the leading edge these discrete jets would eject obliquely to the direction of the air flow and thus cause overlapping plumes of spray, see Fig. 7. (Valuable information on the penetration of liquid jets ejected perpendicularly into the airstream at high velocity was found in Report N.A.C.A. RM E.50F21. (Ref. 10).)

A fairly good estimate of the water volume which has to be sprayed to simulate a cloud can be derived on the following basis. Fairly heavy rain fall would correspond to about 0.5 in. per hour.

By assuming rain drops of varying sizes and calculating their terminal velocity, taking into account change of drag with Reynolds number, the water content per cubic foot of air was estimated. The results are given in the following table.

Diameter of droplet in inches	.05	.15	.30
Terminal velocity U ft/sec.	14.25	33.9	47.00
Density of water content in rain cloud. lb/ft^3	.000057	.0000213	.0000154
Number of droplets/ft^3	21.1	0.333	0.030

Assuming a mean droplet size of 0.15 in., the water content per cubic foot would be of the order of 2×10^{-5} lb of water. Considering a wing area of 3,000 sq.ft and a mean thickness/chord ratio of 9%, the frontal area is 270 sq.ft.

At a flying speed of 250 ft per second (365 m.p.h.) $2 \times 10^{-5} \times 270 \times 250 = 1.35$ lb per second of water will impinge on the projected surface in the form of droplets, or one ton of water in 27.65 minutes.

In order to give some idea of the quantity and impact speed of water necessary to remove insects, flies were blown on to the front of a motor car with which runs were made through a curtain of spray. The spray was made by a fire hose at right angles to the path of the car. A water catchment was mounted on to the radiator so as to measure the quantity of rain fall to which the flies were subjected.

Six runs were made through the spray at 40 m.p.h. and no significant change in the condition of flies was observed. Six more runs were made at 50 to 60 m.p.h. and these were sufficient to remove completely the bodies of the flies. A few traces of dry blood and smears of about 0.001 to 0.002 in. high remained. It is possible that the success of the second series of runs in removing the flies was due to the fact that the bodies of the flies had time to become saturated with water, and that this fact rather than the increased speed, resulted in almost complete removal.

One can, therefore conclude that the best technique would be to apply water plus a detergent in the form of a continuous stream over the surface, or spray with low impact speed, for the purpose of moistening the fly remains, and after a brief interval to apply a spray with an impact speed of at least 70 to 80 miles per hour. If the total period of water release were 3 to 4 minutes - a very ample period compared with the tests on the motor car where the total period of exposure to spray could only be measured in seconds - the estimated total weight of water to be carried is about 240 to

300 lb., a minute increase of take-off weight in the case of an aircraft weighing at take-off 225,000 lb (0.15%).

The water would have to be stored in pressure accumulators, preferably of spherical shape, with an expanding bladder containing air and nitrogen at a pre-determined pressure.

The weight of pressure accumulators, pipes, etc., would be of the order of 260 to 300 lb, and this additional weight would have to be permanently carried, at least during the critical season. Carrying this additional weight over the London/New York stage distance and assuming £12/lb airframe costs and 13.5d/Imperial Gallon for fuel, the direct operating costs per flying hour would be increased by £0.33. This compares with an estimated £0.61 per flying hour for washing and cleaning the aircraft after each flight.

The method will be tested in the near future in the Handley Page wind tunnel.

Simplified scraper

In view of the observed brittleness and low adhesion of eroded fly deposits it is felt that they could be swept off the wing by the single passage of a much simplified scraper.

The scraper being light, very simple and cheap could be expendable. (Fig. 8)

No driving mechanism is required. The scraper is pressed against the nose of the wing by horizontal pressure vanes and propelled along the span by vertical vanes. Construction is by plastic mouldings. Instead of the wire loop, felt wiping pads are used. The scraper is released from the sides of the fuselage and after scraping the leading edge flies off after passing the wing tip.

4.3 Application of intensified suction near the leading edge

In view of the observed contraction of the critical fly accretion zone due to erosion at high altitude on a swept wing aircraft cruising at high subsonic Mach number, the suggestion of removing the turbulent boundary layer close to the leading edge (at about 2 or 3% of the chord) has been reconsidered.

The results of an estimation of the values of C_Q required to remove the turbulent boundary layer of a swept wing at various chordwise positions and flight Reynolds numbers are given in the following table. (For details of the calculation see Appendix II.)

Table II

Values of C_Q for H.P.113 leading edge

Slot position % chord	R_c 10×10^6	15×10^6	20×10^6	25×10^6
1	.000574	.000531	.000504	.000490
2	.000868	.000826	.000784	.000756
3	.001190	.001106	.001064	.001008
4	.001442	.001357	.001288	.001233

Note:- The above figures are for one surface only and can be doubled to include both surfaces.

Assuming/

Assuming, for example, a chord Reynolds number of 20×10^6 and a position of the suction slot at 0.02C the value ΔC_Q, additional to C_Q necessary for stabilising the laminar flow, is $2 \times 0.000784 = 0.001568$.

This corresponds to an increase of 300% of the value of $C_Q(\sim 0.0005)$ necessary to maintain laminar flow.

If the suction slot were placed at 0.03C the corresponding increase of C_Q would be 400%.

The method is, of course, put right out of court if such big increases of suction are experimentally verified.

5. Conclusions

There is a distinct possibility that when the cruising altitude and speed of laminarised aircraft are high enough fly accretions will be eroded to such an extent that the Roughness Reynolds number will be subcritical.

Alternatively, two promising methods remain:-

(a) Protective films or adhesive fibrous mats applied to the leading edge prior to take-off and ripped off after reaching cruising altitude would seem to be the most practical form of protection

(b) Spraying the leading edge with water mixed with a detergent appears to be the most promising form of removing fly deposits in flight.

Flight trials on a laminarised aircraft will help to decide whether fly contamination can be ignored altogether or, alternatively, which of the two methods deserves preference in operational service.

APPENDIX I/

APPENDIX I

Notes on the Aerial Insect Population

Variation of Insect Density with Height

Insects are not confined to the first few hundred feet above ground but are found at heights of up to a few thousand feet. The variation of insect density with altitude has been measured by Johnson (ref. 11), who has found that the profile is a smooth logarithmic curve. Johnson's and Penman's logarithmic relation only holds between about 30 ft and 1,000 ft, which is, of course, the important region. The density at any height is the net effect of an upwards movement caused by turbulence and convection currents and a downwards movement caused by gravity and biological impulse.

Distributions in a temperate climate are of the following order:-

Height, ft.	No. per 10^6 cu.ft.
10	250
150	40
500	15
1,000	5

Nature of Aerial Population

This was determined by Hardy and Milne (ref. 12). They found that the distribution of the various insect types varied very much with altitude. Samples collected between 150 and 2,000 ft were all small insects with very low wing loadings of which Aphidae were the largest single class (28%).

APPENDIX II

APPENDIX II

Method of Estimating the Suction Quantity Required to Remove the Turbulent Boundary Layer of a Wing

The method of J. C. Cooke (ref. 13) is used to estimate the momentum thickness of the turbulent boundary layer at the leading edge region of the H.P.113 wing. (Mean chord = 10 ft. Leading edge sweep = 37°) For this purpose, it is assumed that the potential flow distribution over the leading edge of the wing is substantially the same as that of a yawed parallel wing.

From the report by Cumming, Gregory and Walker (ref. 9) the critical suction quantities for design purposes is given as

$$Q = 14\, U_1 \theta_1$$

Thus to determine this quantity we must calculate the momentum thickness at the slot.

J. C. Cooke (ref. 13) gives an equation for the momentum thickness

$$\frac{\partial}{\partial \phi} \frac{\Theta\, T^{\frac{14}{5}}}{p^{\frac{3}{5}}} = 0.0106 \frac{T^{\frac{9}{5}}}{p^{\frac{3}{5}}} \qquad (1)$$

where T = total potential flow velocity

p = integrating factor

$\Theta = \theta \left(\frac{T\theta}{\nu} \right)^{\frac{1}{5}}$

θ = momentum thickness

ϕ = velocity potential

Also $\frac{\partial}{\partial \phi} = \frac{U}{T^2} \frac{\partial}{\partial s}$

For a parallel yawed wing, $p = \frac{\text{const}}{U^2}$

where U is the velocity round the surface measured normal to the leading edge.

We can also for the yawed parallel wing case, rewrite equ. 1 (substituting for ρ at the same time) as

$$\frac{\partial}{\partial s} \left\{ \Theta\, T^{\frac{14}{5}} U^{\frac{6}{5}} \right\} = 0.0106\; T^{\frac{19}{5}} U^{\frac{1}{5}} \qquad (2)$$

where s is measured round the surface normal to the leading edge.

$$\therefore \quad \Theta = \frac{0.0106}{T^{\frac{14}{5}} U^{\frac{6}{5}}} \int_0^s T^{\frac{19}{5}} U^{\frac{1}{5}}\, ds \qquad (3)$$

$$C_Q = \frac{Q}{U_\infty c} = \frac{14\ T\ \theta}{U_\infty c} = 14\ \bar{T}\ \frac{\theta}{c}$$

$$\Theta = \theta\left(\frac{T\theta}{\nu}\right)^{\frac{1}{5}} \therefore \frac{\theta}{c} = \frac{\theta}{c}\left(\frac{Tc}{\nu}\cdot\frac{\theta}{c}\right)^{\frac{1}{5}} = \frac{\theta}{c}\left(\bar{T}\ R_c\cdot\frac{\theta}{c}\right)^{\frac{1}{5}}$$

$$\therefore \frac{\theta}{c} = \left(\frac{\Theta}{c}\right)^{\frac{5}{6}} \bar{T}^{-\frac{1}{6}} R_c^{-\frac{1}{6}}$$

$$\therefore C_Q = 14\ \bar{T}^{\frac{5}{6}} \left(\frac{\Theta}{c}\right)^{\frac{5}{6}} R_c^{-\frac{1}{6}}$$

where Θ is given by equ. (3) and $R_c = \dfrac{U_\infty c}{\nu}$.

APPENDIX III

A very recent investigation by A. E. von Doenhoff and A. L. Braslow (not yet published) was received by the author after this report had been written.* This report entitled "The effect of distributed surface roughness on laminar flow" provides additional and more detailed information on methods of estimating tolerable surface roughness.

Most of the data from eight different investigations of 3-dimensional roughness particles were applied in the form of the square root of the roughness Reynolds number for transition $\sqrt{R_k.t}$ as a function of the particle fineness ratio $^d/k$. (d = diameter of roughness particle, k = height of roughness particle.) Only those data that satisfy reasonably well the conditions for flow similarity about the roughness have been included, that is, the roughness was submerged in the boundary layer. Furthermore, those cases in which there was some doubt as to whether the transition was actually caused by the roughness, or was so-called "natural" transition at the position of observation were also included. The data cover a wide range of particle shape, distribution, number, submersion in or protrusion through the upper portion of the boundary-layer thickness, distance from model leading edge, and the degree of laminar boundary-layer stability as effected by pressure gradient and boundary-layer control. In spite of the differences, the values of $\sqrt{R_k.t}$ for a given value of $^d/k$ varies only within a factor of approximately 2. The highest values of $\sqrt{R_k.t}$ of 40 refer to the lowest ratio of $^d/k = .15$. The lowest values of $\sqrt{R_k.t}$ refer to the highest ratio of $^d/k$ (about 20). Estimation of the critical height can be made from this correlation if the roughness is well submerged in the boundary layer. For roughness heights about equal to the total boundary-layer thickness the critical Reynolds number appears to be increased somewhat (perhaps of the order of 40%). For these heights, or greater, however, the condition of flow similarity about the particles, upon which the concept of a critical Reynolds number is based, is not satisfied.

Making a pessimistic assumption ($\sqrt{R_k.t} = 14$) the permissible roughness height of a particle located at 2 in. from the stagnation point becomes 0.0073 in. for a flight Mach number $M = 0.85$ at an altitude of 50,000 ft.

However, if $\sqrt{R_k.t}$ were increased to 17 the permissible roughness height becomes 0.011 in. The smallest value found experimentally for $^d/k = 1$, (the value for spherical particles), is $\sqrt{R_k.t} = 23$.

It is thought that either cones or spheres are more representative of eroded fly impacts than the flat discs of high $^d/k$ ratio.

References/

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* To be published in "Boundary Layer and Flow Control - Principles and Applications", Pergamon Press Ltd.

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No.	Author(s)	Title, etc.
1	Coleman, W. S.	Experiments on the artificial contamination of aerofoils by insects. Blackburn and General Aircraft Ltd. Note W.T.126, November, 1951.
2	Johnson, D.	Brief measurements of insect contamination on aircraft wings. May, 1952. A.R.C.14,999.
3	Atkins, P. B.	Wing leading edge contamination by insects. A.R.L. (Australia) Flight Note No.17, Oct. 1951.
4	Coleman, W. S.	A review of various proposals for the prevention of insect contamination on wings. Blackburn and General Aircraft Ltd. Note W.T.129, February, 1952.
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6	Beech, G. and Nicholas, W. M.	A mechanical type of scraper for dealing with insect contamination of aircraft wings. Sir W. G. Armstrong Whitworth Aircraft Ltd. Report No. W.T.53/18, July, 1953.
7		Note on the Blackburn and General Aircraft Limited's wind tunnel tests of the A.W.A. mechanical fly scraper. Unpublished paper.
8	Coleman, W. S.	Wind-tunnel experiments on the prevention of insect contamination by means of soluble films and by liquids discharged over the surface. Blackburn and General Aircraft Ltd. Note W.R.131. July, 1952.
9	Cumming, R. W. Gregory, N. and Walker, W.S.	An investigation of the use of an auxiliary slot to re-establish laminar flow on low drag aerofoils. R. & M.2742. March, 1950.
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11	Johnson and Penman	Nature, Vol.168, p.337, 1951.
12	Hardy and Milne	Journal of Animal Ecology. Vol.7, p.199, 1938.
13	Cooke, J. C.	A calculation method for three-dimensional turbulent boundary layers. Oct. 1958. A.R.C.21,059.

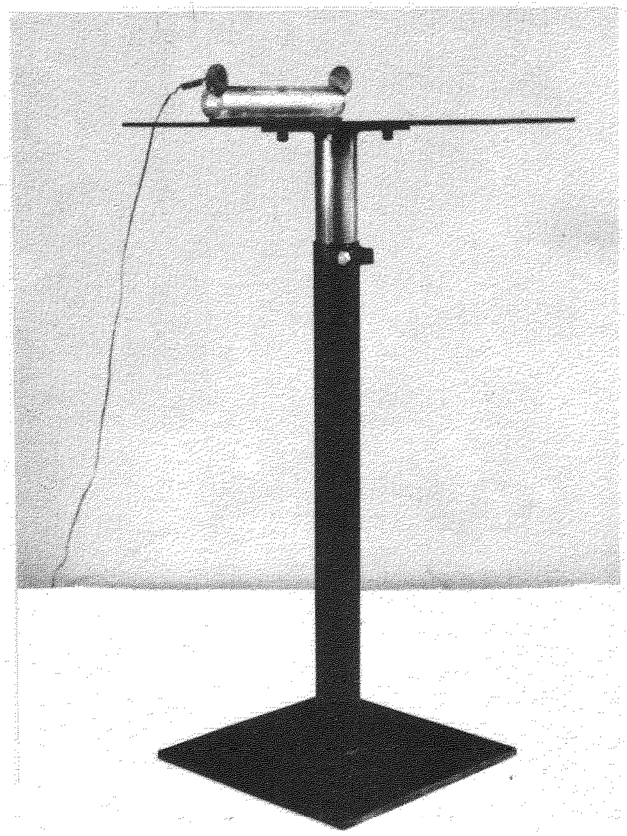
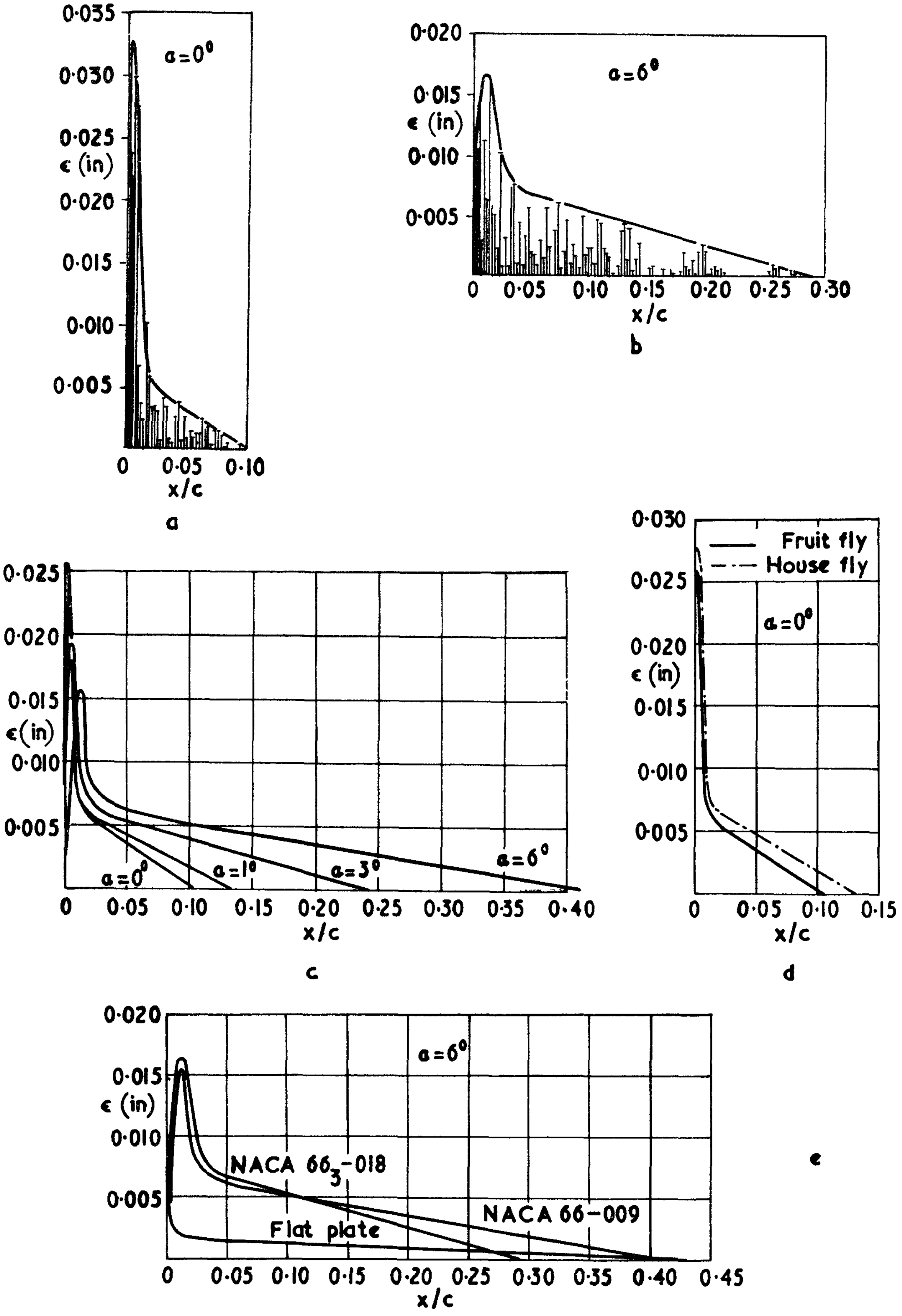


Figure 1.



a Distribution of roughness obtained in the wind tunnel with fruit-flies on the lower surface of N.A.C.A.66_3-018. High speed flight condition. $R_c = 6.9 \times 10^6$

b Corresponding roughness distribution on the lower surface of N.A.C.A.66_3-018 under take-off or climb conditions approximately. $R_c = 6 \cdot 9 \times 10^6$.

c Effect of incidence on the lower surface roughness envelope. N.A.C.A.66-009. $R_c = 6.9 \times 10^6$.

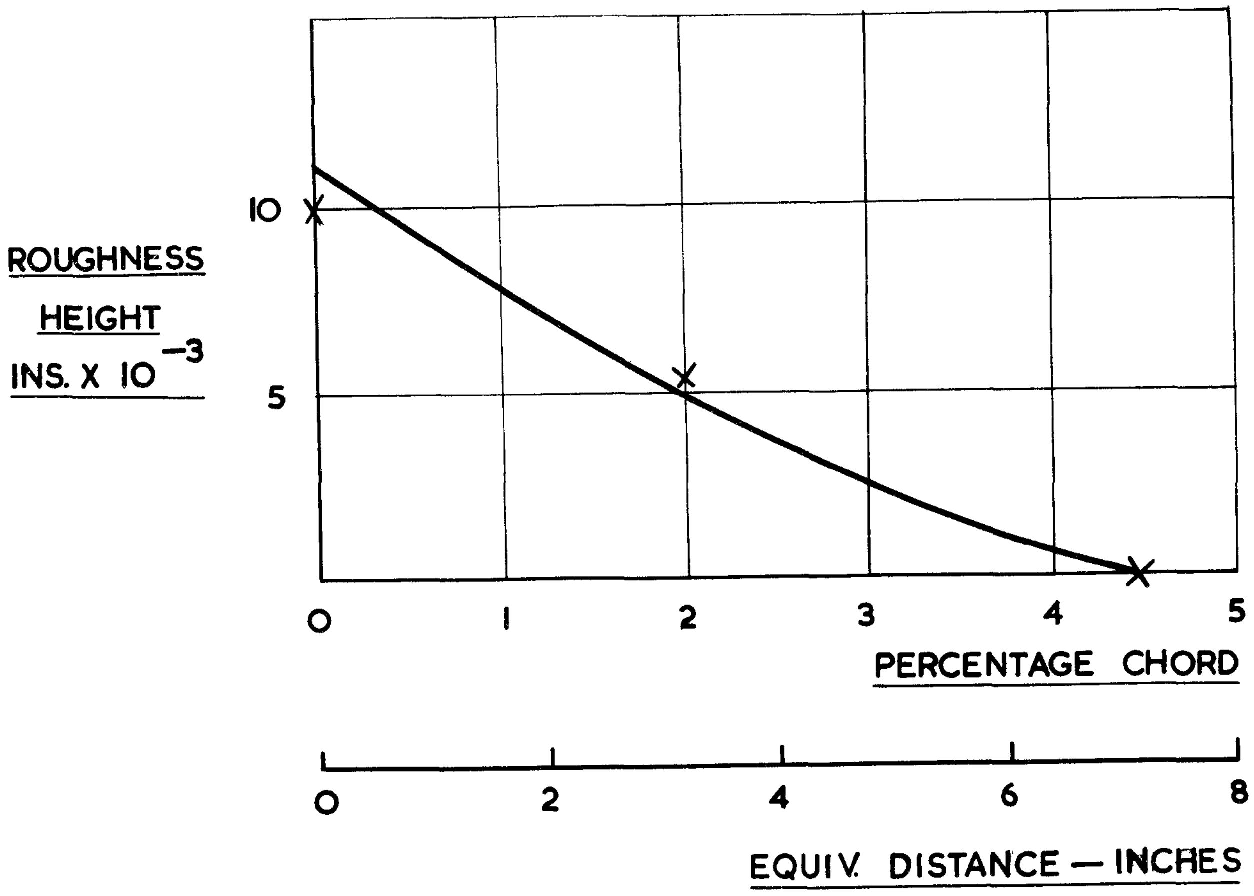
d Effect of a pronounced change in the particle properties on the lower surface roughness envelope. N.A.C.A. 66–009. $R_c = 6.9 \times 10^6$.

e Effect of surface curvature (wing profile) on the lower surface roughness envelope. $R_c = 6.9 \times 10^6$.

FIG. 2.

MEASURED ZONE & DEGREE OF RESIDUAL FLY ACCRETION ON VICTOR LEADING EDGE AFTER EROSION

AVERAGE DURATION OF FLIGHTS — 3 HRS.
MAX. HEIGHT — 47,000 FT.
MAX. SPEED — 375 KTS. M=·9



FRUIT FLIES & HOUSE FLIES IMPACTED BEFORE TAKE OFF

NOTE
COMPLETE REMOVAL OF ALL ACCRETIONS OCCURRED WHEN THE AIRCRAFT FLEW THROUGH A RAIN CLOUD

FIG. 3

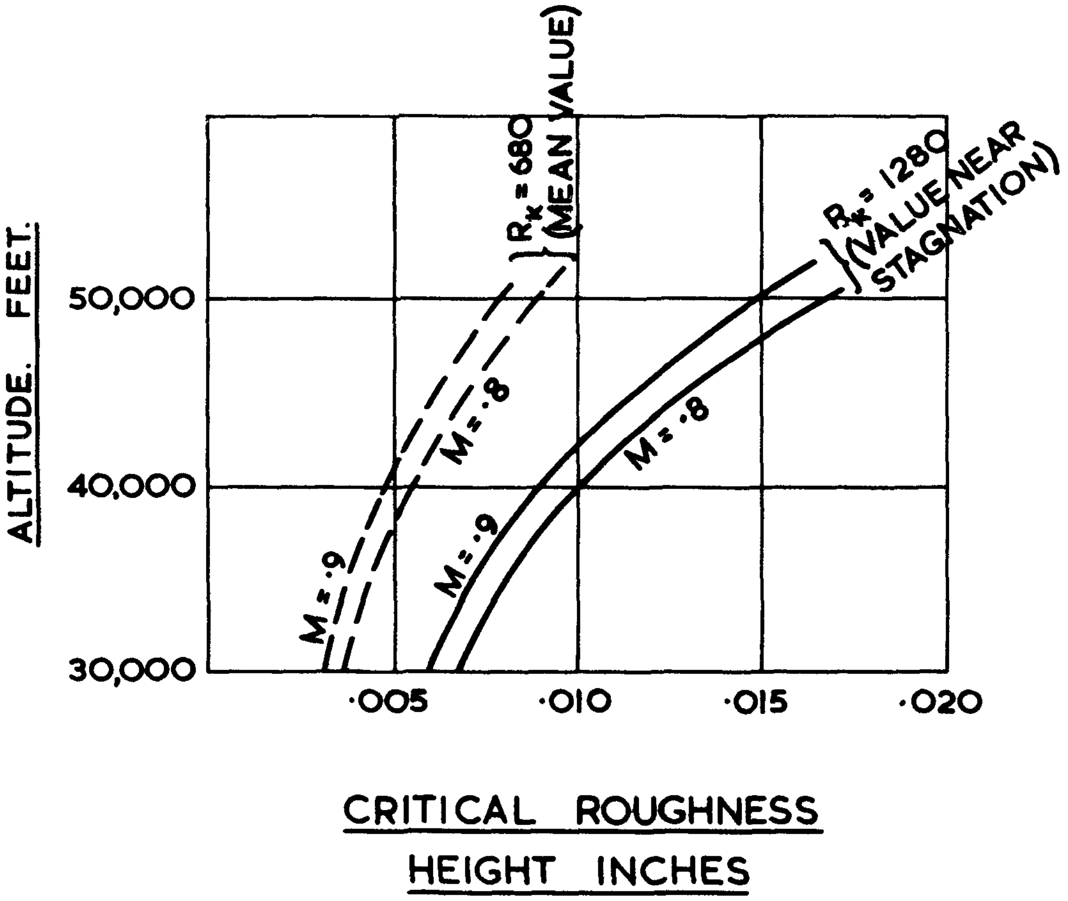
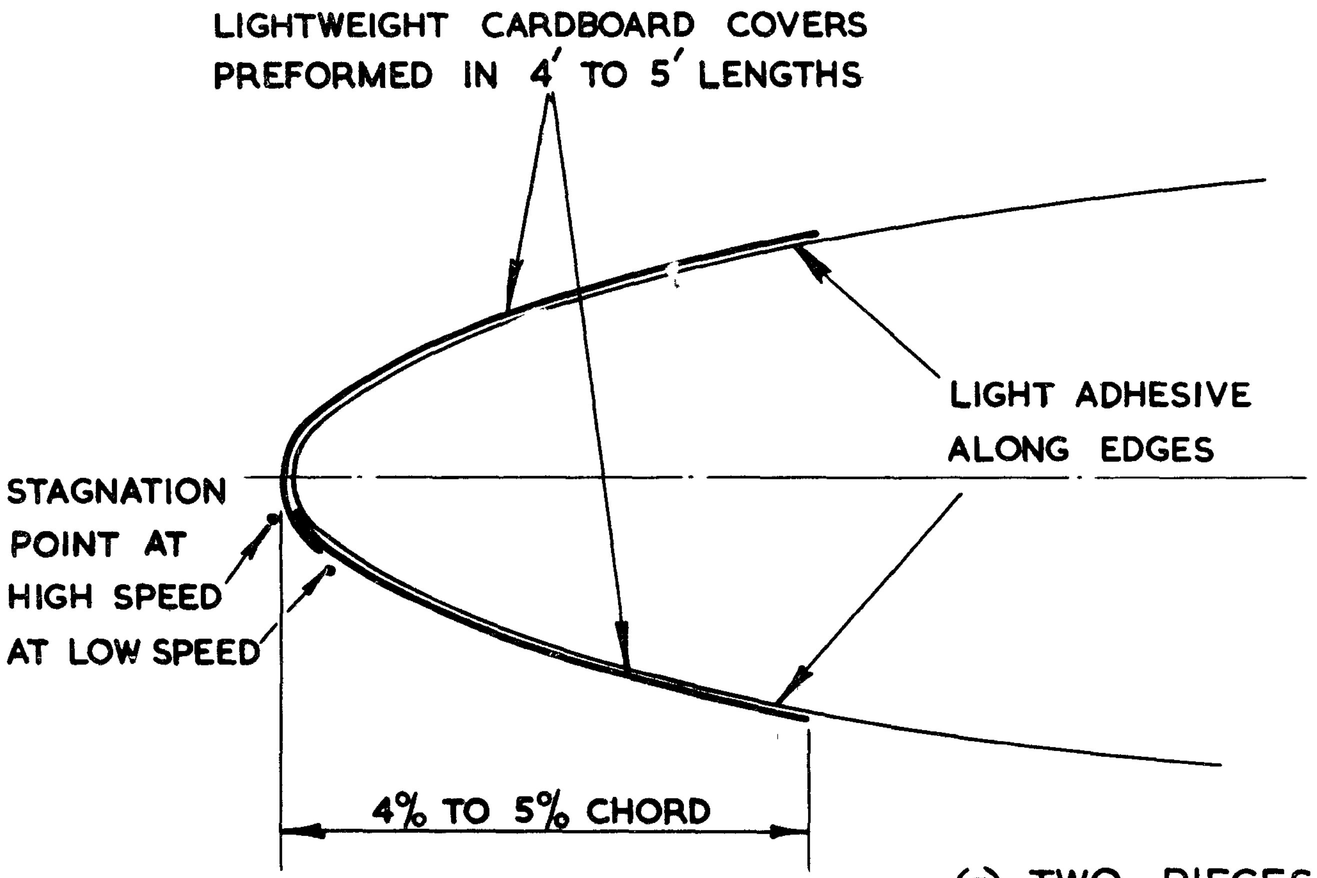
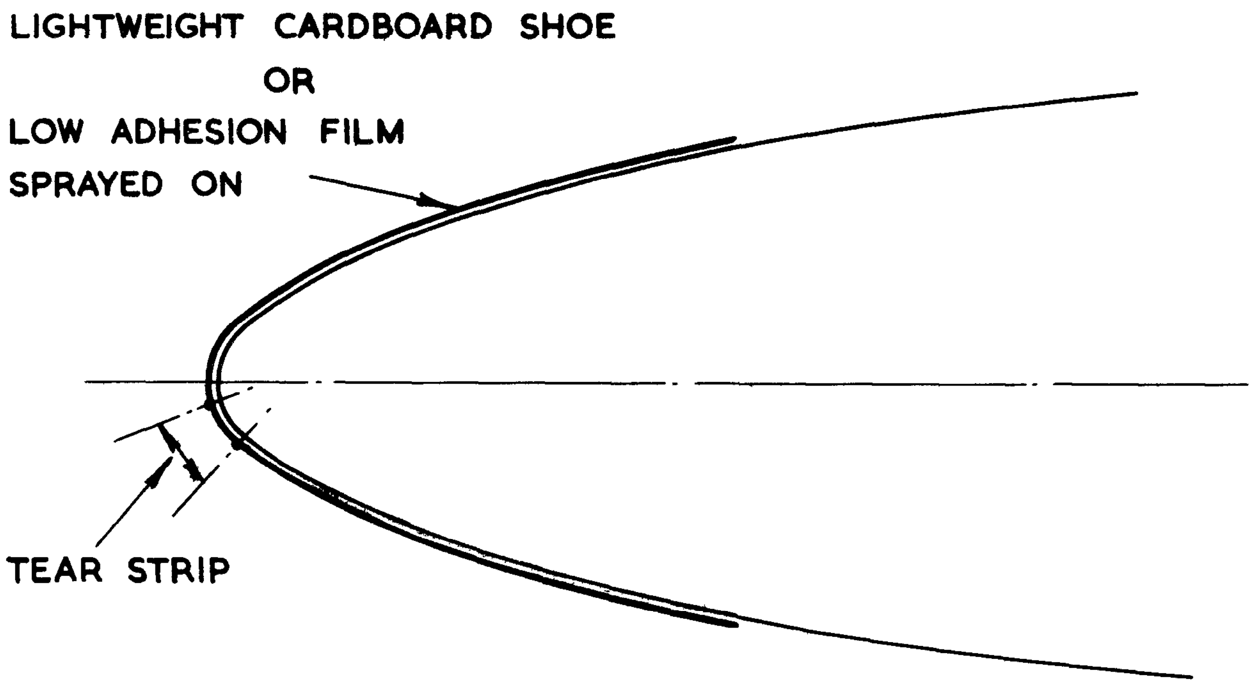

ALTITUDE. FEET.
50,000
40,000
30,000
·005
·010
·015
·020
CRITICAL ROUGHNESS HEIGHT INCHES
Rk = 680 (MEAN VALUE)
Rk = 1280 (VALUE NEAR STAGNATION)
M = ·9
M = ·8
M = ·9
M = ·8

FIG. 4



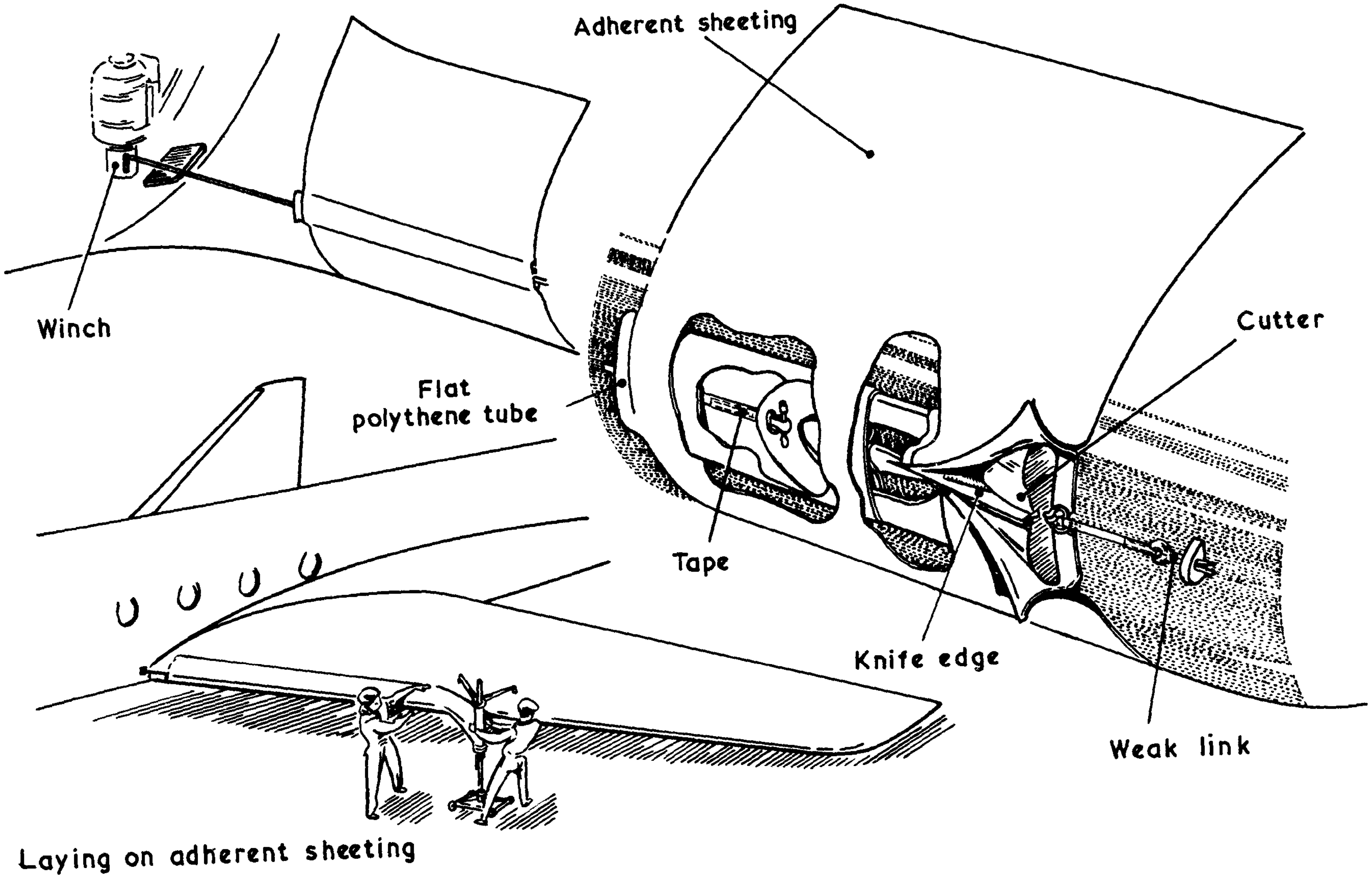
(a) TWO PIECES



(b) ONE PIECE
WITH TEAR STRIP

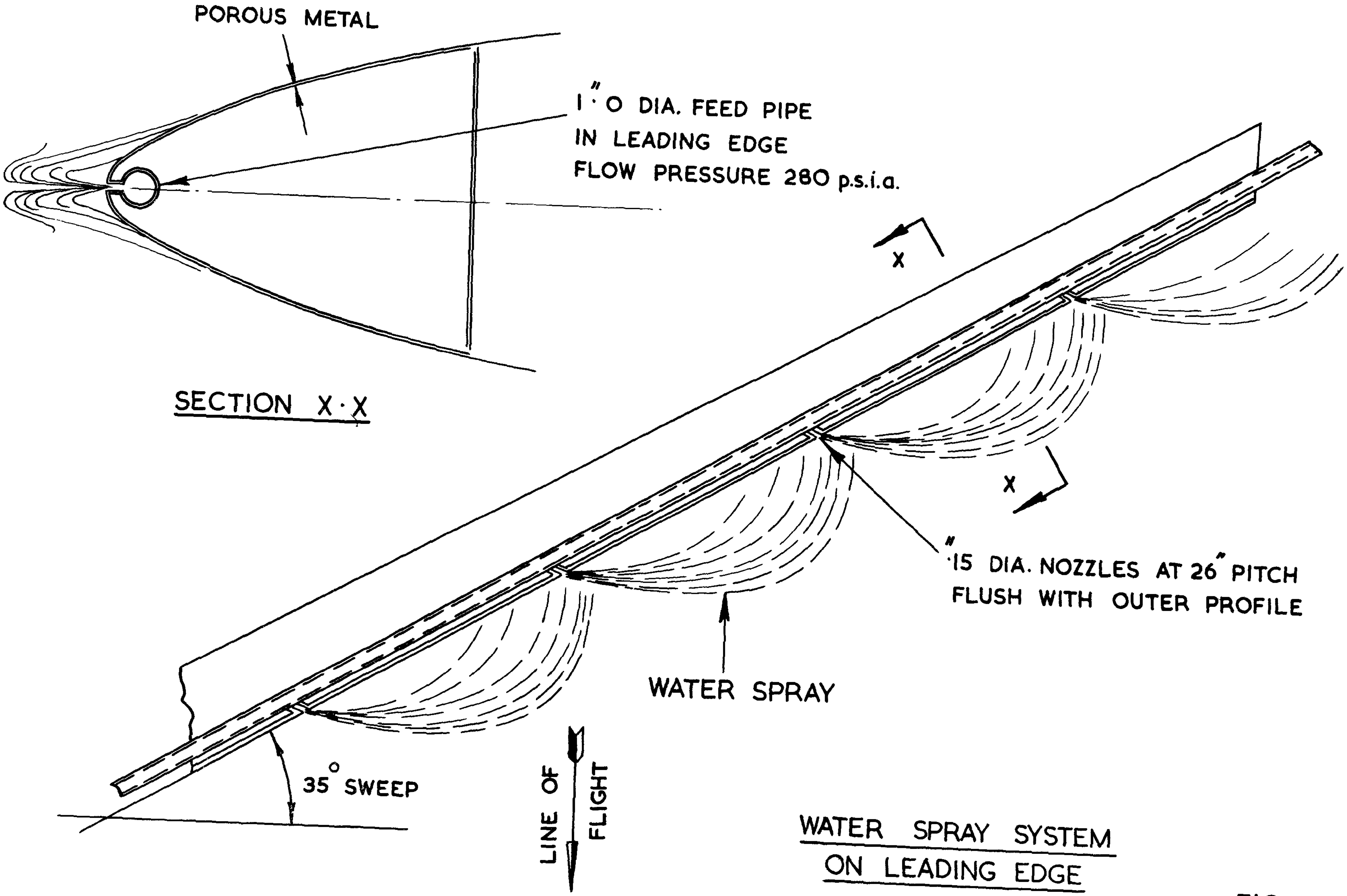
PROTECTIVE COVERS & FILMS

FIG. 5



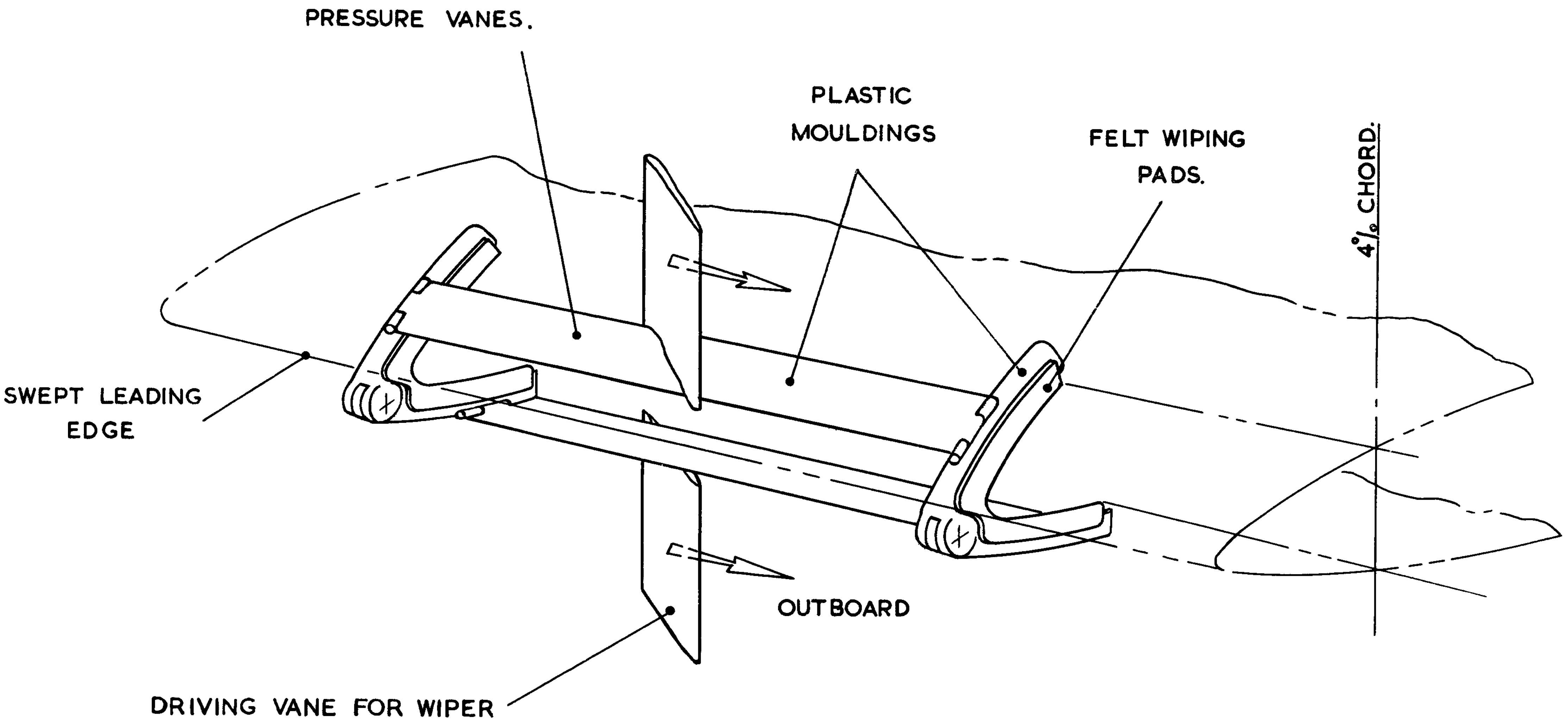
Self adherent protective cover

FIG. 6.



WATER SPRAY SYSTEM ON LEADING EDGE

FIG. 7



VANE DRIVEN FLY SCRAPER

FIG. 8

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