THE ROYAL AIR FORCE CHINOOK HELICOPTER SNOW AND ICING FLIGHT ENVELOPE

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Abstract

The Royal Air Force Chinook Mk 2 helicopter has, like the previous variant, the Chinook Mk 1, a limited capability to operate in snow and icing conditions. The current snow and icing conditions are based on experience gained in the early 1980's. An investigation into the current clearances indicated that the full capability of the aircraft in snow and icing conditions had not yet been explored.

DERA Boscombe Down carried out an extensive trials programme during the winter of 1996/97 to gain data to expand the current flight envelopes for operating in snow and icing conditions. The primary aim of the trial was to improve the icing clearance to a temperature of -10°C and to relax the limitations for operation in snow. These clearances were to be investigated for higher aircraft all up mass and at an increased pressure altitude. A number of different engine intakes were tested and a snow/icing detection and measurement system was evaluated for possible incorporation into the aircraft to provide pilots with information on the severity of the conditions.

This paper briefly summarises the previous snow and icing clearance work carried out in the early 1980's and covers, in more detail, the recent trial. A description of the trials aircraft, aircraft modifications tested and the instrumentation suite fitted are included. A resumé of the problems associated with flying in snow and icing conditions is given. The flight test methods employed, reasons for choosing Halifax, Canada for the trial and the flight test data analysis system are also covered.

Introduction

The Chinook HC Mk2 helicopter is fitted with a comprehensive suite of avionics to allow operation in IMC conditions and the aircraft has mission roles which require all weather operations during any part of the year. The current clearance for flight in icing conditions was based on limited testing carried out in the 1980's on the Chinook HC Mk 1 and limits operations based on temperature, altitude and aircraft mass. In addition, operation in precipitating and re-circulating snow is dependent on visibility and is restricted to temperatures below -3°C.

DERA Boscombe Down was tasked by the UK Ministry of Defence (MoD) to carry out testing to quantify an expansion of the current icing and snow flight envelopes. The aim was to expand the flight envelope to allow operation at maximum all up mass (MAUM) in temperatures down to -10°C and at pressure altitudes of up to 10000 ft. An additional requirement was to relax the current restrictions on operation in precipitating and re-circulating snow. The icing environment to be considered is defined in Table 1.

In order to give an extension to the existing icing and snow clearance a large amount of data had to be gathered and the following had to be investigated:

- Any degradation of the rotor performance and handling implications in icing conditions
- Any degradation of engine performance
- The degree of engine protection afforded by the standard aircraft intake mesh screens and the PALL Aerospace Engine Air Particle Separator (EAPS) Modules.
- Whether ice and snow accretions affect the functioning of aircraft systems.
- The effectiveness of the windscreen anti-icing and windscreen wipers.
- The usefulness and performance of a snow and icing severity measuring system.

Test Vehicle

General

The test vehicle was a standard Chinook HC Mk2 (ZA718) which was instrumented and re-configured during the summer of 1996 at DERA Boscombe Down. This aircraft was originally built as a Mk1 and was fully re-furbished by Boeing as part of the mid-life update conversion programme.

A baseline flight programme was carried out prior to the aircraft departure for Canada. These flights checked the function of the instrumentation and gave baseline figures to predict the aircraft torque for different flight conditions.

The aircraft was fitted with a comprehensive instrumentation suite and an automatic data acquisition module (ADAM) which was used to record data during the trial. The instrumentation suite and ADAM recording system were designed and fitted by DERA Boscombe Down.

Engine Intakes

For the trial the aircraft was fitted with a variety of intake configurations. Three different types of engine intakes were tested, namely:

- The standard Chinook engine All Weather Screens (AWS) which were cleared for use on the aircraft.
- The US Army fine mesh All Weather Screens which had not been assessed by Boscombe Down. Information from the design authority indicated that they provided better FOD protection than the standard AWS without any significant effect on the engine performance.
- The Chinook Engine Air Particle Separator (EAPS) modules. These had previously been assessed by Boscombe Down throughout the flight envelope with the exception of their use in snow and icing conditions. The EAPS modules were normally fitted with external stone guards. Flights were carried out both with and without these stone guards fitted in order to assess their snow and ice accretion characteristics. Data from previous snow and icing trials on other aircraft with EAPS type intake modules fitted indicated that in some circumstances slush and ice could form inside the plenum chamber. To enable the safe testing of the EAPS a conical mesh screen was manufactured and fitted inside the EAPS modules. This screen was designed to prevent any ice or snow accretions on the inside of the plenum chamber being ingested by the engine. The conical mesh screens were removable and flights were carried out both with and without the screens fitted.

Test Equipment

Instrumentation

All the relevant aircraft and systems parameters were recorded on the ADAM along with the environmental parameters such as liquid water content (LWC), snow severity and outside air temperature (OAT). An instrumentation console was installed in the cabin to accommodate the flight test engineers. The instrumentation console is described in more detail later.

Blade Camera

A fixed view still camera was used to record the blade icing. The camera was positioned in the forward bubble window on the port side of the cabin and was operated from the instrumentation console by the flight test engineers. The camera, once activated, took a series of four photos, a set up sequencing photo, and then one photo of each blade on the aft rotor head.

Video Camera Installations

A video system was installed to allow in flight monitoring and recording of ice accretions in and around the engine intakes. Cameras were installed in the plenum chamber of the port EAPS and external to both the port and starboard engine intakes. The images from the cameras were presented to the flight test engineers at the instrumentation console. It was possible to display different images as dictated by the test conditions. The design, manufacture and flight clearance of the instrumentation fit was the responsibility of DERA, although PALL Aerospace provided clearance for the internal EAPS camera and the engine pressure drop instrumentation.

Penny & Giles Ice/Snow Detection System

Two Penny & Giles Ice and Snow Detection Systems (ISDS) were installed on the trials aircraft to allow environmental information to be measured, displayed and recorded. One system was to a production standard whilst the other was a designed specifically for flight testing. This flight test system provided additional outputs to allow more thorough interrogation of the measured data and enabled certain detection thresholds to be changed. The use of this unit also allowed some development work to be carried out to optimise the detector output in an attempt to define a production fit detector for this aircraft. Both installations required bleed air which was provided by the engines and the pressure of the bleed air was controlled by valves in the aircraft cabin. Initially one detector was located on the underside of the starboard forward fuselage whilst the second detector was mounted on the port side fuselage. Later in the trial the port detector was moved to try to optimise its ability to detect and categorise precipitating and re-circulating snow. The new location was on the starboard side of the fuselage in front of the cabin door.

Soot Gun

A hand held "soot gun" was used to take samples of the supercooled water droplets in the icing cloud. This device was developed by Aeronautical Research Laboratories (ARL) in Australia and consisted of a treated slide which was placed in the aperture of a barrel like device. This 'gun barrel' was held out of the pilot's window whilst flying in icing conditions and was exposed to the cloud by operating a trigger which momentarily opened a shutter exposing the slide to the water droplets in the cloud. Analysis of the exposed slide was accomplished by creating a magnified image using a microscope. This was transferred to a computer and the diameter of the droplets was subsequently measured. The volumetric median diameter (VMD) was calculated by use of a ground station computer. The computer program compensated for the actual measured diameter by correcting for true diameter based on true airspeed and calibration of the splash effect. An average of 5 slides was obtained from each flight where icing was encountered.

Vernier Accretion Meter

A *Britavia* Vernier Accretion Meter (VAM) was fitted to the starboard side of the fuselage immediately below the pilots sliding window. This device was based on existing systems fitted to other service helicopters and was used to estimate the airframe ice growth. The trials unit had a de-icing facility so that accretions could be removed when required, or when 20mm of forward ice growth was reached. The unit was controlled by the pilots from the aircraft cockpit.

Ballast System

A ballast system was used to vary the aircraft all up mass (AUM) and centre of gravity (CG) over a limited range during trials flying. The installation consisted of one water ballast tank located on the starboard side of the aft cabin and a solid ballast box on the port side in the centre of the cabin. The water ballast tank had a maximum capacity of 850 gallons (3856 kg) and up to 1000 kg of solid ballast could be added to the ballast box. Water could be dumped in flight via two manual valves which were operated by the crewman and it was possible to dump almost 2000 kg of water in 55 seconds. This would be sufficient to get the aircraft to a safe single engine mass in level flight.

Ferry Fuel System

One Robertson extended range fuel tank was fitted in the aircraft cabin which enabled the duration of the testing to be increased during an icing encounter. The ferry system consisted of an additional 2400 kg of fuel and the associated fuel transfer pumps and plumbing to transfer the fuel into the normal aircraft fuel system.

Portable Video System and Stills Photography

On return from each icing sortie a portable video camera was used to record all the remaining rotor and airframe ice accretions. The system was occasionally used in flight. In addition we had the support of DERA photographic services on-site which enabled all film etc. to be processed within a short time of finishing a sortie.

On Board Data Systems

A general view of the flight test engineers station in the aircraft is shown in Figure 1. All the controls for the instrumentation and test equipment were located on the panels for ease of operation by the flight test engineers. Data displays were provided to the flight test engineers on the two colour LCD computer screens. Three video monitors enabled the ice accretion in and around the engines to be monitored.

The on board computer system allowed the flight test engineers to access, in real time, a wide range of pertinent engine and aircraft data. The flight test engineers were able to access a number of pre-programmed pages of information on the computer terminals at the flight test engineers station (see Figure 1). The displays gave both analogue and digital data for the following measurements:

- Power Plant: Engine torque, turbine inlet temperatures, engine inlet static and total pressure, oil temperatures, etc.
- Basic Aircraft Parameters: The control positions, aircraft attitude and rates, actuator positions, load factor, airspeed, altitude, rotor speed, fuel contents, fuel used, rate of climb/descent and referred aircraft mass.
- Environmental: OAT, LWC and snow severity.

Access to this information enabled the flight test engineers to constantly monitor the aircraft performance and identify any problems early.

Ground Station Computer Systems

The DERA portable computer ground station contained all the hardware necessary for on-site retrieval and replay of flight data. This facility was in continual daily use throughout the trial and provided the following:

- Production of secondary tapes from the primary flight tapes and the secondary tapes were available within one hour of the completion of each sortie.
- Production of tertiary tapes which were written from the secondary tapes. These were primarily used by the flight test engineers to analyse the data. The analysis process is detailed later in the paper.
- The plotting, tabulation and analysis of the flight data to produce data on the torque increases due to icing, the average liquid water content, the snow severity, and the total time accumulated in icing.

The DERA portable data system is diagrammatically detailed in Figure 2.

Test Site

The selection of a test site for a snow and icing programme is at best a "risky business" since information regarding snow/icing conditions and their severity in the helicopter altitude range is sparse. No data bank of encounters or meteorological records of actual, as opposed to forecast conditions are available. Coupled with these factors are the variations from year to year in the local weather conditions that produce good snow and icing conditions at a particular test site. The selection of site is thus based on three major factors:

- Statistical meteorological conditions.
- Precise trials requirements and previous experience.
- Facilities, access, security, hangarage etc.

The test sites considered for this trial included venues in Europe, Canada and the United States. Previous experience indicated that the probability of getting the required conditions for this trial in Europe was not high. The probability of obtaining low temperature icing and warm, wet snow conditions in parts of the USA was high but the probability of obtaining a range of OAT coupled with a wide range of liquid water content (LWC) in icing was considered low. A number of sites in Canada had been used by DERA Boscombe Down on numerous occasions for snow and icing trials and following considerable investigation, the locations considered were:

- Ottawa (Ontario)

- Moncton (New Brunswick)
- Fredricton (New Brunswick)
- Halifax (Nova Scotia)

Based on previous experience of known operational restrictions and weather patterns, combined with analysis of existing meteorological data the choice was narrowed to Ottawa and locations in the Maritimes. It was considered that all the locations in the Maritimes would have been acceptable, however, it was also necessary to have suitable hangars, a variety of ground support services and a comprehensive range of navigational aids available. Based on the data available and the fact that the large bodies of water around the Maritimes would generally result in higher liquid water contents in the clouds, a site was chosen in this region. The Canadian Forces Base (CFB) at Shearwater was selected as it had the required meteorological conditions, suitable hangars and sufficient ground support. CFB Shearwater, near Halifax, Nova Scotia was well positioned to enabled a wide range of locations to be flown to in the Maritimes (with auxiliary fuel) and thus the probability of obtaining the required conditions was high. In addition, ease of access, regular flights to and from the UK and the support available from the Canadian Forces were paramount in selecting the site.

Test Approach - Icing

Summary of Previous Experience

The testing carried out in the early 1980's consisted of trials flights at Tirstrup in Denmark and Halifax in Canada and as a result of the data obtained a limited flight clearance was given for the HC Mk 1 Chinook (unheated rotors). The two Winter seasons spent in Halifax were concerned with the development of a heated rotor blade de-icing system which was not subsequently incorporated into service aircraft. The current aircraft has un-heated rotor blades.

Icing flights were carried out during these trials down to -10°C with LWCs up to 0.56 g/m^3 (mean) at altitudes up to 9000ft. On the basis of these results a limited release for flight in icing was recommended to -6°C at pressure altitudes up to 7000ft, provided that non-icing conditions existed for 1000ft below the cloud.

Icing Experience 1996 - 97, Halifax - Nova Scotia

Initial ground tests and flights covering the normal flight envelope were made to assess the integrity, vibration characteristics and effect on the aircraft of the various trials installations and the instrumentation system. These tests commenced at Boscombe Down prior to departure and were completed on arrival in Canada.

In the early stages of the trial the need was identified for a reliable and easy method to calculate the power increment (ΔP), defined as the difference between the rotor power required in icing conditions and a clear air baseline power required at the same "referred" flight condition (i.e. referred speed, gross weight and rotor speed). The value of ΔP was calculated for each engine via the use of a program developed for a hand-held *Psion* calculator. A set of power polars were flown at a range of referred weights and speeds which were commensurate with those expected to be flown during the trial. These tests were carried out at Boscombe Down and in Canada at the beginning of the trial. The program resulted in the flight test engineer taking data from the real time display and entering it in the hand-held calculator to get a prediction of the level flight torque required in still air.

Once testing commenced in Canada the trials team worked closely with the meteorological sections in the Maritimes to define the areas where icing conditions were most probable. The aircraft was flown on all possible occasions when icing conditions were forecast. The testing was carried out within the trials limitations which meant that we needed a minimum of 1000 ft clear air below the cloud. The maximum pressure altitude for testing was limited to 10000 ft since the aircraft was not fitted with oxygen breathing apparatus. An incremental approach was taken with the OAT and airframe accretion limits gradually being expanded as test data was gathered and experience gained in operation in these conditions.

Preparation of detailed test profiles was not possible as the desired icing conditions cannot be "dialled up". A test technique was soon evolved whereby level flight was established at the intended speed just below the cloud, and a clear air datum was recorded (engine torques, engine speeds and collective lever position were noted). The aircraft was then climbed into the cloud at approximately 500 feet per minute with the flight test engineers monitoring the LWC and OAT, throughout the cloud band, to determine the altitude for the optimum combination of LWC and OAT.

Altitudes which were likely to give the required conditions were noted during the climb and the regions that showed promise were then re-visited. The aircraft was stabilised straight and level in the chosen conditions and was accelerated to the test airspeed which was usually in the range of 80 kn IAS to Vmax depending on the aircraft mass and test altitude. The pilot was then required to maintain the test airspeed and altitude by adjusting the collective control as necessary to compensate for any degradation in aircraft performance (often seen as a torque rise) as a result of ice accretion on the rotor system.

Throughout the flight the flight test engineers and aircrew were monitoring a number of parameters associated with the aircraft's performance, including the engine temperatures and pressures, engine inlet blockage, the change in required rotor power, and the prevailing environmental conditions. During the encounter, regular readings of the VAM were taken by the right hand seat pilot (to gauge airframe ice growth) and soot gun slides were taken by the left hand seat pilot through his sliding window. When conditions had stabilised in the icing cloud various aircraft manoeuvres were flown, these included climbs and descents, speed changes up the maximum permitted, rate one turns and then increasing to the maximum bank angle of 30° (IF bank limit for the Chinook). Details of the handling manoeuvres flown are contained in Table 2. Once the maximum ice had been accreted by the airframe a collective pull to 100% torque was often conducted to assess the aircraft handling and the effect of the engine intake blockage on the differential pressure across the intake at the higher engine power levels.

Results and Discussion - Icing

Summary of Icing Flights

During the trials period from Nov 1996 to April 1997 a total of 102 flights were made and these covered the datum flying, natural icing flights, precipitating snow and re-circulating snow flights. Only one encounter with freezing rain was experienced and the conditions were vacated rapidly due to the danger of large torque rises. The total time on icing flying was 68 hours of which 23 hours was spent accreting ice on the aircraft. The longest period in icing was 95 minutes and this encounter was concluded due to low fuel (F33N9). In contrast the shortest time in icing was 3 minutes (F21N5) and the conditions had to be vacated due to high Cruise Guide Indicator (CGI) activity and asymmetric shedding of the ice from the rotor system. These two encounters represent the extremes seen during the trial.

The two main types of airframe and rotor ice accretion are rime and glaze ice. Rime ice forms when the water droplets freeze on contact with the surface; this normally occurs in conjunction with low temperatures below -4°C. This type of icing often results in an effective extension of the leading edge of the rotor and very little torque rise, if any, is evident. On the other hand, glaze ice occurs when the droplets do not freeze on contact, but run back before changing state. This often occurs at warmer temperatures and at higher LWCs when larger droplets are often present. The result of glaze ice on the blades is often a "rams horn" formation that leads to very high drag and high torque rises, as the efficiency of the aerofoil is significantly reduced. It is usual to get a combination of these two icing types on the rotor blades due to the temperature gradient along the span of the rotor.

Figures 3 and 4 show the conditions that were experienced in Canada. Figure 5 presents the icing experience in terms of the time in icing versus outside air temperature for four altitude bands. The majority of the icing (67%) was encountered below a pressure altitude of 4000 ft, 15% was accumulated between 4000 ft and 6000 ft, 12% between 6000 ft and 8000 ft and only 6% was accumulated above 8000 ft.

The time spent in icing, however, gives little indication of the value of the icing experience. Figure 4 shows that most of the icing encounters were in cloud with low liquid water content, typically 0.05 to 0.25 g/m^3. The highest mean values of LWC recorded were 0.44 g/m^3 at an OAT of 0°C for 5 minutes and 0.38 g/m^3 at a temperature of -12.1° C for 10 minutes, however, the latter condition had to be vacated due to asymmetric shedding of the ice from the rotors. All the encounters at LWC values above 0.25 g/m^3 and temperatures below -10°C were vacated due to high CGI activity and/or asymmetric shedding. The test conditions, where the aircraft was forced out of icing, were experienced at altitudes above 5000 ft; however, insufficient data was obtained at these temperatures (i.e. -10 to -12° C) at lower altitudes to show whether the problems would have been any less severe. It should be noted that satisfactory data was gathered at temperatures down to -11.5°C at altitudes above 5000 ft, however, all this data was at LWC values less than 0.25 g/m^3. From previous trials (References 1 & 2) very little testing had been achieved at LWC values above 0.25 g/m^3 at temperatures below -10°C, as these conditions have only rarely been encountered during trials. At LWCs above this value and at temperatures below -10° C, the ability of rotary wing aircraft to operate is severely limited without a means to accurately gauge the severity of the icing atmosphere. The severity could be judged by the use of an LWC meter such as those under development during this trial.

Based on the data collected, the icing conditions encountered during the trial were less severe than previous Winters at the same location, although the conditions may have been more representative of those encountered during a European Winter. LWC's were low compared to the UK design icing atmosphere (Reference 3) and test points at the continuous maximum were not achieved. In terms of the LWC, the highest value recorded was 0.38 g/m^3 at -12.1° C; this value represented 65% of the design icing atmosphere maximum. It should be noted that this test point was unsatisfactory due to asymmetric ice shed from the rotor.

For an icing clearance to be recommended, DERA Boscombe Down has developed requirements which state the minimum amount of time that has to be spent in the various environmental conditions defined in Reference 3. The icing atmosphere is divided into altitude and temperature bands and the aircraft must satisfy the following requirements:

- A minimum of 1.5 hours should have been spent at LWC in excess of 25% of the continuous maximum for the altitude and temperature at which the test was conducted. Two separate events should contribute to at least 30 minutes each to this total experience. These proposed requirements are considered to represent the minimum experience which can be accepted in order to underwrite even an "experimental" clearance. The user will almost certainly experience conditions more severe than those encountered during testing and hence a low confidence level is associated with any recommendations made.

- A minimum of 10 consecutive minutes should have been spent at LWC in excess of 60% of the continuous maximum for the altitude and temperature at which the test was conducted. In any case the maximum pressure altitude justified for an icing clearance will not normally be higher that that at which the test was actually performed. This is to restrict the altitude at which the user can fly as flight at higher altitude than that tested may result in increased rotor degradation which may lead to handling difficulties arising from premature blade stall. If sufficient data is available at other temperature bands to permit a reasonable appreciation of the effects of altitude on the degraded rotor then this will be taken into account when establishing an overall altitude limitation.

These minimum levels of icing experience apply to a number of discrete temperature bands; sufficient, satisfactory experience must be gained in each temperature band down to the lowest temperature for which certification is sought. The temperature bands are discussed below.

0° to -5°C

A total of 10 flights were achieved in icing conditions in this temperature range and this resulted in 27 icing encounters. All of the encounters were at LWC values less than 60% of the continuous maximum and only 5 encounters were above the 25% value. A total of 1hr 15mins was spent at LWC values in excess of 25% of the continuous maximum which was below that required for clearance of these temperatures based on the Boscombe Down criteria. This area, however, was explored during the earlier trials on the HC Mk 1 aircraft (Reference 1) and the results seen on the HC Mk 2 were similar to the earlier trials. It would be reasonable therefore, not to expect any difference in performance on the Mk 2 aircraft in this temperature band.

-5°C to -10°C

Icing conditions were encountered on 11 flights in this temperature range and there were 29 icing encounters. All the encounters were at LWC values less than 60% of the continuous maximum and 16 of these were between 25% and 60%. A total time of 3hrs 5mins was spent in icing conditions in excess of the 25% minimum specified, however, no time was spent at LWC values in excess of 60%. The data from the earlier trials also falls into this category with very little experience at LWC values greater than 60% of the continuous maximum (one encounter at -6°C at an LWC of 0.55 resulted in high CGI and the condition was vacated).

-10°C to -15°C

Six flights in icing conditions were carried out in this temperature range and there were 14 icing encounters. Three encounters were at LWC values in excess of the 60% value and in all cases asymmetric shedding or high CGI readings forced the aircraft out of the conditions. Only 5 encounters were at LWC values between 25% and 60% of the continuous maximum with one encounter at -12.3°C being abandoned due to high CGI. The remainder of the points were below 25%. The minimum temperature experienced was -13°C. A total of 34mins was spent at LWC values greater than 25% of the maximum at which a manoeuvre capability was demonstrated. The total time spent at LWC values greater than 60% was 26 minutes, however, in all cases the conditions had to be vacated due to high CGI and asymmetric shedding.

Based on the data which was gathered it can be seen that none was collected at low altitude (< 2000 ft) and low OAT (-7 to -10°C). A number of data points were flown at higher altitudes at the same low temperatures and no handling difficulties were found. It has been found that the LWC tends to increase with altitude in the cloud (i.e. high LWC are often found in the cloud tops) and the severity of the icing condition is consequently greater. As the altitude is increased the blade angle of attack is also increased to achieve the same lift and any reduction in the retreating blade stall margin caused by ice accretion is more apparent. Consequently, it was considered acceptable to allow operation at the lower temperatures at these low altitudes, provided that satisfactory data had been obtained at the same airspeed at a higher altitude.

In addition, experience was gained in a region of relatively warm temperatures (0 to -2°C) at the higher altitudes (6000 to 8500 ft), where a number of satisfactory data points were recorded. At these temperatures, the kinetic heating of the blade leading edge minimises ice buildup on the blades. The torque rises seen in this region were therefore low and it is unlikely that significant handling/power rise problems would be encountered, even at high LWC values.

The supercooled water droplet size in the clouds (calculated from the soot slides) ranged from under 3 microns to 27 microns and the maximum airframe ice accretion (from the VAM) was 54 mm in glaze icing and 113 mm of rime ice.

In summary the trials experience gave 4.75 hours in icing between -5 and -10°C and 5.22 hours between 0 and -5°C at LWC's greater than 25% of the UK continuous maximum icing requirement. At LWC's greater than 60% of the continuous maximum the time spent in icing was only 0.72 hours between -5 and -10°C.

Rotor Performance

The aircraft rotor system was found to be very tolerant of icing conditions. Figure 6 shows the aft blade with ice out to around 50% of the span at -7°C, 4000 ft pressure altitude and mean LWC of 0.2 g/m^3. Figure 7 shows ice almost to the blade tip at -12.2°C, 5400 ft and a mean LWC of 0.34 g/m^3. Figures 8 and 9 show the ice remaining on the rotor system after returning from an encounter. Rotor governing was good and excursions from the 100% Nr datum setting were insignificant.

Torque Increases

Increases in torque required to fly in icing conditions compared to the clean aircraft at the same flight condition were observed on many flights and later confirmed during post flight analysis. Turbulence and frequent collective inputs tended to mask small torque rises making them difficult to quantify. Often, in flight photographs showed some ice where torque rises were small (less than 5%) or not evident at all as shown in Figure 10. In these cases the ice tended to be of the rime type, forming an extension to the blade leading edges as shown in Figure 8. Figure 11 shows the time history of a 69 minute encounter at 4880ft, -6° C with a mean LWC of 0.17g/m^3 and the 5% torque rise can clearly be seen. In the majority of cases where a torque rise was seen in the region of 5-8% per engine, flight could be maintained indefinitely.

During several flights torque rises of up to 20% were seen and these were generally associated with glaze ice at mid and outer span of the rotor blades. This ice formation reduced the aerodynamic efficiency of the blades (loss of lift and increased drag), resulting in high torque rises to maintain level flight. The time history of an encounter at 5400ft, -12° C with a mean LWC of 0.34g/m^3 in presented in Figure 12; a torque rise of 20% can be clearly seen.

Aircraft Vibration

The subjective vibration levels in the aircraft often increased with operations in icing conditions. This was expected and has been seen many times before when operating in these conditions. As would be expected the vibration was worse when operating at high AUM and at higher speeds. It was necessary during the trial to dump water ballast and/or reduce speed on several occasions to decrease high levels of vibration. The worst vibration was experienced when ice shed asymmetrically from the blades (Figure 13); on several occasions it was necessary to vacate the conditions to allow the remaining blades to shed their ice and reduce the vibration levels. Whilst the vibration levels in these instances may have been slightly unpleasant for the crew on no occasions was it considered a flight safety hazard.

Engine Intakes

Both the standard HC Mk 2 all weather screens (AWS) and the US Army AWS were flown in both rime and glaze icing conditions. The maximum accretion with the standard AWS was 55mm and the ice growth and shedding characteristics were identical to those seen on previous trials. The standard AWS already had an unlimited accretion capability and this was confirmed during the trial.

The US Army AWS has a finer mesh and this was found to vibrate more than the mesh on the standard AWS. Maximum accretion achieved on this screen was 54mm. Ice on the fine mesh screen shed more frequently than accretions on the standard AWS. Overall the US Army AWS provided excellent protection to the engine during operation in icing conditions.

Two standards of Engine Air Particle Separators (EAPS) were tested during the trial. The standard EAPS and the EAPS with an external stone guard (a mesh screen) and/or an internal conical mesh screen. Both standards of EAPS would rapidly accrete ice on entry into icing conditions. On the clean EAPS, the ice would tend to grow on each vortex tube as shown in Figure 14 and whilst it would often appear that the front face of the EAPS was totally blocked, this was never the case. The pressure drop across the standard EAPS did increase with ice accretion, however, the drop was well within the acceptable limits. Typically the pressure drop increased from 12mb (clear air) to between 15 and 20 mb; the maximum pressure drop recorded was 27 mb and this was well below the 100 mb limit. The standard EAPS was considered to be satisfactory for use during icing operations. Fitment of the external stone guards or the internal conical mesh screen had little effect on the capabilities of the EAPS in icing. Although ice was found to accrete and shed slightly more readily on the external mesh guard and the front face became slightly more blocked, these issue were considered insignificant. Neither the external stone guard nor the internal screen caused any increase in pressure drop across the intake nor did they affect the engine performance or handling.

Post Flight Inspection and Analysis

When the icing conditions "ran-out" in the trials area and/or the aircraft's endurance was reached, the aircraft returned to base at a height above the freezing level whenever climatic conditions and air traffic control regulations permitted. On landing, a detailed examination of the extent of the residual ice accretions was made on the airframe, rotor blades, rotor heads and all parts of the engine intakes. All ice accretions were logged and most were recorded on stills and video photographs. Figures 15 and 16 show typical accretions following an icing flight.

Post flight analysis started with the processing of the aircraft flight data tape on a computer ground station. The data was ultimately converted to a computer tertiary file which was used by the flight test engineers to perform in depth analysis of the data recorded. This included an estimation of the torque rises during the encounter, LWC values and the duration of the encounters. Statistical analysis was carried out on the LWC data to determine the mean values for the encounter and this data was used to plot overall planning charts which are reproduced in Figures 3 and 4. Typical aircraft data traces are shown in Figures 11 and 12.

Ice Detectors

One of the secondary test objectives of the trial was to evaluate a state of the art ice detector. The two Penny & Giles Ice and Snow Detection Systems (ISDS) that were fitted to the aircraft functioned well throughout the complete trial. The sensing heads and electronic units were interchanged on a number of occasions during the trial in order to allow a better understanding of any "location related" behaviour. Towards the end of the trial two major changes were made to the systems; the port side (production) unit was re-positioned to the forward starboard side of the fuselage (just aft of the cockpit window) and the following icing related software changes were made to one of the electronic units: The "severity system" that utilises an OAT/LWC relationship to categorise the severity of the icing condition, was upgraded to give an amber indication; this was in addition to the green and red indications that were already installed. The amber indication was designed to show when a limiting condition was being approached. Furthermore, to prevent flashing of the lights from one severity to another, the software was re-configured to average the LWC output over a given time and update the severity system less often.

Differences in the indication from the two units were identified early in the trials programme. The LWC output of the starboard underside unit was almost always higher than that of the port fuselage mounted head, often by up to 30%. Comparisons of the output LWC and those calculated from measurement of the airframe accretion levels (100% catch efficiency), revealed that the starboard system was relatively accurate, whilst the port unit was consistently under-reading. This finding was also confirmed by comparison of the depths of airframe ice in the vicinity of the port measuring head - these were often 30-40% less than that seen on the Vernier Accretion Meter. The original location of the port head was considered to be unsatisfactory and it was therefore moved to the starboard side of the aircraft for the final part of the trial.

In the re-located position the measuring head gave improved performance in icing conditions. At all LWC values encountered its output reasonably reflected that of the (underside) flight test system and its reaction to the presence of icing conditions was similar. The performance in the revised location was satisfactory.

The reliability of both systems was good. The systems were fitted for 102 flights encompassing in excess of 120 hours flying, with 68 hours in actual icing and snow conditions. Neither system required any maintenance, although the optics of one head were cleaned as a precautionary measure when it was re-positioned. The flight test head suffered from slightly dirty optics (one source) about mid-way through the trial, but the control system automatically compensated for this and no effect was seen on the LWC output. As a test point, this optic was not cleaned for the remainder of the trial; no ill effects were seen. The reliability of the Penny & Giles ISDS was satisfactory, however, statistically only a small number of hours were flown.

Results and Discussion - Snow Tests

Mixed Snow & Icing

Flight in mixed snow and icing conditions was approached with extreme caution due to the inability to accurately determine the severity of the snow when operating in cloud. Although the Penny and Giles ISDS gave good indications of the snow severity, the system was under development and therefore during the initial phases of the trial the outputs were not relied upon. When snow was encountered in the cloud, whether the aircraft was accreting ice or not, particular attention was paid to ensuring that no significant amounts ice or slush formed inside the EAPS; this could have resulted in damage to an engine or the engine flaming out. The test technique used in mixed snow and icing conditions was identical to that for pure icing, however, on occasions speeds were reduced to minimize the likelihood of an engine flame out due to ice/snow ingestion.

Precipitating Snow

Every opportunity was taken to fly in precipitating snow whilst remaining in sight of the ground. A total of 16 precipitating snow flights (16 hrs total) were undertaken. Snow flying was limited to a pre-reconnoitered low level route or the immediate vicinity of the airfield. The vast majority of the flight tests were carried out over the airfield due primarily to the difficulties associated with flying under visual flight rules (VFR) when the visibility dropped below 800m. This situation did not restrict the amount of evidence that was gathered in precipitating snow over the trials period and offered a safe alternative to route flying in moderate and heavy precipitation.

Two particular flight conditions were of interest in precipitating snow; the hover and operation in forward flight at the maximum speed that could be achieved with the prevailing visibility. Often, when the visibility dropped to below 400m , the forward speed was severely limited and, in effect, only hover taxiing and hovering was possible. During the initial flights in precipitating snow, regular inspections of the intakes were carried out to ensure that no ice or slush growths were occurring outside the field of view of the internal video cameras. This dictated that a series of short encounters in the condition were undertaken. As experience was gained considerably longer excursions in the condition were carried out.

During snow flying the severity of the condition was judged primarily by estimating the prevailing visibility, although reference was made also to the indications from the Penny and Giles ISD system. The following visibilities were used as a guide: > 2000 m - trace, 1200 m to 2000 m - light, 400 m to 1200 m - moderate, < 400 m - heavy.

In addition to the variety of engine intakes tested in precipitating snow, the effects of other changes in configuration, such as the use of modified windscreen wipers and de-selection (to simulate failure) of the windscreen anti-icing systems were investigated.

Re-circulating Snow

Flights in re-circulating snow were conducted over the airfield to simulate the effects of numerous take-offs and landings from snow covered areas. A number of techniques were investigated to maximise the extent of the re-circulation and subject the engine intakes and forward fuselage to the most severe conditions. Often, the lack of visibility dictated that two and four wheel taxiing were the only viable operating conditions. This did not detract from the experience gained, as taxiing almost always resulted in more severe and consistent test conditions. Hover tests showed that re-circulation was less extensive and generally short lived as the downwash tended to blow the snow away from the aircraft. During taxiing tests consistent conditions could be established by moving at 5-10kn over the ground, although prevailing wind direction and strength sometimes required variation of this technique. The severity of the re-circulation was judged against the ability to see beyond the snow cloud; heavy re-circulating snow was present when objects beyond the cloud could not be seen.

The difficulty in getting constant heavy re-circulating snow clouds to form in any landing or taxiing condition were seen as an advantage in service. This should result in less snow being re-circulated around the engine intakes and a lower probability of ingested snow resulting in an engine flame out.

Engine Intakes

The standard and US Army AWS were found to offer a limited capability with regard to prevention of slush entering the engine. If large slush accretions were to be dislodged from the airframe (particularly the top decking) during flight it is most likely that they would strike the intake. In this case there was a high probability that sufficient slush would "shred" through the screen and cause a flame out and engine damage. Conversely, the EAPS was found to offer total protection against slush and high volume water ingestion. Furthermore, even after prolonged operations in heavy re-circulating or precipitating snow, no appreciable slush or ice growth was seen inside the intake. The EAPS was the preferred intake for operation in snow; this configuration will have the most relaxed limitations.

Flight with Skis Fitted

The opportunity of operating in a "Winter" location was taken to assess the suitability of the Chinook snow skis. The skis can be fitted to each undercarriage leg to aid operation on snow covered ground. An engineering assessment of the installation was made, covering fitment, removal and robustness. The aircraft performance with skis fitted was established at a single referred mass over the speed range of 60-130kn IAS. This enabled the effect of fitting skis on the aircraft's performance in forward flight to be determined. The aircraft handling with skis fitted was also assessed including the general handling and classical stability tests. The engineering aspects of the skis were found to be satisfactory and little effect on aircraft handling was apparent, except when operating in turbulence. Greater than normal pitch oscillations were experienced in these conditions; this behaviour was attributed to fitment of the skis and further flight testing will be required to enable a safe flight envelope to be defined.

Concluding Remarks

The natural icing conditions which were available during the trial were not as severe as had been hoped for, although a considerable amount of flight testing in icing was achieved. However, a significant amount of snow late in the season allowed more work to be carried out in re-circulating and precipitating snow than had been expected. The snow conditions were typical of those found in the Maritimes; mostly "wet and warm" and ideal for snow testing.

The data gathered during the trial enabled the following conclusions to be drawn:

- There were no significant handling problems identified during testing with the exception of the flights at low OAT and high LWC where asymmetric ice shedding occurred and the conditions had to be vacated.
- The performance of standard AWS, US Army AWS and EAPS were satisfactory during all icing encounters and provided sufficient protection to the engines in all the conditions tested.
- The EAPS would provide satisfactory engine protection in virtually all conditions where precipitating and re-circulating snow were encountered, regardless of the temperature or duration of the encounter. The AWS and US Army AWS provided less protection in these conditions; time and visibility limits will have to be placed on operation in snow, particularly at low airspeeds, due

to the high rate of accumulation of slush on the top decking of the aircraft. This slush is a potential danger to the engines when dislodged, possibly causing engine damage or flame-out.

- No significant problems were noted with the antenna, windscreen heating, windshield wipers, heater drains, pitot-static system or sideslip ports due to ice or snow accumulation.
- The on board computer systems and instrumentation systems performed well and provided the flight test engineers with valuable real time data that increased the flight productivity and accelerated the development of the flight experience.
- The computer based ground station used for detailed analysis was essential for the icing trial.
- The icing encounter data from this trial was an addition to the database already obtained for the RAF Chinook from earlier trials. Based on the overall test conditions achieved, an improved icing envelope can be recommended. The trial allowed a significant amount of testing and development to be carried out on the Penny & Giles ISDS. In particular, the ice detection system was found to be very reliable and accurate and, with this incorporated into in-service aircraft, a further improvement to the icing envelope should allow operation in more severe conditions.
- An improved snow flight envelope can be recommended for the RAF Chinook as a result of the additional experience gained. The EAPS offers an excellent capability in all snow conditions.

References

1. "Chinook HC Mk1, ZA704 - Icing Trials in Denmark During Winter 1982/83", A&AEE Boscombe Down Report. Unpublished MOD(PE) Report.

2. "CA Release Recommendations for Flight in Icing and Snow Conditions for All Marks of Lynx Fitted with Composite Main Rotor Blades", A&AEE Boscombe Down Report. Unpublished MOD(PE) Report.

3. UK Ministry of Defence, Defence Standard 00-970, "Design and Airworthiness Requirements for Service Aircraft", Volume 2 - Rotorcraft, Book 3, Chapter 711.

Condition	Air Temperature (° C)	Liquid Water (g/m³)	Horizontal Extent (km)	Droplet Size Median Volumetric Diameter (microns)	Altitude Range (Ft)
I Continuous Maximum Icing	+5 0 -10 -20	0.90 0.80 0.60 0.30	Continuous	20	4,000 to 10,000
II Periodic Maximum Icing	+5 0 -10 -20	1.35 1.20 0.90 0.45	6km every 100 km of Condition I	20	4,000 to 10,000

Table 1: Defence Standard 00-970 Icing Conditions Design Atmosphere

Turns	Rate 1 turns at 80kn IAS
Climb	Climb at 500 fpm and 80kn IAS
Descent	Descent at 1000 fpm and 80kn IAS
Acceleration	Accelerate to Vmax
Deceleration	Decelerate to 60kn IAS
Autorotation	Autorotation at 80kn IAS

Table 2: Flight Manoeuvres During Flight

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Figure 1: Flight Test Engineer's Station.

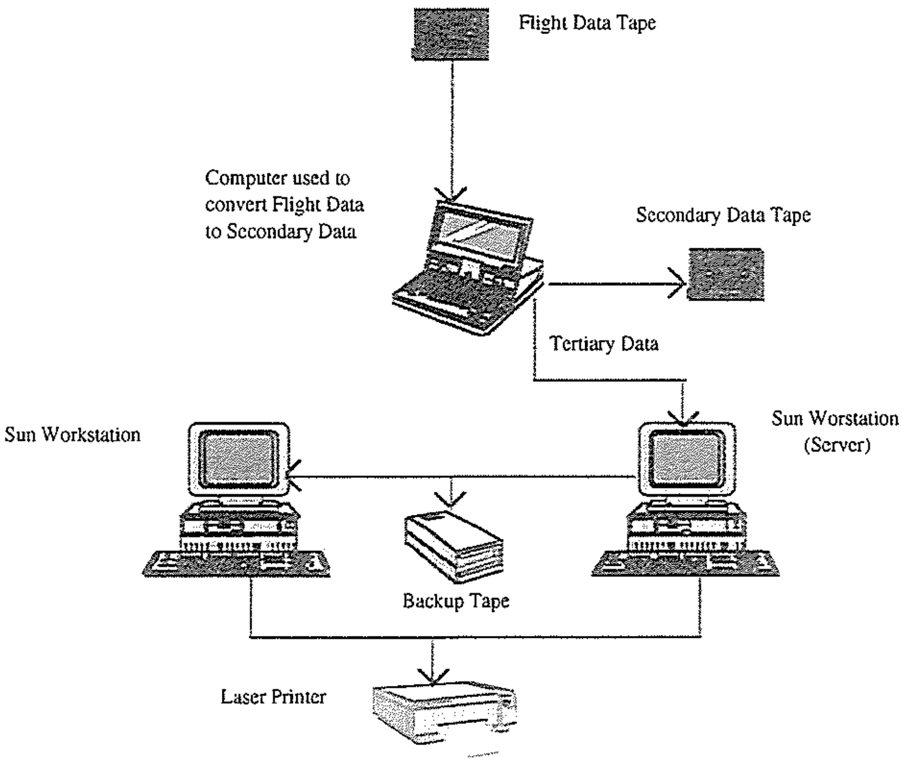


Figure 2: Ground Based Computer Sysyem.

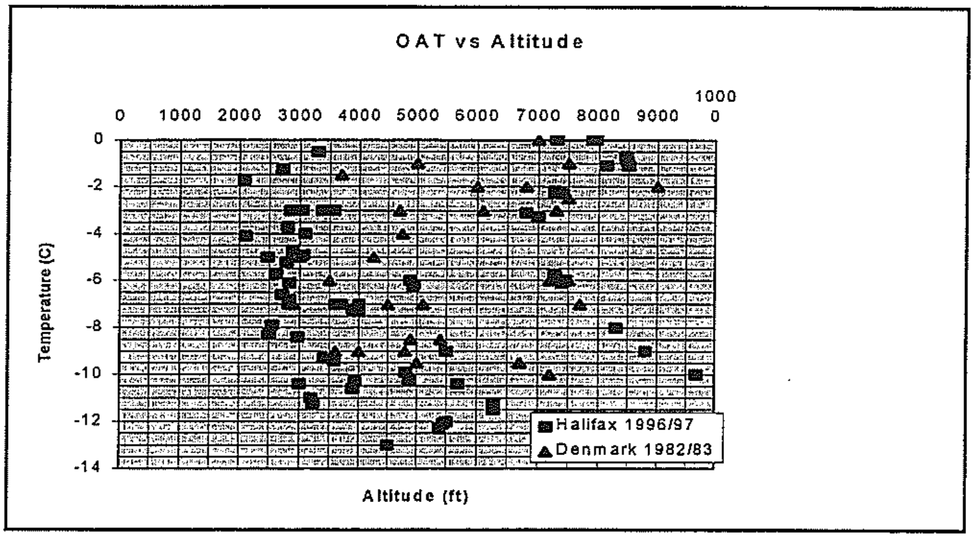


Figure 3: OAT vs Altitude Planning Chart

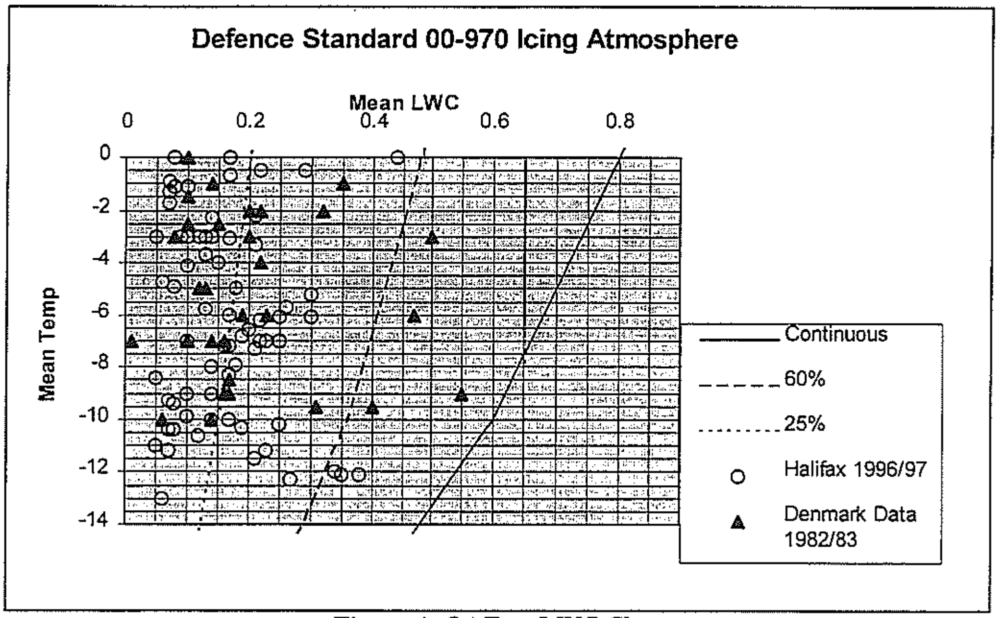


Figure 4: OAT vs LWC Chart

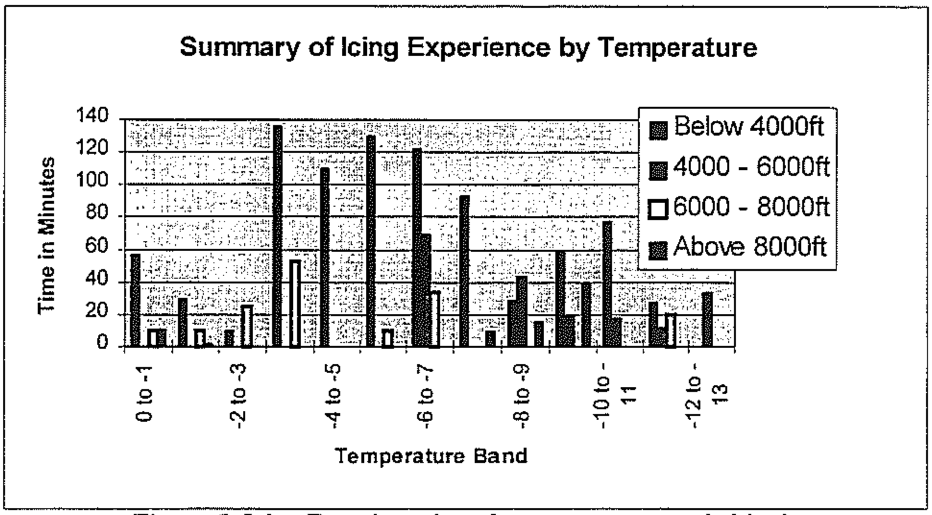
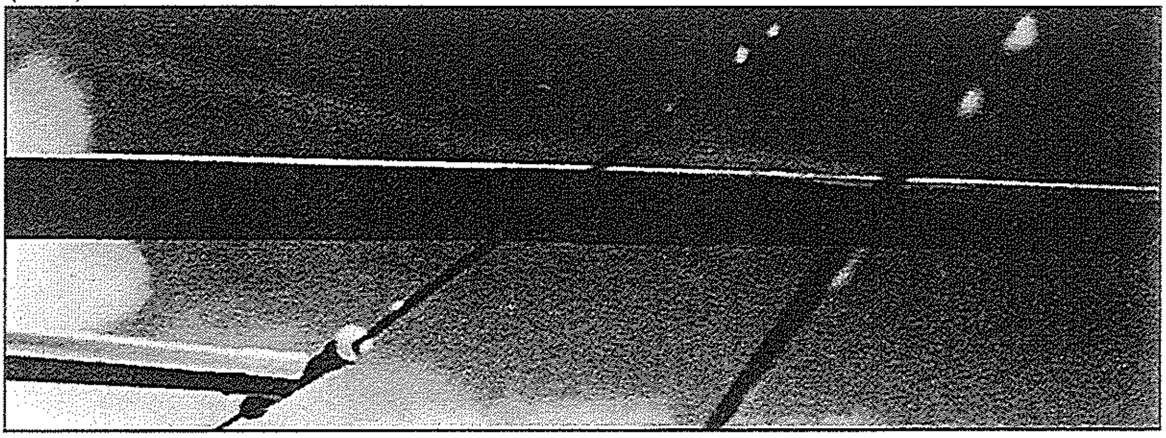
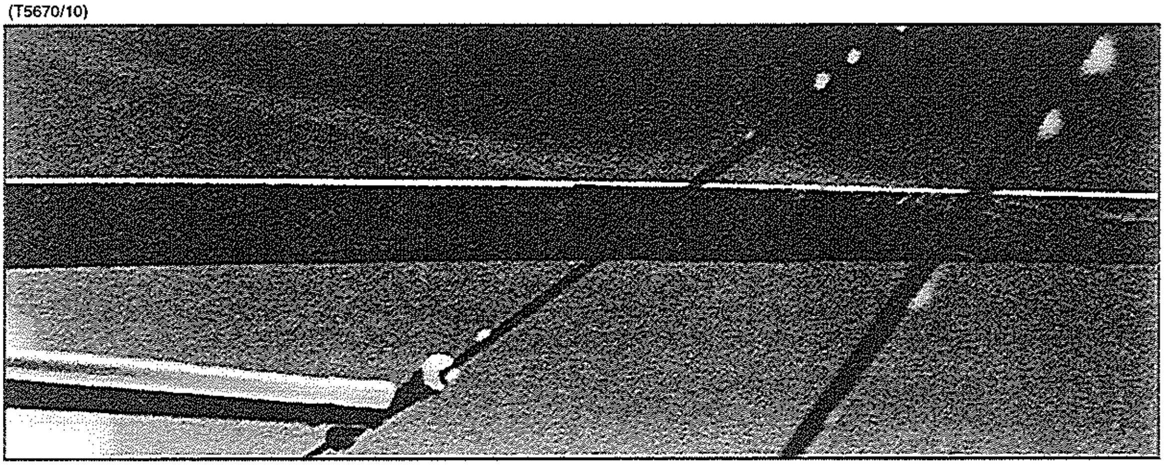


Figure 5: Icing Experience based on temperature and altitude

(T5670/9)



(T5670/10)



(T5670/11)

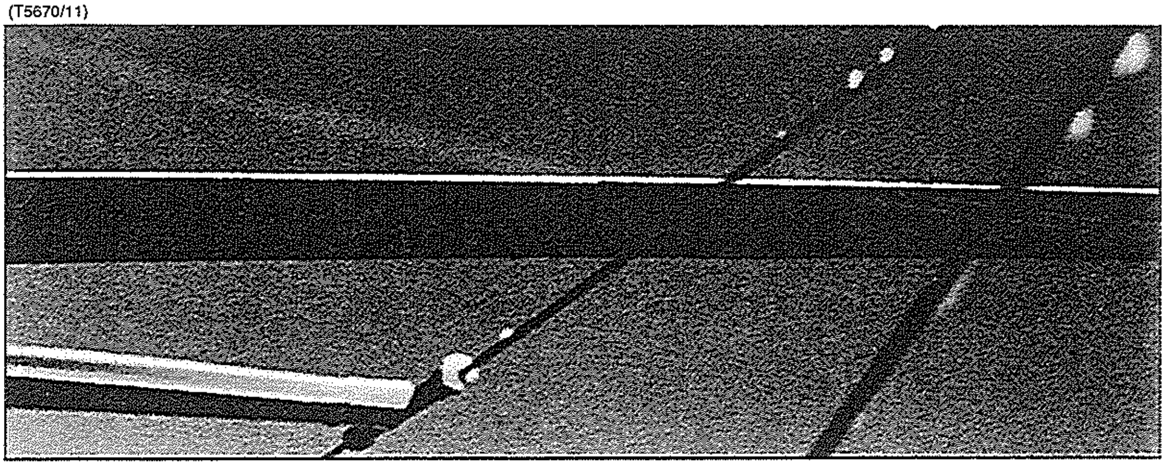
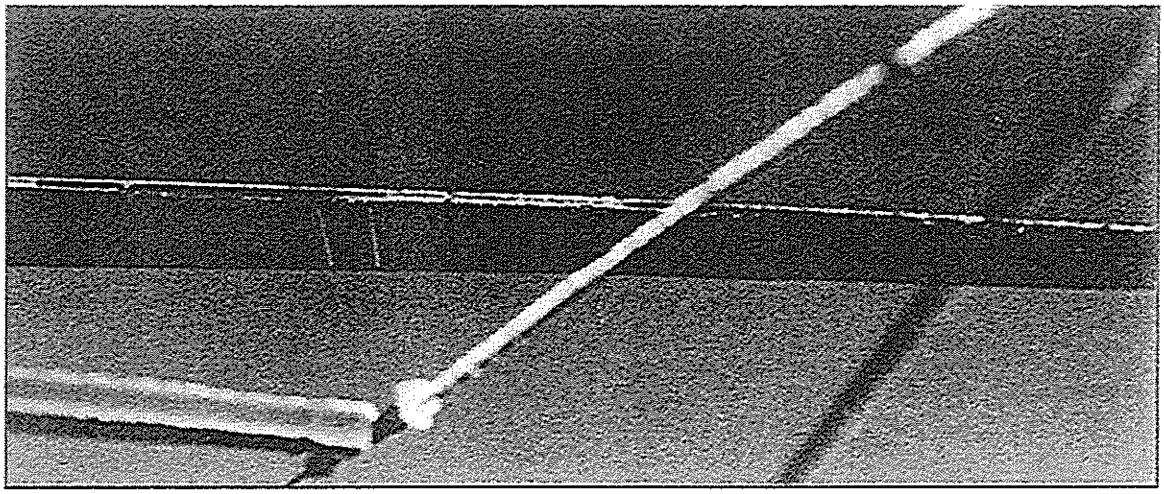
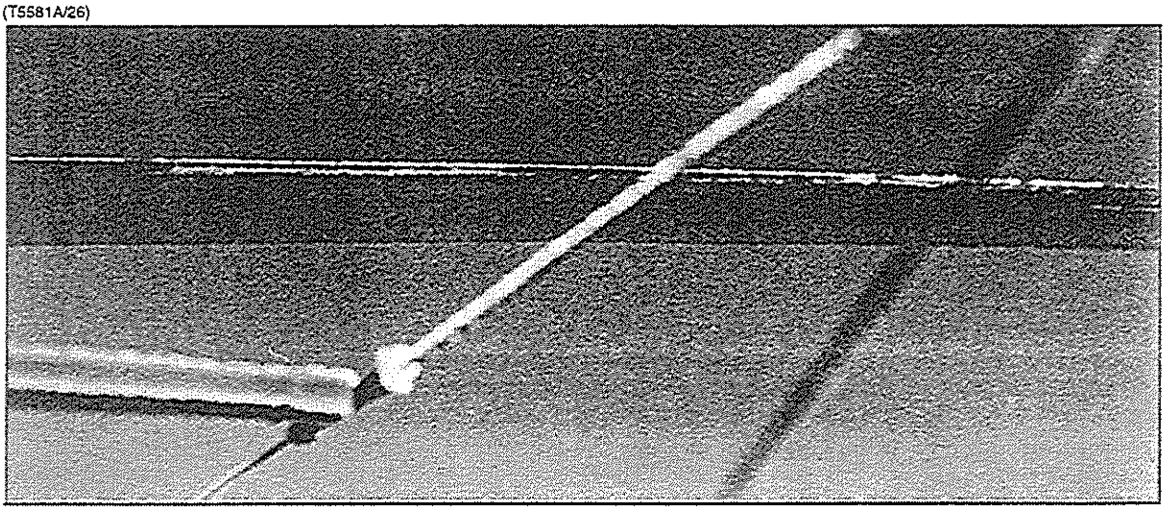


Figure 6: Ice to 50% span on rear rotor blades.

(T5581A/25)



(T5581A/26)



(T5581A/27)

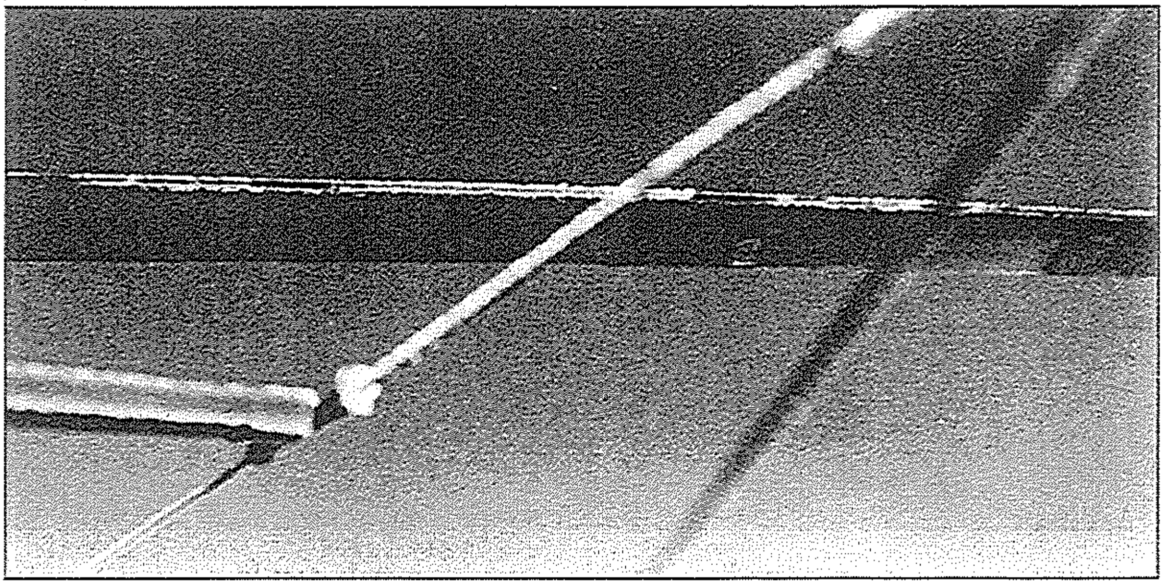


Figure 7: Ice nearly to blade tip.

(T5671/24)

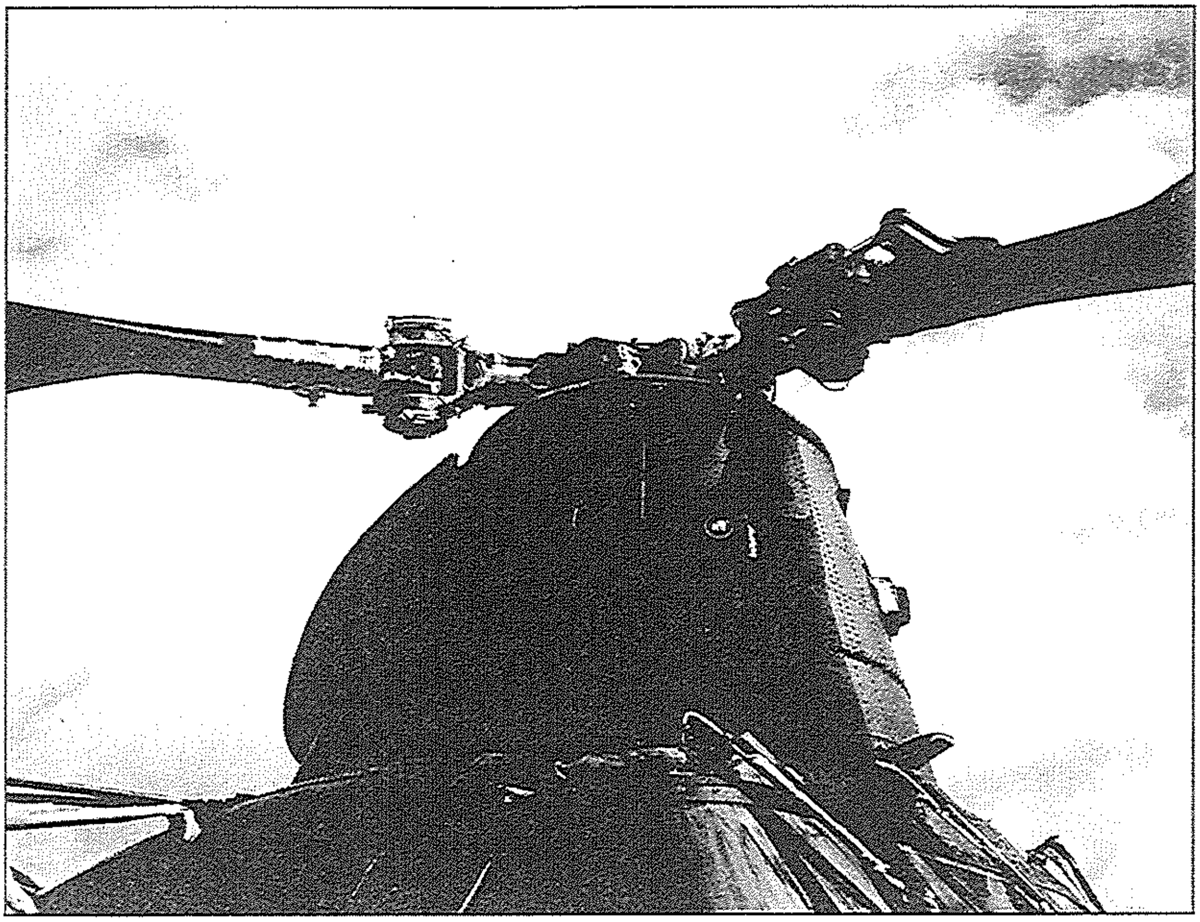


Figure 8: Rotor Ice after flight.

(T5581/15)

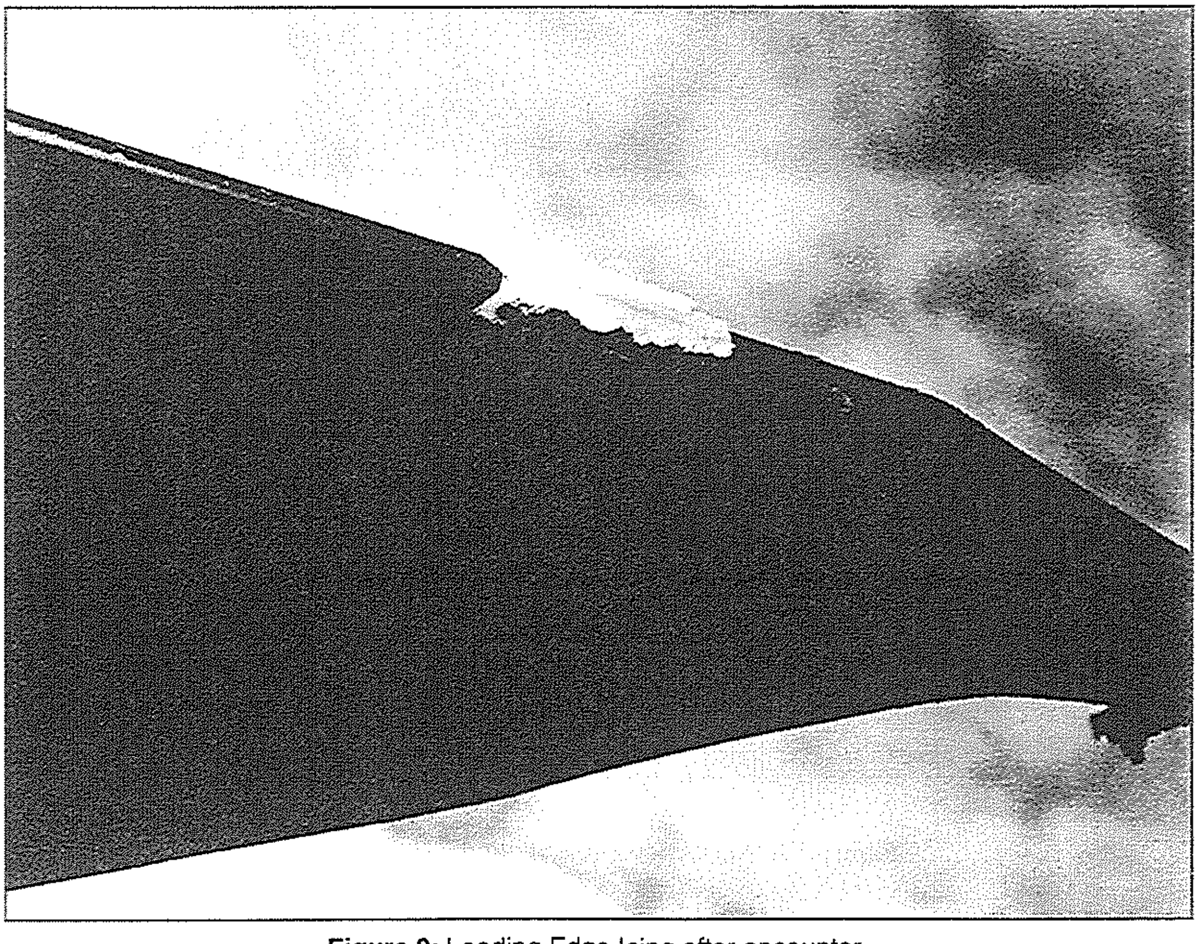
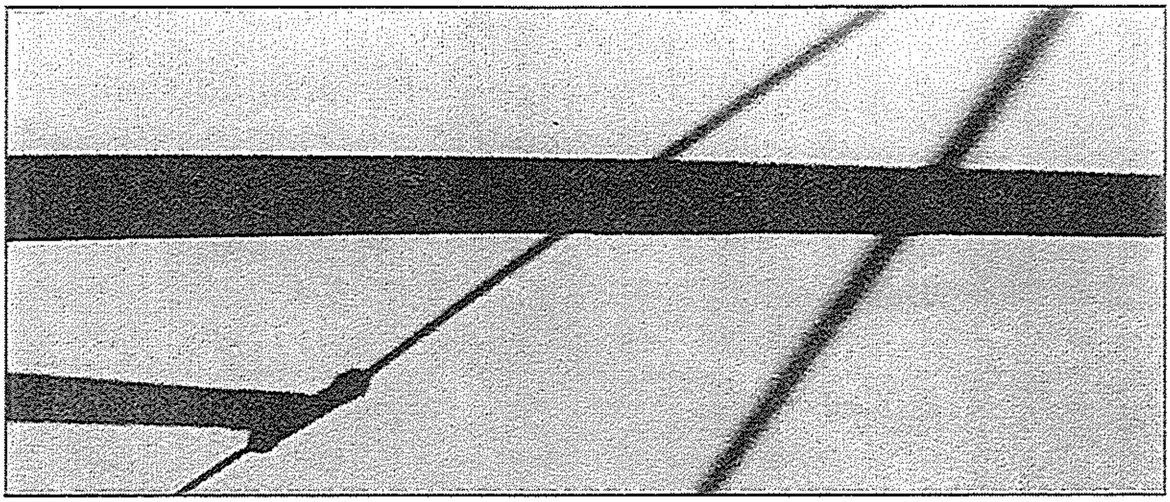
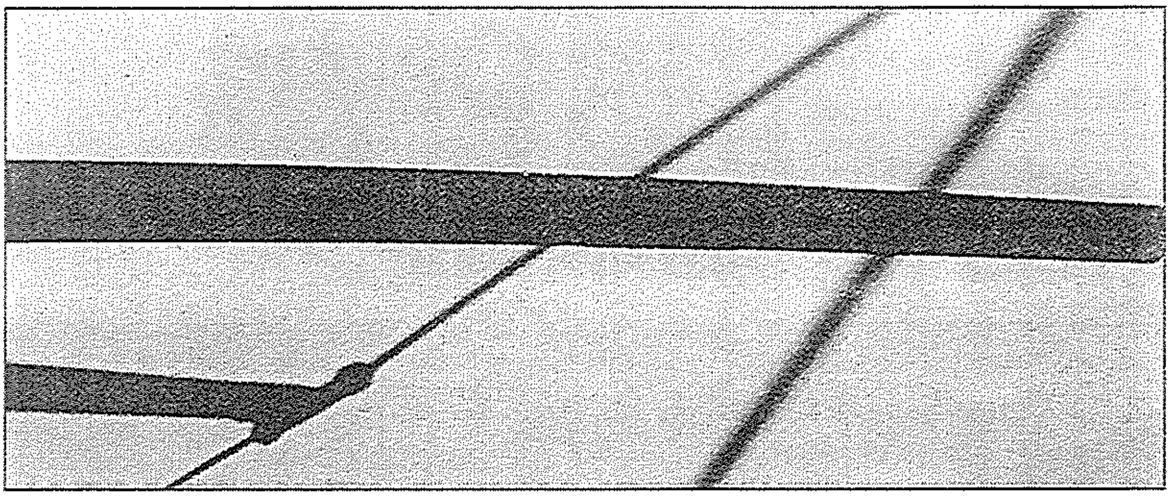


Figure 9: Leading Edge Icing after encounter.

(T5580/6



(T5580/7



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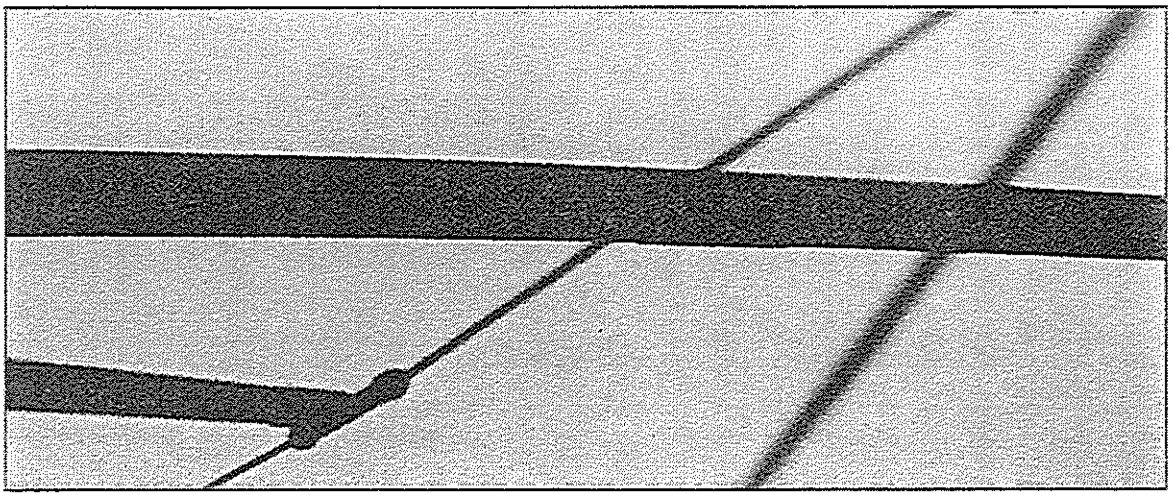


Figure 10: Non evident leading edge ice during flight.

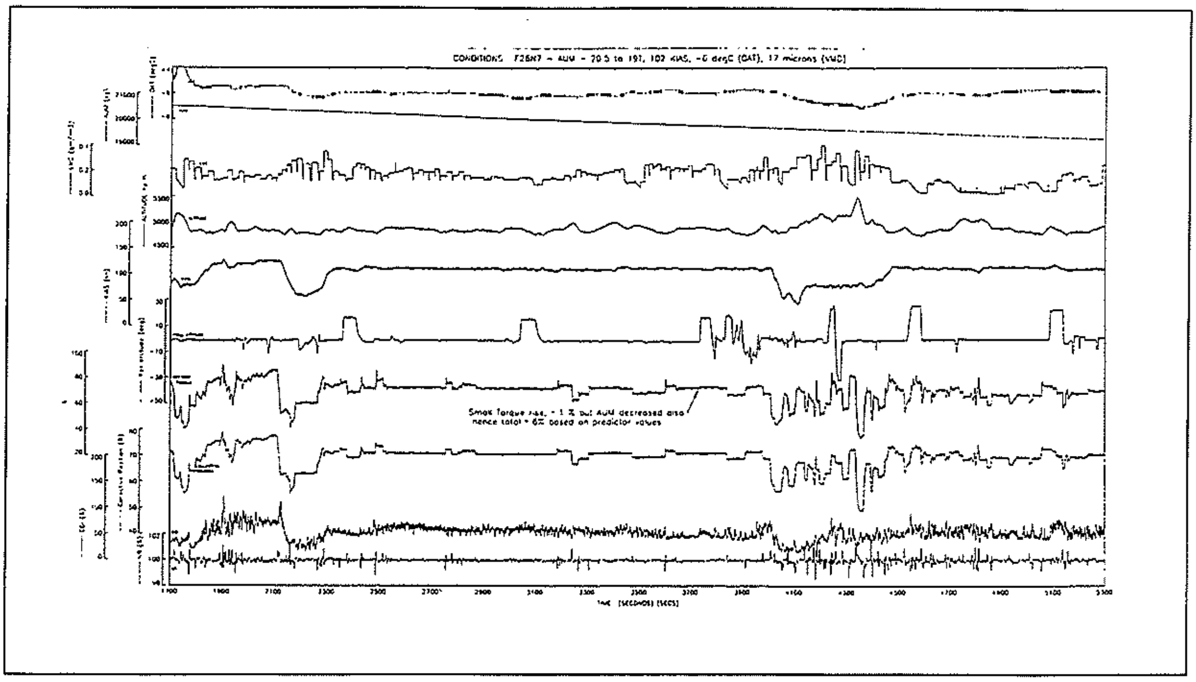


Figure 11: Time history of an encounter with a small torque rise

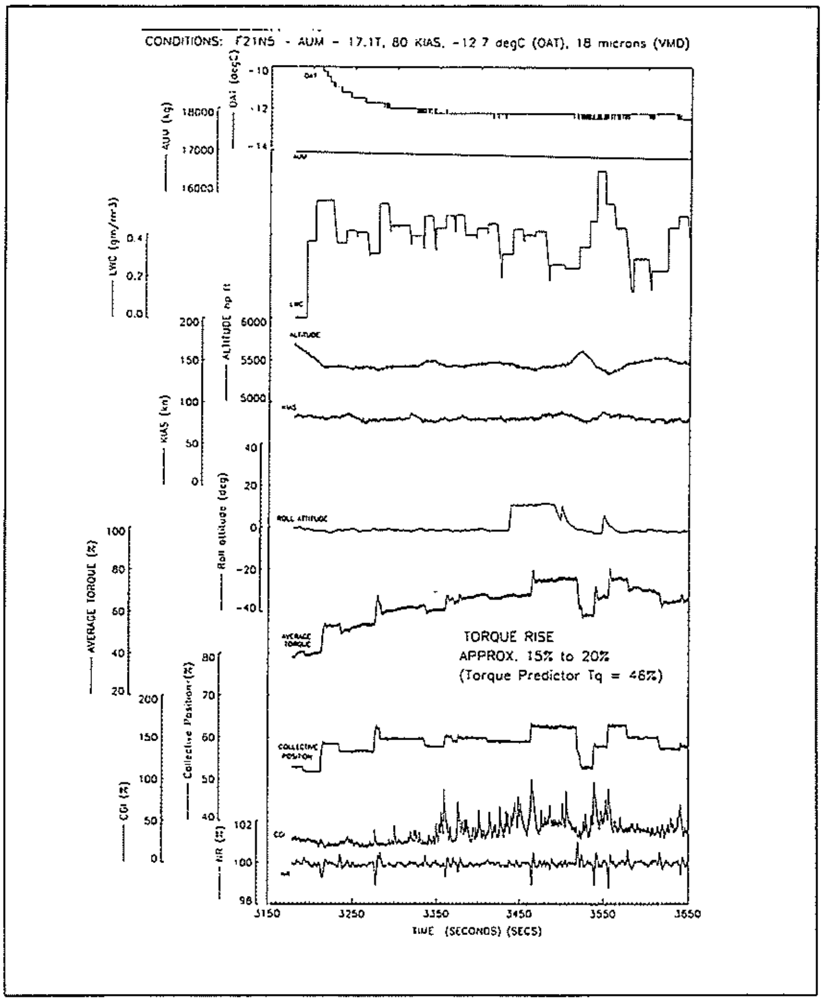
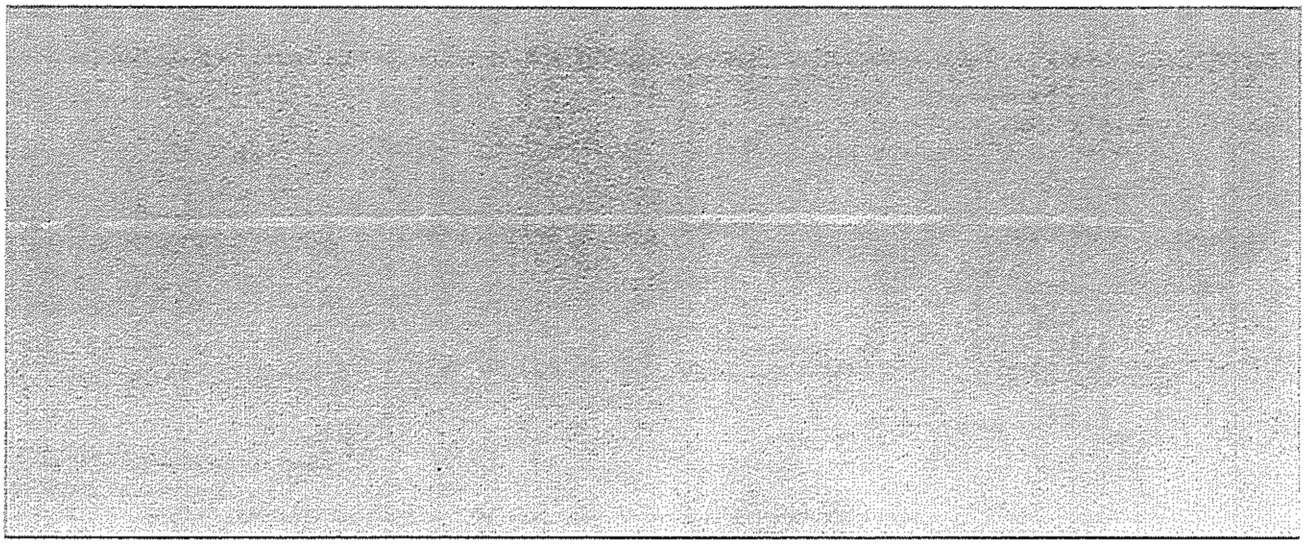


Figure 12: Time history of an encounter with a large torque rise

(T5581A/9)



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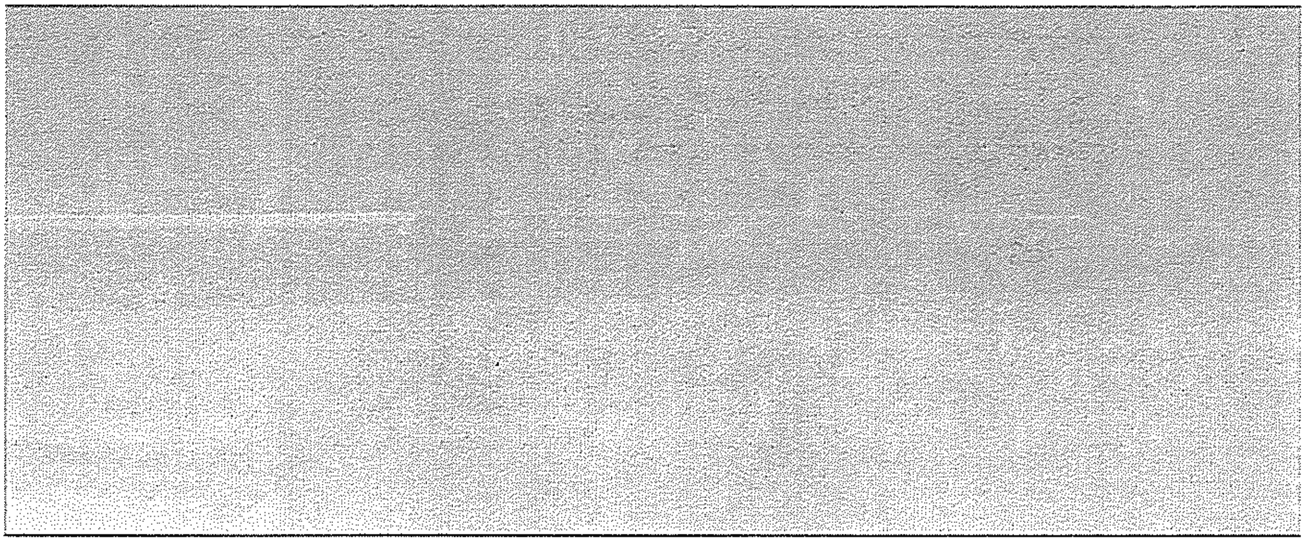

(T5581A/11)

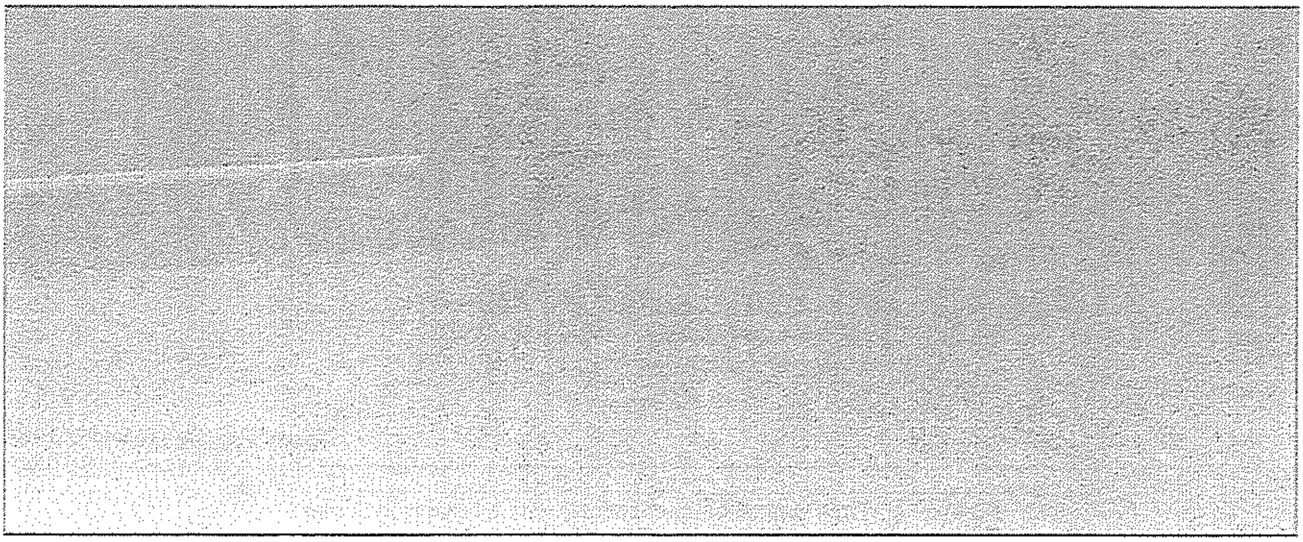

Figure 13: Asymmetric Shedding of Rotor Ice.

(T5591/9)

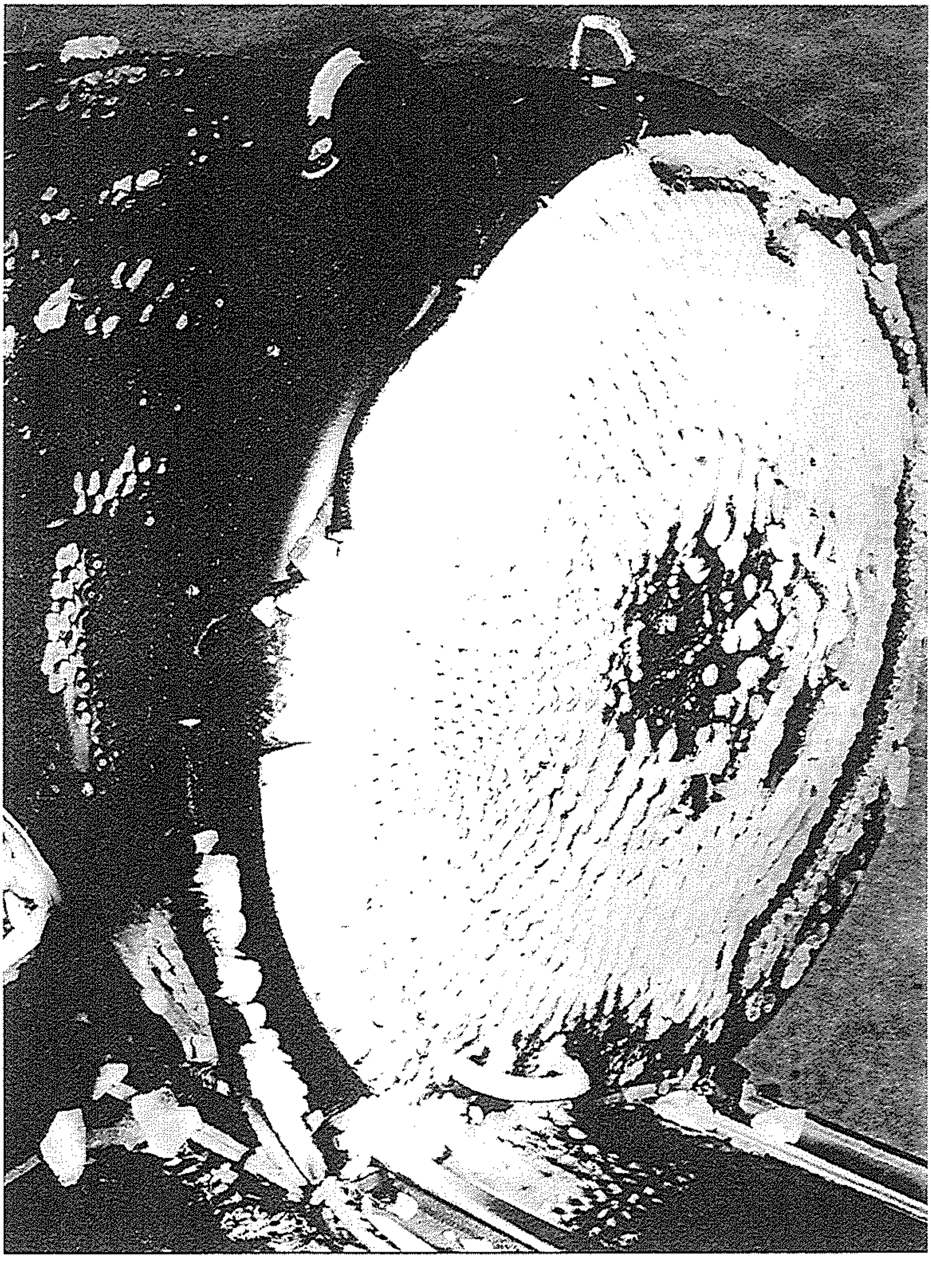

Figure 14: Ice Growth on EAPS Vortex Tubes.

(T5591/24)

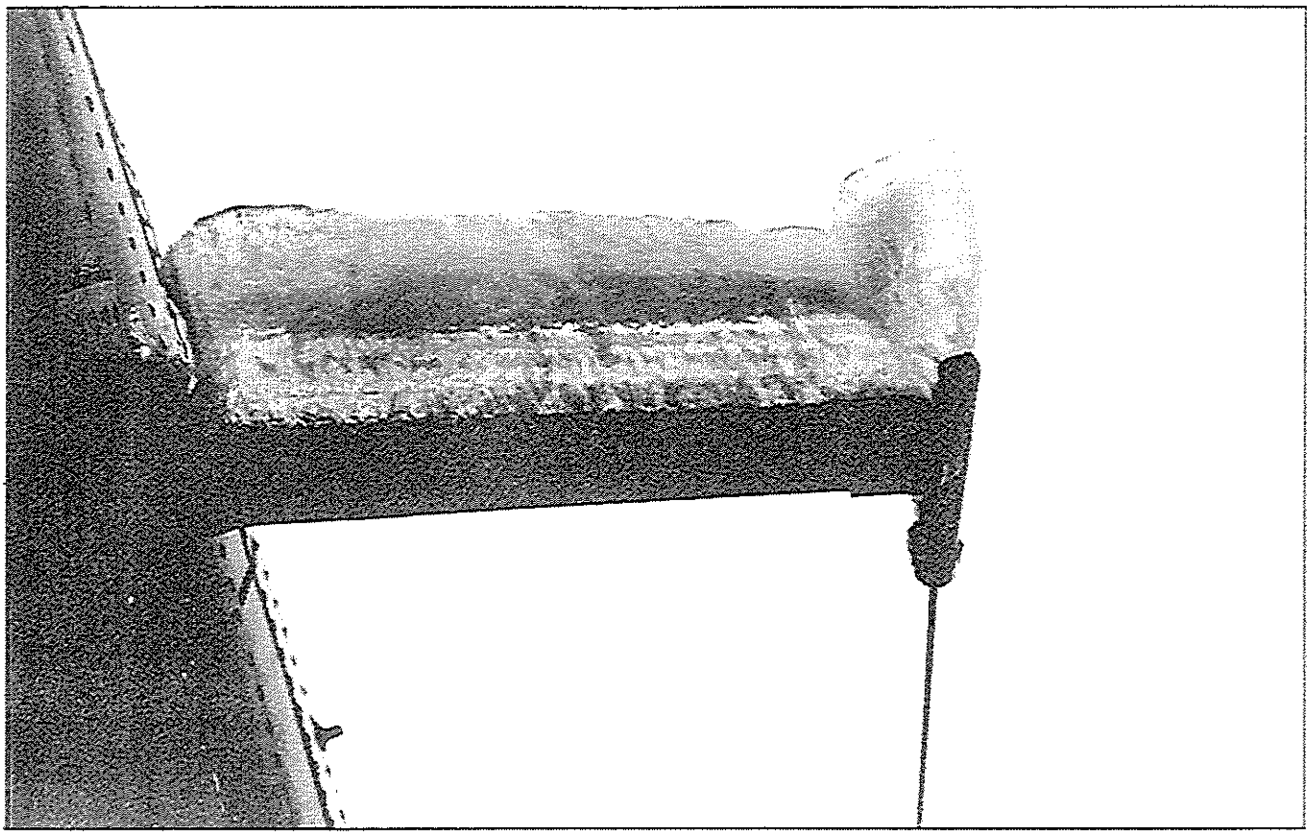

Figure 15: Ice Accretion on Radio Aerial.

(T5591/13)

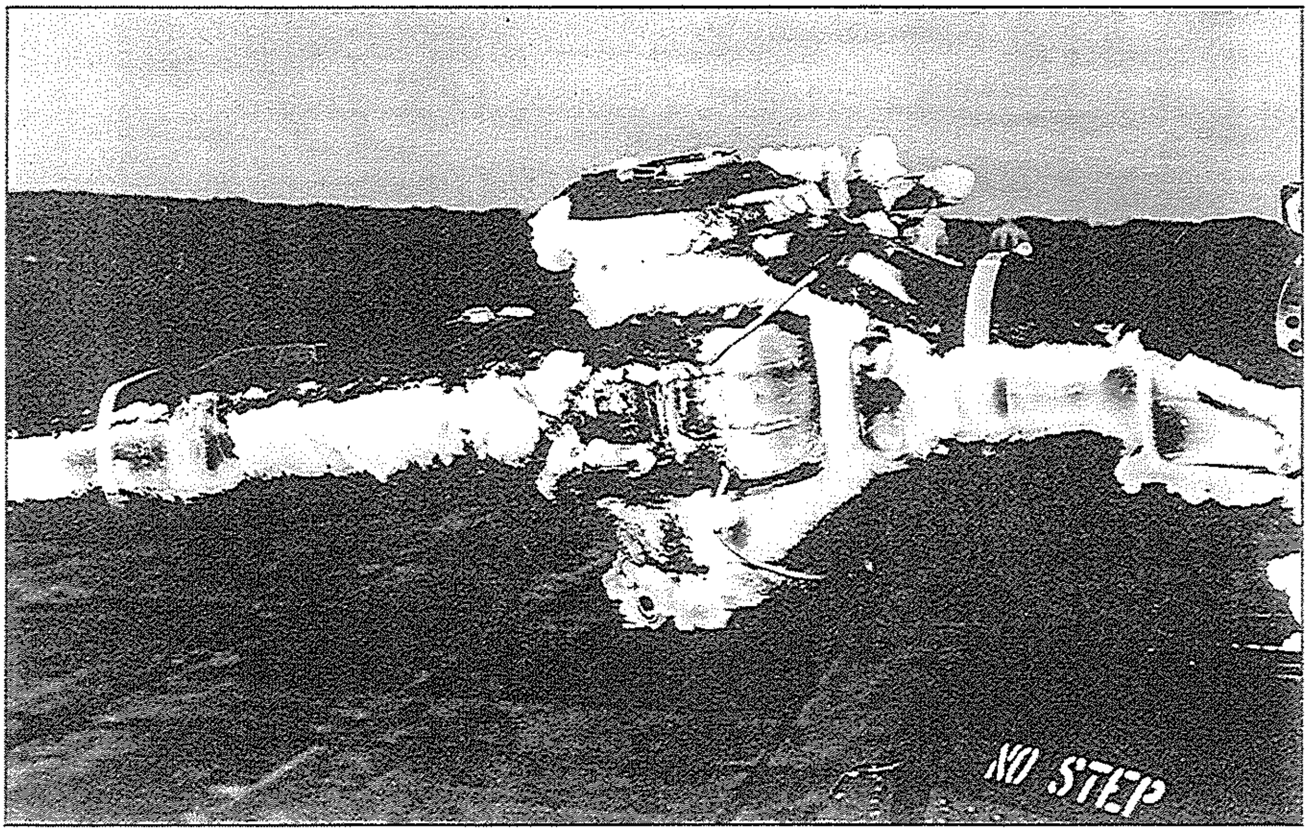

Figure 16: Rotor Head Icing After flight.