PAPER Nr.: 105

HC-Mk1 (CHINOOK) HEATED ROTOR BLADE ICING TEST
PART II
ANALYSIS OF ATMOSPHERIC CONDITIONS, AIRCRAFT AND SYSTEMS CHARACTERISTICS

PHIL DUNFORD

SENIOR FLIGHT TEST ENGINEER
BOEING VERTOL COMPANY,
PHILADELPHIA, PENNSYLVANIA U.S.A.

AND
ROGER FINCH

ROTARY WING PERFORMANCE TRIALS OFFICER,
AEROPLANE AND ARMAMENT EXPERIMENTAL ESTABLISHMENT
BOSCOMBE DOWN, ENGLAND

TENTH EUROPEAN ROTORCRAFT FORUM
AUGUST 28 – 31, 1984 – THE HAGUE, THE NETHERLANDS

HC-MkI (CHINOOK) HEATED ROTOR BLADE ICING TEST

PART II

ANALYSIS OF ATMOSPHERIC CONDITIONS, AIRCRAFT AND SYSTEMS CHARACTERISTICS

PHIL DUNFORD
Senior Flight Test Engineer
Boeing Vertol Company
Philadelphia, Pennsylvania U.S.A.

AND

ROGER FINCH
Rotary Wing Performance Trials Officer,
Aeroplane and Armament Experimental Establishment
Boscombe Down, England

ABSTRACT

The Royal Air Force requirement for a heated rotor blade de-ice system, the environmental conditions in which the system was required to operate satisfactorily and the general areas in which aircraft characteristics could not be degraded have been discussed in Part I of this paper.

Part II will extend and amplify the information contained in the above paper with respect to the types of analyses performed, the test methods used, the environmental conditions encountered and the optimised performance attained.

Plans for the next certification phase of the programme will also be discussed.

INTRODUCTION

General

Part I of this two-part paper described the extensive modifications made to a standard Royal Air Force HC-MkI Chinook to provide a test vehicle that could take full advantage of available natural icing conditions. It went on to describe the reasons for selecting CFB Shearwater in the Canadian Maritimes as the test site and presented data to support this choice. Part II of the paper will present and discuss the procedures employed to develop and optimise the heated rotor blade de-ice system. It will cover the analytical aspects of the test programme with special emphasis on the analysis techniques employed to process performance, flight loads and blade temperature data in flight. It will present the test results from this winter's trial and will outline the plans for next winter's testing.

Test Objectives

Before discussing the test techniques and results in detail, a review of the test programme objectives is in order. The overall aim of the programme is to provide a Controller of Aircraft (CA) Release for flight in icing conditions down to -20°C after two seasons' testing. In order to realise this aim, the Boeing Vertol Company (BVC) and the Aeroplane and Armament Experimental Establishment (A&AEE) Boscombe Down have worked together since the programme go-ahead in April 1982. The primary objective of the first season's testing was to define an optimum rotor blade de-icing system for evaluation by A&AEE during the second season. The primary, secondary and concurrent objectives of the first season's testing are shown in Table 1. Although the first season's testing was aimed at developing the de-icing system, it was hoped that a good proportion of the test results could be used to provide the evidence required for CA Release.

Presented at the 10th European Rotorcraft Forum, The Hague, The Netherlands, August, 1984.

Primary

- Determine optimum Element On-Time (EOT) schedule (heater mat heating period as a function of Outside Air Temperature) for operation to -20°C in maximum continuous conditions.
- Determine optimum heater mat sequence to shed ice with minimal run back in conjunction with EOT schedule established above.
- Define requirements for change in EOT or mat sequencing to ensure survivability objectives are realized in periodic maximum conditions to -20°C.
- Define an acceptable droop stop configuration for flight in icing conditions.

Secondary

- Determine acceptability for flight in snow, freezing rain and mixed conditions.
- Determine whether engine inlet anti-icing bleed air could be deleted or reduced, with All Weather Inlet Screens installed.
- Define the most cost effective ice detector, OAT sensor and satisfactory locations for both.
- Determine acceptability of pitot, static and sideslip port heaters and windshield anti-ice.

Concurrent (As time permits)

- Evaluate mission equipment (rescue hoist, cargo hooks, heater, antenna and venting, etc.
- Determine limits for operation with unheated rotor blades.

TABLE 1 TEST OBJECTIVES - FIRST SEASON'S TESTING

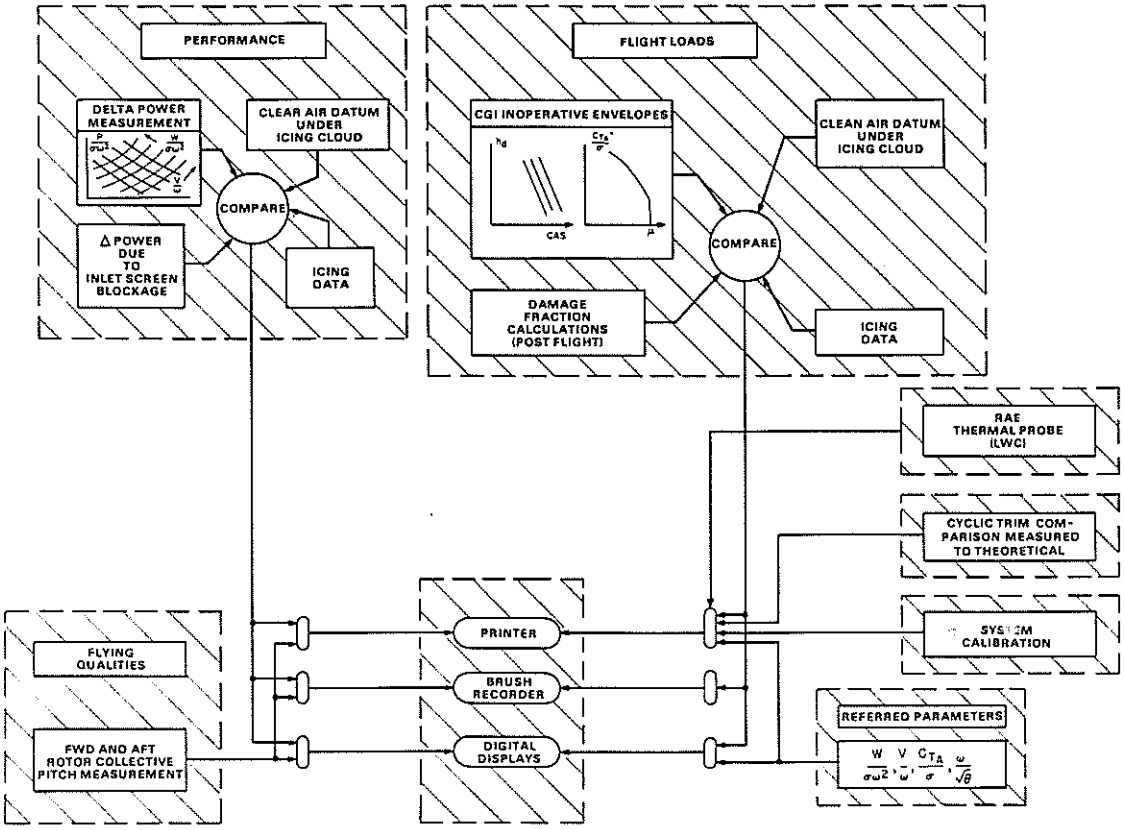


FIGURE 1 COMPUTER FLOW DIAGRAM

DATA ANAYLSIS

Before detailing the test results, it is pertinent to explain the software formulated specifically for these tests.

In order to make optimum use of available icing conditions and working within the constraints of a two-year icing program, an on-board computing capability was developed by BVC, that, in conjunction with a sophisticated Blade De-Ice System control, provided the capability to synthesize data and present it to the flight engineer in-flight.

Three primary categories of analysis were developed:

1) Performance
2) Flight Loads
3) Flying Qualities

The basic system concept was to provide the engineer with icing to clear air data comparisons in each of these categories in flight, which afforded the following advantages:

- It provided an on-board, real time capability that could be used without telemetry.
- It reduced post-flight analysis.
- The real time determination of rotor icing induced power and flight loads accelerated de-ice system optimization.
- It provided increased test flexibility when used in conjunction with the aircraft's extended range capability.
- It reduced 'down time' and costs.

Total system calibration capabilities were also incorporated which completely divorced the aircraft from the requirement to be 'tied-in' to a ground station for preflight calibration.

Figure 1 is a simplified computer flow diagram, illustrating the varied capability of the system. The extent of the instrumentation standard has been defined in Part 1 of this paper and will not be repeated here.

Level Flight Performance Analysis

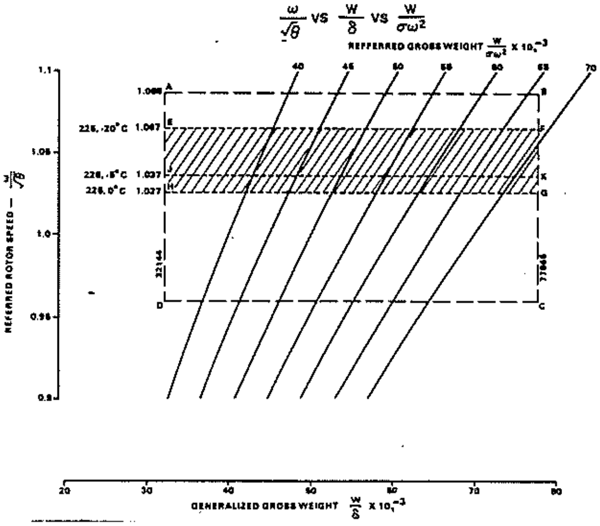
Of primary concern to the development phase of the test program was the derivation of 'Delta Power', which was defined as the difference between rotor power required in icing conditions and a clear air baseline power required at the same 'referred' flight condition (i.e., referred speed, gross weight, and rotor speed). 'Delta Power' was calculated separately for each rotor head using data averaged over a 15-second time slice. The primary advantage of measuring individual rotor power contributions was that when optimising a given control law and or heating sequence, the power degradation attributed to each rotor head could be separated. This was particularly important in more severe icing conditions when the 'inactive' (unheated) rotor was free to build ice rapidly while the 'active' (heated) rotor was de-iced. (Note: Alternator capacity restricts the system from de-icing both rotors simultaneously.)

Baseline Power Derivation and Storage

(Figure A1 of Appendix)

A set of speed power polars, flown at a range of referred gross weights that were comensurate with the conditions anticipated at the test site, were flown at the Boeing Test Center at Wilmington, Delaware in temperate weather conditions (see Figure 2).

FIGURE 2 HC Mk1 BASELINE PERFORMANCE TESTING ENVELOPE



NOTES:

1. BOX ABCD CORRESPONDS TO LIMITS OF RFP REQUIREMENTS AND AIRCRAFT LIMITATIONS.
2. BOX EFGH BASED ON SAME AS (1), BUT ROTOR SPEED FIXED AT 100%.
3. LINE JK DEFINES THE RANGE OF TEST POINTS AVAILABLE FOR $\frac{\omega}{\sqrt{\theta}} = 1.037$.

This provided baseline, clear air, carpet plots for each rotor head which were stored in the on-board computer. This data was gathered in the same external airframe configuration as was subsequently flown in icing.

The on-board computer was given the capability to interpolate linearly between any two referred gross weights to obtain the equivalent clear air rotor power that corresponded to the referred values of icing test airspeed, gross weight and rotor speed.

Blade Tip Mach Number Corrections

The baseline testing was flown at a referred rotor speed of 1.037. This corresponded to an actual rotor speed of 225 rpm @ -5°C. A correction for variations in blade tip mach number drag characteristics at referred rotor speeds other than 1.037 was included in the computer software. Real time power adjustments were incorporated that corrected the clear air data for the effects of the icing condition referred rotor speed. This correction was derived from an extensive CH47 fiberglass rotor blade (FRB) cold weather data bank.

Correction for Change in Altitude

In straight and level flight with only small variations in altitude, the delta power programme worked well. Discrepancies were encountered when accounting for altitude changes in turbulent conditions and in high rates of descent as a result of insufficient rate of climb/descent resolution.

For the second phase of the programme, a 'complimentary filtering' technique will be incorporated to account for the effects of 'quasi static' climbs and descents and gust upsets. This technique will sense vertical acceleration and absolute pressure altitude in lieu of rate of climb and descent.

Pre-Icing Power Checks

Before entering the icing cloud, clear air power checks were made below the icing cloud at the test airspeed to provide a check on the stored data base. A capability was incorporated that allowed the engineer to update the data base with an increment of power to correct significant discrepancies. As the test progressed and confidence in the system improved, the accuracy of the on-board computer interpolating procedures negated the need for this correction.

Concurrent Performance Analysis

A similar icing to clear air power-required analysis was made using engine torques and fuel flow as the basis for comparison.

Engine Inlet Screen Blockage

One of the secondary objectives of the testing was to confirm that the Lycoming T55-L-11E Engines, fitted with All Weather Inlet Screens, could be flown without incurring serious performance penalties with bleed air anti-icing off, and with iced over screens. The derivation of engine power available degradation due to inlet screen blockage was determined in flight using inlet total and static pressure measurements, engine torque and rotor speed.

Rotor Flight Loads Evaluation

(Figure A2 of Appendix)

An icing/clear air flight loads comparison was made to identify the effects of blade icing on the HC-MkI cruise guide indicator (CGI) inoperative flight envelopes based on: a) aft rotor stall characteristics, and b) forward rotor tip mach number induced loads. (The latter is normally critical at high speed and low ambient temperature; the former at high speed, high weight and high altitude.)

The data base used for the analysis was from data obtained on YCH-47D and CH-47C/FRB aircraft.

Aft Rotor Blade Stall Effects

On the CH-47 the primary rotor control components do not incurr fatigue damage as long as the cruise guide indicator remains in the 'green band' (the acceptable level). The CGI is fed by two processed 'fixed link' loads, one on the forward rotor and one on the aft. Should the load in either of these links exceed predetermined levels, the CGI will indicate an excursion above the green band and the rotating and fixed controls may incur fatigue damage.

The purpose of the in-flight monitor was to be able to quickly assess whether blade ice accretion induced significantly higher flight loads than in clear air.

The aft fixed link load was monitored over a 15-second time slice and the value of aft rotor thrust coefficient (Cta/σ) and advanced ratio (μ) derived, for that period of time.

The comparison between icing and clear air data was made when the aft fixed link load parameter exceeded a given load threshold. Loads below this value were ignored. The value of μ was calculated at the Cta/σ for the test condition and compared with the clear air value of μ at the same Cta/σ. Any reduction in μ, with these conditions satisfied, represented a degradation in flight envelope limits due to icing.

Forward Rotor Flight Loads - The forward swiveling actuator load was monitored to measure advancing blade tip mach number induced loads. The data obtained in icing was compared to the extensive BV clear air data base using a similar method to that used for the aft fixed link data.

Fatigue Damage Rate Calculations

(Figure A3 of Appendix)

Damage Rate Monitor - A microprocessor was programmed to convert the peak-to-peak loads of six critical components to DC voltage levels to facilitate real time fatigue rate and damage fraction analyses. These critical components were:

1) Aft Rotor Shaft
2) One Forward Rotor Pitch Link
3) One Aft Rotor Pitch Link
4) Forward Swiveling Actuator
5) Aft Fixed Link
6) Forward Fixed Link

These loads were monitored real time for proximity to a predefined fatigue damage rate limit. A 15-second time slice of data for each load was analyzed in four rotor cycle segments (12 load cycles in the case of a 3/rev load, or 4 load cycles in the case of a 1/rev load).

The microprocessor was used to select the maximum alternating (peak-to-peak) load in each four-rotor cycle sample. The assumption was made that all load cycles in the data sample achieved the same value as the maximum minus the minimum load encountered in that sample. (Used to ensure conservatism.) The microprocessor then derived a 'DC' voltage level equivalent to this maximum alternating value.

For each of the selected components, a table of load increment vs. a percentage of 10-hour damage rate cut-off (Kn) was developed and stored in the on-board computer. For each four-rotor cycle sample, the computer selected the load increment with a maximum load closest to, but greater than, the measured load and summed the values of Kn over the 15-second time slice. At the end of the time slice, the equivalent Kn factors were averaged and presented on the digital displays for the flight test engineer.

Kn was calculated from S/N curve data for each component part.

A wild point edit programme was also included to eliminate any effects of occasional noise spikes in the output not associated with real data.

Damage Fraction Analysis

Traditionally, fatigue life calculations are a time-consuming post-testing requirement involving mission spectrum definition and damage fraction calculation for critical component parts. A continuous on-board computer-based damage fraction analysis has been developed for the icing programme which will considerably reduce the post-flight requirements. The same critical loads that were monitored for the 'damage rate' calculations will be analysed for this programme, using the same AC to DC load level conversions. The concept was proven during the Phase I testing and, after minor software changes have been incorporated, will be used to calculate critical component fatigue lives in icing with the optimised de-ice system control laws functioning during Phase II.

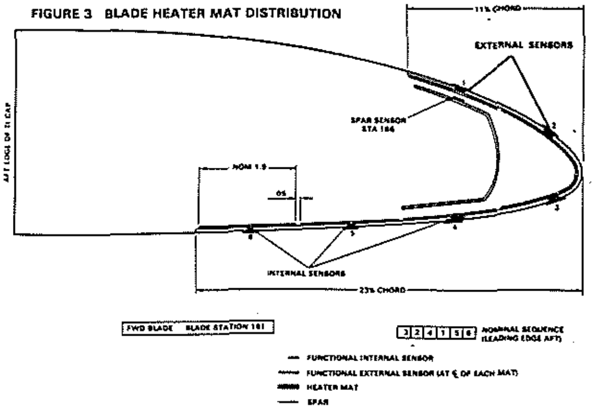
Flying Qualities-Blade Angle Measurement

An estimate of the effect of icing on the blade lift characteristics was obtained by monitoring trends in collective pitch required to hold a given level flight condition. This was calculated for each rotor head individually and derived from summations of differential collective pitch inputs resulting from longitudinal stick, collective lever and the Differential Airspeed Hold Actuator (DASH). (Pitch SAS was not instrumented, because its effect was only contributary in turns.) This data, averaged over a 15-second time slice, was presented to the flight test engineer on a brush recorder and on the digital printer.

Blade Thermal Analysis

Internal and external blade temperature measurements were made on one aft rotor blade and one forward rotor blade. Figure 3 is a diagrammatic cross section of a forward instrumented blade which shows the relative positions of internal and external temperature sensors.

FIGURE 3 BLADE HEATER MAT DISTRIBUTION



In addition to providing an in-flight blade temperature monitor during de-ice cycles, these temperature measurements have been used as the basis for temperature extrapolations to the limits of the optimized element on-time law.

Blade Temperature Monitor

In order to ensure that blade adhesive layer temperatures remained at acceptable values during all de-icing operations, blade temperature monitor software was employed in the on-board computer. This routine monitored two critical blade temperatures and the de-ice system element on-time. If either of the two parameters exceeded predefined values, the engineer was advised by a flashing display.

The on-board computer was also programmed to count the number of heating cycles accomplished per flight and to sum times in excess of limit temperatures, providing printed data output at the end of the flight.

Extrapolation Techniques

We are currently exploring the possibility of using a combination of blade temperature data, rotor head camera photographs, math model predictions and a knowledge of the icing environment to predict the acceptability of aircraft performance and flight loads in icing conditions not encountered during testing.

These predictions will be the result of a continuous 'feed back' of actual test data to a math model at each test condition. Correlations between LWC, OAT, droplet size, shedding characteristics, aircraft performance, flight loads and blade temperatures will be formed as the basis for this extrapolation technique. The complexity of the technique and the variable nature of icing warrants the incorporation of an iterative procedure that may require considerable revision before a reliable method is established.

BASELINE TESTING

The test equipment installed on the HC--MkI considerably altered the external configuration of the standard aircraft increasing the flat plate area by approximately ten square feet. The majority of this drag increase was comprised of the rotor head camera and pedestal (see Figure 4). This configuration change was significant enough to warrant the following clear air investigations to establish confidence in the integrity of the package and to establish flight loads and performance baselines for real time icing/clear air comparisons.

FIGURE 4 PICTURE OF HC-Mk1 AFTER FLIGHT IN FREEZING RAIN)

Flight Load Survey

An extensive flight load survey was conducted to determine the dynamic stress levels in the rotor blades, rotor hubs, rotor shafts and control linkages. Testing was conducted throughout the aircraft's flight envelope and results fell within the scatter of flight loads data from previous CH-47C&D testing. In-flight stress measurements of the camera support pedestal were found to be well within design limits.

Flying Qualities

Positive lateral and directional static stability was observed throughout the flight envelope with the rotor head pedestals installed. Dynamic stability characteristcs were unaffected.

Vibration Survey

The size and weight of the rotor head camera installation warranted a careful approach to in-flight evaluation. A detailed bench and progressive in-flight vibration evaluation was conducted. Tests included:

- A shake test and endurance run of the rotor head camera at frequencies and vibration levels equivalent to normal CH-47 hub measured values.

- Bench shake tests to determine complete installed system resonant frequencies.
- On-aircraft 'bang' checks to determine the installed natural frequency.
- Blades off-ground run.
- Blades on-ground run.

The resonant frequencies of the installation did not coincide with Chinook rotor harmonics, and in-flight vibration levels were acceptable in all aircraft loading configurations.

Performance Baseline

The performance baselines were flown to define a comprehensive set of speed power polars for the HC-MkI in the external icing configuration. These formed the basis of the icing to clear air performance comparison. Six (6) speed power polars were flown between 60 and 140 KTAS. Data was analysed real time on the BVC Real Time Data System. The referred gross weights were chosen at 5000-lb intervals to provide acceptable resolution in the on-board computer interpolation process.

Blade Temperature Considerations

The HC-MkI rotor blades are fabricated from fiber composite materials. It was therefore necessary to provide a blade temperature monitor in critical areas of the blade lay-up. A comprehensive set of surface and leading edge sensors was installed in one forward and one aft blade. (See Figure 3)

Two specific locations were chosen, one in the area of the spar and the other under the titanium cap on the leading edge.

Before applying heat to the rotor blades, a comprehensive thermal and fatigue analysis study was conducted. This work encompassed:

- Thermal Test Panel Tests - The panel was used to measure the thermal profiles across representative blade section to calculate material conductivity values for use in the Thermal Math Model.
- The Thermal Models were based on one and two-dimensional finite difference analyses developed at the University of Toledo. Results were later correlated with flight data at the locations of the blade temperature sensors and used to predict blade temperatures at element on-times (EOTs) in ambient conditions not encountered.

An evaluation of the effect of de-ice system heating cycles on the HC-MkI composite blade structure was also conducted. The following tests and analyses were made:

- Calculation of Ultimate Fatigue Margin of the Basic Blade
- Calculation of Blade Spar Thermal Forces and Moments
- Calculation of Longitudinal Thermal Strain and Shear Stresses
- Calculation of Shear Stress in the Nose Block Area
- Calculation of Interlaminar Shear Stresses
- Nastran Finite Element Analysis
- Coupon Tests for Adhesive Tension Fatigue Strength

DE-ICE SYSTEM OPERATION

As outlined in Part I, for development purposes, the de-ice system was controlled by a test engineer using the Development Test Panel (DTP). The DTP allowed the engineer to accomplish the following tasks, in flight when necessary:

- Change the element heating sequence.
- Vary the Element On-Time (EOT) as a function of OAT.
- Select one of three Ice Detector Units (IDU's) and one of two OAT sensors for de-ice system control.
- Change the ice thickness threshold at which the de-ice system was triggered (thus controlling the off-time).

As the trial progressed and a wider range of LWC/OAT conditions were encountered, the nominal settings were varied as necessary in accordance with the optimization procedures shown in block diagram form in Figures 5 and 6.

A nominal de-ice system mat sequence and on-time law were employed initially. Shown on Figure 3 is the heater element arrangement around the blade leading edge. Each mat or heating element is 1.9" wide and is separated from its adjacent element by a 0.50" gap. The elements extend from the leading edge to 11% chord on the blade upper surface and to 23% chord on the blade lower surface. All six elements extend spanwise along the entire length of each blade. In the icing environment, the de-ice system worked as follows:

- With the system 'ON', the ice detector (IDU) triggered the de-ice controller to apply electrical power to the aft rotor first, once a pre-selected thickness of ice had accreted on the probe of the IDU. Power was applied simultaneously to corresponding elements on each blade of one rotor in a pre-selected sequence.

The 'nominal' heating sequence activated Mat 3 first then 2, 4, 1, 5 and 6. The heating time of each element was a function of OAT as shown by the optimized on-time law in Figure 14. Typically, EOT's varied from some 3 seconds at 4°C to between 19 and 26 seconds at -20°C depending upon the heater mat. When the mat sequence had been completed on the aft rotor, power was switched to the forward rotor and the process repeated. When both rotors had completed their heating cycle, the system either:

- Switched itself off and waited for the IDU to accrete the required amount of ice to trigger the system again

or

- operated continuously if during the previous de-ice cyle the IDU had accreted sufficient ice to trigger the system. (This was always the case in high LWC's.)

Blade de-icing was inhibited above 0°C or following the failure of either generator. The system design allowed continued heating in the event of a single heater element failure and some double element failures. Various failure tests were conducted during the trial and these are discussed later in the paper.

TEST APPROACH AND OPTIMISATION TECHNIQUES

Chinook icing experience prior to the start of this test programme was limited to flight in natural icing conditions with an unheated rotor system and limited testing with a breadboard blade de-ice system behind the HISS tanker (CH-47C/FRB and YCH-47D US Army Trials and HC-MkI Trials in Denmark). During these trials, the Chinook had demonstrated some degree of tolerance to flying in icing conditions without the use of blade heat and both the UK and USA Military clearance agencies have recommended "unheated" icing releases for the HC-MkI and CH-47D respectively. However, the icing clearances recommended are limited, particularly in terms of Outside Air Temperature (OAT) because of:

(1) Unacceptable aircraft lateral vibration resulting from asymmetric rotor blade ice shedding at OAT's around -9°C and colder

and

(2) The problem of blade damage caused by shed ice.

The nature of icing testing precludes the preparation of detailed test profiles, since the desired icing conditions cannot be 'dialed-up' in advance.

A test technique was soon evolved, however, whereby level flight was established at the intended icing test airspeed just below the cloud, and a clear air "datum" recorded (rotor power, engine torques, and collective lever position were noted.) The aircraft was then climbed into the cloud at best climbing speed with the de-ice system 'ON' with the aircrew monitoring Liquid Water Content (LWC) and Outside Air Temperature (OAT) in the climb to determine the altitude for the optimum LWC/OAT combination (this was usually 50 to 100 feet below the cloud tops). At a height which appeared to give the best icing, (i.e. highest LWC) the aircraft was levelled and accelerated to the test airspeed which was usually in the range 100 to 130 knots Indicated Airspeed (IAS) depending on the aircraft weight and test altitude. The pilot was then instructed to maintain the test airspeed and altitude by adjusting the collective control as necessary to compensate for any degradation in aircraft performance caused by ice accretion. Throughout an icing encounter the aircrew monitored the main parameters associated with rotor performance (i.e. forward and aft head "Delta Powers"), engine inlet screen blockage and the prevailing icing conditions, including regular readings of the Vernier Accretion Meter (VAM). Soot-gun slides were taken by the co-pilot (left-hand seat) through his sliding window. When the de-ice system was activated by the de-ice controller, its efficiency was monitored in terms of its ability to reduce loads and rotor performance degradation back to datum levels by reference to the alpha-numeric displays and the strip chart trend recorder located at the test director's station. When conditions had stabilised in the icing cloud, various aircraft maneuvres were flown. These included climbs and descents, speed changes up to the maximum permitted for Instrument Flight (IF) and turns, initially at Rate 1 and then increasing to a maximum bank angle of 30° (the IF limiting bank angle for the Chinook).

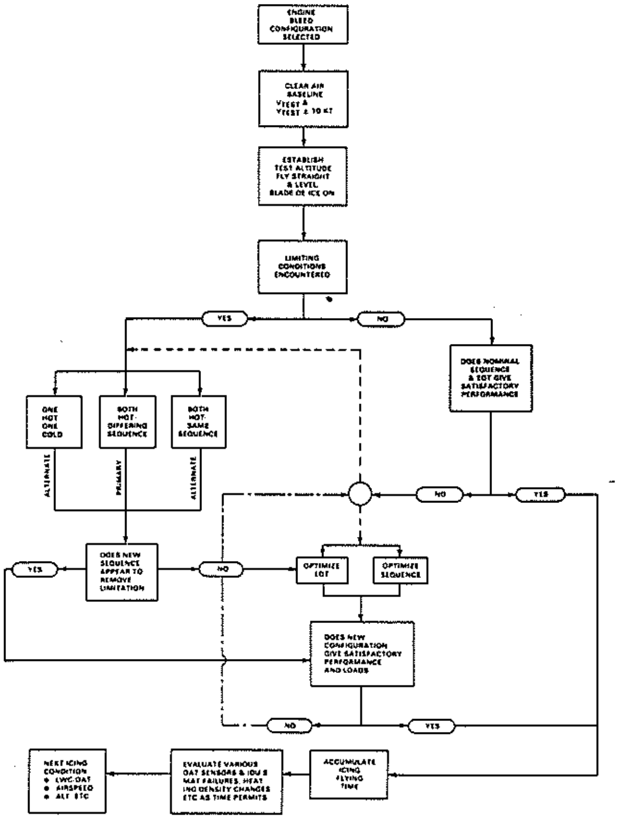


FIGURE 5 DECISION TREE FOR HC Mk1 DE-ICING SYSTEM OPTIMIZATION

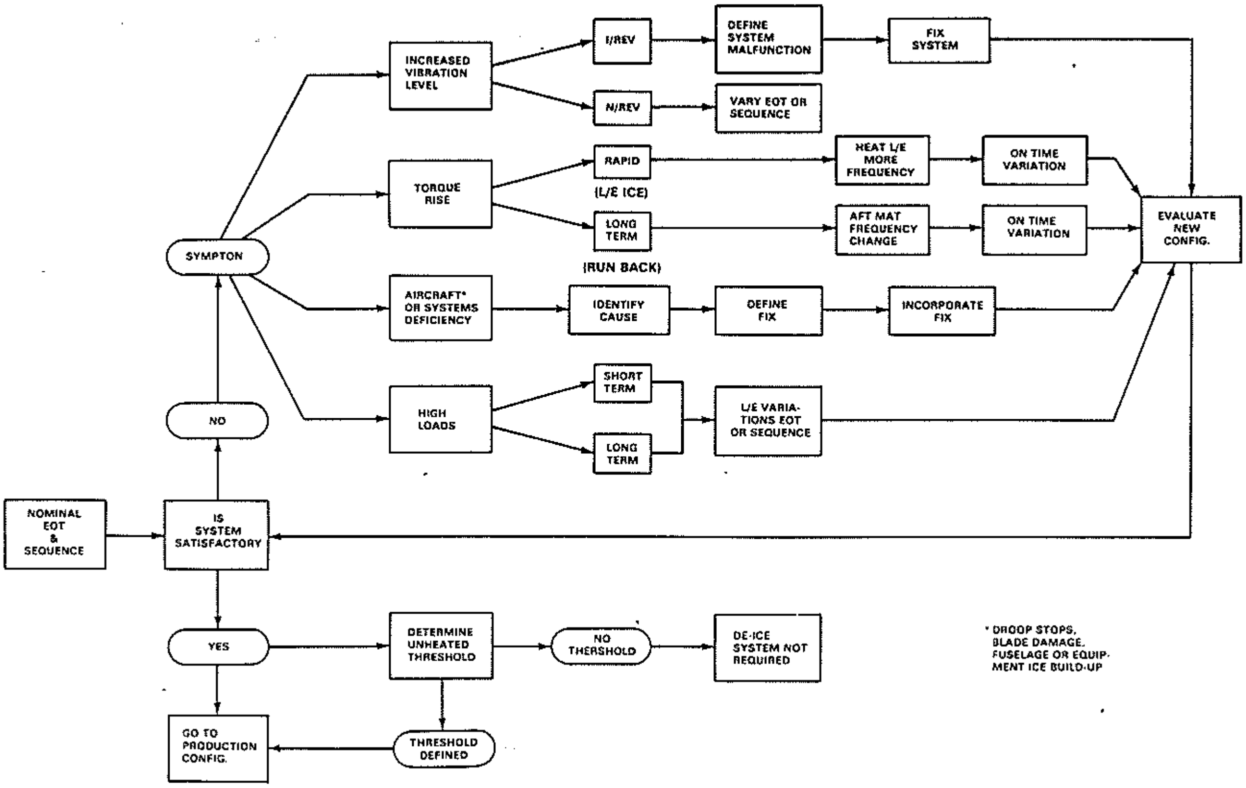


FIGURE 6 DE-ICING SYSTEM OPTIMIZATION

Post-Flight Inspection and Analysis

When the icing conditions 'ran out' in the designated trials area(s) and/or the aircraft's endurance was reached, the aircraft returned to base at a height above the freezing level whenever climatic and air traffic control patterns permitted. On landing, a detailed examination of the extent of residual ice accretions on the engine intakes, the rotor heads, blades and the airframe was made. All ice accretions were logged and most were recorded on video and stills cameras. Figures 7 and 8 show typical ice accretions following an icing flight.

Post-flight analysis included:

° Interpretation of the rotor head camera films using a Film Motion Analyser.

° Processing the aircraft's flight data tape in the computer ground station and producing time histories of calibrated parameters, including 'derived' parameters such as forward and aft rotor delta power and RAE Probe LWC. (See Appendix A4)

° Transferring selected parameters onto a second Winchester disc and accessing this disc via the Trials Officer's intelligent terminal to perform a more in-depth analysis of rotor performance, blade temperatures and icing severity using a suite of programmes specially written by A&AEE.

The various de-ice system variables (mat sequence, element on-time, etc.) were established for individual flights in the light of experience gained from previous testing and the forecast weather conditions for the test area, and were often modified in-flight as a result of the conditions encountered.

FIGURES 7 AND 8

ROTOR HEAD ACCRETION

TEST CONDITIONS ENCOUNTERED

Part I of this paper outlined the conditions experienced in the Canadian Maritime region last winter and presented a summary of the icing flights (Part I, Appendix A). Forty-one natural icing flights were flown. The lowest temperature encountered was -24°C with mean LWC's in the range 0.05 to 0.64 gm/m^3 and transient LWC's over 1.0 gm/m^3. The aircraft's speed in icing was in the range 100 to 130 knots IAS over the altitude range 1,500 to 10,000 feet. Aircraft gross weight at take-off varied between 45,000 lb and 50,400 lb (maximum all-up-weight of the HC-MkI is 50,000 lb). As mentioned in Part I, the longest flight time in icing was 2 hours 17 minutes; in addition, a further 17 flights of one hour's duration or more in icing conditions were experienced. Figure 9 presents the icing conditions encountered in terms of LWC and OAT. Mean LWC's up to 0.5 gm/m^3 were quite common down to -12°C. Two other notable test points were at -11.5°C, with a mean LWC of 0.64 gm/m^3 and 0.15 gm/m^3 at -24°C (approximately 115% and 85% of the continuous maximum values of AvP 970, respectively). The extent of the icing experience in relation to FAR AC 29-2 altitude requirement is shown in Figure 10.

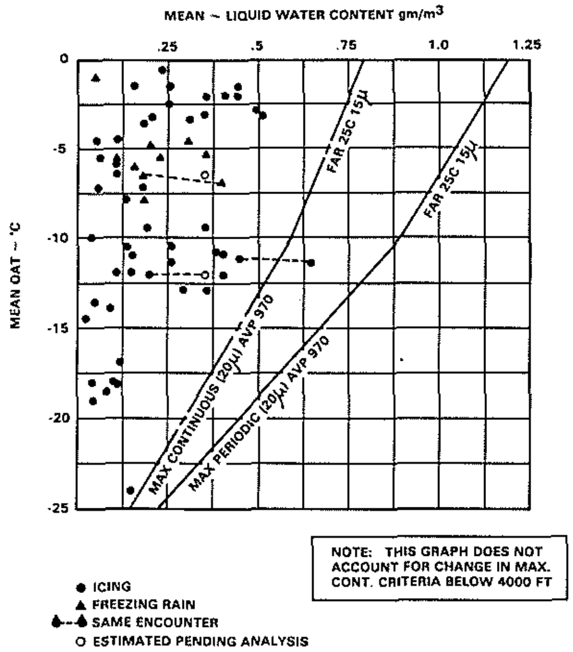


FIGURE 9

SUMMARY OF ICING EXPERIENCE—WINTER 1983/1984 MA020

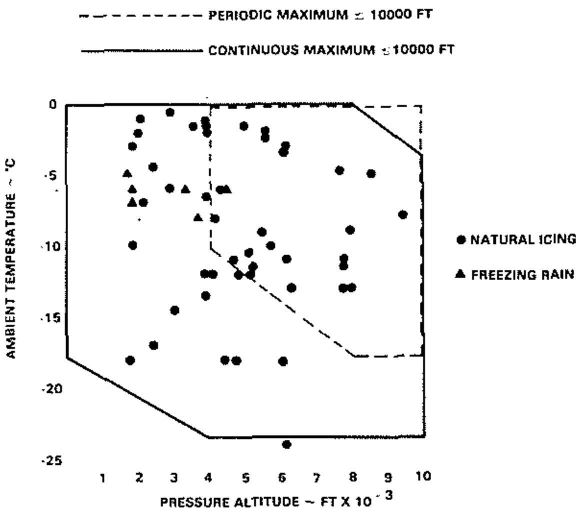


FIGURE 10 RAF ICING TESTS—WINTER 1984/85 ICING EXPERIENCE OAT VS PRESSURE ALTITUDE

As mentioned in Part I, the whole range of icing conditions, including freezing rain and mixed icing/snow, were experienced. The amount of snow flying achieved was low, although the area does experience large seasonal snowfalls. A&AEE will place more emphasis on snow flying in the second, certification winter season. In contrast, the hours spent in freezing rain, some 6 hours, were much higher than anticipated and in the conditions experienced caused no handling or significant performance degradation. Figure 4 shows the large quantities of ice that can accrete on the airframe in freezing rain.

In addition to the greater-than-expected exposure to freezing rain, two other interesting observations have emerged from the winter's testing and the earlier A&AEE trials in Denmark during the winter 1982/83. In all the trials, water droplet size has been measured using a Knollenberg nephelometer and the results have been compared with the ARL soot slides which were exposed periodically during icing flights. Generally, the soot slides have shown droplet sizes between 2 and 5 microns lower than comparable values from the Knollenberg. The mean diameter of droplets in the temperature range tested has usually, with the exception of freezing rain, been lower than anticipated, between 5 and 15 microns. Further analysis is planned to relate water droplet size to ambient temperature. The data was presented more fully in Part I of this paper.

In the UK AvP 970 (Icing Atmosphere), it is assumed that the maximum LWC decreases as a function of altitude below 4,000 feet. During the trial at Shearwater, it was noticed that LWC values below 4,000 feet appeared on a number of occasions to be higher than would be expected from the AvP 970 relationship. Further analysis is needed to show the extent of the discrepancy.

RESULTS AND DISCUSSIONS

With the optimized control laws implemented, the blade de-ice system functioned satisfactorily in all severities of icing to -24°C (the coldest temperature at which significant icing was encountered).

At the time of writing, both A&AEE and Boeing Vertol are engaged in finalizing the analysis from this development phase. Enough has been accomplished, however, to present preliminary results in the following areas:

- Performance - Range, airspeed and rate of climb degradation.
  - Engine inlet blockage characteristics.
- Flight Loads Preliminary Summary
- Blade Temperatures
- In-Flight Simulated Failures Analysis

Before describing specific results, the following qualitative comments are pertinent and are presented in specific temperature ranges that seemed to form natural divisions in the environment. The comments apply to the system operating with optimized control laws.

Temperature Band 0°C to -4°C

- Test data confirmed that with the possible exception of extended flight in freezing rain, the blade de-ice system was not required to maintain acceptable performance levels.
- Surface temperatures remained positive in the blade working area. The blades did not accrete significant amounts of ice outboard of 40% span and satisfactory shedding was achieved along the entire span.
- Prior to system optimization, run-back ice was observed on the upper blade surface out to 45% span.
- High LWC's were often encountered in these warmer OAT's and large airframe ice accretions were common after long immersions. Only small performance penalties were incurred.

Temperature Band -4°C to -8°C

a) Natural Icing

- The blade de-ice system, with optimized control laws, always contained the cyclic performance degradation to within specified limits.
- Ice accretions were characteristically rough and did induce increased cruise guide indicator activity.
- Leading edge heater mat failures were easily tolerated although performance degradation and CGI activity increased. An aft rotor Mat 2 failure was the worst case. (See Figure A4.)

b) Freezing Rain

- Nodules of ice formed inboard of 35% span behind the run-back mats (1 and 6). These formed a barrier to any run-back water and instigated the growth of a run-back ridge behind Mats 1 and 6. This induced a long-term performance penalty that was never fully eliminated by the de-ice system; however, this was within the RFP objectives.
- Large water droplets in freezing rain caused ice to grow well over Mats 2, 3, and 4 in a 'clam shell' pattern. However, satisfactory leading edge shedding was achieved with optimized control laws along the entire span.
- The blade de-ice system was required to contain performance and flight loads to within acceptable levels.
- Heavy airframe ice accretions, even on low catch efficiency bodies (i.e. nose of aircraft) were characteristic of extended flight in freezing rain and were very similar to those observed on the YCH-47D after flights behind the Helicopter Icing Spray System (HISS), prior to water droplet size improvements.

Temperature Band -8°C to -14°C

- This temperature band produced the most significant performance and flight loads degradation and CGI activity, thought to be the result of the combination of more extensive chordwise and spanwise accretions.
- Leading edge differential heating was required to ensure complete shedding below -10°C at LWC's up to maximum continuous. At higher LWC's it was necessary to reduce the de-ice cycle length to keep the leading edge free of fast growing ice.
- Leading edge mat failures were more critical in this temperature band. However, performance degradation remained within the RFP requirements.

Temperature Band -14°C to -24°C

- No significant performance degradation was noted in the conditions experienced. Data has shown that the small droplets associated with these colder temperatures only produce small chordwise accretions, effectively extending the blade profile.

- The probability of finding icing in this temperature band is historically low, especially at LWC's approaching maximum continuous values. At OAT's below -16°C, LWC's were normally limited to about 25% of maximum continuous and were characteristically intermittent.
- Increased ice tenacity at these cold temperature opposed the blade natural shedding tendency even after accretion rates had dropped to zero. Ice was observed on the blade leading edge out to 100% span between heating cycles even after the cloud had been exited in intermittent (relatively broken cloud) conditions.
- Run-back mats were not required in this temperature band.

Comments Applicable to All Temperature Bands

- No flying qualities or engine handling problems were observed.
- Occasional mild increases in ambient vibration levels were noted, coincident with the start of a de-ice cycle, cueing the pilot to system operation.
- At no time did the de-ice system induce asymmetric shedding.
- Higher torque increases and CGI activity were noted at high weight and altitude (effect of Cta/σ).
- The Chinook's extended range capability allowed icing contact times of up to 2½ hours. When high LWC's were experienced during these long encounters, large airframe ice accretions resulted. Superficial rotor blade damage was incurred as a result of airframe ice shedding during high rate descents into air masses with temperatures above the freezing level.

ICE SHEDDING

The Rotor Head Camera (RHC) provided a good understanding of the blade ice accretion areas and the effectiveness of the de-icing system in shedding ice from the blade leading edge. The ice thickness threshold setting was optimised during the early part of the trial in order to minimise blade damage as a result of shed blade ice, to keep any one per revolution vibration caused by asymmetric/incomplete shedding to acceptable levels, and to provide continuous de-icing at high Cta/σ when small amounts of ice resulted in premature incipient blade stall.

In natural icing (i.e. no snow or freezing rain present), the primary accretion areas were on Mats 3 and 4 (refer to Figure 3) occasionally extending aft to Mat 2. The spanwise extent of ice increased outboard as OAT decreased; blade photographs showed ice out to approximately 40% span at -4°C, whereas at -18°C full span ice was evident. Figure 11 shows full span ice which was recorded at -18°C prior to de-ice system activation.

Satisfactory removal of ice was achieved during icing encounters, as verified by the blade photography. Figures 12 and 13 illustrate the de-ice process at -10°C.

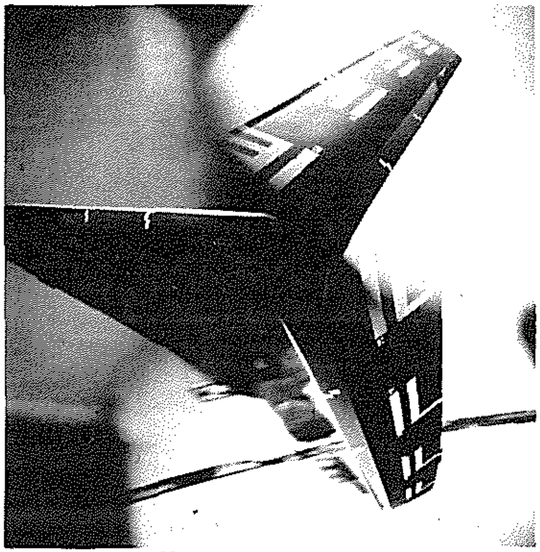


FIGURE 11 (RHC PICTURE 100% SPAN)

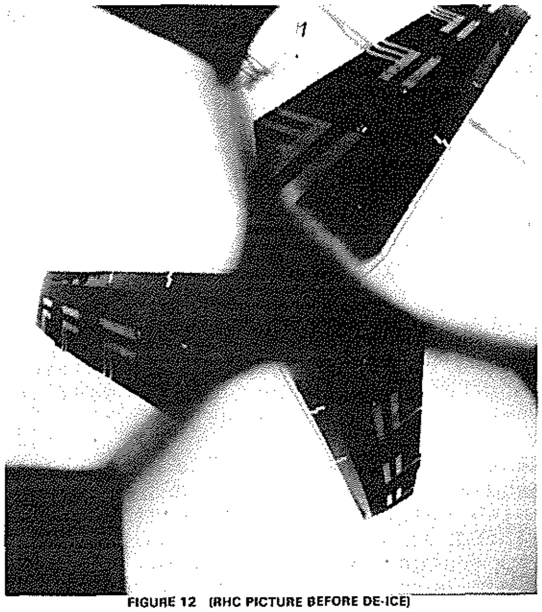


FIGURE 12 (RHC PICTURE BEFORE DE-ICE) -10°C

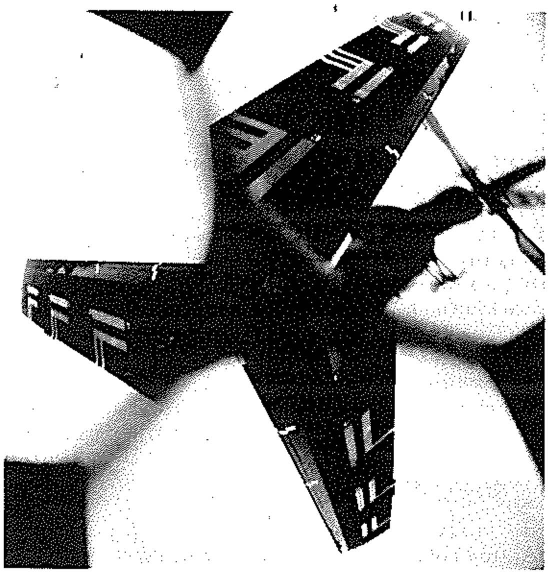


FIGURE 13 (RHC PICTURE AFTER DE-ICE)
−10°C

Analysis of the RHC films showed that some blades were more efficient at shedding ice than others, probably the result of manufacturing tolerances. It was also discovered that the blade surface temperatures were slightly warmer on the forward rotor compared to the aft rotor, this was attributed to voltage losses in the power cables to the rear rotor which will be reduced for the Phase II testing.

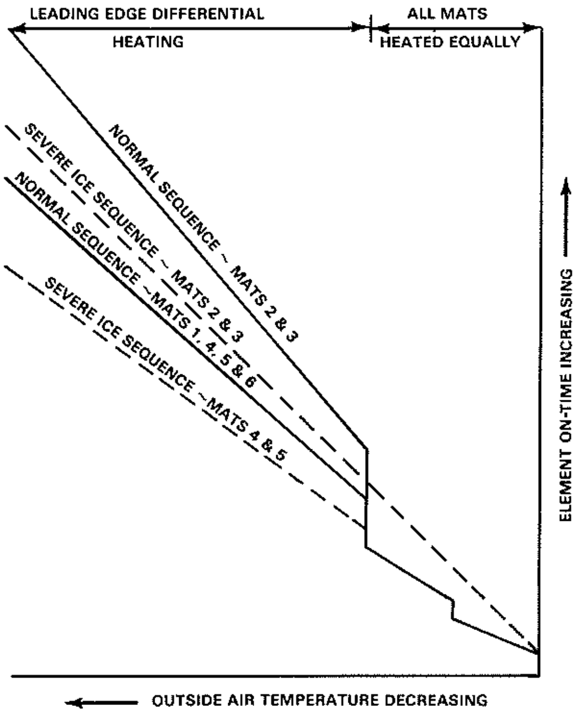
CONTROL LAW OPTIMISATION

Three de-ice system control parameters were varied to optimise the de-ice system:

1) System Ice Thickness Threshold - Measured at the primary system ice detector unit on the forward pylon of the aircraft. This parameter effectively controlled the system OFF time between de-ice cycles. Reducing this parameter, in conjunction with efficient mat sequencing, alleviated performance and flight loads levels, particularly at high Cta/σ. Ice thickness is a direct function of LWC and droplet size. At high LWC's where ice accretion rates are high, the threshold level was easily exceeded before a cycle was completed, thus providing continuous de-icing where it was most necessary.

2) Heater Mat Sequence - The mat heating sequence controlled the order in which the mats were activated and was varied as a function of outside air temperature and LWC. For example, the 'short', severe de-ice cycle was developed to provide a reduced cycle length to return heat to the critical leading edge mats quickly in order to contain performance and loads increases. In the production system, this sequence will be automatically switched in at average LWC's above 60% maximum continuous.

3) Element On-Time (see Figure 14) - which controlled the heater element on-time as a function of outside air temperature. At colder OAT's, a leading edge differential heating function was incorporated which increased the heat to the leading edge mats by a factor of 1.33. When the severe icing option was used, the associated reduced total cycle time allowed the leading edge differential heating factor to be reduced to 1.125 because blade surface temperatures remained elevated using this shortened sequence.



NORMAL SEQUENCE A324156 F324156

SEVERE SEQUENCE A3245 F3245
TWICE THEN ONE NORMAL
'CLEAN UP' SEQUENCE

FIGURE 14 ELEMENT ON-TIME LAW)

These primary system control parameters were fully controllable in flight during development testing. For the CA Release trials in 1984/85, the optimised control laws will be 'hard wired' into the microprocessor controlled system.

PERFORMANCE ANALYSIS

Like other helicopters fitted with de-ice systems, alternator power constraints make it necessary to de-ice the HC-MkI rotor blades rather than anti-ice them. The fact that the rotor blades must be de-iced dictates that one rotor head be heated before the other, thus allowing ice to accrete during a given de-ice cycle on the inactive (unheated) rotor. This ice accretion period, although limited in extent, does cause a finite lift loss and drag increase which is manifested as a cyclic rotor performance penalty. Recognizing that the optimised de-ice system must, by definition, incur a limited performance degradation, the RAF's requirement specification was structured accordingly (see Tables 2 and 3).

- ° Not more than 10% decrease in range.
- ° Not more than 10% decrease in V_{ne}.
- ° Ability to perform a rate 1.5 turn (4.5°/sec) at cruise speed.
- ° Capability to perform 100 fpm rate of climb at maximum weight (50,000 lb.) at minimum power required speed, one engine inoperative at temperatures of 0°C or below, at sea level.
- ° No significant degradation of engines, aircraft and avionics systems.
- ° Component loads below the values which result in a 10% decrease in component lives.

TABLE 2

REQUIREMENTS/TEST OBJECTIVES
FOR CONTINUOUS OPERATIONS

- ° Ability to perform rate 1 turn (3°/ sec).
- ° Flight envelope limit at least 20 kt. above minimum power required speed.
- ° Vibration levels below Pilot Vibration Rating (PVR) of 8. Handling qualities below a Cooper-Harper rating of 7.
- ° Component loads less than values which result in Steady State CGI readings of 125%. (100% is equivalent to the unlimited life limit of aft rotor fixed link.)

TABLE 3

REQUIREMENTS/TEST OBJECTIVES
FOR SURVIVAL IN PERIODIC
MAXIMUM CONDITIONS

Commensurate with this requirement, the performance analysis has been structured to quantify degradation in the following areas:

- Range
- Maximum Level Flight Speed
- Rate of Climb at Cruise Speed
- Engine Inlet Blockage Effect on Power Available
- Heater Mat Failures

Boeing is currently engaged in quantifying the performance penalty throughout the 0°C to -20°C temperature range to show compliance with the RFP, in the above areas. Figure 15 presents preliminary range data and compares the penalty in each temperature band to the RFP requirement. The contributions of screen blockage and rotor performance degradation are identified. The largest degradations occurred at temperatures between -8°C and -12°C.

Between 0°C and -4°C, the combination of the kinetic heat and OAT tends to reduce spanwise extent. Ice accretions were smooth and glazed in character; i.e., caused by impact of relatively large water droplets.

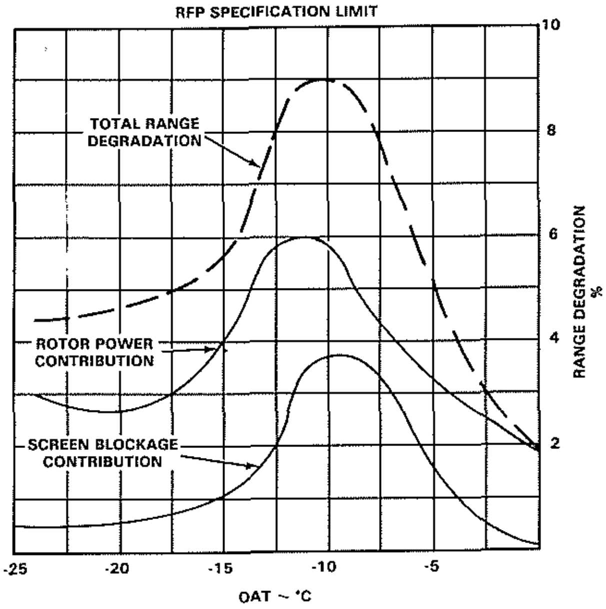


FIGURE 15 PERFORMANCE DATA

Between -6°C and -14°C, the combination of increased chordwise and spanwise extent produced the highest rotor and engine power requirements. The beneficial effect of blade kinetic heat was reduced as the OAT decreased producing spanwise growths well into the blade 'working area'.

Between -15°C and -20°C, the ice was rime in nature, the result of small water droplets. These small droplets tended to extend the profile of the blade only and did not induce significant chordwise coverage. The kinetic heat/ OAT effect was insufficient to prevent ice growing to 100% of span at temperatures approaching -20°C but the small chordwise coverage offset the anticipated performance penalty.

The effect of rotor blade and airframe icing on power available to climb and reduction in maximum speed is still being quantified. As an example, preliminary results indicate that in the worst case (Flight X-120 at -12°C), an 8-knot reduction in maximum speed can be expected at 47,000 lb and 4,000 ft density altitude. The power reduction will result in a degradation of about 200 ft/min in climb capability at this flight condition.

ENGINE INLET CHARACTERISTICS

Bleed Air Anti-Icing

YCH-47D tests in 1980 were conducted successfully with one engine anti-icing bleed air system switched off to evaluate the effectiveness of the All Weather Screen in protecting the engine. The results of this testing and previous extensive wind tunnel testing provided a sound basis for the decision to incrementally reduce engine anti-ice bleed air contributions until they were totally eliminated. Extensive engine ice ingestion tests were conducted by A&AEE prior to their unheated rotor blade tests in Denmark and had shown the engine to be very tolerant of ice. The HC-MkI, therefore, provided the vehicle to substantiate these earlier claims in an intensive period of representative icing flying.

Seventy-five percent of the icing encounters were flown without engine bleed air anti-icing, and all flights were flown with at least one engine anti-icing switched off.

A fibre-optic engine inlet monitor was installed which allowed the flight test engineer to observe the engine 'D' ring for the duration of the icing encounter. No significant accretions were noted either in-flight or during post-flight inspections.

The total elimination of engine inlet bleed air provides approximately 3% improvement in range performance which effectively offsets the degradation incurred by partial screen blockage.

Inlet Screen Blockage

In-flight observations and photographs have also shown that due to the flexible characteristics of the engine inlet screen, they never become completely blocked. See photograph at Figure 16.

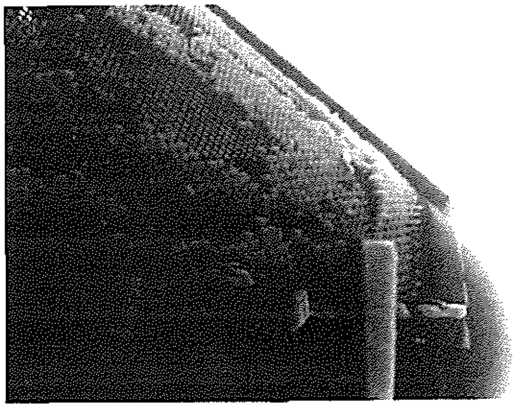


FIGURE 16 ENGINE INLET SCREEN ICING

Total and static engine inlet pressure measurements were used to provide a real time 'engine blockage' power available degradation measurement with partially blocked screens. In the more critical LWC/OAT combinations, an average value 4% screen blockage over an extended icing encounter was incurred (see Figure 17).

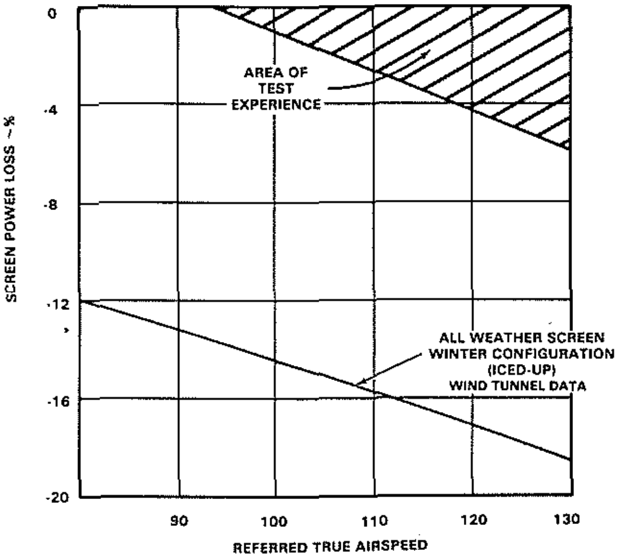


FIGURE 17 ENGINE BLOCKAGE DATA AS A FUNCTION OF AIRSPEED

FLIGHT LOADS

The usefulness of the Cruise Guide Indicator (CGI) in icing conditions and its integrity and value as a cue to increased loads due to icing was an important aspect of the data review. Of particular importance was the need to determine whether the Cruise Guide Indicator protected rotating and stationary components to the same degree as in clear air flight.

A flight envelope is available to military Chinook users that defines airspeed limits in the event of a CGI failure. This is a conservative envelope which is based on the aft rotor fixed link load level. On some occasions in the icing environment in moderate to severe turbulence, this envelope was exceeded (see Figure 18), indicating that there was an effect of ice on rotor loads. With optimised de-ice system control laws, this occurs when the aft rotor is not being heated during the de-ice cycle and is free to accrete ice in high LWC's.

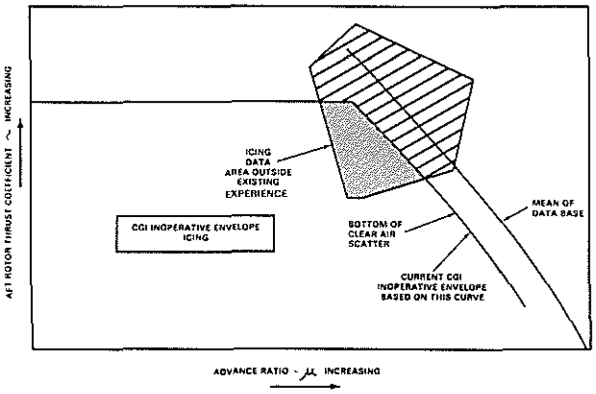


FIGURE 18 CGI INOPERATIVE ENVELOPE—ICING

The problem becomes more accute at high weight, high altitude and high speed (high CT/σ) when the aft rotor is closer to incipient blade stall. Piloting techniques to avoid these high load levels were evaluated during the icing tests. These necessitate a reduction in speed or altitude.

FLYING QUALITIES

Aircraft handling was satisfactory in all the icing conditions encountered, including freezing rain, at speeds up to 130 knots and aircraft all-up-weights up to 50,000 lb with only occasional mild increases in the1/rev and 3/rev vibration levels at the start of a de-ice cycle.

BLADE TEMPERATURES

Both clear air and icing de-ice cycle blade temperature data was used to "fine tune" the thermal math model. A good correlation with flight test data was obtained early in the program, before really low temperature flights were conducted. This allowed us to confidently predict blade temperatures at low OAT's when the occasion to operate there arose.

Figure 19 shows the correlation obtained between math model data and flight data. The math model data consistently gave a conservative temperature margin, which was used as a built-in factor of safety.

Towards the end of the program, sufficient flight test blade temperature data had been obtained for both the spar and ti-cap location, to allow accurate prediction of the blade surface temperature associated with the defined control laws. Figure 20 presents typical blade temperature trends obtained during the program with optimised control laws.

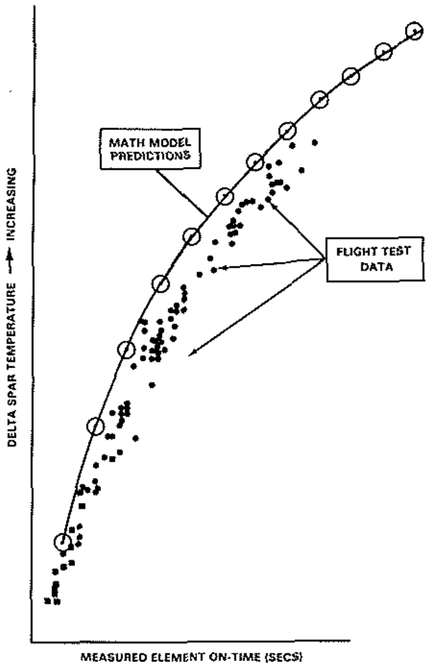


FIGURE 19 MATH MODEL TO FLIGHT TEST BLADE TEMPERATURE DATA COMPARISON

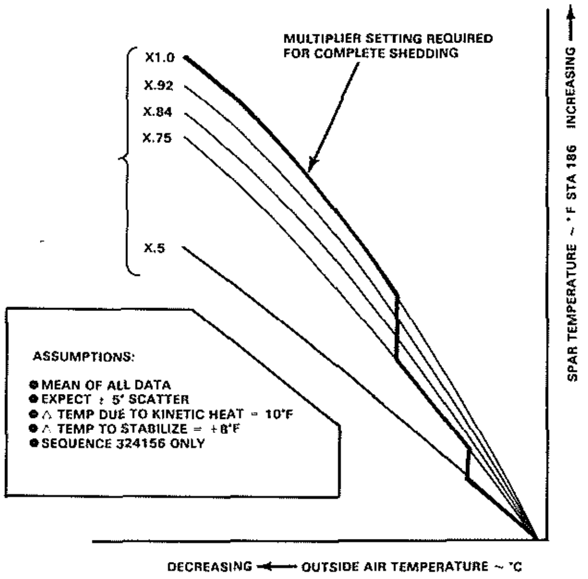


FIGURE 20 BLADE TEMPERATURE TRENDS—STAR SENSOR,

DROOP STOP PROTECTION

The previous winter's trial in Denmark had shown that the rear rotor head droop stop covers did not prevent the ingress of ice and that ice accretion on the droop stop interposer plate frequently caused the stops to fail to engage on rotor shutdown. Two standards of modified lower cover were tested during this last winter and both standards gave satisfactory protection to the droop stops in all the conditions encountered. Figure 21 shows a typical ice accretion on the droop stop covers after an icing flight. Covers ordered by the RAF as part of the 'unheated' icing clearance will be modified to this latest standard and will permit the removal of the severe ground temperature and rotor shutdown limits currently imposed with the earlier standard of cover.

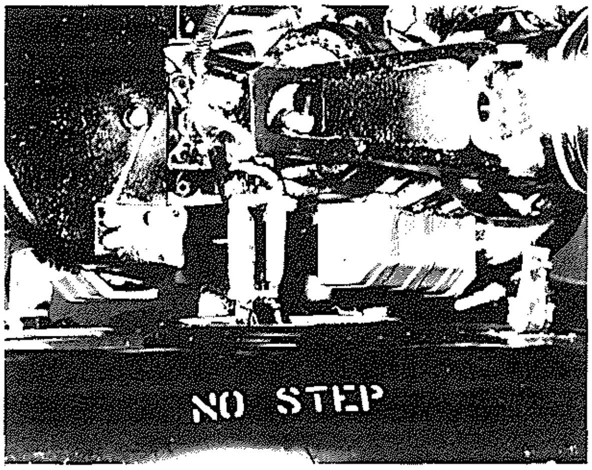


FIGURE 21

OTHER AIRCRAFT ANTI-ICING SYSTEMS

Windscreen anti-icing and wipers provided adequate ice and snow clearance throughout the trial. Blockage by ice and snow of the centre windscreen, which has de-mist only, often occurred and anti-icing of this screen is recommended. Ice accreted on the wiper blades causing the wipers to drift outboard from their parked position. Selection of "park" normally returned them to their stowed position. Under conditions tested, the aircraft pitot and static port anti-icing systems were adequate.

AERIAL ACCRETIONS

No problems attributable to icing were experienced with the navigation and radio equipment fitted to the aircraft. Ice accretions on the various aerials were logged after each icing flight for record purposes, and were often extensive.

ICE DETECTORS AND OAT SENSORS

One of the secondary test objectives of this first season's testing (see Table 1) had been the determination of the most cost-effective ice detector and OAT sensor and satisfactory locations for both. Most of the testing was conducted with the non-aspirated Rosemount ice detector on the forward pylon controlling the de-ice system, a task which it performed reliably. Unfortunately, as currently configured, the probe does not provide LWC indication. If the provision of LWC is required by the RAF for the pilot, three types of detectors are currently commercially available and were evaluated; they were:

- Leigh Aspirated Mk XII
- Aspirated Rosemount
- The RAE/Plessey Probe

Although all three ice detectors, when serviceable, gave good indications of icing, all three had reliability problems. The Leigh often gave spurious fault indications. In addition, installation problems coupled with poor unit reliability failed to allow a working unit for the first half of the trial, despite having three units available. Towards the end of the trial, the Leigh worked well and gave believable LWC indication.

The Rosemount unit was reliable but tended to overread the LWC during intermittent and variable icing conditions compared to the Leigh and RAE Probe IDU's. This fault had been seen on earlier trials and the problem is under investigation by the manufacturer.

The RAE Probe, now being marketed by Plessey in the UK, was prone to damage from shed ice due to its delicate sensing head. The unit had to be replaced twice during the trial. In all other respects, this probe behaved satisfactorily and it is understood the production version will have a more robust sensing head.

At present, neither Boeing Vertol nor A&AEE are able to recommend a reliable, accurate LWC indicator based on the last two winters' testing (i.e. Denmark and Canada). It is hoped that further investigation next winter may enable us to recommend one of these detectors if it is required for Service use.

Four OAT sensors were fitted to the trials aircraft; two manufactured by Lewis, one by Rosemount and one Tinsley reference sensor. Good agreement was observed between all sensors during most icing flights, with all usually reading within one degree C. However, both Lewis sensors did occasionally drift by up to 4°C, the Lewis sensor located in the starboard wheel well being the more frequent offender. It was thought that this may have been caused by warm oil leaking from the aft pylon area running over the surface of the sensor.

The Rosemount non-aspirated ice detector and the Rosemount OAT sensor were considered to be the best units for controlling the de-ice system and have been recommended for production..

Failure Cases

A comprehensive failure simulation program was conducted during the course of the test flying.

Tests included:

- Generator failures, to confirm the correct power transfer logic.
- Heater mat failures, both leading edge and run-back mats.
- Pitot tube and sideslip port heater failures to assess the effects on the AFCS and handling qualities.

In the most severe icing conditions, the loss of a generator and, consequently, the de-ice system resulted in a relatively rapid increase in rotor performance and CGI activity which eventually made it necessary to vacate the environment.

In contrast, leading edge heater mat failures could be tolerated, although an increased performance penalty, rotor speed droop and CGI activity was incurred (see Figure A4). Mat 2 failures were the worst case. Failure of the run-back mats (1 and 6) during flight in freezing rain induced a small increase in the long term performance penalty normally associated with that environment. A rotor speed degradation was the most noticeable cue to this degradation.

The pitot tube heater failure was an 'actual' failure in high LWC's at relatively 'warm' OAT. Although the eventual blockage of the co-pilot's pitot tube resulted in incorrect airspeed indications and AFCS and cyclic speed trim anomolies, positive cues to the blockage and its consequences were readily available to the pilot who reported no associated handling difficulties.

CONCLUDING REMARKS

The availability of natural icing conditions throughout the temperature range required by the RFP, in conjunction with the on-board real time trend monitor and extended range capability of the HC-MkI, enabled the development phase of this programme to be completed during a single season's testing. The following significant conclusions were drawn from the programme:

- A blade de-icing system was required at OAT's colder than -6°C, to contain performance and CGI activity to within the RFP requirements.
- Blade de-ice system control laws and sequencing have been defined for the 0°C to -20°C temperature range.
- The 'nominal' sequence afforded satisfactory protection at LWC's up to the maximum continuous value in each temperature band.
- For LWC's above maximum continuous, a shortened sequence was required to contain torque rises and CGI activity. A 'severe icing' switch (software controlled) will be incorporated at 60% max continuous LWC which incorporates a run-back mat clearing cycle every third sequence. A manual override will also be incorporated.
- No significant problems were encountered during a comprehensive systems failure program.
- There were no engine handling or response problems with bleed air anti-ice off on both engines. There was no evidence of ice accretion in the intakes. Significant performance gains will result from the deletion of engine bleed air, and will offset the losses due to partial screen blockage.
- The modified droop stop shroud configuration was effective in eliminating droop stop engagement problems encountered during previous HC-MkI testing.
- No significant problems were noted on standard antenna, windshield heaters, windshield wipers, heater drains and inlets, pitot-static and sideslip ports.
- The on-board computer worked well and provided the test engineers with valuable real time data that increased flight productivity and accelerated development.
- The computer based ground station, used for detailed post-flight analysis was essential for icing tests.
- The blade de-ice system is ready for MOD(PE) CA Release tests. BVC and A&AEE hope to be able to announce successful completion of this program at the 11th European Rotorcraft Symposium.

SECOND SEASON'S TESTING

The Chinook Heated Rotor Blade De-Ice System has now accumulated sufficient time in a variety of icing conditions throughout the temperature range 0°C to -20°C to define the system control laws and is ready for full certification. The planning for next winter's testing is well advanced and the aircraft will return to the same test site, CFB Shearwater, in mid-November 1984 and continue through to mid-April 1985 in order to take full advantage of icing conditions in the area at the end of the winter. Snow flying will have a high priority since snow can be present in cloud and thus any meaningful icing release must allow for this eventuality. Every opportunity will also be taken to increase our experience in freezing rain.

The aim of the trial will be the clearance of the system control laws that evolved from development testing and to quantify the performance and flight loads degradation with the optimised de-ice system control laws incorporated. The control laws will be 'hardwired' into the Development Test Panel. System components will remain essentially unchanged from the first season's testing and in some areas will not be to the final production standard. Some form of endurance-type test of the full production standard system, not necessarily in an icing environment, is under consideration as part of the certification programme.

References:

1) P. Dunford, R. Lacy, "Analysis and Discussion of YCH-47D Icing Tests", Boeing Vertol Report No. D414-10048-1.

2) P. Dunford, "Tandem Rotor Helicopter Characteristics in a Continuous Icing Environment", American Helicopter Society National Forum, Aneheim, 1981.

3) P. Dunford, K. Lunn, "RAF Icing Program Handbook", Boeing Vertol Document No. D414-10073-1.

4) "Service Rotorcraft" Design Requirements, AVP 970 Volume 3.

5) FAR 29 AC-29-2,

6) C. Jones, M. Battersby, R. K. Curtis, "Helicopter Flight Testing in Natural Snow and Ice", AIAA-83-2786 2nd Flight Test Conference, Las Vegas, Nevada.

Acknowledgements:

The authors wish to express their thanks to the United Kingdom Ministry of Defence for permission to publish this paper.

The authors also wish to thank Mrs. Judy Jones and Mr. Rick Miller for their help and assistance in word processing and analysis/illustrations respectively.

APPENDIX A

FIGURE A1 DELTA POWER PERFORMANCE ANALYSIS—ROTOR TORQUE

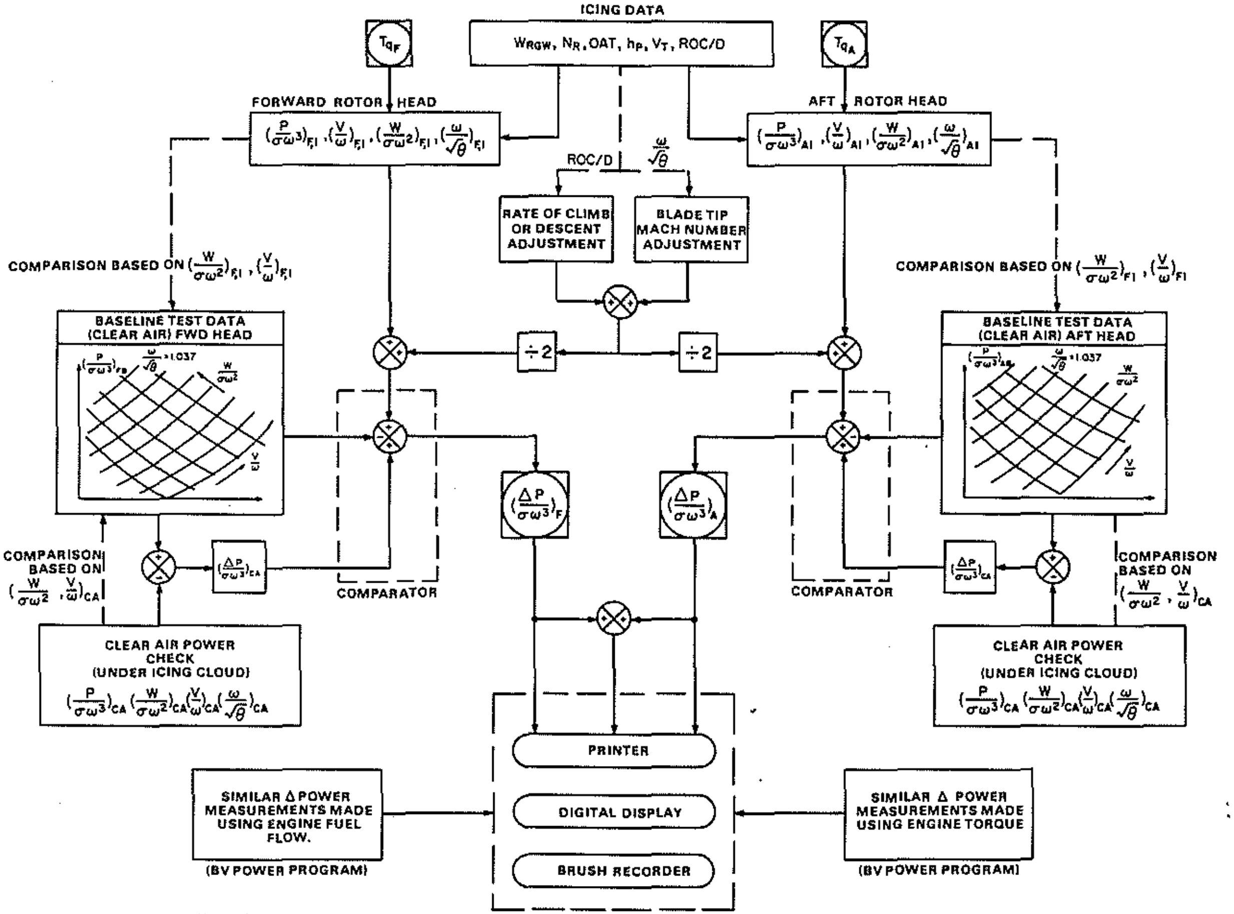


FIGURE A2 RAF ICING TEST VEHICLE—INFLIGHT, REAL TIME FLIGHT LOADS EVALUATION–CGI INOPERATIVE ENVELOPE

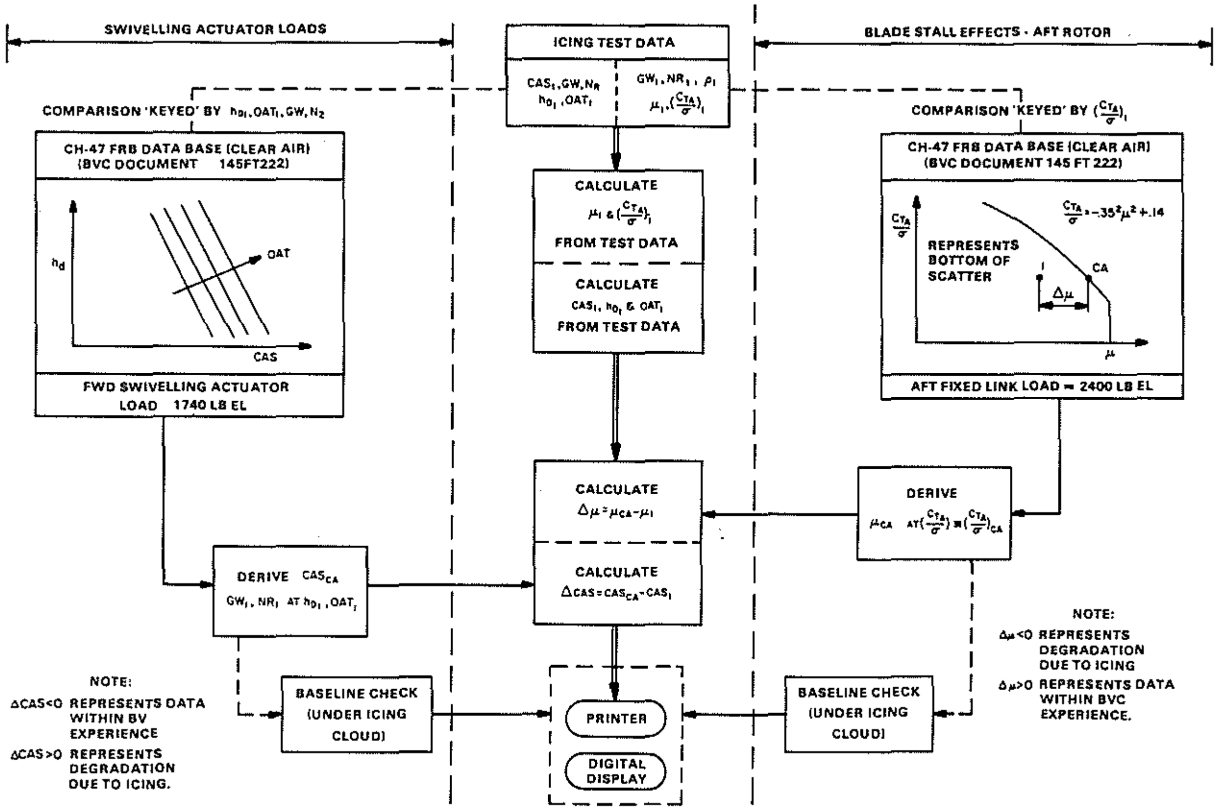
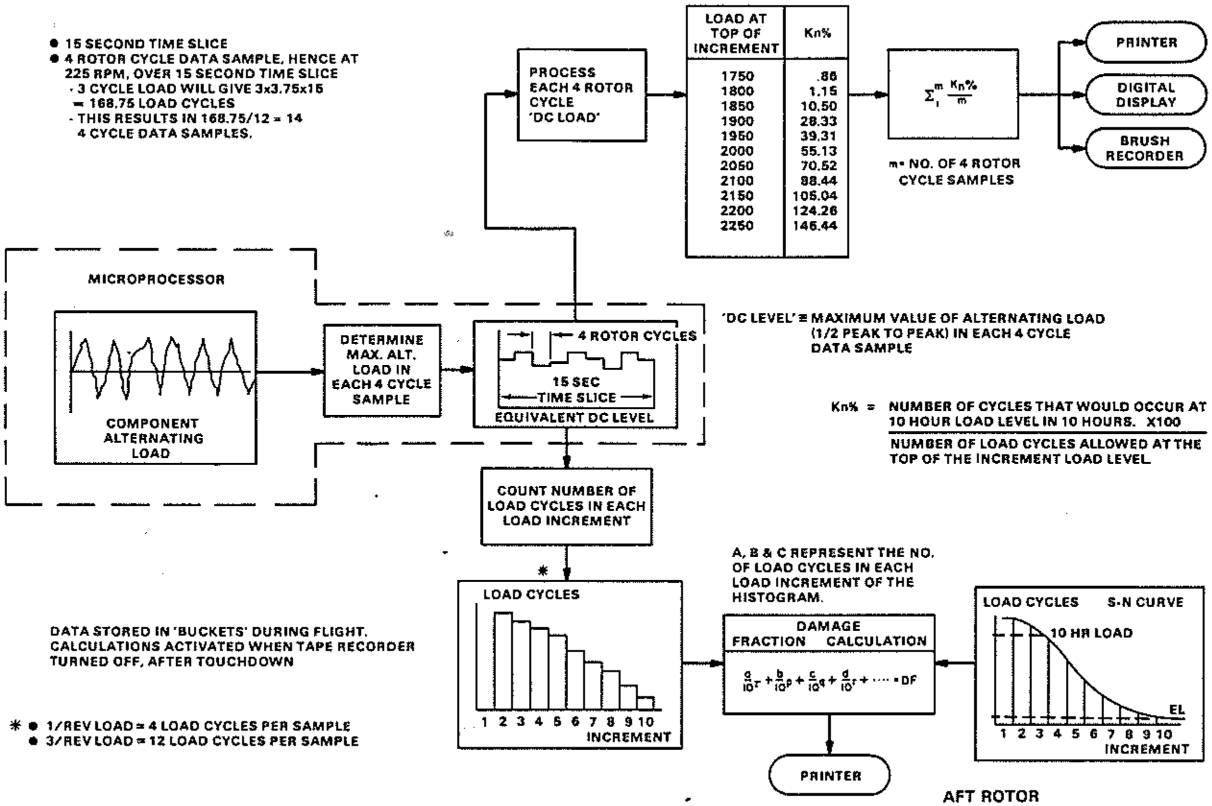


FIGURE A3 COMPONENT FATIGUE DAMAGE CALCULATIONS



- 15 SECOND TIME SLICE
- 4 ROTOR CYCLE DATA SAMPLE, HENCE AT 225 RPM, OVER 15 SECOND TIME SLICE
  - 3 CYCLE LOAD WILL GIVE 3x3.75x15 = 168.75 LOAD CYCLES
  - THIS RESULTS IN 168.75/12 = 14 4 CYCLE DATA SAMPLES.

LOAD AT TOP OF INCREMENT	Kn%
1750	.86
1800	1.15
1850	10.50
1900	28.33
1950	39.31
2000	55.13
2050	70.52
2100	88.44
2150	105.04
2200	124.26
2250	146.44

m = NO. OF 4 ROTOR CYCLE SAMPLES

'DC LEVEL' ≡ MAXIMUM VALUE OF ALTERNATING LOAD (1/2 PEAK TO PEAK) IN EACH 4 CYCLE DATA SAMPLE

$$Kn\% = \frac{\text{NUMBER OF CYCLES THAT WOULD OCCUR AT 10 HOUR LOAD LEVEL IN 10 HOURS. X100}}{\text{NUMBER OF LOAD CYCLES ALLOWED AT THE TOP OF THE INCREMENT LOAD LEVEL}}$$

A, B & C REPRESENT THE NO. OF LOAD CYCLES IN EACH LOAD INCREMENT OF THE HISTOGRAM.

DATA STORED IN 'BUCKETS' DURING FLIGHT. CALCULATIONS ACTIVATED WHEN TAPE RECORDER TURNED OFF, AFTER TOUCHDOWN

* ● 1/REV LOAD = 4 LOAD CYCLES PER SAMPLE
● 3/REV LOAD = 12 LOAD CYCLES PER SAMPLE

FIG A4 EFFECT OF AFT MAT 2 FAILURE
-11°C, °3 TO °4 LWC