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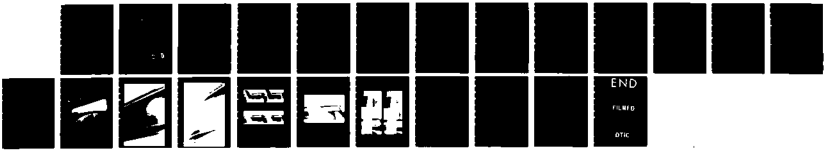

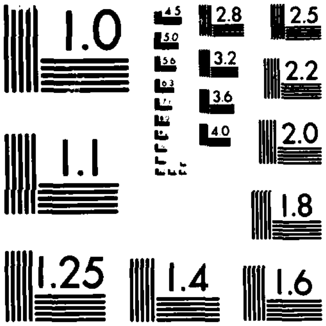
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ROYAL AIRCRAFT ESTABLISHMENT

THE 'MINITUFT' SURFACE FLOW VISUALISATION METHOD; EXPERIENCE OF USE IN THE RAE 5m PRESSURISED LOW-SPEED WIND TUNNEL

by

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SUMMARY

The development and use of a 'minituft' surface flow visualisation technique in the RAE 5m Pressurised Low-Speed Wind Tunnel is described.

The method, due to Crowder, uses very fine nylon monofilaments to show surface flow direction. These tufts are made visible by coating them in a fluorescent dye and then illuminating them with a powerful ultra-violet light source.

Because of their small size, a large number of tufts may be used without interfering with the flow to a great extent. However, it is shown that if accurate force measurements are required, then it is advisable to test the model in the absence of tufts.

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1 INTRODUCTION

The tufting of aerodynamic surfaces for flow visualisation is a long-established experimental technique. Its advantages as a flow visualisation method stem largely from the fact that once a model is fitted with tufts it can be used for a number of tests, without having to stop the test sequence to re-apply tufts, etc. By contrast, if oil is used to indicate the surface flow pattern, then the oil must be re-applied after each run. This is particularly inconvenient where access to the model is restricted, as in a pressurised wind tunnel. In this case, the working section must be depressurised, the oil applied and the working section pressurised again before the next oil flow pattern can be recorded. However, unlike tufts, the oil flow gives a continuous pattern that is easier to interpret than that suggested by the rather more discrete distribution of surface flow direction given by the tufts. The rather sparse information from tufting could be improved if more tufts were used, but as the tufts must be large enough to be visible, the flow interference induced by a large number of tufts would not be negligible. This would affect the aerodynamic forces on the model, and so separate 'tuft-off' runs would be needed to obtain reliable force measurements, thus negating some of the advantages of tufts.

Until recently, the tufts in general use in the RAE 5m Tunnel were typically about 1 mm in diameter. An illustration of the results obtained with these tufts is shown in Fig 1. Note that relatively few tufts are used, making it difficult to resolve the surface flow in any detail.

A novel solution to the dilemma of wanting more tufts but less flow interference has been proposed by Crowder in Refs 1 and 2. He recommends the use of extremely fine nylon monofilaments ('minitufts'), which have a diameter of about 0.04 mm. These tufts are barely visible to the naked eye, even when the model is inspected closely. However, by coating the monofilaments in a fluorescent dye, and exposing them to ultra-violet light, the tufts fluoresce and have a large apparent optical diameter, which may be readily photographed. Crowder presents results from a range of low- and high-speed tunnel tests which indicate that the minitufts have only a small effect on the overall forces measured on the model.

In view of the impressive results obtained by Crowder, and the apparent suitability of the minituft technique for use in a pressurised wind tunnel, it was decided that a similar system should be installed in the RAE 5m Tunnel. This Memorandum records the development of the system, and presents results from the use of minitufts on two models - a combat aircraft research model, and a propeller-driven civil transport model.

2 TUFT PREPARATION

The material used for the tufts was a monofilament fibre, some 0.04 mm in diameter, obtained from the Coventry Yarns Division of Courtaulds. This corresponds to a 20 denier fibre. The fluorescent dye chosen was Elbenyl Flavine A-FF which was obtained from L.B. Holliday and Co. Ltd. The dye was supplied in the form of a powder from which a solution was made up of 1% powder, by weight, in water. Two cubic centimetres of concentrated formic acid was added to each litre of the solution. The acid attacks the surface of the monofilament and increases the amount of dye absorbed. For the dyeing process, the 'raw' monofilament material was wrapped around a large test-tube, boiled in the solution for 2 hours and then dried in an oven.

3 SURFACE PREPARATION

The minituft technique has been used on two types of model surface in the RAE 5m Tunnel to date; polished aluminium and painted surfaces. In the case of aluminium, especial care was taken to ensure that the surface was clean, so that the tufts would adhere firmly. The model surface was first cleaned with paper tissues and a solvent. For this process, solvents that do not evaporate too quickly are preferred, *eg* Inhibisol as opposed to alcohol, so that the solvent can be removed before drying. Each area of the surface was wiped once only with the tissue to avoid re-depositing contaminants on the surface, this process being repeated until the tissues showed no staining. The surface was then wetted with chromate conversion solution ('Alocrom') to promote adhesion, any parts of the surface that resisted wetting with the solution being scrubbed with very fine wet and dry paper, before more of the solution was applied. However, in order to avoid the need for this if at all possible, the alocrom was used in conjunction with a photographic wetting agent ('Kodak Photo-Flo').

The solution was then left on the surface for 5 minutes, after which it was washed away with water and clean tissues. When treating a painted surface no Alocrom was used - the surface was simply cleaned with Inhibisol.

A grid of suitable positions for the tufts was then marked out using a straight-edge and soft pencil. The grid typically comprised a series of spanwise lines at approximately constant local chordwise positions, and a set of chordwise lines, along which the tufts lay.

4 TUFT ATTACHMENT

One end of the nylon monofilament was taped to the underside of the leading edge near the wing root, and then run along the upper surface of the wing along one of the chordwise lines previously marked in pencil. Care was taken not to stretch the filament, as otherwise it would curl after cutting. The monofilament was then taped to the lower surface of the trailing edge, this process being repeated for each spanwise station. To speed the process of 'laying up' the tufts, it would found convenient simply to run the monofilament diagonally across the lower surface of the wing to the leading edge at the next spanwise station to be tufted, rather than cut the filament where it was last taped. The result of the laying up process was than a single strand of monofilament wrapped around the wing in a spiral. A steady, low-power, ultra-violet light was used to illuminate the very fine tuft material.

Adhesive (nitrocellulose dope) was put in a hypodermic syringe, and applied to the tufts by 'dotting' adhesive onto the monofilament where the spanwise lines of the pencil grid ran across the filament. A very fine hypodermic needle was used, and was allowed to touch the surface only briefly. The glueing process was repeated until the entire grid was 'dotted' with adhesive in this way, and the adhesive allowed to dry. The tuft material was then severed just upstream of each adhesive drop, with a new razor blade. The tufts thus formed tails downstream of the glue drops. A typical tuft length was about 1 inch.

5 PHOTOGRAPHY OF MINITUFTS

The very small minitufts are made visible for photographic purposes by illuminating them with a strong ultra-violet light. They then fluoresce and may be easily photographed. To make the tufts fluoresce for continuous periods, in order to see their time-dependent behaviour, would call for high power levels to be supplied to the lamp, with attendant cooling problems. However, for short duration illumination, electronic flash may be employed, without the cooling problems. Electronic flash is rich in ultra-violet emission (at approximately 365 nm), which, in commercial units, is usually unwelcome and is partially suppressed at the manufacturing stage. However, some UV emission remains and, in initial tests, commercial flash units were used to illuminate the minitufts.

In order to use the commercial flash as a pure UV source, visible light must be filtered from the flash emission and only UV light emitted. This was achieved by fitting a Wratten 18A/Chance OX-1 filter over the light source. The UV light source could then be used to excite the minituft dye momentarily. Excited in this way, the dye fluoresces in the visible spectrum so that the tufts may be photographed normally. Photographic emulsions are, however, very sensitive to UV light, and will respond to the 'raw' UV flash even if no visible light is present. The UV light must, therefore, be absorbed at the camera lens before it reaches the photographic emulsion. For this purpose, a Wratten 2B filter was placed in front of the camera lens. This filter absorbs UV light up to about 400 nm. Thus the filter on the flash and the filter on the camera lens perform complementary functions - the flash filter permits only the passage of UV light, while the camera filter will allow only visible light to pass.

Initial tests were conducted with two 800J commercial flash heads illuminating a test-piece 10 ft away. Typical results are compared in Fig 2. Fig 2a shows the results with no filters being used, while Fig 2b shows the effect of placing UV transmitting filters over the flash units, and UV absorbing filters over the camera lens. These tests proved that both sets of filters were essential if the minitufts were to be seen clearly. However, when this installation was used in the tunnel it was found to be unsatisfactory, as both the camera and flash units had to be placed behind perspex windows some 25 mm in thickness which absorbed an appreciable fraction of the emitted UV light. Further tests outside the tunnel revealed that more powerful flash units would be needed in any case. A commercial firm was contracted to produce two high power (5500-6000J) Xenon flash units with a maximum output at the UV end of the spectrum. One of these flash units was placed behind a filter that was mounted flush with the tunnel wall for the initial tests. A later, roof-mounted, installation has been made available in the 5m Wind Tunnel, so that minitufts may be used on conventionally mounted complete models.

To summarise the results of the photographic study, the following specification for the optical system was obtained:

Camera

Hasselblad EL/M remotely operated from control room.

Film

Ilford HP5, 220 size. Processed for 12 minutes in Kodak D76 at 20°C.

Lens

100 mm f/3.5, set to f/4.

Speed

1/8 second. Light metered to record model outline using tunnel lights.

Flash

Approximately 5700J Xenon flash unit synchronised to camera shutter.

Recharge time

Three minutes to fully charged, but may be used after 90 seconds.

Flash filters

Wratten 18A/Chance OX-1 (to absorb visible light but pass UV Light).

Camera filters

Wratten 2B or 2E (to absorb UV light but pass visible light).

6 RESULTS

Minitufts have been used on two half-models in the RAE 5m Low-Speed Pressurised Wind Tunnel to date; a cranked-delta/canard combat aircraft model and a propeller-driven civil transport model. Half-models are tested in the 5m tunnel by mounting them on a turntable on the tunnel floor. Both the canard and main wing upper surfaces of the combat aircraft model were tufted, with about 300 tufts on the canard and about 1200 tufts on the wing. The preparation of the aluminium surface of the wing and actual tufting took about 1½ days to complete. Some tufts were damaged while installing the model in the tunnel, but these were easily replaced individually. The model was tested over a range of incidence with two canard deflections: 0° and -20°. Some of the photographic results are shown in Fig 3. Points of note are the development of the canard stall, via a leading-edge separation, shown by the spanwise deflection of the tufts, and secondly the path of the vortex resulting from the leading-edge separation which appears on the highly-swept inboard part of the main wing. It will be noted that the negative deflection of the canard causes the wing vortex to move inboard.

Two other points of interest are the spanwise flow just aft of the outboard leading-edge droop, showing the flow to be locally separated there, and the spanwise flow at mid-chord in the wing root. This root flow is the result of not sealing the gap between the wing and the fuselage body panel, allowing venting of flow from inside the fuselage into the low-pressure region above the wing.

Some tufts did not appear to move at all during the tests. This was attributed to 'static cling', where a small electrostatic charge of the tuft causes it to adhere to the wing surface. As the tests proceeded, some of the tufts disappeared - notably from the wing apex, along the highly-swept inner leading edge and some parts of the outboard panel. Fig 4 is a 'wind-off' picture of the tufts at the end of the tests, and shows the 'bare patches'. The mode of tuft failure is one of fatigue near the glue dot holding the tuft to the wing. It occurs in regions of separated and unsteady flow, where the tufts can be seen to 'cone'.

During the tests, it was found that the tunnel working lights could be left on while the minituft flash photograph was taken. The flash was powerful enough to illuminate the tufts against the ambient light levels. The flash unit took some 3 minutes to become fully charged, but satisfactory photographs could be taken after 1.5 minutes of charging. It was also possible to capture the illumination of the tufts on a video recorder connected to a closed-circuit television (CCTV). Usually, the image lasted for about two frames (about 1/10 second), and could be found by stepping through the recording a frame at a time. The image was available for recording because of the persistence of the image on the vidicon tube of the CCTV, although the actual flash illumination time was an order of magnitude smaller (about 1/100 second).

The second application of the minituft technique was a civil transport model. Here, some 750 tufts were used, covering the wing, flap and engine nacelle. Fig 5 shows 'before' and 'after' photographs of the tufts, comparing the original condition of the tufts with their state at the completion of the tests. Most marked is the loss of tufts from the flap, which was tested at large deflection and had a large amount of separated flow. Also apparent is the loss of tufts from the wing inboard of the nacelle. This also exhibited large-scale flow separation during the tests.

In Refs 1 to 3, it was noted that the most marked effect of the minitufts on forces was an increase in drag (although Ref 3 records a decrease in drag for one case). This is the result of two effects:

(i) movement of the position of transition from laminar to turbulent flow forward as a result of roughness elements;

(ii) modification to the characteristics of the turbulent boundary layer after transition as a result of the 'roughening' of the aerodynamic surface.

The effect of (i) may be reduced by not applying tufts to the forward part of the wing, *eg* leaving the first 10% of the chord clear of tufts. With so-called laminar flow sections the first row of tufts would have to be even further aft.

To discuss these effects in more detail, we consider some typical values of the parameters that describe the likely effects of the minitufts on the development of the boundary layers.

For the case where the minitufts cause premature transition from laminar to turbulent flow in the boundary layer, the relevant parameter is taken to be the Reynolds number based on the 'roughness height' (say, the tuft diameter, d) and the external velocity at the tuft position, U_e :

$$R_d = \frac{U_e d}{\nu} .$$

This may be written as

$$R_d = \frac{U_0 d}{\nu}\sqrt{1 - C_p} ,$$

where U_0 is the free stream speed, and C_p is the pressure coefficient at the tuft position. Taking a specific case of a free stream Mach number of 0.2, and a typical value of C_p for a high-lift system as -2.0, then the value of R_d will vary from 300-900 for the pressure range of the 5m tunnel. Although there is scant data on the effects of pressure gradients on critical R_d's, the work of Feindt (reported in Ref 4) indicates that this range of Reynolds number is likely to encompass that where the tufts could cause transition. The tufts cover relatively little of the surface, but the discrete roughness elements they present are likely to be effective transition trips.

Once transition has occurred, the effect of the tufts is a roughening of the aerodynamic surface. The appropriate parameter to describe this roughness is the viscous sub-layer Reynolds number based on tuft diameter:

$$d^+ = \frac{U_\tau d}{\nu} ,$$

where U_τ is the friction velocity given by

$$U_\tau = \frac{\tau_w}{\rho} = U_e\sqrt{\frac{C_f}{2}} = U_0\sqrt{\frac{C_f(1 - C_p)}{2}} ,$$

where U_e is the local velocity external to the boundary layer, and U_0 is the free stream velocity. C_p and C_f are the pressure coefficient and skin friction coefficient respectively. Inserting typical values for C_p of -2.0, C_f of 1.5×10^{-3}, the inner-layer roughness Reynolds number ranges from about 2-44 over the tunnel operating envelope. At $M = 0.2$, the range is 9-27. The tufts are therefore not small enough to leave the surface aerodynamically smooth ($d^+ < 5$) or fully rough ($d^+ > 70$, say).

It may be speculated that a third effect of the tufts could arise as a result of their behaviour in unsteady flow, where they exhibit a characteristic 'flapping' motion. The flapping of the tufts may have some effect on the local momentum exchange across shear layers and wakes, and thus modify the flow. Such an effect, although difficult to quantify, could conceivably arise in high-lift flows where extensive flow separation may be present on, say, a highly-deflected flap.

The approximate calculations given above suggest that the tufts may not have a negligible effect on the development of the boundary layers, and thus the overall forces. Furthermore, the changing roughness Reynolds number with free stream Reynolds number may mask the 'real' scale effects of the clean wing.

The results from the civil transport tests did indeed reveal non-negligible effects of the minitufts on drag, and also on lift. Fig 6 shows the lift curve for two cases - tufts on and tufts off. There is a change in the lift-curve slope, and in the maximum lift achieved. This is an extreme case, where the minitufts showed the flow on the flap to be separated. The tufts may have affected the degree of separation and hence flap effectiveness. The corresponding drag results are shown in Fig 7, where the tufts are seen to give a drag increase of about 20 counts. Ref 3 notes a drag increase of up to 30 counts in the tests reported there. Moving the first row of tufts to 50 mm aft of the leading edge lowered the drag by four counts. These values should be compared with the scale effect on drag, which produced a 50 counts reduction in drag in going from 1-3 bars total pressure in the tunnel. It should be borne in mind, however, that the overall drag level, at high lift, was of the order of 2000 drag counts.

7 CONCLUSIONS

The minituft surface flow visualisation method has been used successfully in the RAE 5m Low-Speed Pressurised Wind Tunnel to give quite detailed photographs of the surface flow on models. The method is well suited to use in a pressurised tunnel, as no access to the model or photographic system is required between runs, apart from occasional loading of film cartridges and tuft repairs. It has been found possible to record the tuft illumination on a video recorder, enabling the test controller to examine the results quickly. It is recommended that if accurate force measurements are required (*eg* within five drag counts), then separate force runs should be used, without the presence of minitufts on the model.

Appendix

SUPPLIERS

Nylon monofilament: Courtaults Ltd, Coventry Yarns Division.
Telephone 0203 88771

Fluorescent dye: L.B. Holliday and Co. Ltd., Leeds Road, Deighton, Huddersfield,
W Yorks HD2 1UH.
Telephone 0484 21841

Flash units: Pulse Electronics, Shepherds Road, Bartley, Southampton,
Hants SO2 2LH.
Telephone 042 127 2869

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No.	Author	Title, etc
1	J.P. Crowder	Fluorescent minitufts for non-intrusive flow visualisation. McDonnell-Douglas Report MDC J7374 (1977)
2	J.P. Crowder	Add fluorescent minitufts to the aerodynamicist's bag of tricks. AIAA Aeronautics and Astronautics, November 1980
3	M.J. Mann J.K. Huffman C.H. Fox Jr R.K. Campbell	Experimental study of wing leading-edge devices for improved manoeuvre performance of a supercritical manoeuvring fighter configuration. NASA TP 2125 (1983)
4	D. Arnal	Description and prediction of transition in two-dimensional flow. AGARD R 709 (1984)

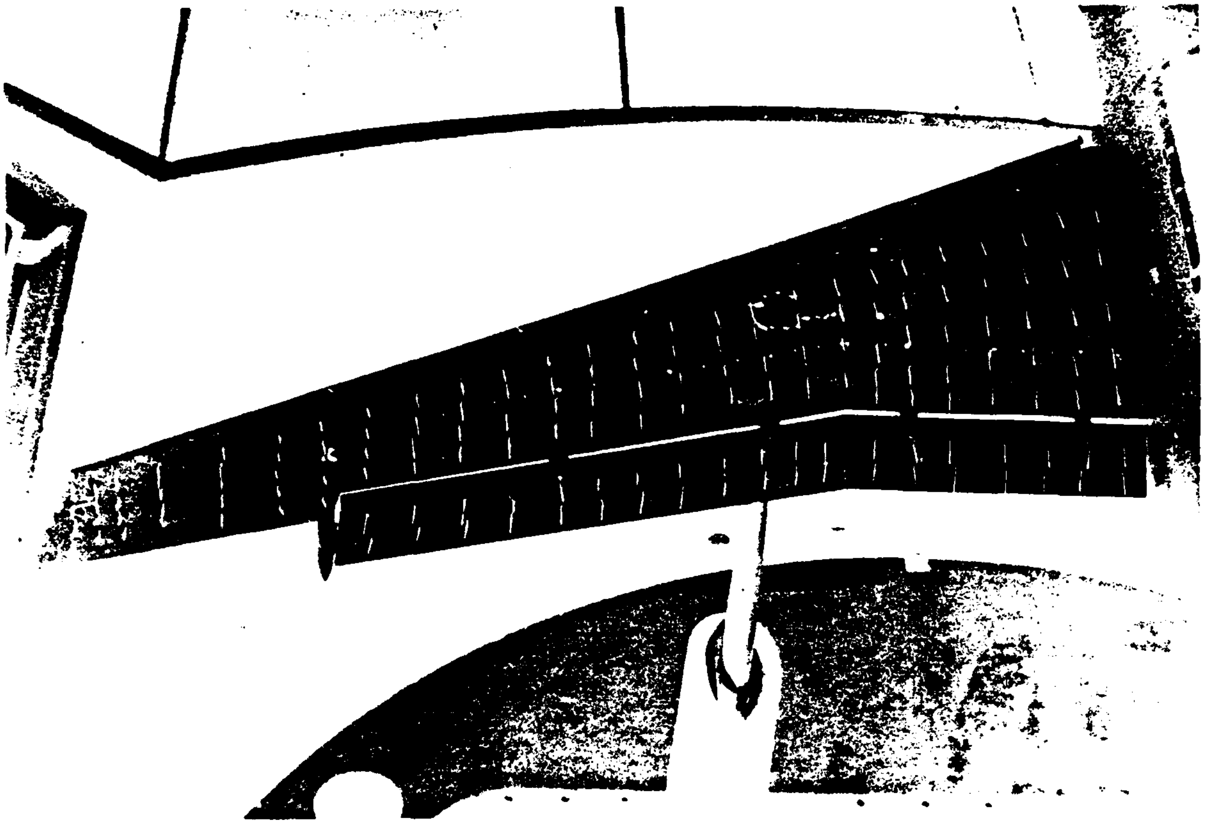


Fig 1

Fig 2a

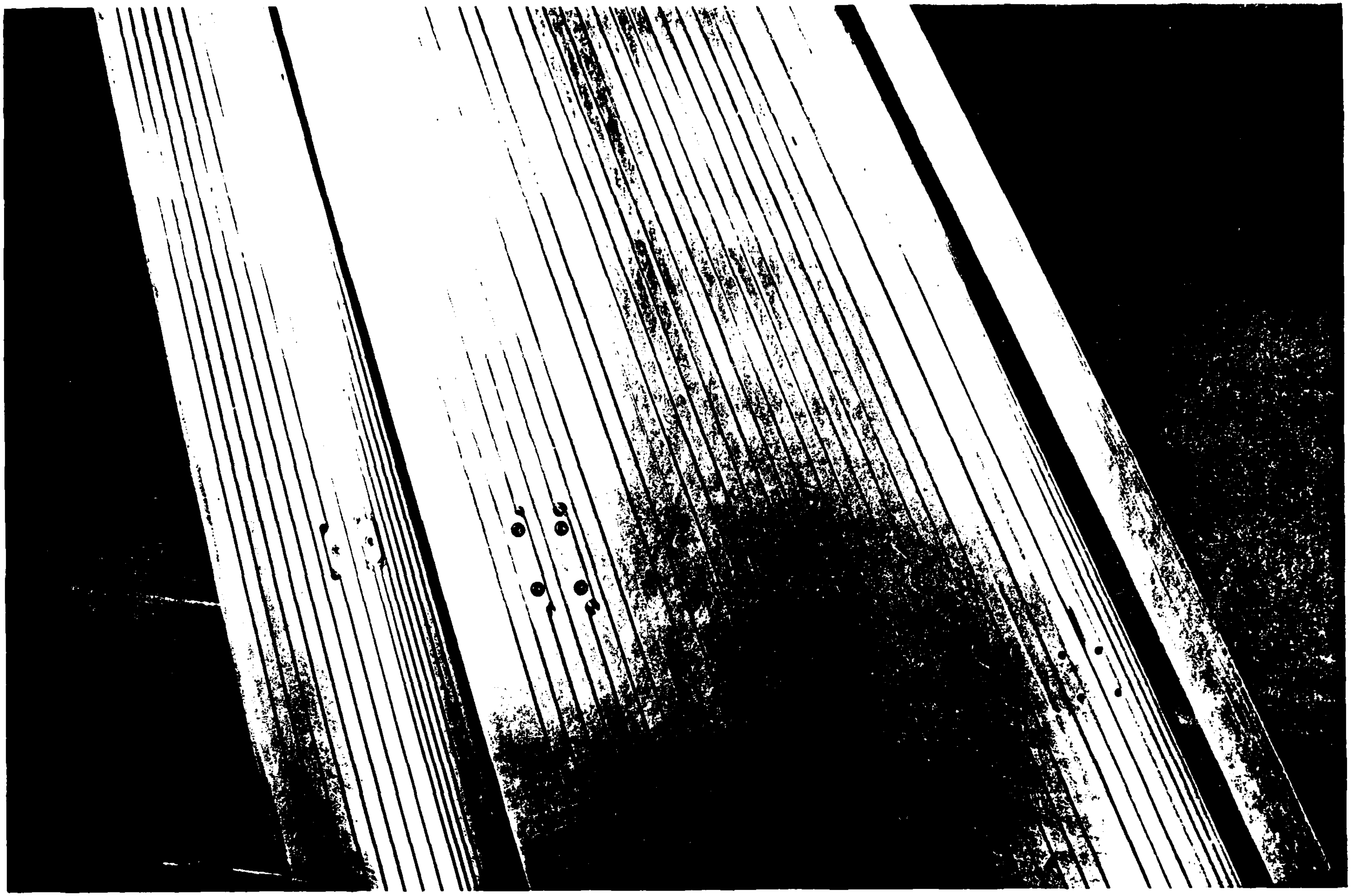


Fig 2a Fluorescent mini tufts on Model 477 - Normal flash in 5m tunnel rigging bay at night

Fig 2b

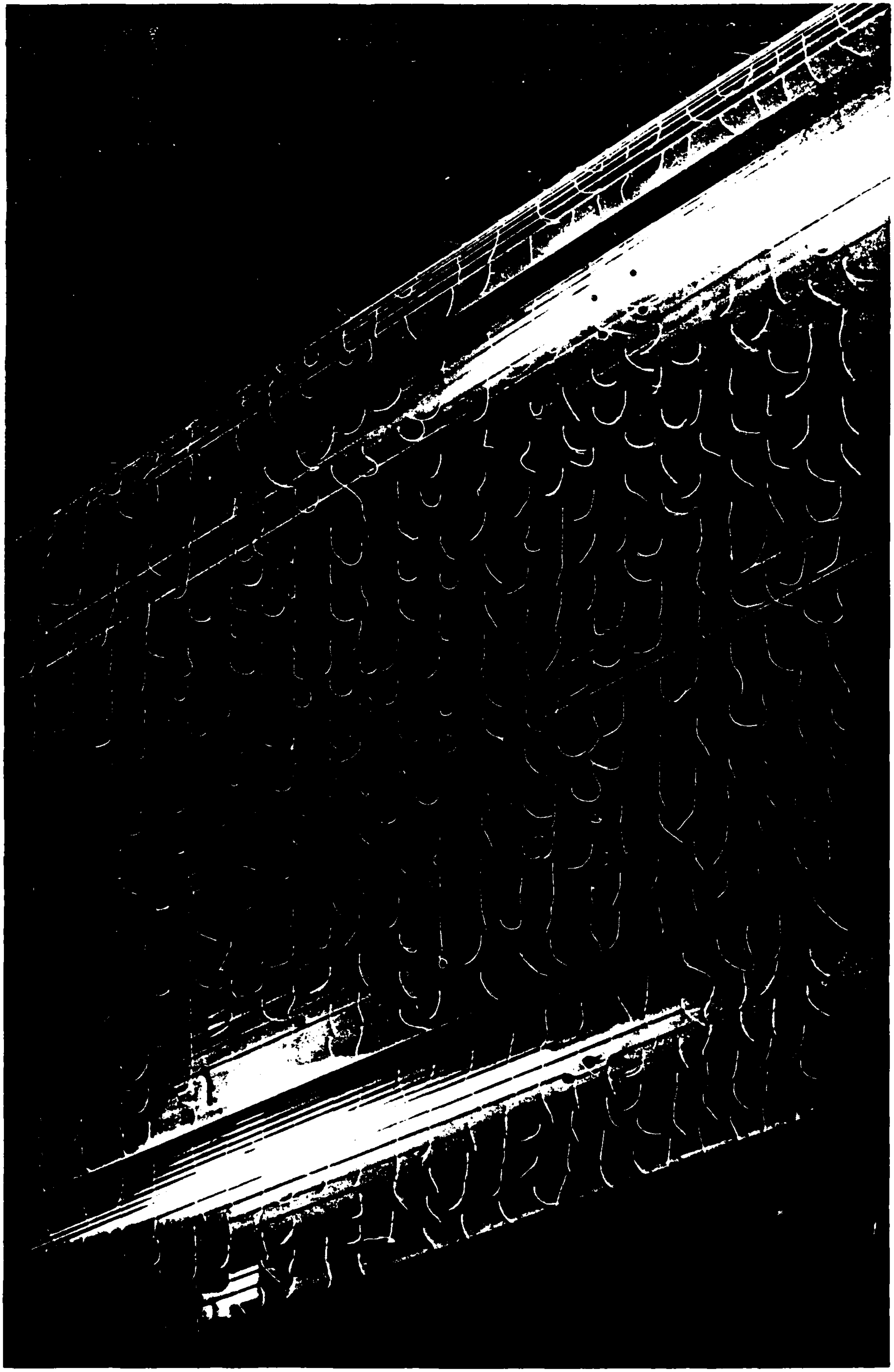
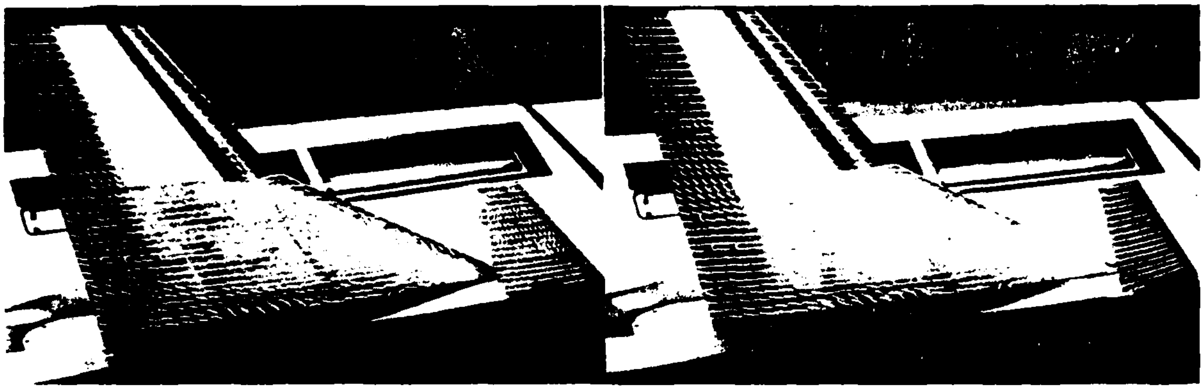


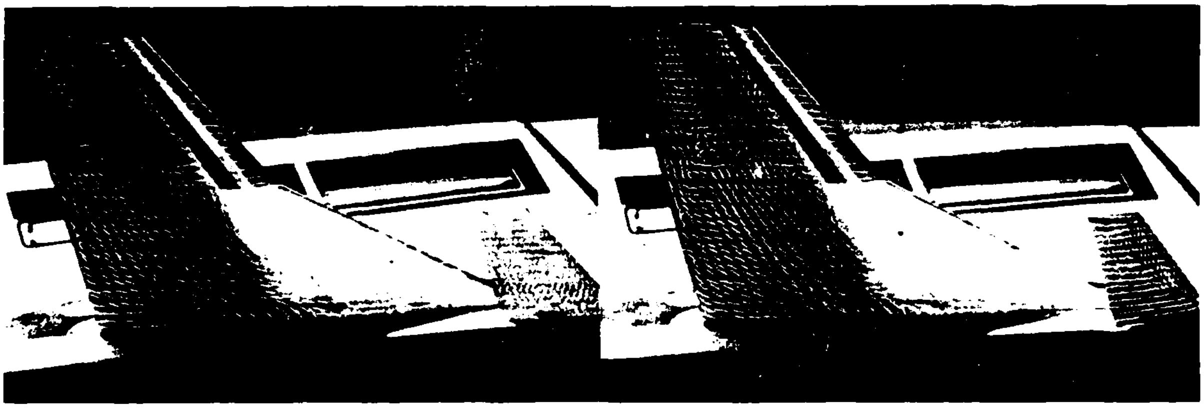
Fig 2b Fluorescent mini tufts on Model 477 - UV flash in 5m tunnel rigging bay at night



Canard 0°

Canard -20°

Alpha = 9°



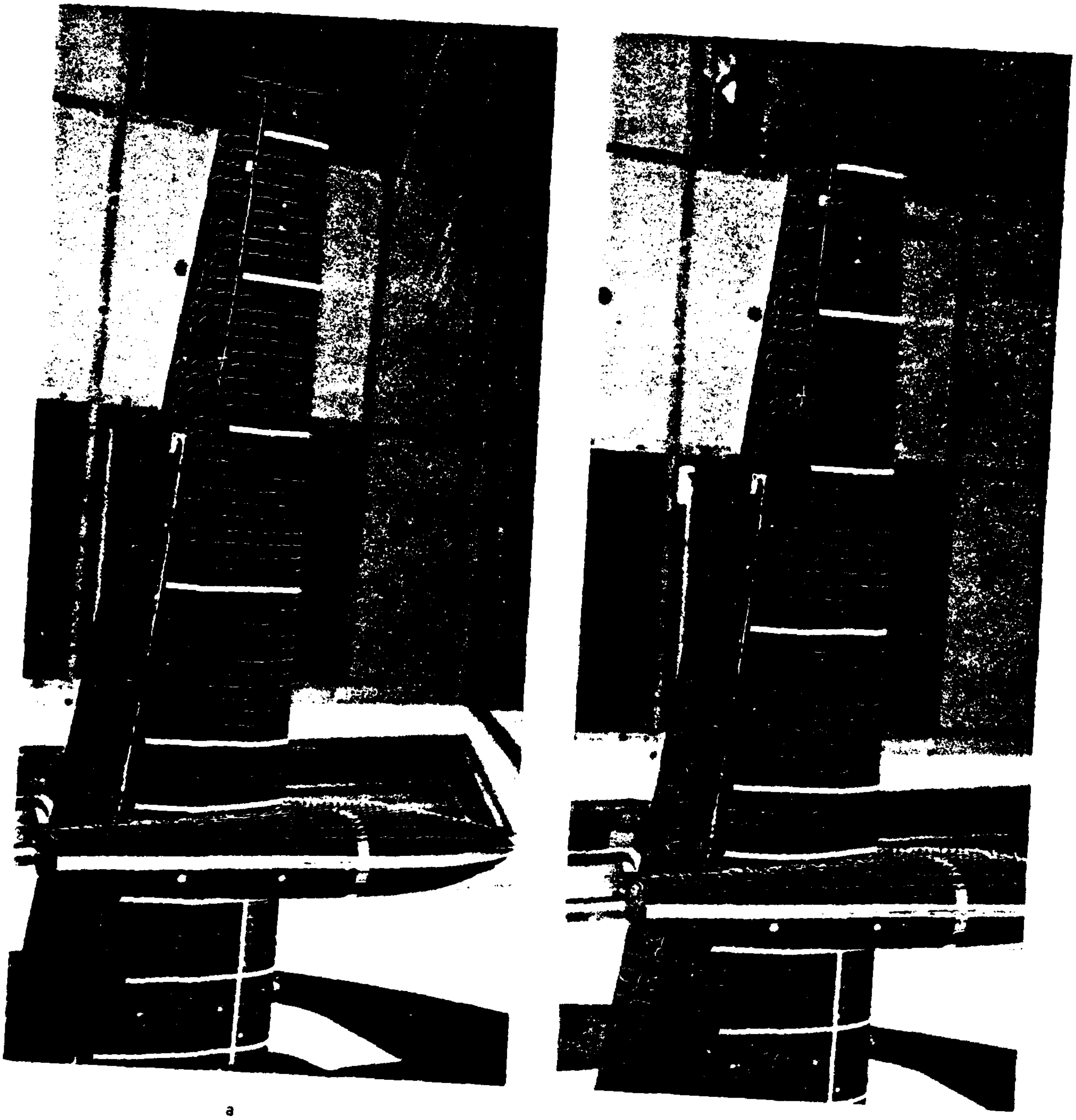
Canard 0°

Canard -20°

Alpha = 21°

Fig 3

Fig 4



a

b

Fig 5a&b

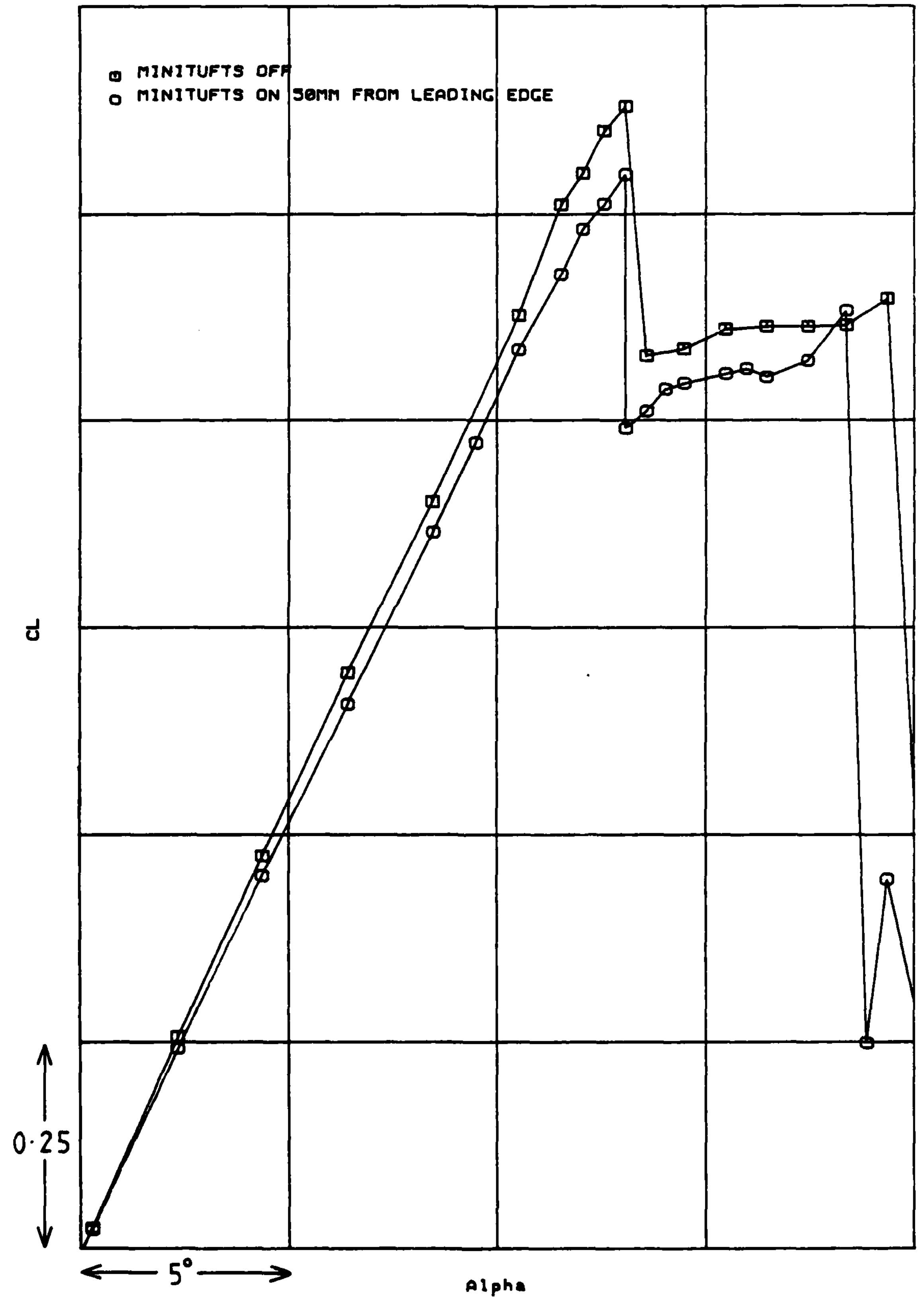


FIGURE 6. EFFECT OF MINITUFTS ON LIFT OF CIVIL TRANSPORT MODEL.

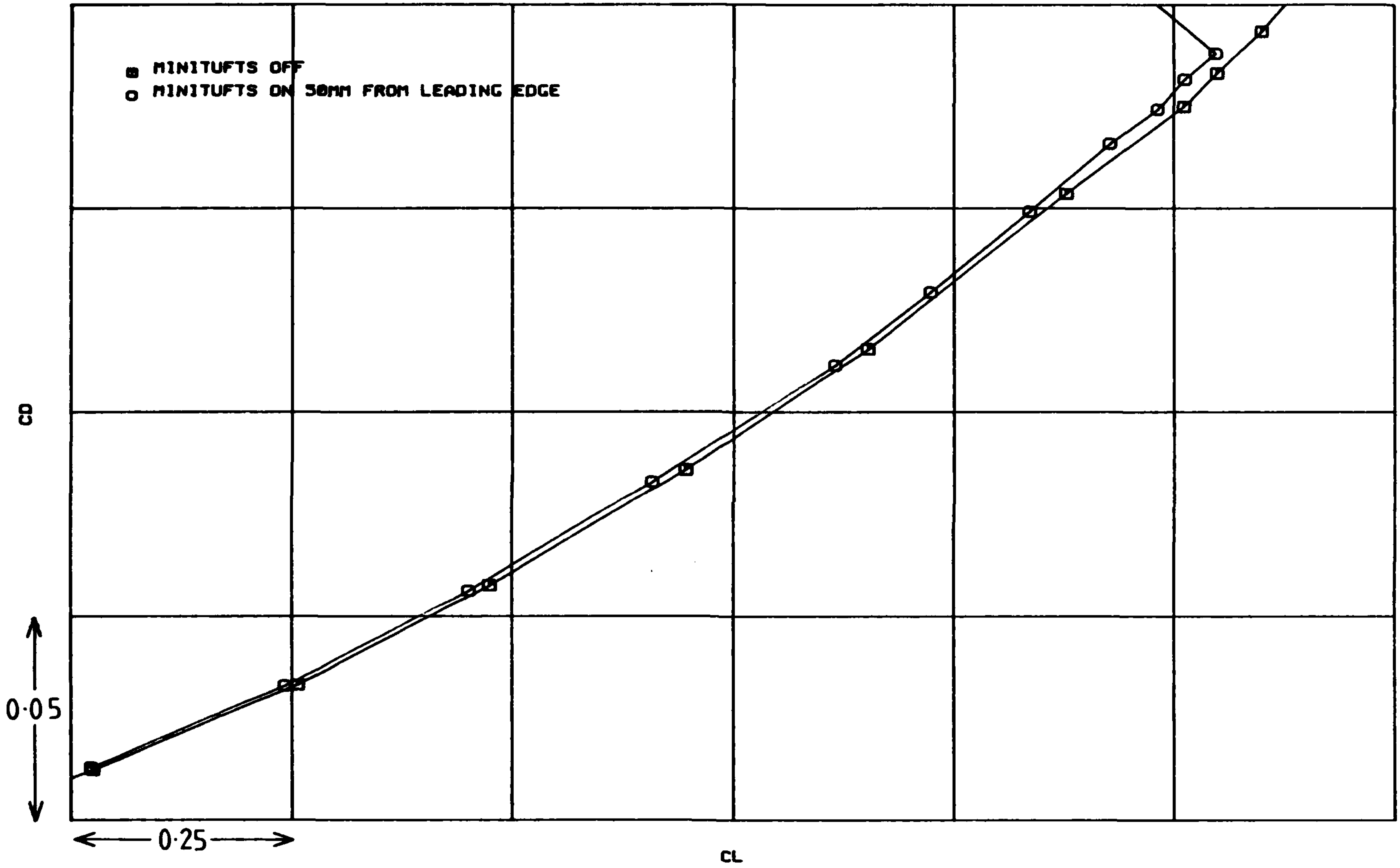


FIGURE 7. EFFECT OF MINITUFTS ON DRAG OF CIVIL TRANSPORT MODEL.

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNCLASSIFIED

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17. Abstract

The development and use of a 'minituft' surface flow visualisation technique in the RAE 5m Pressurised Low-Speed Wind Tunnel is described.

The method, ~~due to Crowder,~~ uses very fine nylon monofilaments to show surface flow direction. These tufts are made visible by coating them in a fluorescent dye and then illuminating them with a powerful ultra-violet light source.

Because of their small size, a large number of tufts may be used without interfering with the flow to a great extent. However, it is shown that if accurate force measurements are required, then it is advisable to test the model in the absence of tufts. Keywords. [illegible]