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HC-Mk1 (CHINOOK) HEATED ROTOR BLADE ICING TEST
PART I
TEST VEHICLE, TEST SITE, APPROACH AND SUMMARY OF TESTING

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ABSTRACT

Until recent years, the lack of true capability for helicopters to conduct routine operations in Instrument Meteorological Conditions (IMC) has resulted in a lack of urgency to qualify these helicopters in icing conditions. When icing testing has been conducted, it has often been a somewhat protracted procedure, encompassing many winters of testing at a site (or sites) conducive to icing conditions. The reasons for the length of these programmes have, in general, been due to the following three factors:

- Failure to consider ice protection during the initial aircraft design and, subsequently, "piece meal" protection system development.
- The difficulty in finding the required range of icing conditions at a single test site and limitations in the time the test helicopter could operate in icing when these conditions occurred.
- The lack of capability to vary the control laws of heated rotor blade de-icing systems and obtain rapid feedback of the effects of these variations.

With the introduction of the Royal Air Force HC-MkI (Chinook) into operational service, a high priority requirement existed for all weather flight. Since the helicopter's mission equipment gave the aircraft true IMC capability, the remaining obstacle was to ensure that flight in icing could be carried out with minimal penalties in the flight envelope.

This paper will discuss how the test programme was structured in such a manner that the factors previously mentioned were overcome and will describe how the testing was accomplished. A second paper (Part II) will discuss optimisation techniques, analysis methods, the effects of atmospheric conditions and the status of the programme.

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INTRODUCTION

The Royal Air Force HC-MkI (Chinook) helicopter built by the Boeing Company's Vertol Division includes a full set of avionics equipment to enable the helicopter to operate in IMC conditions. This mission equipment consists of the elements noted in Table 1.

COMMUNICATIONS		NAVIGATION	
UHF/AM	(PTR 1751)	COMPASS	(GM-T)
VHF/AM	(AD 120)	ADF	(AD 380)
VHF/FM	(ARC 340)	VOR/ILS	(DECCA 671)
HF	(718U/4/A)	TACAN	(AD 2770)
IFF/SSR	(COSSOR 1520)	DECCA	(MK 19)
		DOPPLER	(DECCA TYPE 71)
		TANS	(9447 F09)

TABLE 1 HC-Mk1 (CHINOOK) AVIONICS FOR FLIGHT IN INSTRUMENT METEOROLOGICAL CONDITIONS (IMC)

The aircraft has mission roles which require all weather operations during any part of the year. Due to lack of a clearance for flight in IMC conditions where icing may occur, at the time the aircraft was delivered, some restrictions in this ability were present for certain operational theatres. To correct this shortcoming, the United Kingdom's Ministry of Defense, Procurement Executive (MOD/PE) undertook two courses of action:

(a) A request for proposal (RFP) was issued to the Boeing Company to design, fabricate and test a heated rotor blade de-icing system capable of allowing flight in continuous icing conditions.

(b) The Aeroplane and Armament Experimental Establishment (A&AEE), Boscombe Down, UK, were tasked with quantifying the aircraft's capability to operate in icing conditions without rotor protection and to issue a flight clearance, albeit limited, for operations in icing.

The icing conditions in which operation was required has been extracted from this RFP and is shown in Table 2.

(a)	Continuous operation in icing conditions of an intensity of Continuous Maximum down to -20°C outside air temperature.
(b)	Survive an icing intensity of Periodic Maximum down to -20°C outside air temperature.

TABLE 2

REQUIRED OPERATING CONDITIONS FOR HC-Mk1 FLIGHT IN ICING CONDITIONS

The general atmospheric conditions corresponding to these requirements are contained in Reference 1 and are reproduced in Table 3.

Associated with this requirement for flight in icing conditions were certain limits in terms of aircraft and systems performance degradation which could not be exceeded. While the actual values are not germane to this paper, the parameters of interest were as follows:

- Range of Operation
- Maximum Forward Speed
- Maneuvering Capability
- Rate of Climb Performance
- Dynamic and Fixed System Component Loads
- Engine Operation
- Aircraft Systems and Avionics System Operation
- Vibration Levels

The RFP contained a target of system development in one season's test followed by certification by the evaluation agency (A&AEE) during the second season and encouraged an innovative approach to the system optimisation process. From the outset, Boeing's design approach for the test vehicle was to maximise the ability to vary the system control laws in flight while being able to determine the effects of these changes in real time. As the system design evolved, it was decided to include A&AEE as joint partners in the Boeing-lead first season's test and to make use wherever possible of test equipment already in existence (or planned to be in existence at a time consistent with the program schedule) at A&AEE, Boscombe Down and Boeing's Wilmington Flight Test Facility. It was considered that to fully utilise the on-board test equipment in natural icing, a large test area, with a high probability of obtaining the full range of atmospheric conditions was essential. The test helicopter's range was therefore increased by the use of an auxiliary fuel system.

Condition	Air Temperature (°C)	Liquid Water (g/m^3)	Horizontal Extent (KM)	Droplet Size Median (Volumetric Dia-Microns)	Altitude Range (Ft)
I	+5	0.90			
Continuous	0	0.80	Continuous	20	4,000 to
Maximum	-10	0.60			10,000
Icing	-20	0.30			
II	+5	1.35	6 KM every		
Periodic	0	1.20	100 KM of	20	4,000 to
Maximum	-10	0.90	Condition I		10,000
Icing	-20	0.45			

TABLE 3

DESIGN ATMOSPHERIC CONDITIONS FOR FLIGHT IN ICING

Although the planned programme was ambitious and the schedule was tight to meet the 1983/1984 icing season, the goals were realised due to excellent cooperation by all organisations and, at the end of the first season, we exceeded our initial expectations of what would be attained.

The elements of the program structure involving de-icing system design, test equipment, data systems and test site selection and overall results attained are discussed in this paper.

FIGURE 1
ICING TEST AIRCRAFT

TEST VEHICLE

General

The test vehicle, a standard HC-MkI (ZA-708 shown on-site at CFB Shearwater in Figure 1) was withdrawn from normal squadron service and returned to the Boeing Flight Test Facility in Wilmington, Delaware for modification during the spring of 1983. Installation of the required test equipment and an on-board data system was completed during the summer and a baseline programme to evaluate the effects of added equipment on the flight envelope, obtain basic (clear air) reference levels for the on-board computer using the Boeing Vertol Real Time Data System (Reference 2) and check out of the test equipment was completed prior to departure for the test site.

As previously noted, the design and fabrication of the test equipment was accomplished by a number of organisations in the United States and the United Kingdom. Table 4 lists the total airborne and ground-based test equipment together with the responsible organisation. Diagrams of the test vehicle showing the location of the equipment are contained in Figures 2 and 3.

TABLE 4 TEST EQUIPMENT AND SOURCE

ELEMENT	DESIGN	SOURCE
● BLADE DE ICING SYSTEM	OVERALL DESIGN. BOEING VERTOL ELECTRICAL DESIGN GROUP	BOEING VERTOL PROCURED
— CONTROLLER — DEVELOPMENT TEST PANEL — CONTROL LOGIC (SOFTWARE) — POWER STEPPERS	DYNAMICS CONTROL CORPORATION	DCC
— SLIPRINGS	BVC FLIGHT TEST INSTRUMENTATION	WENDON CORP
— STANDPIPE	BVC FLIGHT TEST INSTRUMENTATION	BVC
— HEATER MATS	BVC BLADE DESIGN GROUP	B F GOODRICH
— SENSORS	SELECTED BY BVC ELECTRICAL DESIGN GROUP	ROSEMOUNT
— OAT	ELECTRICAL DESIGN GROUP	LEWIS/ROSEMOUNT
● DATA SYSTEMS		
— MASTER CONTROL UNIT — SIGNAL CONDITIONERS — PCM	BVC FLIGHT TEST INSTRUMENTATION	4th GENERATION CORPORATION
— ON-BOARD COMPUTER	INTERFACE AND SOFTWARE DESIGN. BVC FLIGHT TEST INSTRUMENTATION	HEWLETT PACKARD CONTROL DEVICES CORPORATION
— TREND RECORDER	INTERFACE AND CONTROL. BVC FLIGHT TEST INSTRUMENTATION	GOULD
— ROTOR HEAD CAMERA, INTERFACE AND CONTROL	PHOTOGRAPHIC INSTRUMENTATION GROUP	A&AEE
— ENGINE INLET FIBRE-OPTICS VIDEO INTERFACE, CONTROLS AND DISPLAY	COMPUTER INSTRUMENTATION GROUP	A&AEE
— GROUND STATION	COMPUTER INSTRUMENTATION GROUP	A&AEE
— DATA PROCESSING AND COMPUTER INTERFACE		
— ROTOR HEAD CAMERA PROCESSOR	COMPUTER INSTRUMENTATION GROUP	A&AEE
— KNOLLENBURG WATER DROPLET SIZE MEASURING SYSTEM	PARTICLE MEASUREMENT SYSTEMS CORPORATION	A&AEE
— REFERENCE OAT	A&AEE/TINSLEY COMPANY	A&AEE
— REFERENCE LWC	RAE FARNBOROUGH/PLESSEY COMPANY	A&AEE
— BOOT GUN WATER DROPLET SIZE	AIRCRAFT RESEARCH LABORATORIES (AUSTRALIA)	A&AEE
● TEST EQUIPMENT		
— RAPID LOAD BALLAST SYSTEM	BVC STRUCTURES DESIGN GROUP	BVC
— AUXILIARY FUEL SYSTEM	BVC POWER PLANT GROUP	BVC

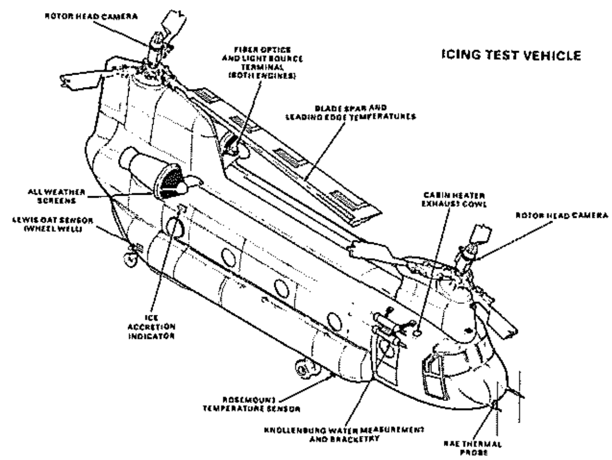


FIGURE 2

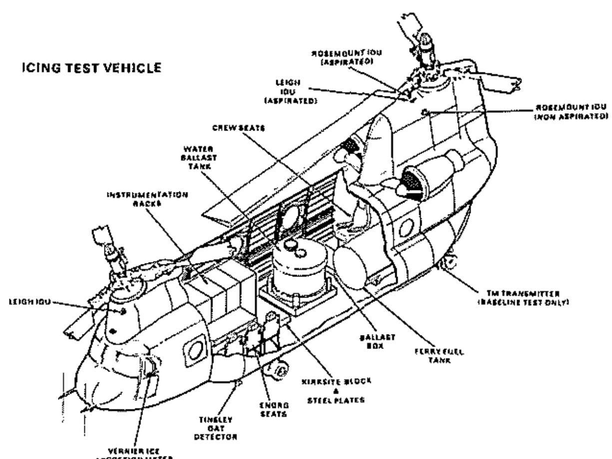


FIGURE 3

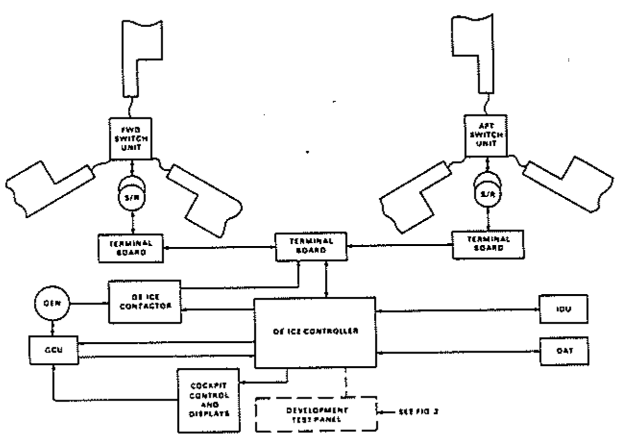
TEST EQUIPMENT

Blade De-Icing

Electro-thermal de-icing of the fibreglass rotor blades was provided by switching the power from the #2 alternator to heater mats on the forward and aft rotor blades. These etched foil mats were bonded into the composite blade during blade fabrication. A microprocessor which will be part of the production controller was used to optimise the various parameters associated with switching; specifically, the sequence in which the blankets are heated, the length of time they are heated (element on-time) and the length of the pause between heating cycles (off-time).

The components included an ice detector unit (IDU), the de-ice controller, two distributors, a pilot control panel, a development test panel and an outside air temperature detector. A block diagram is shown in Figure 4.

FIGURE 4 BLOCK DIAGRAM BLADE DE-ICE SYSTEM



Each rotor blade contains six independent heating elements with each element connected to the corresponding elements on the other two blades on the same rotor to form a set. The six sets thus formed connect to the generator via the distributor on each rotor, as required by the de-icing controller. Electrical power is cycled between rotors, i.e. both rotors are not heated simultaneously.

Power was supplied by the #2 alternator at 200 volts, line to line, three phase, 400 Hz. During de-icing, as previously noted, the alternator was connected to the distributor on one rotor by the de-ice controller and the alternator's excitation was removed so that the distributor was switched at zero current on all three phases. Total power required for the system was approximately 43 KVA.

The ice detector units were mounted on the forward or aft pylon and, where necessary, engine bleed air was utilized to aspirate the IDU. A back-up or alternate ice detector was provided for development purposes and three outside air temperature sensors were also used for development.

During the flight, the controller received control signals from the IDU, the OAT sensor, the pilot control panel, the development test panel (DTP) and the rotor distributors, and commanded the distributors to heat the blades in an appropriate sequence with on and off times based on OAT and ice counts (or ice thickness) respectively. The controller stored up to eight preprogrammed heating sequences of up to 64 steps each and used whichever of these was selected at the development test panel. Programming of the controller stored sequences could be accomplished on the ground or in flight from the DTP. During flight in icing, it computed the proper heating time of each set of heater mats based on OAT as modified by the DTP setting.

The controller also monitored system operation and displayed a fault warning if the system malfunctioned. Typical failure detection elements included:

- Distributor positioning error.
- Faults to ground.
- Short or open circuits which caused the line current in one phase to vary by more than 10% from the other two phases.
- Heater element failure. It should be noted that for all single and some dual element failures the heated rotor blade system would continue to operate, skipping the corresponding elements on the two rotor blades which had not experienced a failure.

The development test panel provided the flight test engineers with the ability to vary parameters which affected system performance and displayed system performance and status in flight. A diagram of the panel is shown in Figure 5.

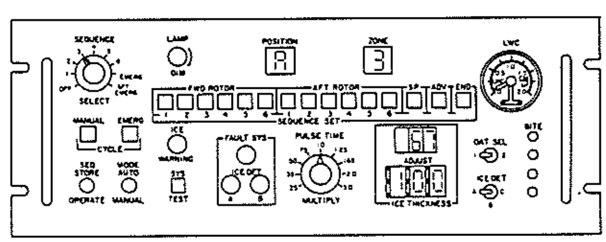


FIGURE 5
DEVELOPMENT TEST PANEL

A modification was made during the programme to the multiplier selections based on in-flight results and rotor head camera photographs. This modification provided additional heat (known as "differential heat") to selected heating mats for severe icing conditions. While most of the controls and displays on the DTP are self-explanatory, Figure 6 shows how the control laws could be varied to operate the blade heating at the optimum value for different atmospheric ranges for a hypothetical situation. This would result in the control laws depicted in Figure 7.

OAT		LWC: LIGHT TO MODERATE	LWC: HEAVY
RANGE 1	THICKNESS MULTIPLIER SEQUENCE	T_1 X_1 1	T_2 X_1 1
RANGE 2	THICKNESS MULTIPLIER SEQUENCE	T_1 X_2 1	T_2 X_2 1
RANGE 3	THICKNESS MULTIPLIER SEQUENCE	T_1 X_3 1	T_2 X_3 (DIFF) 2
RANGE 4	THICKNESS MULTIPLIER SEQUENCE	T_1 X_4 1	T_2 X_3 (DIFF) 2

FIGURE 6 SETTINGS FOR VARIOUS RANGES

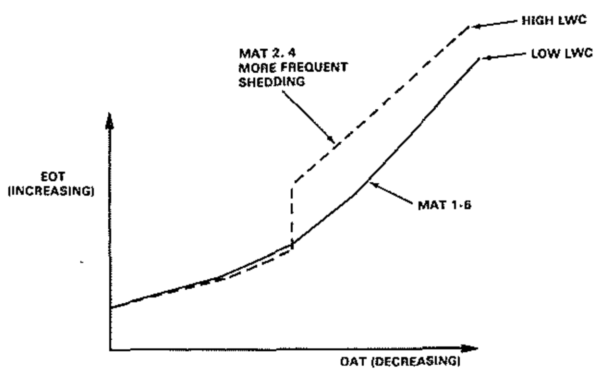


FIGURE 7 GRAPHIC ILLUSTRATION OF HYPOTHETICAL CONTROL LAWS

Rotor Head Cameras - Rotor head cameras were installed on each rotor to photograph the top surface of all three blades simultaneously to identify blade ice acretion characteristics and shedding patterns. The camera assemblies were modified airborne photo reconnaisance (F95) units employing 70 mm colour film, each providing 500 frames per flight. The camera units, shown in Figure 8 with the cover removed, employed a three-way mirror system to transmit the image of all three blades to the camera lens. The camera system could be initiated either manually or automatically (keyed by de-icing system operation). In the automatic mode, photographs could be obtained at precise points in the blade de-icing cycle, either as a function of the entire cycle on the rotor or as a function of individual mat heating periods. A time counter was superimposed on each frame to provide correlation with other flight parameters and, in addition, a special blade paint scheme was employed to facilitate blade and heater mat position identification.

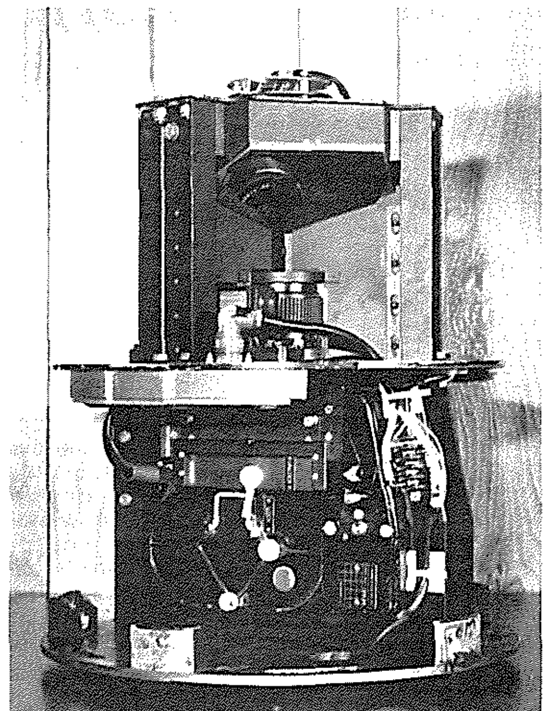


FIGURE 8 ROTOR HEAD CAMERA EXTERNAL VIEW

In Figure 1, the installation can be seen mounted on the forward and aft hub of the test aircraft. The rotor head camera was mounted on the pedestal adapter and base plate which, in turn, mounted to the rotor hub. Instrumentation signal conditioning and sliprings, which carried power and signals for both blade de-icing, instrumentation and the cameras, were located inside the pedestal and are not visible externally. A typical photograph obtained during a test flight is shown in Figure 9.

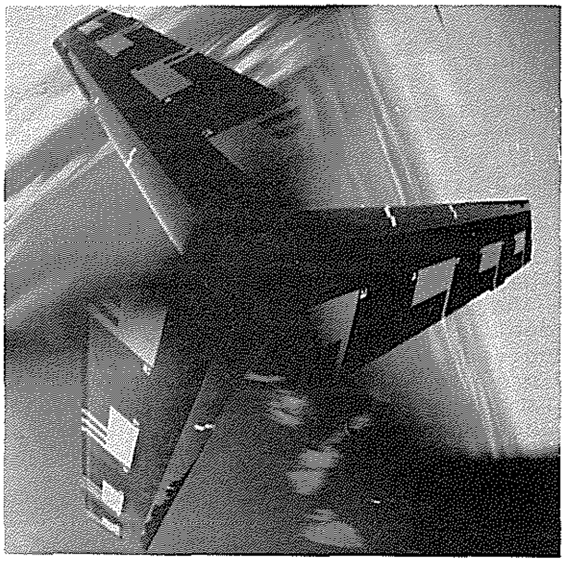


FIGURE 9
ROTOR HEAD CAMERA PHOTOGRAPH

Power and time code to the rotor head cameras were provided from the basic on-board data system. Camera controls were provided to vary the rate at which photographs were taken on the rotor being de-iced while photographing the unheated rotor at a much lower rate. The camera windows were heated to prevent fogging and icing over.

As the test progressed, it was considered highly desirable to examine the undersurface of the blade. This was accomplished by using a 35 mm SLR camera with autowind mounted on a mirrored bracket held in the "bubble" observation window in the fuselage side. With the shutter speed at maximum (1/2000), the optimum F stop was obtained for the light level on each flight and the camera was then operated manually at these optimised settings.

The photographs obtained from the rotor head cameras, supplemented by the undersurface photographs, were an essential component of the in-flight observed and recorded data used to determine de-ice system operation and, finally, to define the control laws.

Rotor Blade Temperatures - One blade on each rotor was instrumented with internal and external temperature sensors at the blade 50% and 75% radius. These measured temperatures were installed to ensure that blade internal temperatures were within acceptable limits, as part of an iterative process in developing computer modelling of the blade thermodynamic mechanism and to identify the surface temperatures required for acceptable de-icing characteristics to allow extrapolation to more severe conditions than those encountered.

RAE/Plessy Thermal Probe - An electrically heated device which protruded into the airstream was used to measure liquid water content (LWC). The methodology of the unit is based on the difference in electrical power required to maintain a cylindrical probe at a constant temperature in icing conditions and the power required in clear air. Operation of the probe is dependent on the electrical properties of a semi-conducting ceramic material having a positive temperature coefficient of resistance. In order for the unit to operate correctly in icing conditions, it was necessary to determine the convective power loss due to the non-dimensionless variables for the particular installation (Reynolds and Nusselt numbers). The LWC for the icing cloud was a function of:

Total Power - Convective Power +
Power to evaporate impinging water.

Course LWC analysis was accomplished in real time using the on-board computer, a post flight analysis at a high sample rate was carried out using the ground station computer. The probe was mounted on the heated rotor blade test aircraft in the same position as used during A&AEE Chinook trials in Denmark (1983).

Fibre Optic Camera Installation - Both engine inlet 'D' rings were monitored from the engineer's station using a system of fibre optic cables, cameras and an electronic control unit. This provided the engineer with a real time monitoring capability of each 'D' ring on two 5-inch video monitors in the instrumentation rack. A TEAC video cassette recorder (VCR) was used to record selected segments of the flight. The selected camera channel was displayed on an 11-inch TV monitor for closer analysis. Flight number, time and flight information from the video number generator were also displayed. It was also possible to dub voice events and commentary onto the tape from the engineer's station.

Knollenburg - Two water droplet measurement sensors were mounted at the winch position over the righthand cabin entrance. The droplet sizes of interest required two "Knollenburg" probes. In one probe, droplets in the 3-45 μm range were counted by a 'Forward Scattering Spectrometer' (FSSP100) probe which measured the light scattered by a droplet as it passed through a linear laser beam. The resultant signal was a function of the droplet diameter and was used to generate a count in one of fifteen 3µm wide 'size channels'. Droplets from 30µm to 300µm diameter were measured by the other, PMS optical array probe (OAP200X). Droplets passing through a laser beam cast shadows on a linear array of photodiodes. The number of diodes that were shadowed determined which of the 20µm wide 'size channels' a droplet was counted into. These probes provided continuous real-time cloud droplet size distribution on an on-board display unit; samples at 0.5 second intervals were also recorded on magnetic tape for post flight determination of volumetric median diameter (VMD).

A hand-held "soot gun" was also used to measure droplet size (diameter) in the icing cloud (Reference 5). This device, developed by Aviation Research Laboratories in Australia, consists of a treated slide which can be placed in the aperture of a rod-like device. This rod, when held out of a window in the aircraft, was exposed to the cloud by operating a trigger which momentarily opened a shutter which protected the slide. Analysis of the exposed slide was accomplished by creating a magnified polaroid photograph of a small area of the slide and measuring the diameter of each droplet using a digitizing tablet. The mean volumetric diameter (VMD) was calculated by the A&AEE computer in the ground station. The computer programme compensates the actual measured diameter by correcting to true diameter based on airspeed and a calibration of the splash effect. An average of ten slides were obtained on each flight.

Ballast System - The ballast system used in the test aircraft consisted of a set of support beams and roller rails anchored to the cargo floor. The system contained a water ballast tank and jettison system with a capacity of 652 gallons. An electrically operated jettison system allowed the pilot to dump the entire contents (6,000 lb) of the tank in approximately six seconds in case of an emergency.

Ferry Fuel System - One-half of a BV234 auxiliary fuel system was installed in the icing test aircraft to provide the capability to increase the duration of testing during an icing encounter and reduce fueling requirements, resulting in a significant increase in productivity. The ferry fuel system consisted of a 500-gallon cylindrical tank, forward and aft fuel boost pumps (internal to the tank) and associated valves and plumbing. The entire tank assembly was mounted to the internal ballast rail system. The ferry fuel tank was plumbed to the normal aircraft ferry fuel connections. This allowed normal single point pressure refueling. A 'ferry fuel' control panel with a contents gage and fuel pump control switches was located in the cockpit.

Portable Video System - Following each icing flight, a portable colour video system was used to record all remaining rotor and airframe ice acretions. The system was also occasionally used in flight.

ON-BOARD DATA SYSTEMS

General

A general view of the test engineer's station in the aircraft is shown in Figure 10. In addition to the control panels for the test equipment previously noted in this paper, this station also contained the trend monitor (strip chart recorder), the alpha-numeric displays, the on-board computer and input/output terminal, the Pulse Code Modulation (PCM) Master Control Unit (MCU), the fixed system signal conditioners and the magnetic tape recorder. The data parameters recorded consisted of the following general measurements:

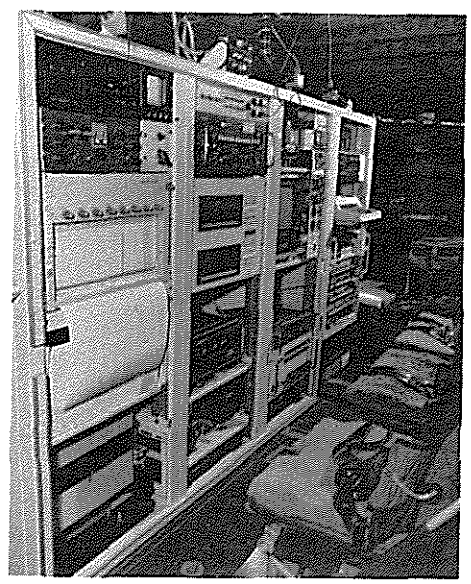


FIGURE 10
TEST ENGINEERS STATION

- Basic Aircraft Parameters - Used primarily to document the aircraft flight conditions, although these parameters were accessed by the analysis routines and certain control functions to initiate data processing.

Control positions, aircraft attitudes, rates, stability actuator positions, load factor, OAT, air speed, altitude, rate of climb, time, event, rotor speed, fuel used and fuel temperature, were included in this package.

- Rotor System - Rotor shaft torque, bending, actuator fixed link load, pitch link load, pitch shaft bending, rotor blade loads and rotor blade temperatures.

- Power Plant - Fuel flow, engine torque, gas generator speed, turbine inlet temperature, engine inlet static and total pressure, 'D' ring and transmission surface temperature.

- Electrical System - Current and voltage to the rotor blade de-icing system, liquid water content, icing rate, threshold signal, ice counts and control discretes, IDU bleed air pressure and temperature.

- Environmental - OAT, liquid water content, water droplet size and distribution, snow severity.

The ground-based data station consisted of equipment to process flight tapes rapidly following each icing flight. This facility was in continuous daily use throughout the testing and provided the following:

- Production of secondary (computer-compatible) tapes whilst simultaneously generating 'quick look' calibrated graphical time histories of up to 20 selectable parameters. This output was normally available for inspection within one to two hours of landing.

- The plotting or tabulation of calibrated and derived parameters as required; typically called-for derived parameters included delta rotor powers, delta engine torques, Plessy/RAE probe liquid water content (LWC) and cloud droplet volumetric median diameter (VMD).

- Writing of tertiary data files to a Winchester disc for data analysis using the trials officer's intelligent terminal.

A computer terminal in the A&AEE trials officer's office provided a multi-purpose interactive data analysis system (MIDAS). This software package consisted of a subset of analysis routines used on A&AEE's mainframe computers which allows comprehensive manipulation and plotting of data. This intelligent terminal also allowed the use of specially written software and permitted on-site software development and modification. Such software provided the following:

- Analysis of cloud droplet sizing gathered using the ARL Soot Gun (this employed a digitizing tablet).

- Analysis of delta powers and torque (similar software to that used on the ground station).

- Statistical analysis.

- Derivation of Plessy/RAE Probe LWC.

- Icing severity analysis.

Data Systems Equipment, Airborne

One alpha-numeric display panel was installed at the pilot's station and two at the test engineer's station. The pilot display and one display at the test engineer's station were fixed format, one display at the test engineer's station was selectable. The display formats were generally in accordance with the following groupings:

- Control Position, Rates and Altitudes
- Referred Performance
- Flight Loads
- De-Ice System
- Blade Temperature

The selectable formats were called up by "press and lock" push buttons. A strip chart recorder was provided to display, in quasi analog format, time histories of up to eight pre-selected parameters at an up-date rate of 15 seconds. This update rate was designed to allow the test engineer to monitor trends over a long period of time (approximately 10 minutes of flight time shown across the recorder face). The terminal used to input pre-flight constants to the on-board computer was also used as a printer. The parameters processed by the computer (i.e., those available in the five formats of the alpha-numeric display plus the strip chart recorder) were printed out approximately every 30 seconds throughout the flight when the "PRINT ENABLE" selection was made. A typical alpha-numeric panel, in this case the pilot's fixed display, is shown in Figure 11.

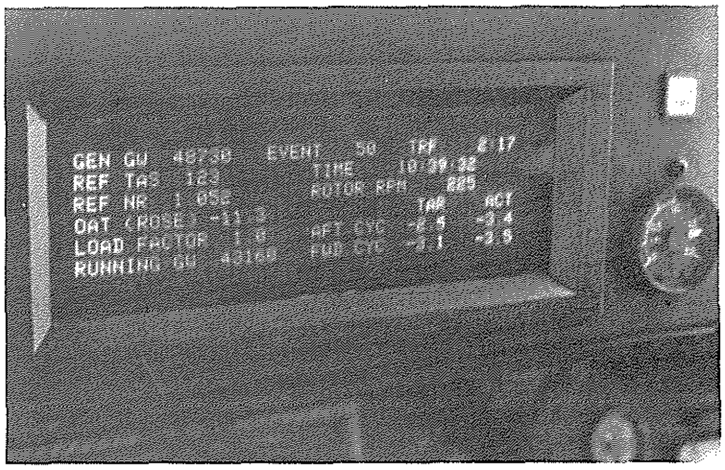


FIGURE 11 ALPHA-NUMERIC DISPLAY

The update rate for this display was one (1) second for the pilot's (and test engineer's fixed display) and 15 seconds for the flight test engineer's selectable display. This rate was determined by the total computational task which was required of the on-board computer.

The parameters monitored on the trend recorder and the typical output from the on-board computer input/output terminals are illustrated in Figures 12 and 13 respectively.

LOCATION	PARAMETER	UNITS
1	TRUE AIRSPEED	KNOTS
EDGE	EVENT	DISCRETE
2	LWC	GM/M^3
3	DELTA POWER (FWD)	% (1)
4	DELTA POWER (AFT)	% (1)
5	FWD ROTOR BLADE ANGLE	DEGREES
6	AFTER ROTOR BLADE ANGLE	DEGREES
7	DE-ICE SYSTEM ON	DISCRETE
EDGE	TIME	1 MIN MARKERS
8	AFT ROTOR SHAFT BENDING	%

(1) PERCENT OF CLEAR AIR BASELINE VALUE

FIGURE 12 STRIP CHART RECORDER PARAMETERS

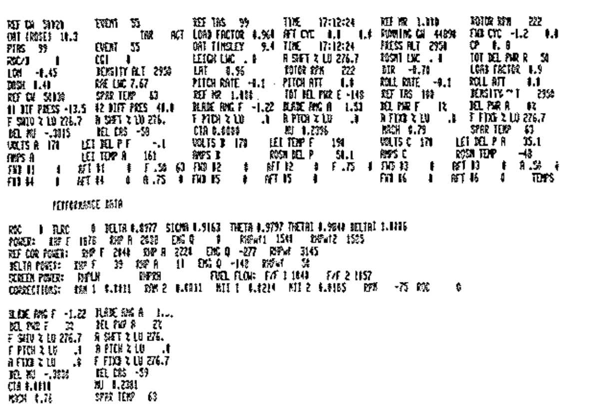


FIGURE 13 TYPICAL PRINTER OUTPUT

All active parameters in the PCM multiplexer were recorded on magnetic tape, plus Knollenburg output and voice (all flight crew communications). The tape recorder on this aircraft was modified to be capable of recording either on forward play or reverse to enable the tape recorder to be run continuously throughout the flight without changing tape reels. Final processing of data during the baseline flights utilised the BVC Flight Test Real Time Data System (FTRTDS) and standard BVC/BCS software. Processing of the Knollenburg output and on-site (Shearwater) processing of airborne tapes was accomplished for day-to-day operations on the A&AEE ground station at the test site, using A&AEE developed software.

The on-board computer system which consisted of the computer, interface to the data system, input/output terminal, displays and trend recorder was an extension of a series of systems which Boeing Vertol has been developing for off-site test programmess in recent years, Reference 3.

The basic objectives, in addition to presenting selected measurements in engineering units to the pilots and test engineers, were to perform analyses to show the effects of aircraft performance degradation and increases in component loads as ice was accreted on the rotor blades. The system block diagram is shown in Figure 14, Part II of the paper will describe the analytical techniques in further detail.

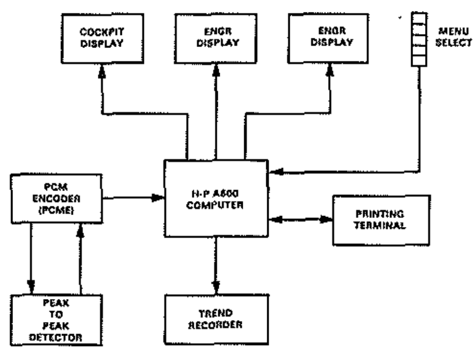


FIGURE 14

ON BOARD COMPUTER SYSTEM

Data Systems Equipment, Ground Station

The A&AEE portable computer ground station contained all hardware necessary for on-site retrieval of flight data calibrated in engineering units. The station contained two DEC PDP 11/24 mini-computers, one dedicated to flight tape processing and time history plotting, the other used for data analysis. Diagrammatic representation of the equipment involved for flight data retrieval, secondary processing and tertiary file generation is given at Figure 15.

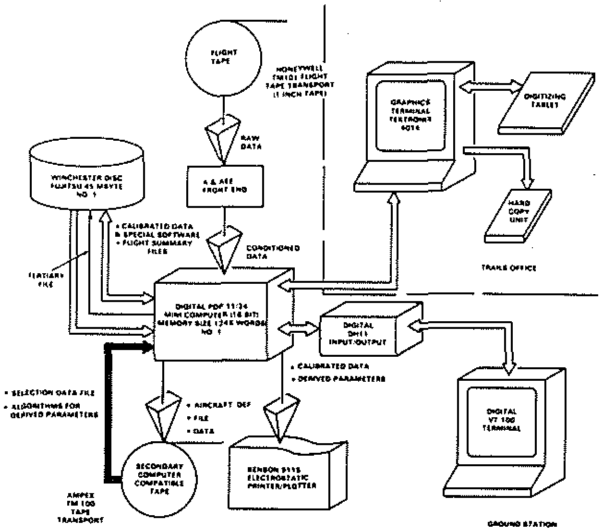


FIGURE 15 (A & AEE DATA SYSTEM)

TEST SITE

Selection

The selection of a test site for an icing programme is at best a "risky business" since most helicopters do not fly in icing conditions and thus acquire a data bank of actual encounters and meteorological records of icing are unavailable. Coupled with the above factors are the variations from year-to-year of the severity of the conditions conducive to icing at a particular test site. The selectors are therefore left with three options on which to base a decision:

- Available meteorological data
- Previous experience
  or
- Folklore (pilot opinion)

The test sites considered included venues in Europe, Canada and the United States. Work carried out by the United Kingdom (primarily A&AEE) had determined that the probability of obtaining the extreme low temperatures and high liquid water content required at a test site in Europe was not high. Previous test programmes conducted by Boeing in support of U. S. Army test agencies had shown that at some sites the probability of attaining the low temperatures was high but the probability of obtaining the full range of outside air temperatures and liquid water content was low. An additional factor favoring a test site in North America was the better support, if required, from the Boeing Vertol plant. The test sites considered in North America were:

- Ottawa (Ontario)
- Summerside (Prince Edward Island)
- Halifax (Nova Scotia)
- St. John (New Brunswick)
- Moncton (New Brunswick)
- Fredricton (New Brunswick)
- Gander (Newfoundland)
- Syracuse (New York)
- Minneapolis/St. Paul (Minnesota)

Based on previous experience of known operational restrictions and weather patterns, combined with an analysis of meteorological data obtained from Reference 4, the choice was narrowed to Ottawa and various sites in the Maritimes. Data was then obtained, in identical formats from the Canadian authorities for each of the remaining sites, this data is shown in Figure 16.

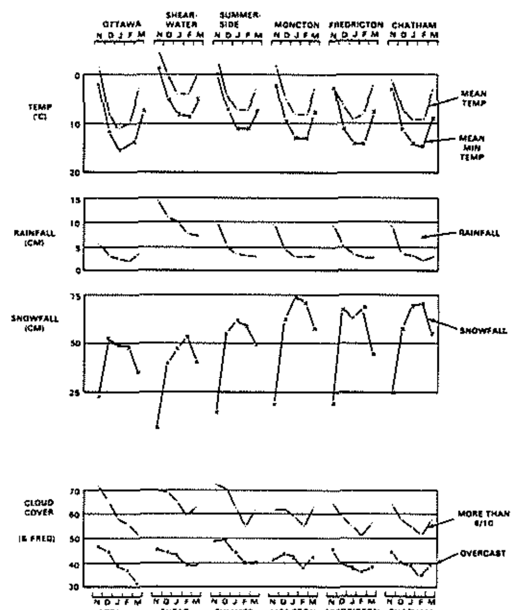


FIGURE 16 (COMPARISON OF TEST SITES)

While each of the sites in the Maritimes had advantages in terms of some portion of the required range of icing conditions, all the sites with the exception of Sommerside and Shearwater had deficiencies with regard to hangar size and ground support. The data in Figure 16 is based on ground recordings; to further evaluate the choice of sites, actual upper air temperatures for 1982/1983 were obtained and a probability analysis of obtaining the extreme low temperatures made. This is illustrated in Figure 17 and indicated that for the Maritimes as a whole, the low temperature probability was slightly less than Ottawa. The area of Chatham/Moncton was shown to have a higher probability of possessing temperatures in the -10°C to -20°C range than Ottawa. It was evident that the full range of temperatures could be obtained in the Maritimes -- if all the sites were considered and due to the large bodies of water, cloud liquid water content should be higher. Finally, CFB Shearwater was selected as the test site based on:

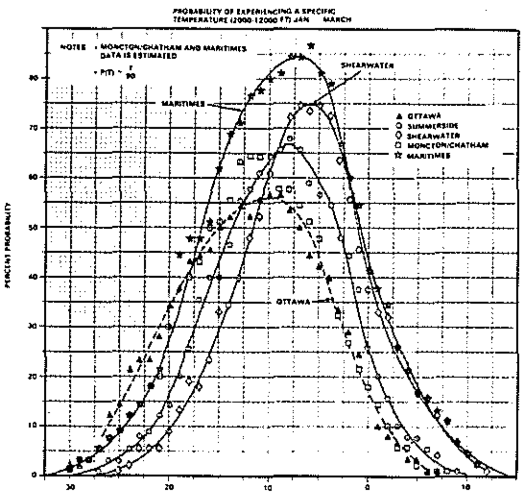


FIGURE 17 STATISTICAL ANALYSIS OF TEST AREAS

- The ability to fly to the airspace of all the considered sites in the Maritimes (with auxiliary fuel) and thus obtain the full range of conditions required.

- Ease of access for personnel and logistics, and the level of support available from the Canadian Forces.

Figure 18 shows the test area for IMC flying to search for icing negotiated with the Canadian Department of Transport and the Canadian Forces.

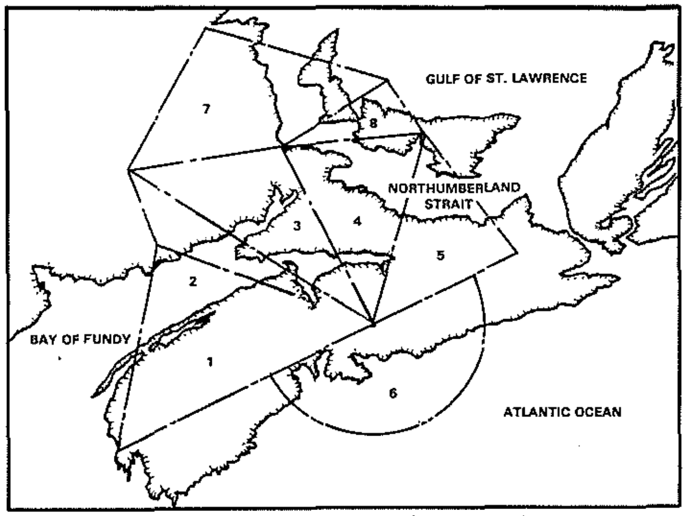


FIGURE 18 TEST AREA

TEST APPROACH

Prior to this heated rotor blade test, an unheated rotor icing test had been carried out on the HC-MkI test aircraft assigned to Boscombe Down. The testing was conducted by A&AEE in Denmark during the winter of 1982/1983. While the test equipment and data system installed on this aircraft were not as extensive as the equipment installed on the heated rotor blade test, certain items were proven during this trial, namely:

- Knollenburg Installation
- RAE Probe
- Leigh and Rosemount IDU Locations

Additionally, the droop stop covers, which had been added to preclude ice build-up on the droop stop interposer blocks, were evaluated. Icing flights were made during this trial to -10°C OAT, LWC's to 0.56 gm/m³ (mean) at altitudes to 9,000 ft. On the basis of the results obtained, a limited release for flight in icing was recommended to -6°C OAT with certain restrictions regarding minimum height above the ground of the icing cloud and a requirement for positive ground air temperatures at the landing site. A primary reason for these restrictions was the inability of the modified droop stop covers to prevent ice build-up on the droop stop blocks; however, in certain conditions, high torque and Cruise.Guide Indicator readings wre encountered and, at times, the test aircraft had to terminate the encounter and vacate the icing could.

It was apparent that at lower air temperatures an icing system for the rotor blades was needed to meet the full icing flight requirement.

Results obtained by A&AEE during a series of ice, snow and water ingestion tests on the Lycoming T55 engine prior to the Denmark icing trial, coupled with the findings of that trial, confirmed that the intake screen/engine anti-icing configuration tested afforded satisfactory engine protection. This work removed the necessity to install the screen monitoring closed circuit television system used in Denmark for the HRB system trial. However, due to a requirement to confirm that engine anti-icing was unnecessary, the heated rotor blade development test did retain closed circuit television employing fibre optics to monitor the engine intake area.

In planning the heated rotor blade testing, it became obvious that optimisation of system operation would require a careful balance of torque and CGI increases (which are a function of shedding characteristics) while maintaining desirable rotor blade internal temperatures. Further, with the controls available in flight to vary heater mat sequence, element on-time and ice thickness (threshold at which electrical power was applied), many combinations were available and discipline to vary these parameters was essential. In optimising the heating characteristics of composite rotor blades, it is essential that the balance of blade external to internal temperatures be carefully controlled so that ice shedding is correct while maintaining blade internal temperatures at levels which have no long term (unlimited life) effects. Part II of this paper discusses, in detail, the "logic trees" used to control the variable parameters and the blade temperature analysis compared to actual flight data. A general outline of the test approach adopted will be given here.

Prior to flight testing, a math model was constructed to predict both internal and external rotor blade temperatures for various element on-times and outside air temperatures. This analysis was supplemented (and updated) by panel testing, initial installation checks on the aircraft and, later, in-flight recorded data in icing conditions. To obtain the correct aircraft baseline levels, performance, flight loads and vibration levels throughout the flight envelope were obtained with all the additional equipment installed prior to departure for the test site.

Once icing flying was started, the test team worked closely with the meteorological sections in the Maritimes to define the area in which icing conditions were most probable. Flights of up to 3.5 hours duration were then launched, initially along airways routes, until icing was found. At this point, the waypoints from the TANS would be noted and the aircraft would depart the airways to fly in icing in the local area under positive radar surveillance. Initial variables were maintained at the "design nominal values" until conditions were encountered which indicated that a change might be necessary.

The "design nominal values" were determined based on a BVC data bank of previous icing development on both metal and fibreglass blades.

The approach of maintaining the initial variables constant compared with running many different combinations and comparing results may appear to be somewhat pedestrian and lenghty. However, with the ability to monitor the aircraft performance, loads and blade temperature effects on board combined with the excellent quality of blade photographs available very shortly after the aircraft landed, this was not the case. In fact, the modifications required to the DTP and de-icing controller to utilise the final control laws were identified prior to Christmas, the ability to manually input the new control laws was available by the beginning of February and the full capability by the end of February. The whole month of March, which was the most productive month in terms of icing encounters, was flown with variables fixed at close to the selected control laws for the production system.

The test procedure during an icing encounter was to immerse the aircraft in the cloud and find and hold the maximum LWC for as long as possible, generally at approximately 120 KIAS. At selected points in the programme, speed was increased to maximum attainable, a full range of maneuvers was conducted and, once the final constants had been selected, system, engine and electrical system simulated failures were accomplished.

Following each flight, the joint team had a full review of in-flight obtained results including examination of shedding patterns from the rotor head cameras and arrived at a decision for the next test. This joint Contractor/ Test Agency effort was highly efficient and data which is applicable toward the A&AEE release was obtained with the final system constants.

To remove the restrictions due to the droop stop icing problem, two new designs of droop stop covers were installed on the aft rotor together with the same cover used in Denmark as a control. Instrumentation was also added to show, by means of a warning light in the cockpit, that one of the droop stops had not engaged prior to shutdown.

After each flight on which significant ice accretion had occurred, the droop stops were examined for evidence of ice build-up until the droop stop with the original cover failed to engage. At this point, a modified cover was installed in place of the control cover and all remaining flights were flown with modified covers, with satisfactory results.

ACTUAL FLIGHT TIME IN ICING: 38.5 HOURS

OUTSIDE AIR TEMPERATURE RANGE: -06°C to -24°C

LIQUID WATER CONTENT RANGE: 0 to 0.6 gm/m(mean)³
TRANSIENTS TO: 1.0 gm/m³

TOTAL ICING ACCUMULATION: 2,027 mm

ICING BY MONTH:	NOV	DEC	JAN	FEB	MAR
(mm)	92	395	324	332	884

MAX FLIGHT DURATION IN ICING: 2 HOURS 17 MINUTES

CONDITIONS ENCOUNTERED:

- FREEZING RAIN
- GLAZED ICE
- GLIME ICE
- RIME ICE
- MIXED CONDITIONS
- RECIRCULATING SNOW } NOTE
- PRECIPITATING SNOW } NOTE

Note: The primary objective was to develop the heated rotor de-icing system; conditions conducive to snow flying were present in the operating area, but were considered a lower priority for the first season.

TABLE 5
RESULTS ATTAINED

OVERALL RESULTS

In practice, it was found that, as hoped, the large bodies of water; i.e.,

- The Bay of Fundy
- The Gulf of St. Lawrence
- The Northumberland Strait
  and
- The Atlantic Ocean

were extremely conducive to the build up of cloud liquid water content regardless of the prevailing air flow direction. Actual test point data is the subject of Part II of this paper; however, the overall results are shown in Table 5 and Figure 19.

It is noteworthy to compare the icing conditions attained during this and one previous icing test. Figures 19 and 19A compare three variables (LWC, droplet size and total ice accretion for the Shearwater and Denmark test sites).

Prior to drawing any conclusions regarding the relative merits of the test sites, it should be borne in mind that the comparison is of a heated rotor blade test versus an unheated rotor blade test. During the test in Denmark the aircraft was occasionally forced out of the icing conditions, particularly at the higher LWC's due to unacceptable performance characteristics as ice was acreted on the rotor blades. If this had not been the case, total ice accretion may have been higher.

With this in mind, the following comparisons can be made:

(a) In terms of the ability to test across a full range of outside air temperatures in which icing may occur, Shearwater is clearly the best site of the two; and, in fact, in the author's opinion, the best test site encountered during numerous icing tests.

(b) In terms of LWC for the range 0°C to -10°C, both sites are comparable with the Denmark site being slightly better. The LWC's at both sites are approximately 60% of the Reference 1 maximum continuous criteria. This also coincides with the A&AEE, CA release criteria which recognises the difficulty in actually testing in design conditions. This may suggest that this is a practical value for test purposes.

(c) Examination of the ice acretion totals by month shows that icing conditions appear to be generally constant at Shearwater for December, January and February and significantly greater in March, while Denmark was generally constant except for less icing in January. For any test organisation developing icing protection, Shearwater offers (based on 1983/84) the opportunity to optimise the system over a three-month period and then obtain a large mass of data in the final month with fixed control laws.

(d) The plots of VMD for both sites have similar trends and indicate that droplet size decreases with temperature.

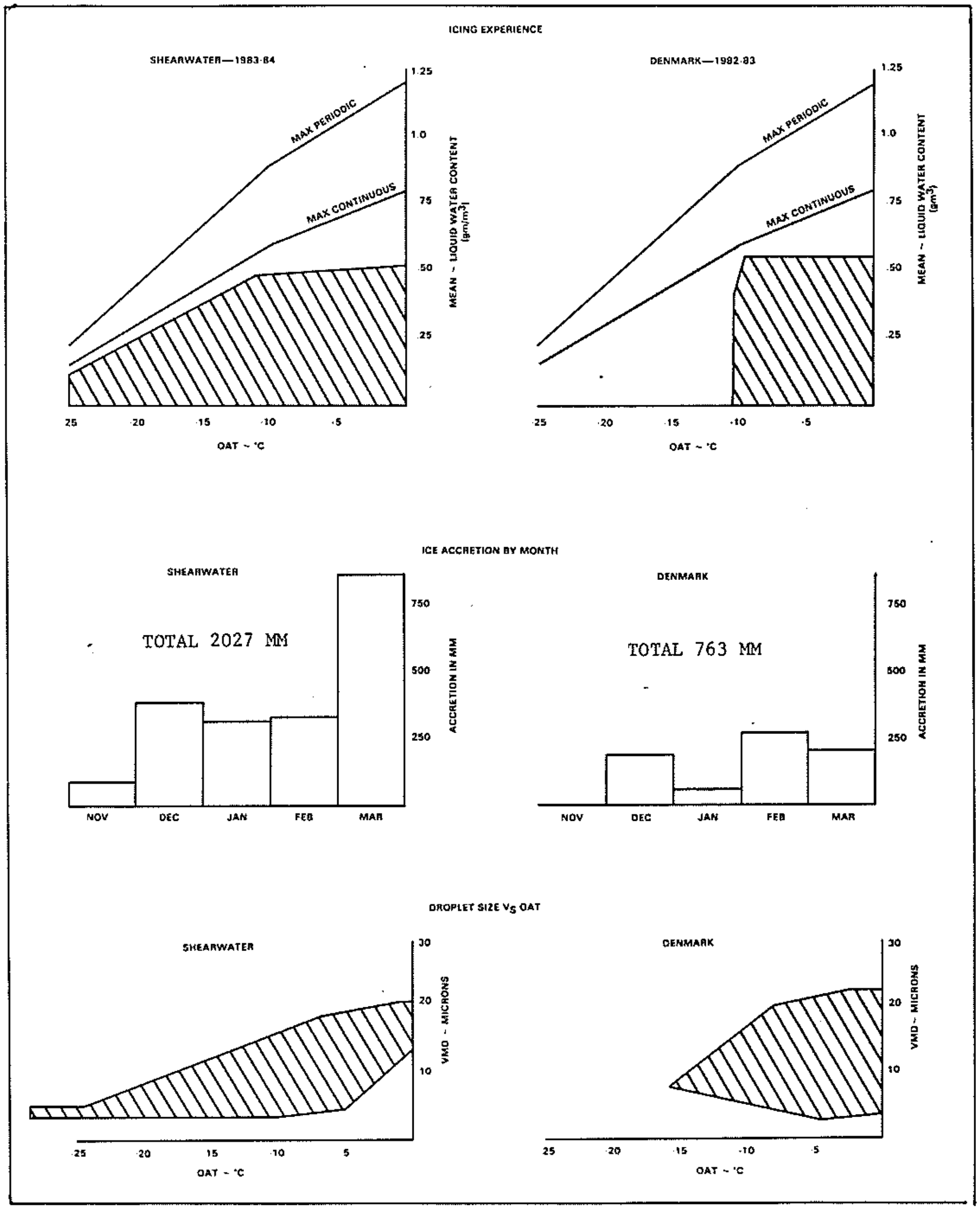

ICING EXPERIENCE
SHEARWATER—1983-84
MAX PERIODIC
MAX CONTINUOUS
1.25
1.0
.75
.50
.25
MEAN ~ LIQUID WATER CONTENT (gm/m³)
25
-20
-15
-10
-5
OAT ~ °C
DENMARK—1982-83
MAX PERIODIC
MAX CONTINUOUS
1.25
1.0
.75
.50
.25
MEAN ~ LIQUID WATER CONTENT (gm³)
-25
-20
-15
-10
-5
OAT ~ °C
ICE ACCRETION BY MONTH
SHEARWATER
TOTAL 2027 MM
750
500
250
ACCRETION IN MM
NOV
DEC
JAN
FEB
MAR
DENMARK
TOTAL 763 MM
750
500
250
ACCRETION IN MM
NOV
DEC
JAN
FEB
MAR
DROPLET SIZE VS OAT
SHEARWATER
30
20
10
VMD ~ MICRONS
-25
-20
15
-10
5
OAT ~ °C
DENMARK
30
20
10
VMD ~ MICRONS
25
-20
-15
-10
-5
OAT ~ °C

FIGURE 19

The actual weather conditions, therefore, exceeded our expectations and while there is always the possiblity that this was an unusual season, our test experience leads us to believe that the 1983/1984 season was close to normal. The data also confirmed the folklore previously mentioned.

While our decision was influenced to a large degree by the Chinook's range capability, in practice we found that the area along the Bay of Fundy shoreline close to CFB Greenwood was extremely conducive to icing conditions. Any helicopter icing test program with a more restricted radius of action should seriously consider Shearwater (or CFB Greenwood) as a test site.

Concluding Remarks

At the end of the first season, sufficient experience of flight in natural icing throughout the required range of test conditions had been attained and data analysed to define the system control laws.

Additionally, sufficient aircraft system operation with regard to dynamic components, airframe, avionics and systems operation had been acquired to indicate that no major problems will be evident during the subsequent evaluation phase.

The duration of some of the icing encounters during which the aircraft was continuously in icing conditions equalled (or exceeded) the aircraft's normal mission flight time. Since this was true for all icing conditions, including freezing rain, the heated rotor blade system should allow operations to be conducted routinely, regardless of icing conditions.

Operation in icing with engine anti-icing deleted was found to be acceptable and affords savings in engine power of approximately 400 SHP at 0°C.

A considerable body of data which could contribute to the United Kingdom's evaluation requirements had been obtained. Discussions with the FAA (USA) and CAA (UK) are in progress which could lead to joint certification of the Chinook for flight in icing conditions.

Part II of this paper will discuss the analysis of the data obtained and the plans to conclude the icing program.

Appendix I contains a summary of all icing flights which serves as a basis for the Part II paper.

References:

1) "Service Rotorcraft", Design Requirements AP970, Volume 3.

2) K. Lunn and J. L. Knopp, "Real Time Analysis for Helicopter Flight Testing", Sixth European Rotorcraft and Powered Lift Forum, Bristol, England, 1980.

3) C. Hutchinson and A. Miller, "Development of an On-Board Computer for Flight Test Data Analysis", American Helicopter National Forum, Washington DC, 1984.

4) United States Navy, World Wide Meteorological Data.

5) C. Jones, M. Battersby and R. K. Curtis, "Helicopter Flight Testing in Natural Snow and Ice", A1AA-83-2786, 2nd Flight Test Conference, Las Vegas, Nevada, 1983.

Acknowledgements:

The authors wish to express their thanks to the United Kingdom Ministry of Defense for permission to publish this paper. In deference to the United Kingdom as the prime mover in this programme, English spelling has been adopted throughout.

The authors also wish to thank Mrs. Judy Jones of the Boeing Vertol Flight Test Staff for her excellent word processing and assistance with the illustrations.

The above is true of Parts I and II.

APPENDIX A

CHINOOK ZA 708 ICING TRIALS FLIGHT SUMMARY - CANADA - WINTER 1983/84

*VISUAL ACCRETION METER

FLIGHT NUMBER	DATE	FLIGHT TIME	TAKE-OFF WEIGHT	GROUND TEMP	TIME IN ICING	VAM * ACCRETION	IAS	PRESSURE ALTITUDE	OAT
		HR:MIN	LBS	DEG C	HR:MIN	MM	KN	FT	C
X-50	13-11	2:05	45100	+1	0:55	40	120	4000	-8
X-55	22-11	2:16	46450	+5	0:35	18	120	3600	-1.5
X-57	28-11	2:08	46600	+2	0:54	28	120	2850	-6
X-58	29-11	1:15	46730	+2	<0:05	6	120	2000	-1
X-60	1-12	2:36	46560	+4	0:33	42	120	5400	-9
X-61	1-12	1:41	46780	+2	0:48	60	110	6100	-11
X-62	2-12	2:05	46640	+0	0:48	56	110	6250	-13
X-66	10-12	1:42	46610	+6	0:21	20	105	8450	-5.5
X-69	12-12	1:50	46800	-0	1:23	57	130	7110	-7
X-71	16-12	1:20	46260	+10	0:29	14	120	6000	-3.5
X-72	17-12	2:05	46410	+4	0:40	48	120	7600	-13
X-73	18-12	1:38	46800	-2	0:23	22	120	3850	-13.5
X-75	19-12	2:26	46390	-3	1:01	70	120	4750	-11.0
X-76	21-12	2:45	46530	-9	<0:05	6	120	4400	-18
X-78	12-1	2:05	46630	-14	<0:05	7	120 90	1400 TO 2000	-16 TO -18
X-80	14-1	2:31	46820	-5	2:00	76	120	4500 TO 3200	-5.5 TO -6
X-81	14-1	1:20	47200	-3	1:02	30	120	3600	-8
X-82	15-1	1:45	47010	-4	0:10	5	120	1800	-10
X-83	16-1	1:55	46960	-2	0:31	30	110 120	7950 3950	-14 -6
X-84	20-1	2:29	46910	-5	1:04	63	120	3800	-12
X-85	21-1	2:40	47130	-8	0:12	12	105	6100	-24
X-86	24-1	3:09	47150	-0	2:11	101	120 120	5600 TO 6000 2400	-3 -4.5
X-92	8-2	1:33	46930	-6	<0:10	4	120	3000	-14.5
X-94	11-2	2:44	46510	+3	2:15	138	120	3000	-1.5
X-96	21-2	1:10	46610	+4	0:17 0:17	20 20	100 120	7900 2850	-9 -0.5
X-97	21-2	1:32	46810	+4	0:52	56	100	7600 TO 8000	-11
X-98	23-2	2:00	46880	+1.0	0:53	20	100	7600	-4.6
X-101	26-2	1:54	46840	+2.5	0:37	36	120	5450	-2.0
X-102	26-2	1:29	46760	+2.5	1:07	38	110	4950	-1.5
X-104	1-3	2:45	47190	+1.0	1:09	52	90 TO 130	5150	-10.5
X-106	4-3	2:40	47080	-7.0	1:56	50	120 TO 130	4660	-18.0
X-113	10-3	2:25	46010	-9.0	0:43	14	120	6000	-18.5
X-115	12-3	2:43	47140	-7.0	1:06	25	120	2400	-17.0
X-116	14-3	2:26	50400	-0.5	2:15	146	120 TO 130	1600 TO 2000	-3.0
X-117	18-3	2:42	50350	+1.5	1:21	60	120	1900	-6.0
X-118	18-3	2:43	50170	+1.0	1:27	100	120	1600 TO 1900	-5.0
X-119	23-3	2:30	50310	+6.5	0:55	38	110	8000 10000	-8.0
X-120	24-3	2:53	50260	+2.0	2:17	134	110	5500	-11.5
X-121	24-3	2:37	50260	+1.5	1:41	80	120	5000	-11.0
X-122	27-3	2:31	50570	-0.0	1:52	100	110	5050	-12.0
X-123	28-3	2:03	50290	+2.0	1:30	71	120	4300	-6.0

• • •