SIXTH EUROPEAN ROTORCRAFT AND POWERED LIFT AIRCRAFT FORUM

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U.K. DEVELOPMENT OF A ROTOR DE-ICING SYSTEM

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ABSTRACT

For a number of years Westland Helicopters have been investigating in co-operation with AAEE Boscombe Down the problems associated with providing a helicopter with an effective Electrothermally Heated Rotor Blade (HRB) system for ice protection. In the last five years Westland have conducted four winter trials developing with Lucas Aerospace the HRB system on a Royal Navy Wessex Mk. V. The first three of these trials developed the system to a high degree of effectiveness in temperatures down to minus 13 degrees Celsius and the results of these trials have been discussed in papers at previous symposia. The most recent trial last winter extended experience with the system to minus 21 degrees Celsius. The paper deals briefly with the need for a rotor ice protection system, the complex instrumentation fit considered necessary for the development task and the results in the higher temperature regime, before discussing some relevant aspects of the recent investigation at very low icing temperatures.

1. INTRODUCTION

This paper deals with the need for a rotor ice protection system, the instrumentation fit considered necessary for its development and the results of flight trials in both high and low icing temperatures.

Because of the necessary time limitation for the paper, it will not be possible to cover here the problems specifically associated with tail rotor protection; nor the wind tunnel and theoretical work which form a valuable part of the UK rotor protection development effort.

2. THE NEED FOR ROTOR ICE PROTECTION

When a helicopter without rotor ice protection flies through cloud at sub-zero temperatures and the cloud is partially or completely formed of supercooled water droplets, the rotor blades will accrete an ice formation on their leading edges. The extent of this accretion will vary spanwise and chordwise depending primarily on the ambient temperature and the droplet size distribution. The surface shape of the accretion is also variable, depending chiefly on the spanwise variation of total temperature. Where the total temperature is only a few degrees below zero Celsius, the surface shape of the accretion is often widely different from the aerodynamic section on which it has grown (Fig. 1). As the ice formation grows the aerodynamic characteristics of a blade deteriorate: increased rotor drag increases the engine torque demand, premature blade stall may occur, aggravated by increased application of collective pitch to restore lift loss, and the pilot may be forced to vacate the icing condition in order to respect limitations of torque or stress in critical components: alternatively the handling qualities of the aircraft may be unacceptably degraded. The ice accretion on the blades is subject to natural aerodynamic and centrifugal shedding forces: shedding is also promoted by the blade's vibration modes. When these shedding forces are sufficient to overcome the bond of a section of ice accretion to the blade and to the remainder of the ice accretion, shedding will occur. Above about -10°C static air temperature, natural shedding tends to occur in small increments, such that asymmetric 1/rev vibration is not excessive, but below this temperature, where the ice bonds are stronger, severe 1/rev vibration may result from large masses of ice being shed from one blade.

WHL have accumulated experience on unprotected rotors which suggests that the combined effect of ice accretion and natural shedding leads to an equilibrium rotor performance penalty after (typically) 5 minutes in a given icing condition, (ref. 1), although the extent of this penalty varies with different helicopter/rotor combinations. Thus it is possible with a given helicopter to map out icing conditions for which this equilibrium performance penalty is acceptable, providing sufficient icing conditions can be found (and measured) during test flights. Providing, then, that the helicopter customer's requirements are not for icing conditions more severe than those found acceptable and providing the previously mentioned limitations of vibration, handling and stress levels are not exceeded, then a rotor protection system is not needed.

Fig. 2 shows a typical example of combinations of liquid water content (LWC) and outside air temperature (OAT) that lead to acceptable penalties of torque, stress, handling and vibration. The Av.P.970 continuous maximum icing severity at 2000 and 4000 feet is plotted for reference, showing that this standard is typically not met with an unprotected rotor below about -4°C OAT without some form of altitude limitation.

When a helicopter's operational requirements are not met by this limited capability, a rotor protection system is required. The development of a rotor protection system may be broken down into 2 stages. Fig. 3 shows the first stage, which I have called survivability. This stage comprises successful development of a system which will enable the helicopter to meet the operator's requirements with respect to icing condition severity and duration without incurring unacceptable in-flight degradation in stress, performance, handling or vibration; although payload, range and flight envelope may be substantially cut back, a mission may be continued until fuel shortage necessitates a return to base. The second stage of development (Fig. 4) is to minimise the penalties to payload, range and flight envelope by optimisation of the system parameters. Fig. 4 shows in diagrammatic form how these penalties are built up from the weight and electrical installation penalties, and from the residual level of aerodynamic degradation on the protected blades.

3. EARLY UK TESTING

Fig. 5 shows the UK helicopter icing trials activity in the period 1961 - 1975. The first testing relevant to the developed UK rotor protection system described in this paper was a test programme of a Wessex 1 helicopter fitted with a Napier electrothermal de-ice system in the NRC Spray Rig at Ottawa in February 1961. This system, which was powered by a cable to a ground generator, carried out initial work on power density requirements and ON and OFF times for the blade heater mats. In 1970, interest by the Royal Navy in an icing release for the Wessex 5 led to the procurement of an electrothermal system from Rotax Limited (now Lucas Aerospace Limited). This was first tested in the winter 1972/73 by A & AEE Boscombe Down at Ottawa both in the NRC Spray Rig and in Natural Icing. As a result of this trial, main rotor blade heater mats were extended to full span and given a 15% increase in power intensity, and improvements made to OFF and ON-time control: the test aircraft then returned to Ottawa for a one-month trial in March 1974 by WHL. 5 natural icing sorties were achieved (in addition to Spray Rig work): these indicated that the automatic OFF-time between heating cycles was too long. A further 6-week trial in 1976 tested further reductions in OFF-time and provided the basis for the cyclic sequence development detailed below.

4. THE TEST AIRCRAFT AND INSTRUMENTATION FIT

The test aircraft and instrumentation fit are depicted in Fig. 6. The aircraft is a Royal Navy WessexMk. 5 fitted with a Lucas Aerospace ice protection system which protects the windscreen and horizontal stabiliser from ice accretion, as well as de-icing the main and tail rotors. Additional AC power supplies are provided and the engine intake is protected by a combination of engine bleed air and TKS anti-icing fluid.

The comprehensive instrumentation fit is necessary to categorise the atmospheric conditions encountered, to measure accurately degradation in aircraft performance and stress levels, and to photograph ice accretion and shedding as a guide to making system improvements. The fit comprises:-

(a) 70 mm still cameras mounted on the rotor head and tail cone to take colour photographs in-flight of the main blade upper and lower surfaces respectively. These cameras have been progressively developed by A & AEE Boscombe Down, and now give excellent results. The tail-cone mounted camera is coupled to a radar unit which can detect a blade passing over the tail-cone and thus ensure that blades are correctly framed. A fast shutter-speed is required for this camera and a flash unit is necessary to provide the required light level. The rotor-head mounted camera does not have the same shutter-speed constraint and requirement for flash: the aperture is automatically controlled for the ambient light-level. Fig. 7 shows the installation of this camera, which faces vertically upwards into a four-way mirror arrangement to view all blades. In the centre of the mirror arrangement is a display of time into flight to 1/10 second for accurate time identification of ice shedding photographed. Fig. 8 is a photograph by the rotor head camera (RHC) showing ice shedding from the blade leading edge. Fig. 9 is a photograph by the tail boom camera (TBC) also showing ice shedding.

(b) Atmospheric sensing equipment

Liquid water content (LWC) is measured by a Leigh ice severity system (Fig. 10) which gives a digital display of LWC averaged over the major part of each probe de-icing cycle. In severe conditions, probe cycling is frequent and a new reading is available every few seconds. The instrument reading is largely independent of aircraft speed, because airflow over the probe is induced by compressor bleed air. The instrument is mounted in the free air stream off the starboard oleo. The analogue signal of probe accretion is also recovered and recorded on trace: this not only enables measurement of instantaneous LWC to be made, but is also useful for detecting the presence of snowflakes, which affect the trace in a characteristic fashion.

Outside air temperature (OAT) is measured by a Tinsley digital instrument with the cockpit Rotatherm as a back-up. Tinsley OAT is continuously recorded on trace.

The atmospheric data are recorded on videotape as well as appearing on cockpit displays and trace records (Fig. 11). The video shows accretion on a simple accretion rod with a manual de-ice facility. This provides approximate LWC information in the unlikely event of a failure of the Leigh instrument. A second calibrated rod is placed at a shallow angle in front of this rod to enable the accretion to be measured to within approximately ½ mm. Digital LWC and OAT information are displayed in boxes at the top of the screen, along with flight number and time into flight. Recently the heated rotor system switch position has been added to this display.

The videotape recorder may also be used to record in-flight views of the engine intake on occasions when ice or snow is building up in the intake and placing the engines at hazard.

(c) Strain-gauges are located at critical stress points in the rotor system, including stationary and rotating swash-plates, tail rotor pitch beam, and main and tail blade spars. Stress records are examined after each flight to monitor any fatigue damage to the test aircraft, to help decide whether the use of the de-icing system imposes an added restriction on flight envelope or component lives, and (in the case of control stresses) as a guide to incipient blade stall.

(d) Rotor performance is monitored via engine torque, main rotor shaft torque, collective pitch and main blade lag angles. Datum flying is carried out to establish the out-of-icing values of these parameters at known conditions of weight, density altitude and airspeed. The main blade lag angles are measured by potentiometers on the lag hinges: The mean lag angle is a measure of the drag on any blade and therefore may be calibrated in terms of contribution to total torque requirement. This is of use in two ways. Since the de-icing system operates on one opposite blade pair at a time, the benefit of ice shedding on one blade pair will be seen in the difference in torque contribution between the two blade pairs, or 'differential torque', as it is usually referred to. This change in differential torque, due to ice shedding on one pair, will be independent of pilot and gust input (which may be assumed to affect both blade pairs equally) and therefore has a much greater analytical value than total torque, on which it is almost impossible to separate de-icing effects from pilot or gust inputs.

The second use of the lag angle data is during test flights in which alternative heating sequences are carried out on the two opposite blade pairs. Because of the difficulty of finding consistent icing conditions and repeating a test with a different heating sequence and the same aircraft weight etc., this so-called 'two-by-two' approach is a more reliable means of comparing the short and long term effects of two heating sequences.

Fig. 12 shows an example of the use of control-load amplitude and differential torque in the first heating cycle after a period with the rotor protection system switched out and the rotor heavily degraded. Note that the reduction in control load amplitude and the torque benefit are clearly identified in the first few seconds of heating the appropriate blade pair. The view of the total torque in the same period (Fig. 13) appears to show a benefit at a different point, when the pilot lowered collective pitch to prevent the aircraft from climbing with restored rotor lift. The rate of deterioration of total torque requirement without rotor protection can be seen to be very rapid indeed (750lbs.ft/minute).

This completes the description of the comprehensive instrumentation fit in the test aircraft: WHL believe that it is only with the benefit of this level of instrumentation that test conditions and aircraft response can be properly identified, and the mechanism of ice shedding studied in sufficient detail to allow protection system improvement.

5. THE BASIC ROTOR DE-ICING SYSTEM

The Lucas rotor protection system in its undeveloped form before the icing trial of 1977/78 is represented by Fig. 14. Electrothermal heater elements spanning the length of the main rotor blade are disposed around the leading edge of the blade from 5% chord on the upper surface to 23% on the lower surface. Behind the upper surface matting is a bus bar common return. Some of the elements are wider and are a full delta-connected phase load, while for phase balance, some are 'half-width' and are electrically connected in parallel with another half-width element across a phase. The heater elements are heated in a simple sequence from the leading edge aftwards on blades 1 and 3, followed by the same sequence on blades 2 and 4. A segment of stabiliser de-icing is followed by an OFF period until a further cycle is required.

The tail rotor is de-iced twice during the cycle and the stabiliser leading edge is protected by a combination of de-iced areas and anti-ice splitter strips in accordance with fixed wing ice protection experience. Total power demand is 15.9 kVA.

In the seasons preceding 1977/78 it was noted that the heating of mats 2 and 3 on the leading edge of the main blade was instrumental in substantially reducing torque increments and control load amplitude, while the remaining segments had little effect on these parameters. On any given blade, therefore, there were 10 segments between torque and control load amplitude reductions even with one cycle immediately following the previous cycle without any OFF period. With the original ON time scheduled for each heating segment, this worked out at 75 seconds between reductions at -5°C and 120 seconds at -10°C. With the rates of torque rise and control load amplitude experienced in severe icing when mats 2/3 were not being heated, these periods between heating were found to be unacceptably long.

6. 1977/78 ICING TRIAL, DENMARK

Accordingly for the 1977/78 icing trial, effort was concentrated at reducing the time between successive heatings of mats 2 and 3. Three methods were investigated. Fig. 15 shows some of the revised sequences tested during the trial. Options 'c' and 'r' exhibit a reduction of lower surface matting coverage. Since there are fewer heating segments on each blade, a return is more rapidly made to mats 2 and 3. Option 'p' features the second approach, that of heating mats 2 and 3 twice on each blade pair per cycle. Option 'q' is shown for interest, as it is an example of the 'two-by-two' method of sequence comparison, with a different heater sequence on the two pairs of opposite blades. The third approach adopted was to investigate a reduction in ON time per segment below that originally designed at a given OAT. Fig. 16 shows the reduction in ON time that was found possible, over the temperature range encountered, on the basis of blade photography and aircraft performance and stress parameters. With the revised sequences and ON-times, the OFF period between successive heatings of mats 2 and 3 was reduced to typically 20 seconds at -5°C and 25 seconds at -10°C. (The OFF period between cycles was deleted, to give continuous cycling).

On this trial the improved standard of in-flight blade photography revealed an interesting insight into the shedding mechanism during heating of the heater mats nearest the leading edge. Fig. 17 demonstrates that, despite the chordwise disposition of the heater strips, the leading edge ice accretion is actually shed in spanwise increments. Heating of mats 2 and 3 in segment one leads to the shedding of the outer 50% span of ice accretion in about 2 seconds at -5°C. Further heating of these mats causes little further shedding, but when mats 1 and 4 are heated, the remaining spanwise extent is shed. Torque and control load amplitude degradation is governed almost completely by the ice accretion on the outer 50% span, at least in forward flight, so the shedding of the inboard ice accretion is not noticeable on these parameters.

Fig. 18 shows the icing conditions achieved during the 1977/78 icing trial in terms of liquid water content and outside air temperature. The spot-points represent the most severe conditions sustained for five minutes during each icing sortie, and the previously mentioned Av.P.970 design icing conditions are shown for reference. On all these sorties the increased rate of heating mats 2 and 3 was sufficient to contain torque and stress increments within the heating cycle to acceptable limits.

However after a number of cycles, a secondary problem was evident on two flights when conditions were both consistent and severe. This took the form of a gradual increase in torque over a period of about 15 minutes: there was no corresponding increase in control load amplitude. In-flight blade photography on these occasions established a substantial build-up of refrozen ice aft of the top surface heated area, usually termed 'runback' ice (Fig. 20). The gradual torque rise was considered to be due to this secondary build-up of ice.

7. 1978/79 ICING TRIAL, DENMARK

For the 1978/79 icing trial, additional heater mats were laid up on the de-icing blades to remove the top surface runback ice (Fig. 21). Top surface matting coverage was now extended to 18% chord. New sequence options were procured to cycle these new heater mats, while preserving the rate of heating found necessary on the mats on the leading edge of the blade (now numbered 6 and 7).

The winter of 1978/79 was particularly severe in Europe and very useful conditions were achieved (Fig. 18) including a 5-minute average of over 0.6 gm/m^3 at -13^oC, the severest icing condition in WHL's experience. In all icing conditions, sustained operation was possible close to the normal flight envelope, although in the very severe condition previously mentioned, the sortie had to be prematurely and somewhat smartly abandoned when an electrical fault developed in the rotor protection system.

One feature of note was the photographic record of shedding mechanism at -13^oC., compared to that previously seen at higher temperatures (Fig. 17). The general pattern of spanwise shedding in the first two heating segments was unchanged, but the shedding in the first segment was only in to 75% span, which left detectable torque and control load amplitude penalties, that were removed with the remainder of the leading edge accretion in segment two.

Thus at the end of the 1978/79 trial, the developed heated rotor system was considered to have achieved the first target of survivability, in conditions of unusual severity down to -13^oC.

8. 1979/80 ICING TRIAL, CANADA

The main aim of the 1979/80 trial was to extend experience with the developed system down to -20°C with liquid water contents as high as could be achieved. For this task, Ottawa was chosen as the venue. Fig. 22 shows how this aim was successfully achieved. The shaded area gives the LWC/OAT spectrum covered by the two previous trials and spot-points show how the lower temperature regime was successfully covered at liquid water contents comparing favourably with the Av.P.970 standard.

On these sorties, survivability in icing continued to be demonstrated in that stress, performance, vibration and handling standards were acceptable up to close to the normal flight envelope.

Various interesting features of blade de-icing at low temperatures were evident. Fig. 23 shows the spanwise shedding pattern during the first heating cycle during a 'two-by-two' comparison of heating sequences at -20°C. The spanwise accretion is no longer removed in the first two segments of heating on the appropriate blade pair (segments 1 & 2 on blades 1 and 3, and segments 4 & 5 on blades 2 and 4) although the majority of ice is removed in the case of blades 2 and 4. Repeated heating, however, causes the eventual shedding of the full spanwise extent. Another notable feature was the apparent effect of ice accretion on rotor torque: the rate of torque rise without rotor protection appeared more gradual, and the effect on torque of shedding large extents of ice accretion was sometimes indiscernible, even by the sensitive 'differential torque' method previously described. This is ascribed to the very smooth nature of the blade ice accretion to 100% span noted on occasions when the aircraft returned with residual ice.

The increased unwillingness of the ice accretion to shed in the first cycle was reflected in a tendency for the blades to feature a level of residual accretion during sustained cycling at these low temperatures. However this residual accretion did not impose an unacceptable penalty, presumably because of the smooth nature and limited extent of the residual accretion, and because such accretions were shed before they reached a sufficient mass to cause significant 1/rev vibration.

Identification of blade lower surface accretion by the tail-boom camera was more easy at these temperatures, because of the white nature of the accretion. Thus it was possible to note, in blade photographs taken before initiation of the rotor de-icing system, the surprising variation in chordwise extent of the blade lower surface accretion. Fig. 24 shows extreme examples with 3% chord accretion extent in the upper example and 14% chord accretion in the lower example.

9. CONCLUDING REMARKS

The Wessex system is now considered to have achieved the first target, that of survivability, in known icing conditions at temperatures down to -20°C. The way ahead for UK development of a rotor de-icing system therefore falls into two categories:

(a) The achievement of the second target, i.e. reduction in operational penalties by further optimisation of shedding efficiency.

(b) The application of the technology gained on the Wessex vehicle to other aircraft with different rotor parameters.

REFERENCE

1. J.E. Clark — Technical Analysis of the 1976 Lynx Icing Trial - Tirstrup, Denmark. WHL Report, WER 141-06-00137.

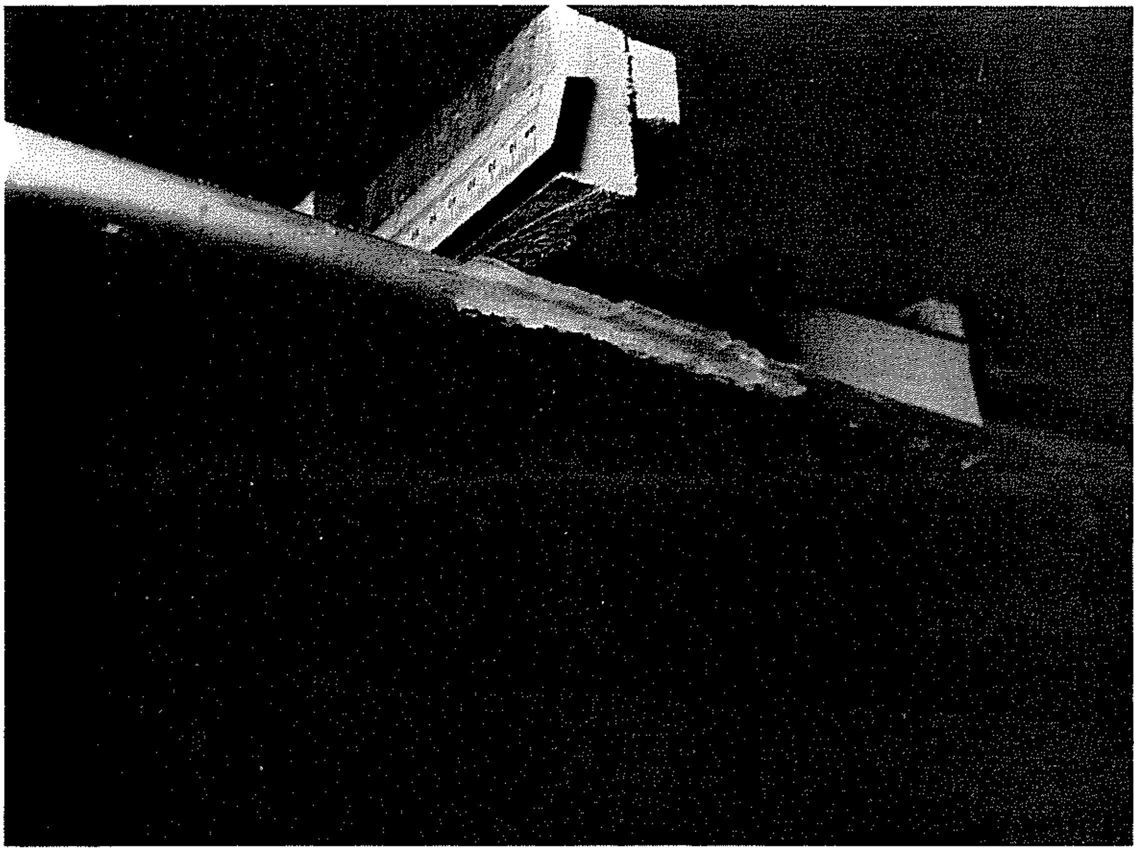


FIG.1 ICE FORMATION ON UNPROTECTED ROTOR BLADE

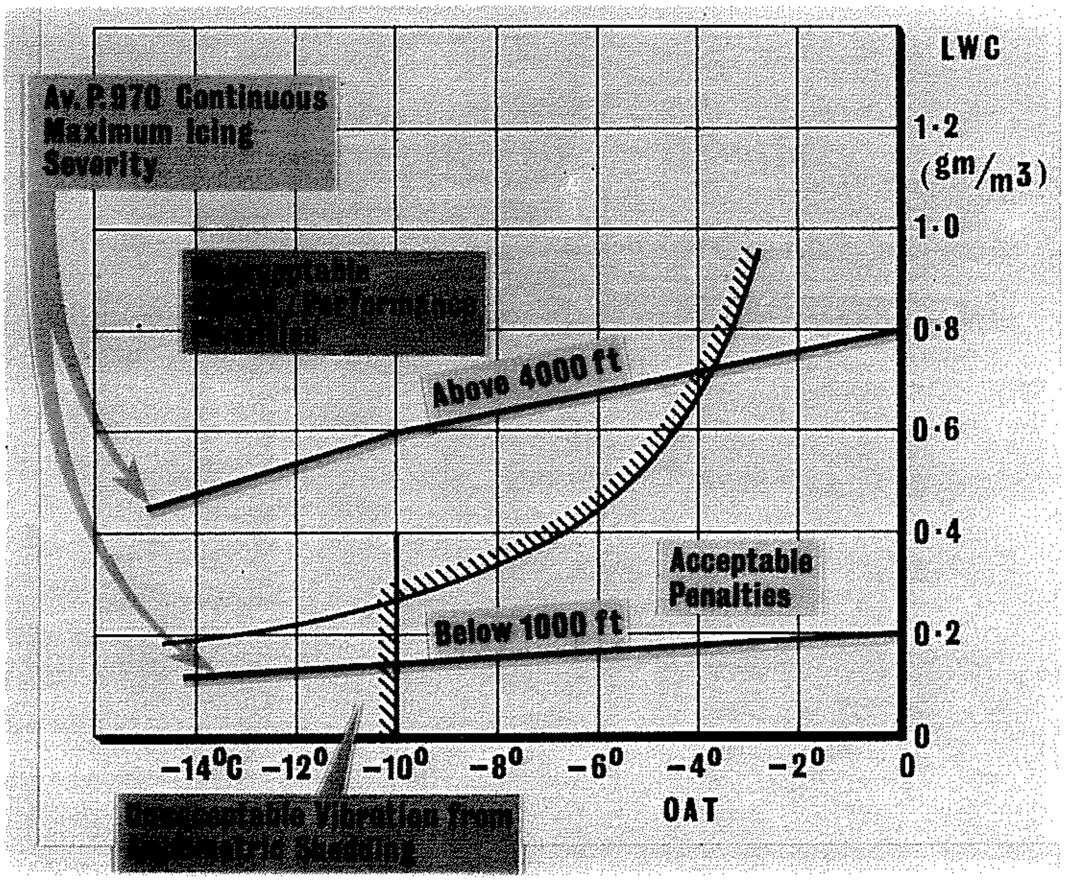


FIG.2 TYPICAL ICING LIMITATION WITHOUT ROTOR PROTECTION

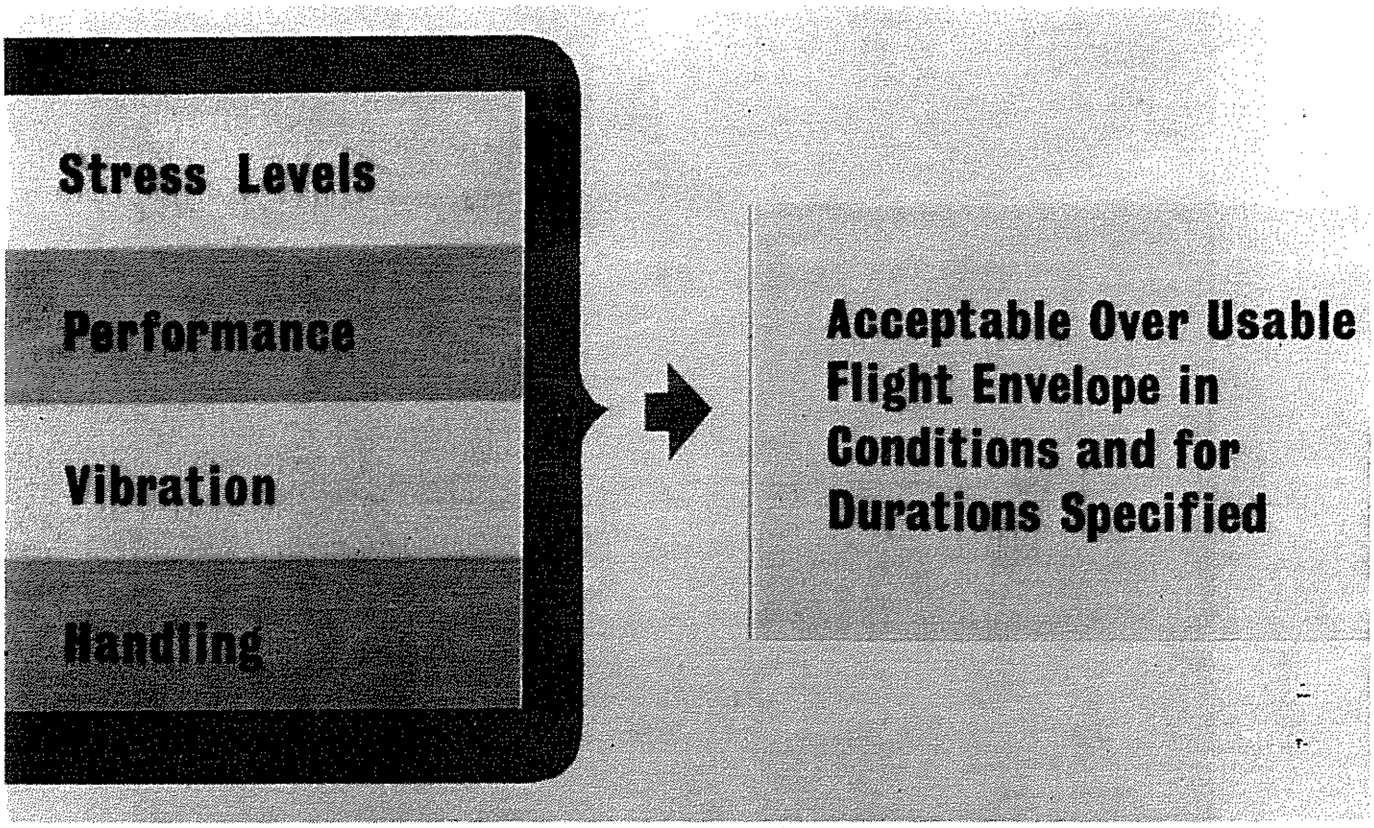


FIG.3 AIMS OF HEATED ROTOR SYSTEM DESIGN (1) SURVIVABILITY

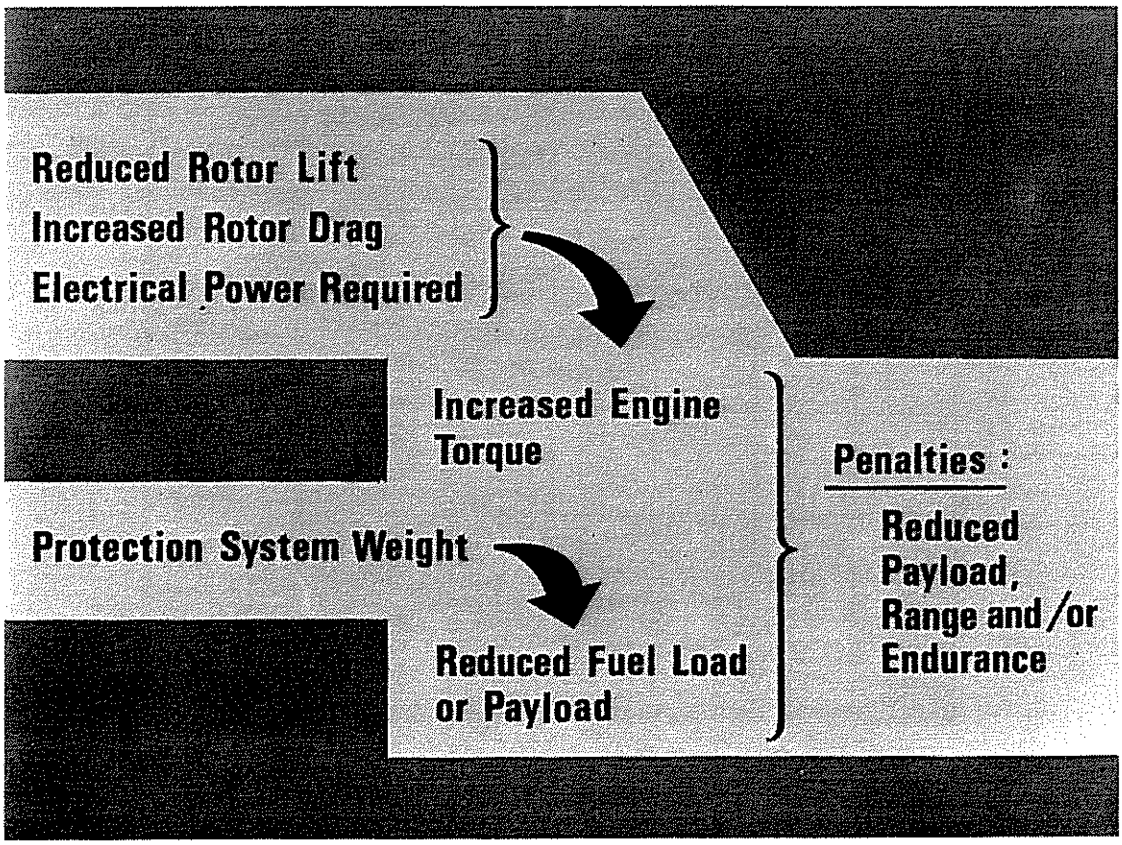


FIG.4 AIMS OF HEATED ROTOR SYSTEM DESIGN (2) MINIMISE PENALTIES

SEASON	AIRCRAFT	LOCALE	TASKS	BEA/BAH
Feb. 1961	Wessex 1	Ottawa	Napier/AAEE Electrical Blade De-Icing	
1964	Sycamore 14	Ottawa	AAEE Fluid Blade De-Icing	
1968/69	Sea King Wasp	Norway	Resumed Icing Programme	
1967/70	Sea King	Ottawa	Mushroom Intakes, Rotor Starload	BEA/BAH
	Wessex 5	Ottawa	1051,+cold Running Nose Door, Rotor Starload	
	Wasp	Ottawa	Basic Trial	Sikorsky S61N
	Wasp	Yeovil	*Fixed Rotor Control Load*	
1970/71	Sea King	Ottawa	Mushroom Intake, Rotor System Strain Gauges, Polyurethane Blade. L.E.	*Civil Operation* Trial
	Wessex 5(2)	Ottawa	Cold Running + Mod 1051 Nose Door Rotor System Strain Gauging Flexible Substrate + Stainless Steel Blade L.E.	
	Wasp	Ottawa	Miscellaneous	
	Wasp	Yeovil	Rotor System Strain Gauging	Limited Icing Release for C of A
	Wessex 5		Elect Blade De-Icing Design Study	

SEASON	AIRCRAFT	LOCALE	TASKS	BEA/BAH
1971/72	Sea King Wessex Puma	Prestwick/ Norway	Mushroom Intakes etc. Cold Running Nose Door etc.	Limited Icing Release for C of A
			Electrical Blade De-Icing	
1972/73	Wessex 5	Ottawa	Nose Doors, Flexible Substrate, Polyurethane L.E.	
	Wessex 5	Ottawa	Mushroom Intakes, Rotor S.G.	
	Sea King			
	Scout		Polyurethane Blade Leading Edge etc.	
	Wessex 5	Sweden	Cold Running Nose Door, Icing/Snow	
1973/74	Wessex 5(2)	Ottawa	*Nose Doors etc.*	
	Sea King	Ottawa	FOD or BARN DOOR, Rotor S.G.	
	Puma	Ottawa	Bouclier Engine Shield	
	Wessex 5	Ottawa	Electrical Blade De-Icing	
1974/75	Wessex 5	Norway	Snow Flying	
	Puma	Norway	Snow Flying	
	Gazelle	Norway	Snow Flying	
	Lynx	*Denmark*	Initial Icing Assessment	
	Wessex 5	Denmark	Flexible Substrate Rotor Blades	

FIG.5 BRITISH HELICOPTER ICING TRIALS ACTIVITY 1961-1975

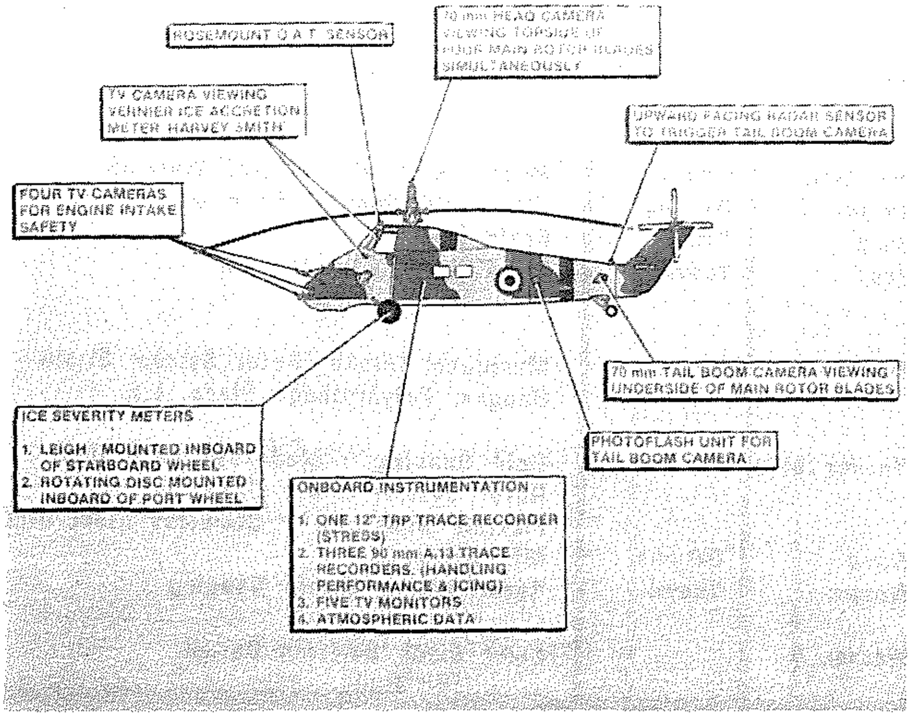


FIG.6 HEATED ROTOR TEST AIRCRAFT & INSTRUMENTATION

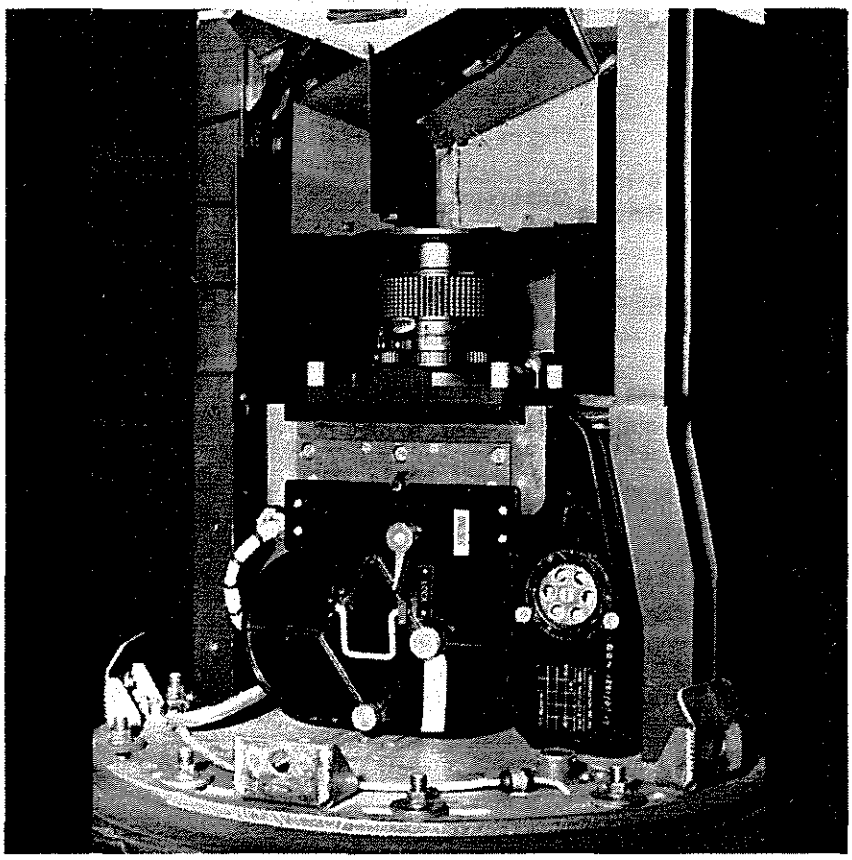


FIG.7 70MM ROTOR HEAD CAMERA INSTALLATION

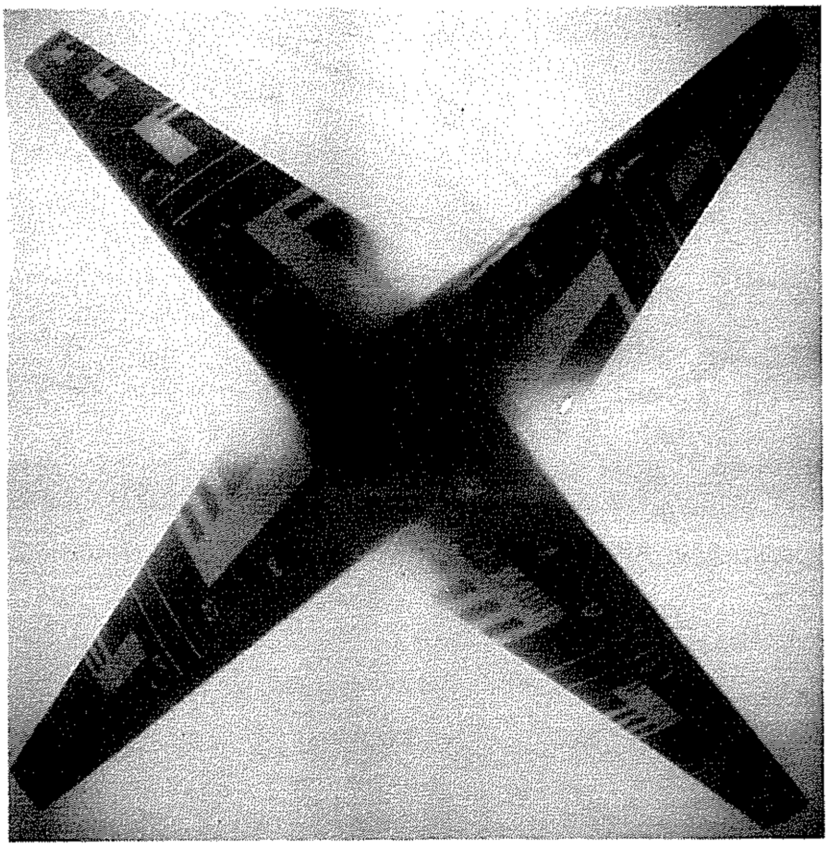


FIG.8 BLADE UPPER SURFACE SHOWING SHEDDING

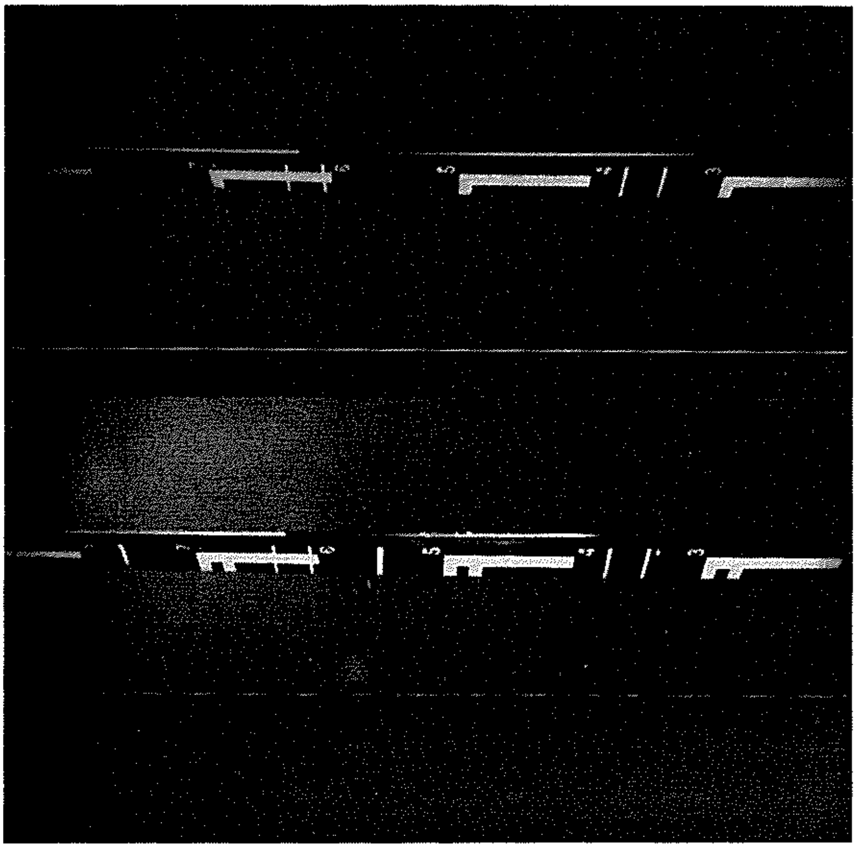


FIG.9 BLADE LOWER SURFACE SHOWING SHEDDING

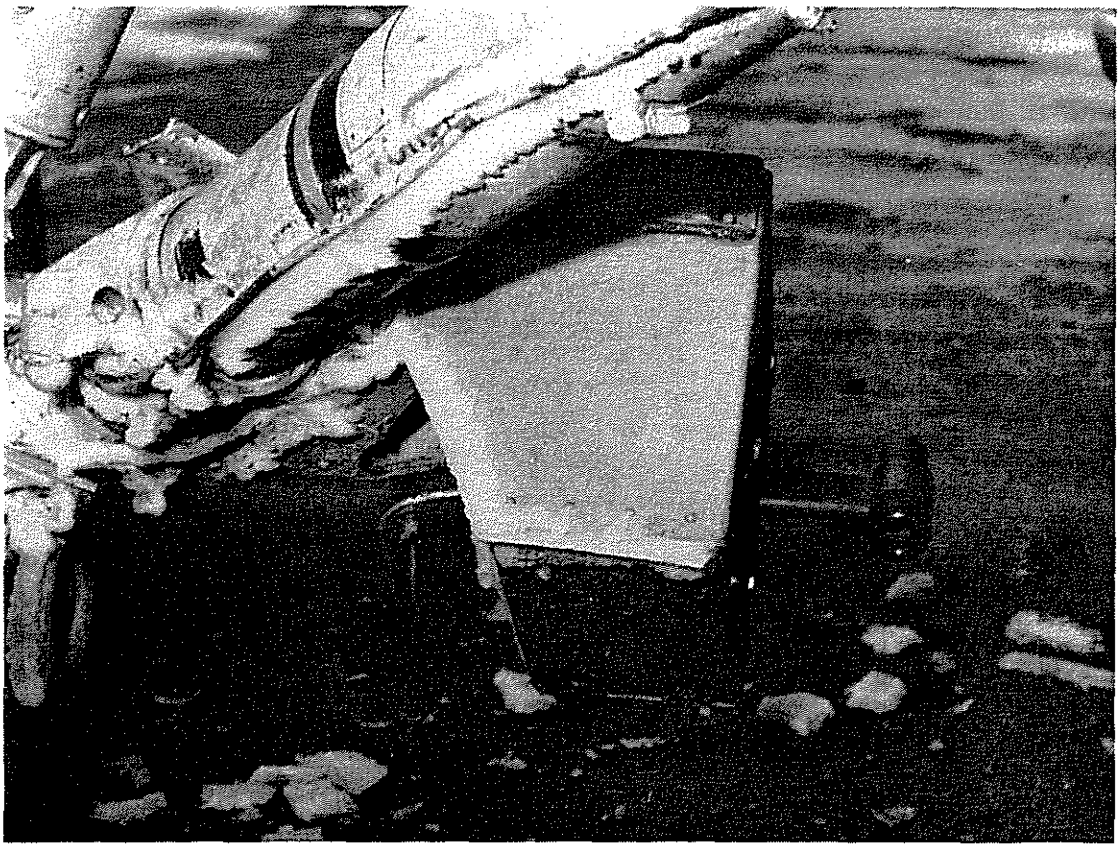


FIG.10 LEIGH ICE SEVERITY METER INSTALLATION

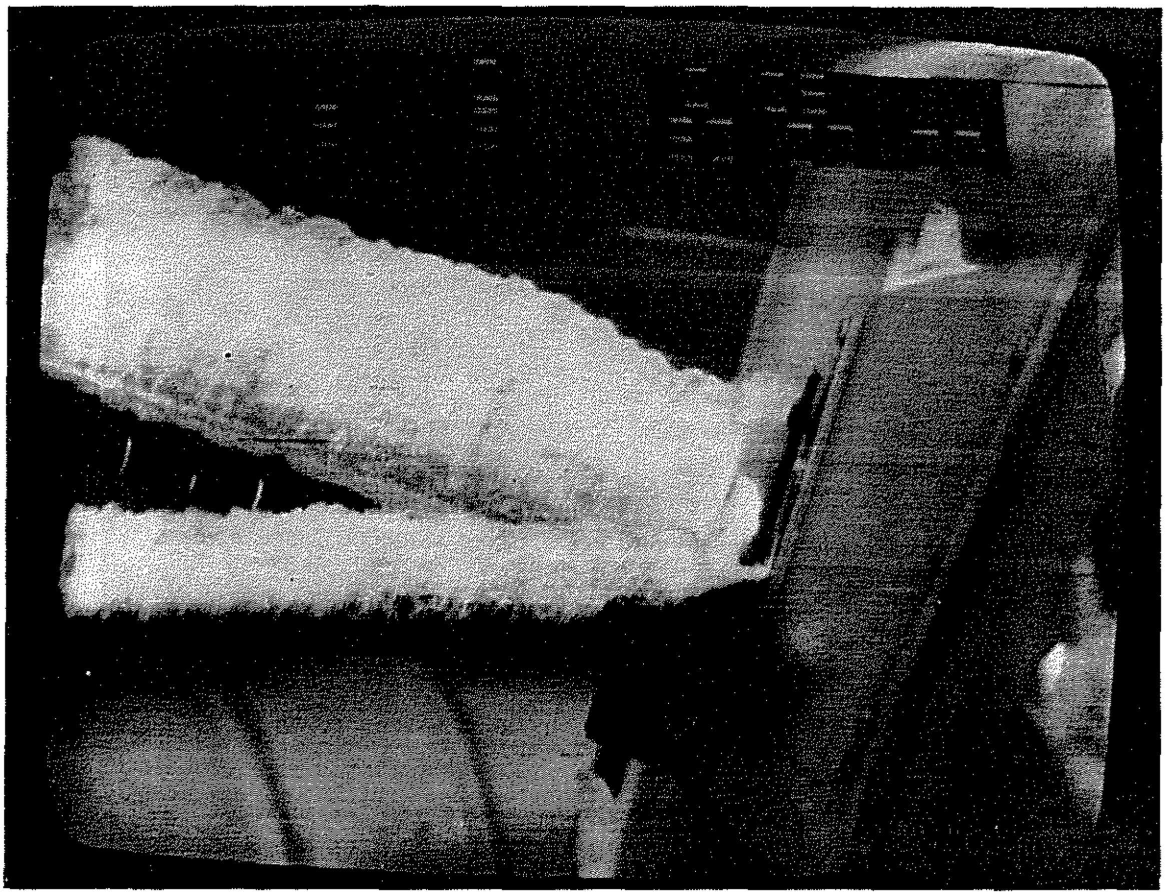


FIG.11 VIDEO RECORD OF ICE ACCRETION

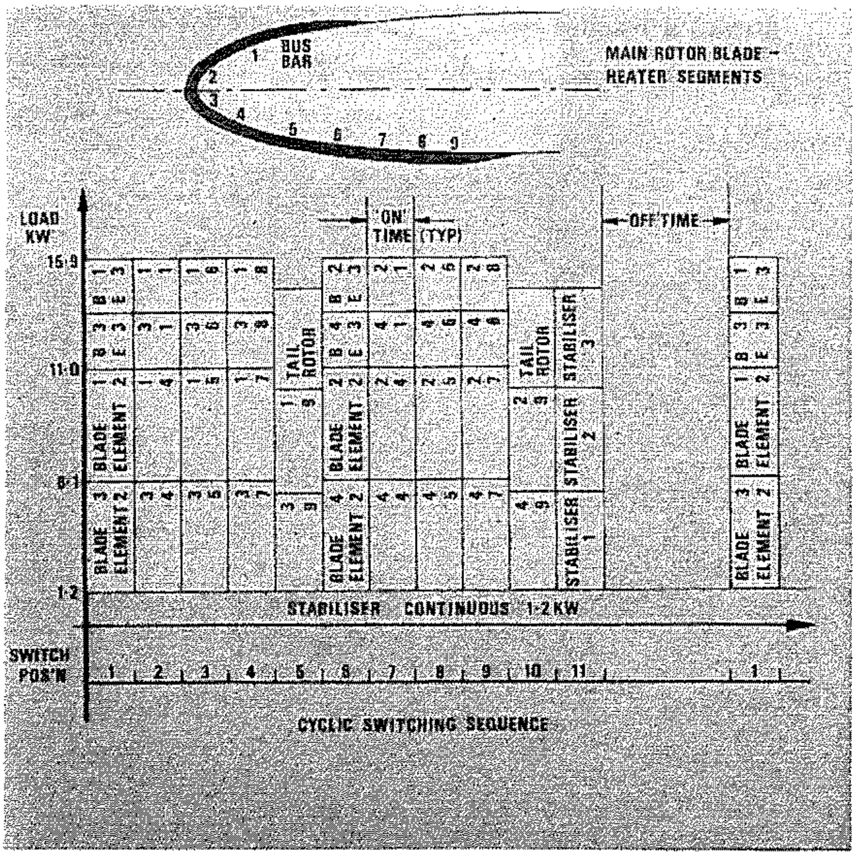


FIG.14 ORIGINAL DE-ICING MATTING AND SEQUENCE

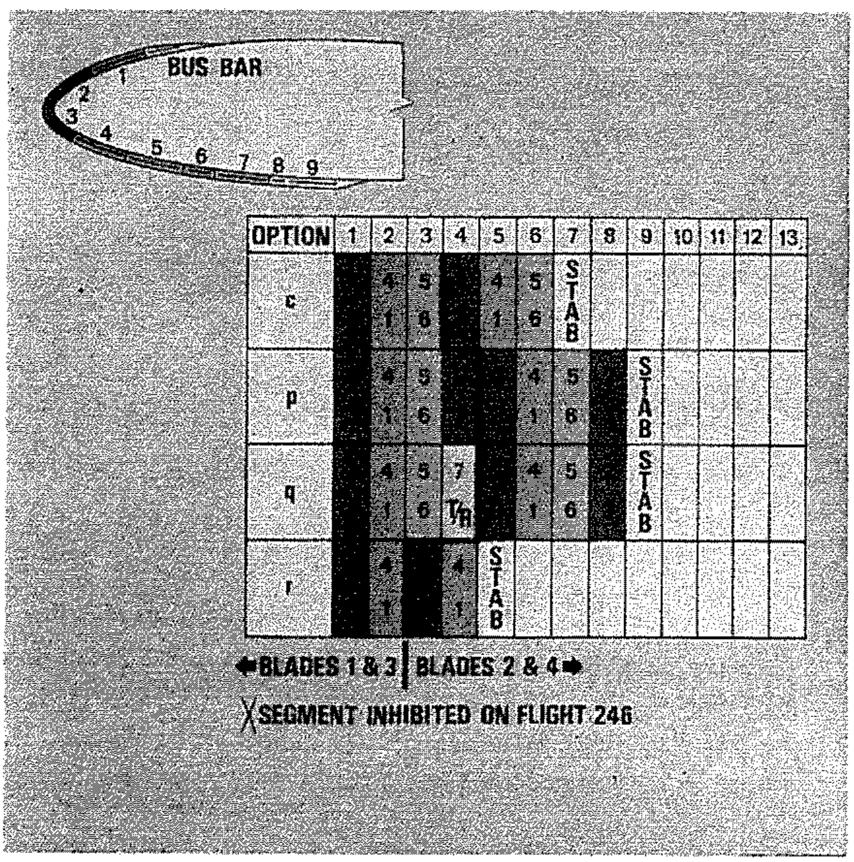


FIG.15 SHORTER SEQUENCES FOR 1977/78 TRIAL

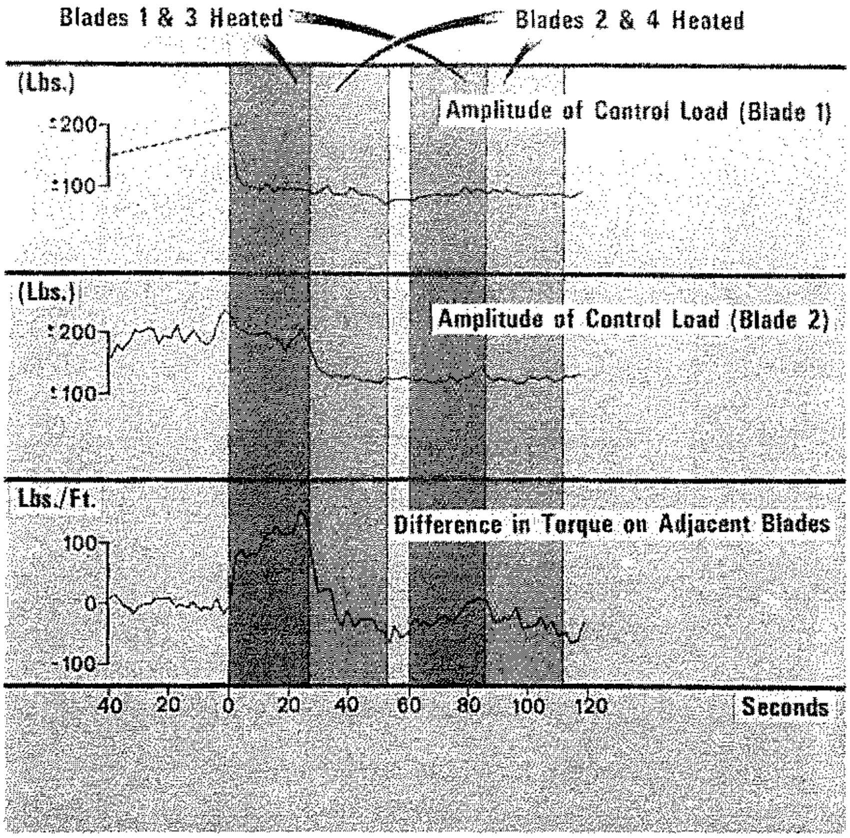
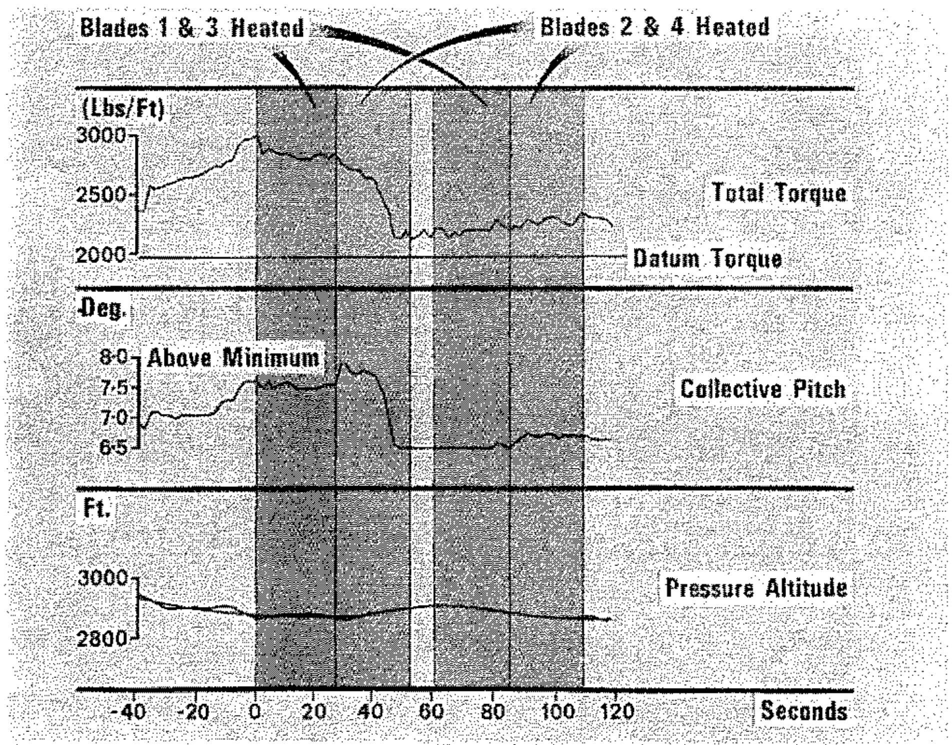


FIG.12 CONTROL LOAD AND DIFFERENTIAL TORQUE DURING DE-ICING



Flight 211 - Flight Time History at Initiation of Blade Heating

FIG.13 EFFECT OF DE-ICING ON HELICOPTER PERFORMANCE

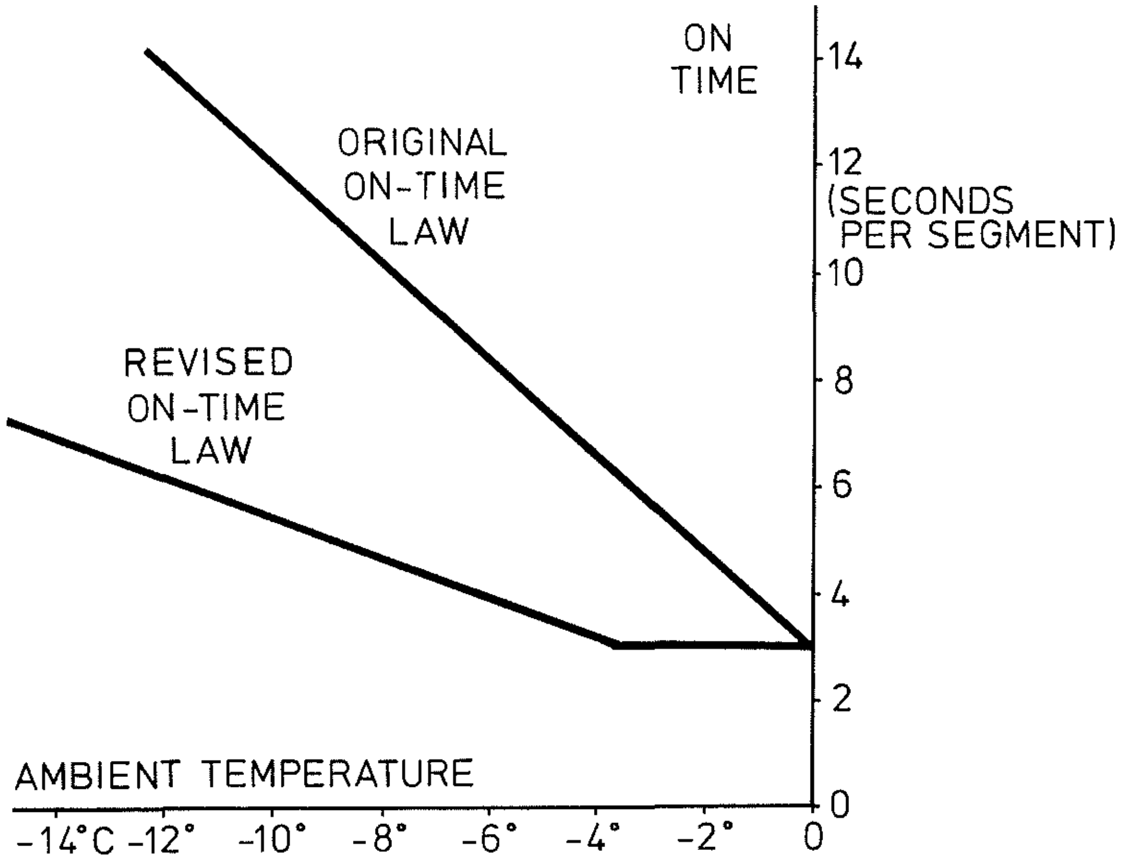


FIG.16 ORIGINAL AND REVISED ON-TIME LAWS

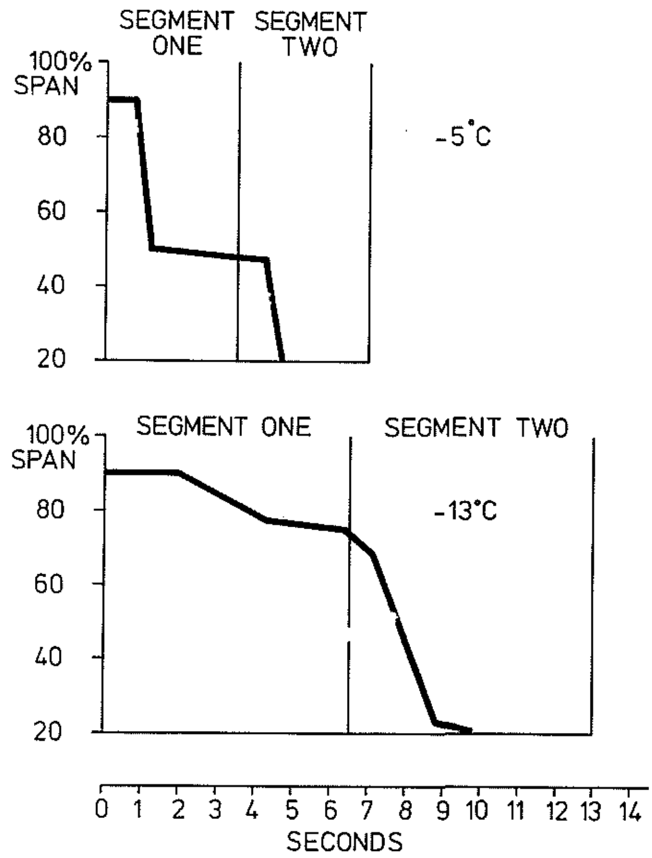


FIG.17 LEADING EDGE ICE SHEDDING BEHAVIOUR

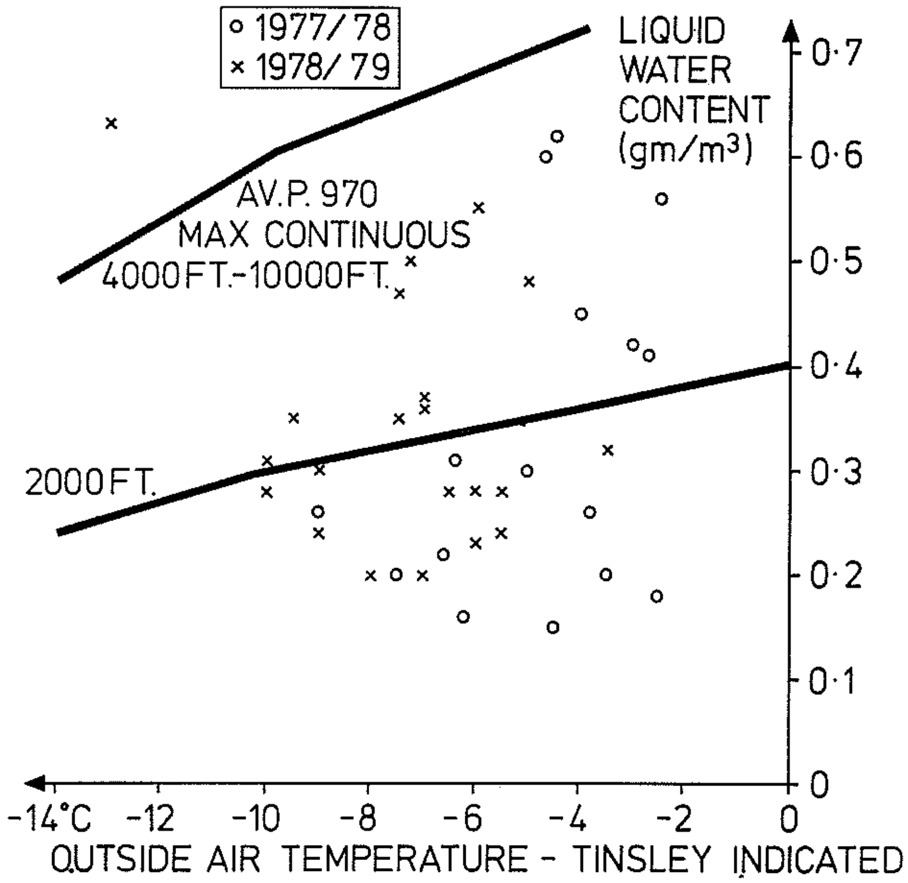


FIG.18 ICING CONDITIONS ENCOUNTERED - 1977/78 & 1978/79

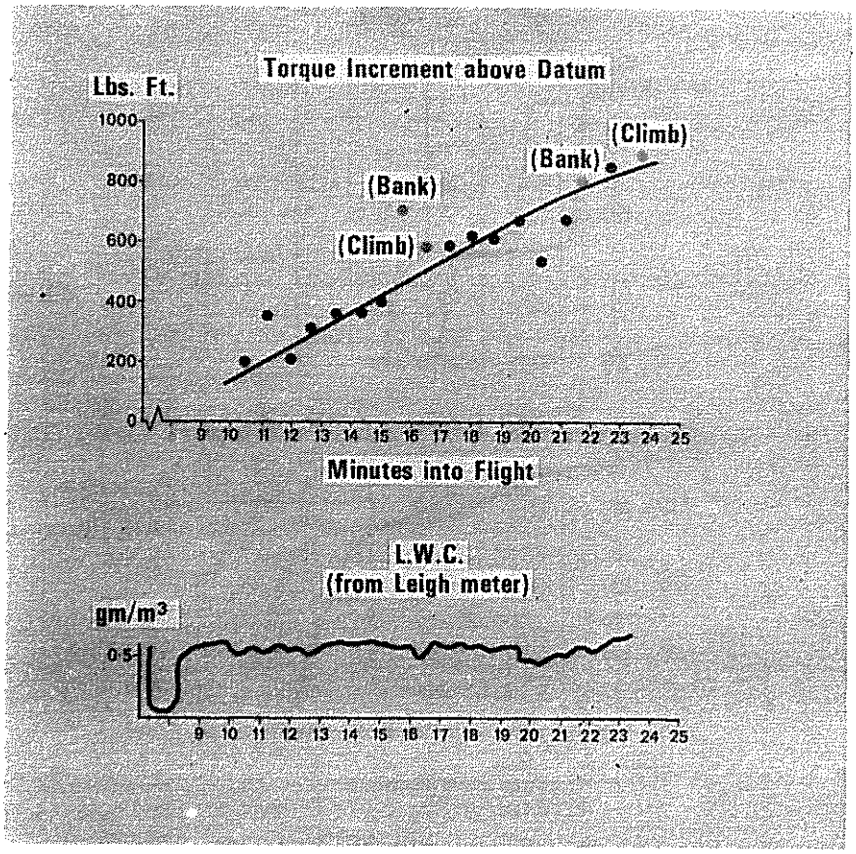


FIG.19 TORQUE RISE IN SUSTAINED CYCLING

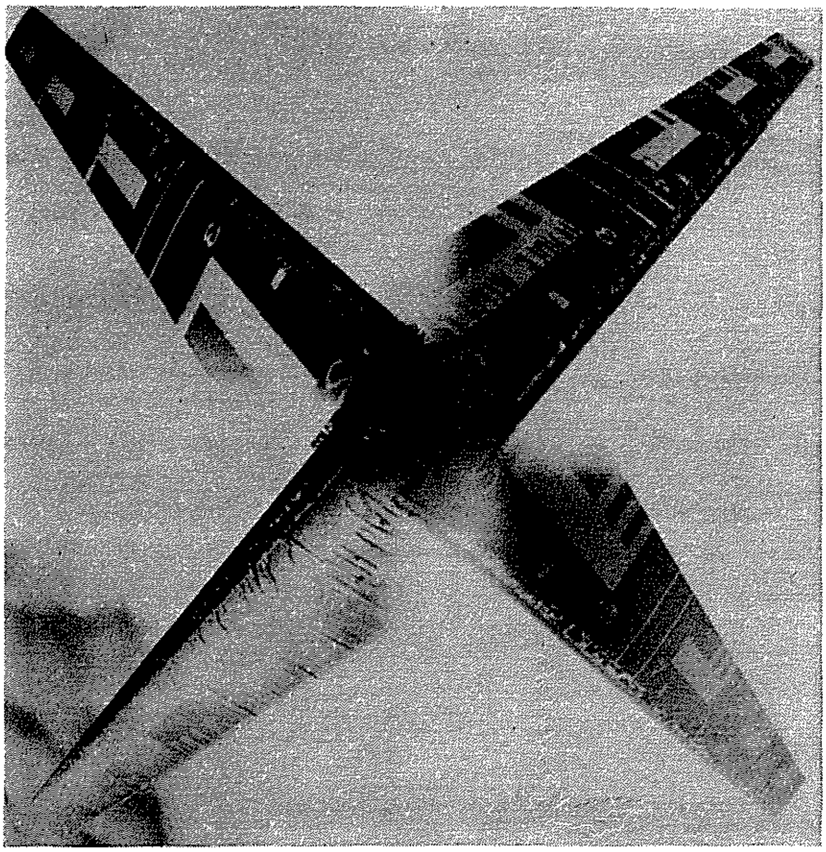


FIG.20 RUNBACK ICE ON BLADE UPPER SURFACE

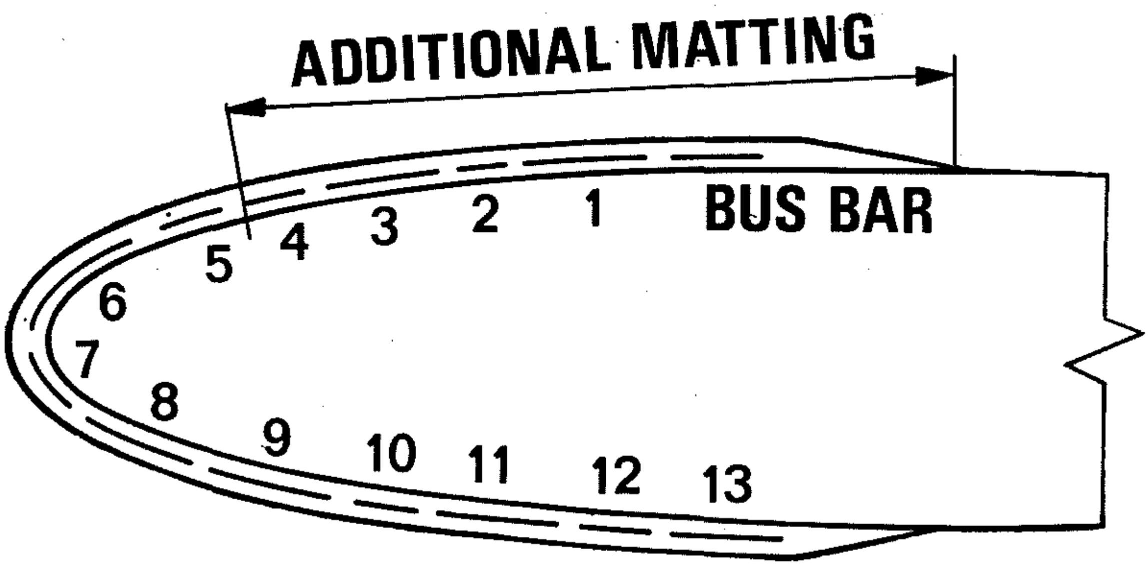


FIG.21 ADDITIONAL MATTING FOR 1978/79 TRIAL

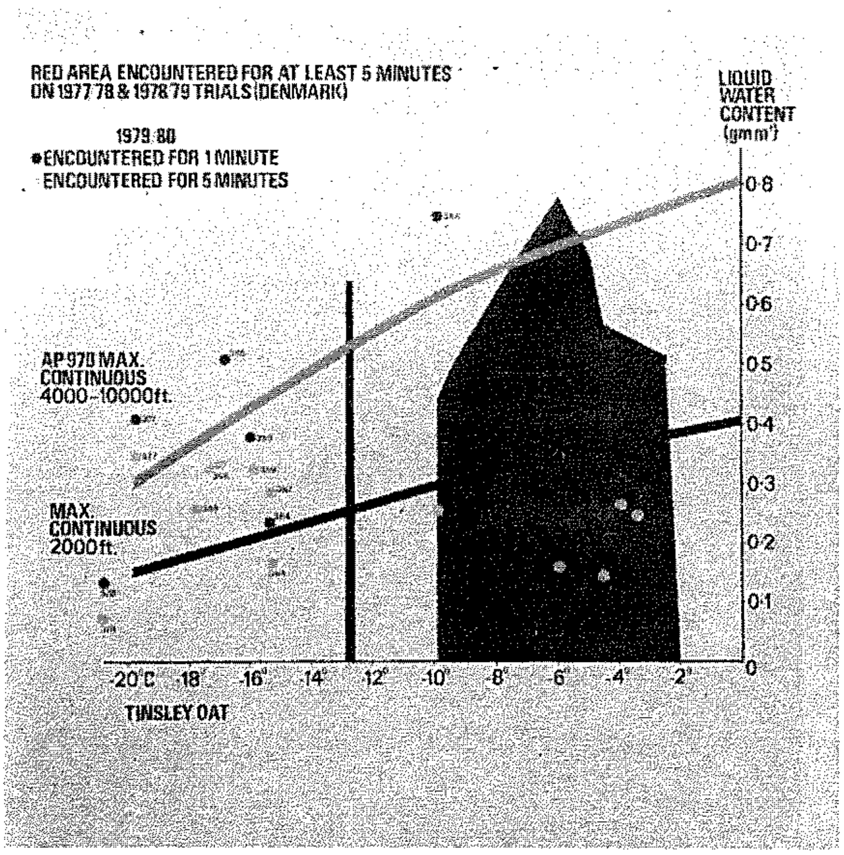


FIG.22 ICING CONDITIONS ENCOUNTERED - 1979/80

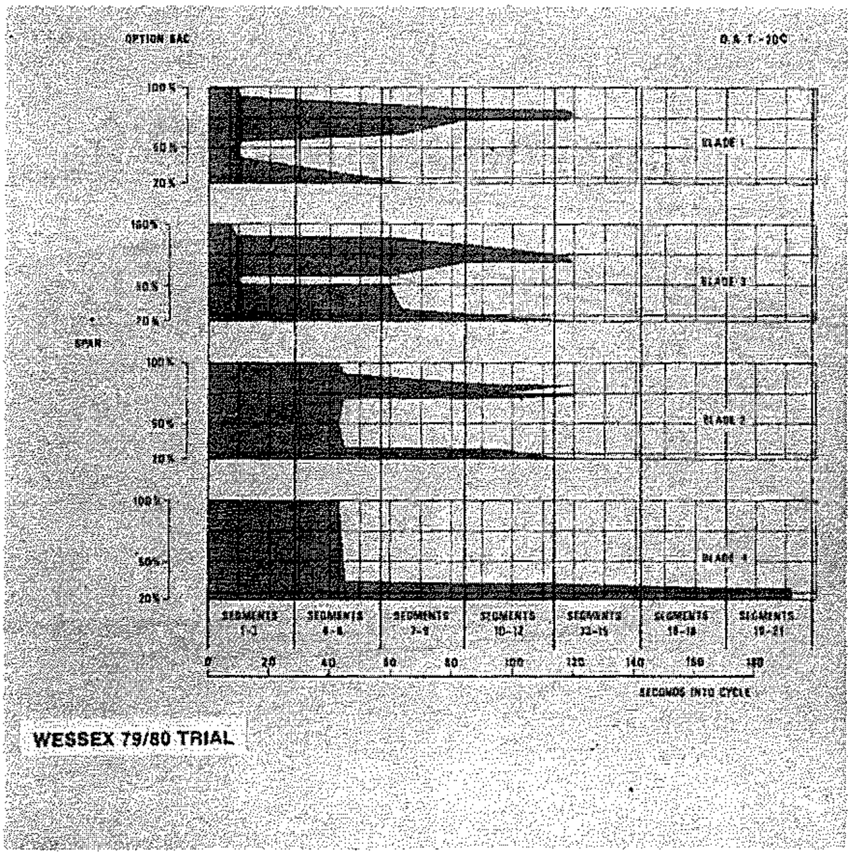


FIG.23 FIRST CYCLE SHEDDING AT -20°C

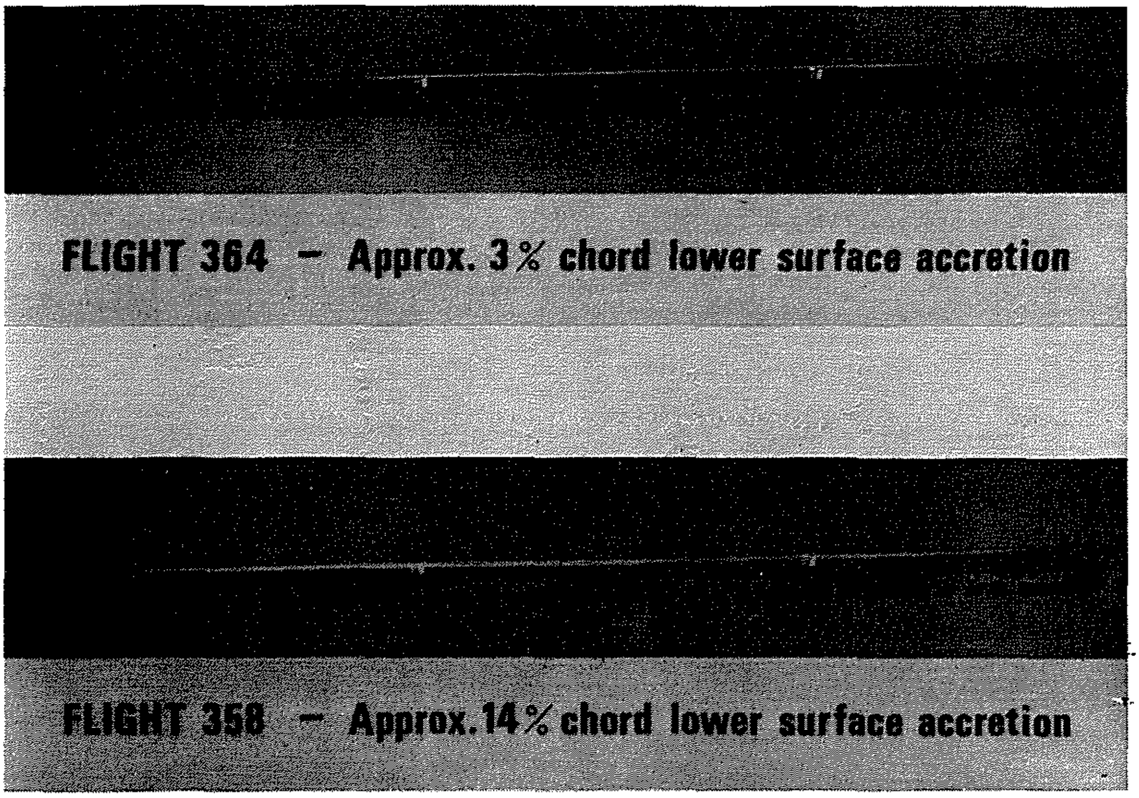


FIG.24 VARIATION IN CHORDWISE EXTENT OF BLADE ICE