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# AGARD

## ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD ADVISORY REPORT No. 223

# Rotorcraft Icing —
# Progress and Potential

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.223

**ROTORCRAFT ICING —**

**PROGRESS AND POTENTIAL**

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This Advisory Report was prepared at the request of the AGARD Flight Mechanics Panel.

## THE MISSION OF AGARD

The mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

— Exchanging of scientific and technical information;

— *Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;*

— Improving the co-operation among member nations in aerospace research and development;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

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# PREFACE

The AGARD Flight Mechanics Panel convened Working Group WG-09, Rotorcraft Icing, during 1979 and 1980 to examine the effect of icing meteorological conditions on helicopter operations, to assess potential technical approaches to improve ice protection, to recommend specific research and development, and to discuss opportunities for future cooperative efforts among member nations. The findings reported in AGARD Advisory Report No.166, "Rotorcraft Icing — Status and Prospects", August 1981, included the following:

Helicopter icing is a significant operational consideration for helicopters operating throughout Europe. Unfortunately, the existing meteorological data base is insufficient to describe the operating environment and increased coordination among cloud physicists, forecasters, and helicopter icing specialists is needed to ultimately develop a new icing atmosphere.

Insufficient attention has been paid to understanding the fundamental mechanisms of ice accretion and shedding from rotor airfoils. Such efforts should be undertaken so that analytical methods can play a role in determining what type of ice protection is necessary or, conversely, what degree of flight envelope release may be permitted for a given level of ice protection.

After a thorough examination of facilities for helicopter icing development and clearance it was recommended that the Canadian authorities retain the Ottawa Spray Rig in operational status; that efforts under way at the NASA Lewis Research Center to rehabilitate the Icing Research Tunnel be continued; and that the possibility of a European airborne icing spray system should be considered.

Electrothermal deicing systems are presently the only effective system for broad application, and it was recommended that work continue on other anti-ice and deice concepts. More importantly, with a new series of ice-protected helicopters — the Black Hawk and Puma — the opportunity now exists to conduct careful exploration of operational limitations with ice-protection systems deliberately turned off so as to simulate an aircraft without an ice-protection system or with an inoperative system. Only through such definition of the actual icing environment can the effect of icing conditions on helicopter flight operations be more accurately predicted.

One of the major products of Working Group 09 was the drafting and initial coordination of a proposed set of standard requirements and procedures for obtaining data from operational experience with the new generation of helicopters in order to validate further and refine this proposed icing clearance procedure.

To follow up the report of working Group 09, the AGARD Flight Mechanics Panel formed an additional Rotorcraft Icing Working Group, WG-14, in March 1983. The objectives of WG-14 were (1) to proceed with the recommendations of WG-09 on rotorcraft icing; (2) to examine rotorcraft icing analysis and modelling efforts; (3) to consider new methods of ice protection; and (4) to compare operational experience with ice-protected rotorcraft with the design and qualification criteria presently established.

The scope of the work was to:

(1) Examine rotorcraft icing analysis and modelling efforts

(2) Review the results of current activities in Canada, Europe, and the United States and to consider them in terms of their role in the design and development process

(3) Assess and report on the analytical state of the art and to provide recommendations for future analysis and modelling efforts

(4) Consider rotor ice protection methods that could be alternatives to electrothermal methods

(5) Examine test results, including pneumatic boots, polymeric icephobic compounds, and electrically equipped but deactivated ice-protection systems

(6) Assess and report on the practicality of less costly protection systems and on limited flight clearances for unprotected rotors

(7) Review icing test experience since 1980 in light of the proposed clearance procedures reported in AR 166

(8) Refine the design and qualification procedures from AR 166 and make proposals to the national authorities regarding implementation of revised standard procedures.

Four meetings of WG-14 were held: at AGARD Headquarters, Paris, France, 17—19 October 1983; at NASA Lewis Research Center, Cleveland, Ohio, USA, 23—25 May 1984; at MBB, Ottobrunn, FRG, 6—9 November 1984; and at AGARD Headquarters, Paris, France, 6—9 May 1985. Each Meeting provided opportunities for valuable information exchanges and discussions of icing topics between all members of the Working Group; in addition, subgroup sessions were set up to plan, develop, and review this report. Of course, the bulk of the work was done by the members back at their home offices, mostly in their spare time; this report is a monument to their efforts.

The following is a list of the members of WG-14.

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# 1. HELICOPTER ICING

## 1.1 SUMMARY AND INTRODUCTION

The AGARD Flight Mechanics Panel Working Group on Rotorcraft Icing (WG-14) held four meetings between 1983 and 1985 in order to proceed with the recommendations of Working Group 09 on rotorcraft icing, to examine rotorcraft icing analysis and modeling efforts, to consider new methods of ice protection, and to compare operational and trials experience gained since the AR 166 report was prepared by WG-09.

This report covers the findings of WG-14 as they relate to (1) icing atmospheres, (2) forecasting, (3) predictive methods and simulation, (4) instrumentation and facilities, (5) flight clearances and requirements, and (6) protection methods. The Working Group's principal findings are summarized in the following paragraphs and then presented in detail in the subsequent sections.

The term "icing atmosphere" is a loose one which might be used for a complete description of the characteristics of the atmosphere relevant to icing, or might simply be a statement of specific points to be used as design or test criteria. In fact, no complete description has ever been attempted and even the relatively comprehensive FAR 29, Appendix C, accepting that it deals only with suprecooled water droplets, was only intended to provide recommended design conditions. For example, it was recognized that drop size was only weakly correlated with either water content or temperature. With one exception, the six atmospheres considered form part of design requirements and little or no guidance is provided for their use as test criteria. The use of helicopters in icing conditions is a developing area and much remains to be learned about it. The various atmospheres are largely based on measurements made over the United States and most lack any information on icing conditions other than those associated with supercooled clouds. There is a need to include more data applicable to cloud types that are not well represented at present, more data from outside the United States, and, if there is a demand for it, data relevant to higher altitudes. Such data, when available, should be widely disseminated and subjected to international discussions on how best a complete icing atmosphere could be expressed and, if necessary, reviewed as more appropriate information becomes available, in order to allow design, testing, and certification criteria to be established for all helicopters, whether equipped with ice-protection systems or not.

AR 166 gave an extensive overview of the operational environment and meteorological conditions that affect the helicopter but presented only limited information on data collection and forecasting. One of the conclusions was that techniques then available were inadequate to allow the planning of unrestricted helicopter operations in icing conditions. Since AR 166 was published, several meteorological agencies have studied the feasibility of improved forecasting techniques, and some promising schemes are emerging; however, it is too early to see any change at the level of the helicopter operator. It is likely that protection will be available for full clearance of helicopters in icing conditions before suitable forecasting techniques are validated and accepted. The need for a forecast is then, theoretically removed. Nonetheless, there will continue to be a significant number of partially protected or unprotected helicopters for the foreseeable future, and they will still require improved forecasting facilities, as will the protected helicopter with icing-system failure. Ongoing efforts to improve forecasting capability with coordination between cloud physicists, forecasters, icing specialists, and helicopter operators should continue to be encouraged.

In the past, the certification of helicopters for flight in icing conditions has been based primarily on the evidence of flight in natural clouds. The problems and limitations of this approach have long been realized: in particular, icing flight trials are very expensive and are dependent on nature to provide suitable weather. Although the aim is to clear the helicopter to extreme conditions, such conditions will by definition occur very rarely, and some compromise has to be reached in terms of the level of experience that is acceptable as a basis for clearance. This philosophy was discussed in AR 166 and is discussed in Sec. 6 of this report. In recent years, much thought and effort have been given to the contribution that other techniques such as the use of predictive methods and simulation may make to design, development, and certification, so as to reduce the duration of natural icing trials. Although it must be accepted that some natural testing will always be necessary, the use of other methods to interpolate and extrapolate from flight results to the extremes of the atmospheric and performance envelopes will be a major benefit. In Sec. 4, a critical review is made of the available techniques as a means of assessing their state of development, their limitations, and their suitability for the various tasks to which they may be applicable. Recommendations are made for further development. The techniques considered cover the full range, from theoretical analysis and mathematical modeling, through laboratory and wind-tunnel experiments at both model- and full-scale, to use of flight-test techniques other than the direct performance assessment in natural icing. The latter includes the use of artificially generated clouds and a brief review of the techniques that may be used to enhance the effectiveness of natural icing trials.

Several discrete instrumentation topics submitted by various members of the Working Group are considered. The first topic presents comparisons of measurements from the most common liquid-water-content instruments, as well as similar comparisons of droplet sizing instruments. Next is presented a new high-speed video camera technique for documenting ice coverage and ice shedding on both the rotors and fixed components. The next two sections describe the development status of two new systems that monitor critical helicopter parameters and feed them into on-board computers, which provide an icing status display and assess the severity of the icing encounter. The last section presents the status of a new liquid-water-content probe developed in the United Kingdom.

The facility tables from AGARD AR 166 have been amended to delete those facilities removed from service and to add new facilities developed within the last 5 years. The U.S. Army Helicopter Icing Spray System (HISS) has been improved somewhat since 1981, and there are plans to make considerable further changes and improvements. The U.S. Army has also developed an Airfoil Section Array (ASA) for use on the JU-21A aircraft. It accepts two 18-in.-span airfoil sections, which can be heated and monitored by video and photographic equipment.

General standard requirements for helicopter flight clearance in icing conditions and associated procedures for compliance have been used for both full and limited clearances. Little operational experience has been gained from helicopters with full icing clearances; much more has been gained from those with limited clearances. In the latter category, some clearances are based on limited liquid water content, and some rely on other limitations reflecting the effect on the helicopter, e.g., increase of power required. In either case the clearance may also be restricted in terms of ambient temperature and altitude and although not well documented, no significant difficulties have been reported in respecting the relevant limitations, and the safety record has been excellent. Nevertheless, feedback of information from operators on icing encounters is most important and may ultimately lead to improved icing clearances. Requirements that must be incorporated in the case of full and limited clearances are discussed, and the means by which compliance may be demonstrated are set out. Possible ways of reducing the cost and time required for icing certification--for example, by incorporating more features from the predictive techniques described in Sec. 4--are considered. The need to correlate natural icing results with this simulated icing and analysis is identified as important for such future goals. A synopsis of both experimental and operational flight experience, gained since AR 166 was published, is given, and, in order to complete the operational scenario, preparation of aircraft for flight in ice-forming conditions is also considered.

AR 166 recommended further research and development of six advanced ice-protection concepts as potential alternatives to the electrothermal system for rotors. Since 1981, only one of the recommended systems, pneumatic deicers, has been developed into a prototype system for rotors and successfully flight tested in icing conditions. Although not recommended for rotor systems in AR 166, the electromagnetic impulse system has since been the subject of extensive research and development flight tested on fixed-wing aircraft. The impulse system is applicable to rotors, but as yet there are no practical designs. Other techniques, still in the conceptual stages, are freezing-point depressant fluid systems and higher harmonic control. The Working Group concluded that except for the pneumatic boot, almost no new work on alternative protection systems has been undertaken and that electrothermal deicing of rotors has become the de facto standard for rotorcraft. Without a major procurement of an all weather rotorcraft for which electrothermal deicing would be inapplicable, there is no strong motivation to expend available resources and expertise to implement alternative methods.

## 2. ICING ATMOSPHERES

### 2.1 INTRODUCTION

Of the icing atmospheres that have been or might be used in relation to helicopters, six will be considered in detail. Others are known to exist (e.g., that used for U.S. Navy helicopters), but it has not been possible to obtain detailed information about them. The six atmospheres that will be examined are the following:

1. That given in FAR Part 29, Appendix C (referred to herein as "App C")

2. That used by the U.S. Army (referred to herein as "U.S. Army")

3. That given in the CAA Draft Paper 610 (referred to herein as "CAA")

4. That in JAR 25 and the associated ACJ (referred to herein as "JAR 25")

5. That given in the UK Defence Standard 00-970, Vol. 2 (referred to herein as "970")

6. That given in 1983 by the FAA in Report DOT/FAA/CT-83/22, entitled "A New Characterization of Supercooled Clouds Below 10,000 ft AGL" (referred to herein as "10,000-ft")

These atmospheres are considered separately below. They are referred to as annexes and are included at the end of this section. Each will be considered in turn, but before doing so some general considerations will be discussed. The term "icing atmosphere" is a loose one which might be used for a complete description of the characteristics of the atmosphere relevant to icing, or might be simply a statement of specific points to be used as design or test criteria. In fact, no complete description has ever been attempted and even the relatively comprehensive App C, accepting that it deals only with small supercooled water droplets, was (from Ref. 1) only intended to provide recommended design conditions, and it was recognized that, for example, drop size was "only weakly correlated with either water content or temperature."

One fundamental difference is that the European atmospheres give specific critical design or test conditions or both in terms of maximum liquid water content (LWC) at various ambient temperatures for one droplet size, whereas the U.S. atmospheres cover a "field" of combinations of maximum LWC and droplet size for various temperatures, and leave the designer, etc., to select the critical points.

All the atmospheres form part of design requirements; test criteria are included only in JAR 25, but in some cases these are provided in other documents such as the FAA Advisory Circulars AC 20-73 ("Aircraft Ice Protection") and AC 29-2 ("Certification of Transport Category Rotorcraft").

All the Atmospheres were basically derived from the same NACA data acquired over the U.S. mainland, except the 10,000-ft atmosphere for which new data (again from over the United States) were used in addition. Some French data collected over Europe and Africa is included in Ref. 2 (from Ref. 3) but has not been used in the 10,000-ft atmosphere because this is at present restricted to data from over the United States. The FAA plans to use European data in future analyses which are expected to be completed in 1988.

With some exceptions the icing atmospheres are concerned with icing caused by small supercooled water droplets, and the presence of snow or ice particles (so called mixed conditions), and freezing fog, freezing drizzle, and freezing rain are not considered.

Apart from the six atmospheres considered, there are two other analyses that may be relevant in particular cases but that are not considered in detail here. One is the "An Icing Climatology for Helicopters" (Ref. 4) which considers icing conditions up to 600 mbars over northwest Europe, the United Kingdom, and the northeast Atlantic and is based on 20,000 World War II reconnaissance flights. The second is the translation of a Russian report, "Icing of Aircraft and the Means of Preventing It" (Ref. 5) in which the characteristics of the icing atmosphere are considered.

In what follows all numerical values of liquid water content (LWC) are given in grams per cubic meter.

### 2.2 DESCRIPTION AND DERIVATION OF ICING ATMOSPHERES

#### FAR Part 29, Appendix C Icing Atmosphere

The atmosphere described in FAR Part 29, Appendix C, is reproduced in Annex 1. Two sets of data are provided, one for "Continuous Maximum Icing" (in stratiform clouds), and one for "Intermittent Maximum Icing" (in cumuliform clouds). For each case three relationships are given: (1) maximum LWC versus mean drop diameter for ambient temperatures of 0°C, -10°C, -20°C, and -30°C; (2) the combinations of pressure altitude and ambient temperature for which the icing condition may be experienced; and (3) the variation of LWC with horizontal distance in clouds.

This atmosphere was defined in the late 1940's to meet the needs of the large transport aircraft of the period. It was based on 1,038 sets of LWC values, drop diameter, and temperature obtained during 252 icing encounters spread over the entire United States. Of these, 344 data sets were obtained during 69 encounters

in cumulus clouds, and the rest were obtained in layer clouds. All the results were from research flights in which icing conditions were actively sought.

The LWC and drop diameter were derived to a large extent from results obtained using multirotating cylinders. The analysis of the results, including the statistical approach used, is reported in Ref. 6. Plots of LWC versus drop diameter for various air temperatures are shown for layer and cumulus clouds over three different areas of the United States: the Pacific coast, the central plateau area, and the Eastern United States. In each case the curves are produced for three different values of probability (Pe), 0.1, 0.01, and 0.001; Pe is the probability that any random icing encounter will be characterized by a combination of values of LWC, air temperature, and drop diameter in which each must simultaneously equal or exceed the specified value. The various plots show that there is some variation in the LWC values between the three geographical areas considered. An extreme case is for cumulus clouds where for Pe = 0.001 the maximum LWC in the Pacific coast area is 2.73, whereas for the Plateau region it is 1.73; no results are given for the Eastern United States because the sample of results available was too small.

In addition, a method is shown which allows LWC values to be varied depending on the length of the icing encounter, when this is not one of the standard values (based on the test evidence) of 3 miles for cumulus and 10 miles for layer clouds. It should be noted that this variation with distance is not intended to imply that for longer distances the probability of encountering the higher values, associated with shorter distances, is reduced.

The LWC data in App C appear to be based on the most conservative results shown in Ref. 6 except that the standard distance for layer clouds is increased from 10 miles to 17.4 n. mi. (although the 10-mile value can of course be obtained from the cloud-extent correction factors), and the slightly higher values of LWC for drop diameters below 15 μm which are shown in Ref. 6, are not included. Also, the data on LWCs above 40 μm do not appear in App C. The atmosphere is stated to apply to pressure altitudes of sea level to 22,000 ft for the stratiform clouds and for 4,000 to 30,000 for cumuliform clouds.

## U.S. Army Icing Atmosphere

The U.S. Army atmosphere is shown in Annex 2. The relationship between maximum LWC and median drop diameter is shown for the continuous maximum case (stratiform clouds) and for the intermittent maximum condition (cumuliform clouds) for ambient temperatures of 0°C, -10°C, and -20°C. This atmosphere was defined in 1975 and was based on a study of radiosonde data reported from selected stations in the northern United States. Data were analyzed to determine the low-altitude conditions (below 10,000 ft pressure altitude) within an exceedance probability of 1%. The analysis is contained in Ref. 7.

## CAA Draft Icing Atmosphere for helicopters: United Kingdom, Civil

The description of this CAA icing atmosphere for helicopters is given in Annex 3. Two icing conditions are specified in tabular form, continuous and intermittent. For each, the LWC and altitude range are given for a unique droplet diameter and for ambient temperatures of 0°C, -10°C, -20°C, and -30°C. In both conditions, some alleviation of maximum LWC is allowed for altitudes below 4,000 ft and 15,000 ft for the continuous and intermittent conditions, respectively. Also the intermittent conditions do not occur below 5,000 ft at 0°C and -10°C, and below 10,000 ft at -20°C and -30°C. For convenience, the CAA LWC values for various altitudes up to 10,000 ft have been plotted and are shown in Annex 3 with faired curves drawn through them.

This atmosphere, if adopted by the CAA, will become part of the CAA design requirements. No firm information is available as to its derivation but it is thought that the continuous icing conditions (similar to those of the 970 atmosphere) were agreed to by the RAE after joint work in the mid-1970s; this is discussed later in this section. The intermittent conditions are thought to have been based on the App C atmosphere, but with a greater alleviation at low altitudes, derived perhaps from United States work.

## JAR 25 Atmosphere

The JAR (Joint Airworthiness Requirements) are used by the all JAR participant airworthiness authorities, for fixed-wing aircraft. The requirements state that airplanes must be designed to operate safely in the icing conditions determined under Appendix C to the Requirements, which it is thought are similar to the App C atmosphere. Two methods of compliance are shown which represent two different philosophies. One is based on the FAA approach and the other calls for tests at the specific points given in the ACJ of JAR 25 and reproduced in Annex 4.

For LWC, these test points are identical to those for the CAA atmosphere except that no alleviation with altitude is allowed and no altitude ranges for particular air temperatures are quoted. However, there is an interpretation of what is required in terms of intermittent conditions. Compared to the App C atmosphere, the maximum LWC's are the same, except that for continuous conditions the droplet size is 20 μm instead of 15 μm.

A feature unique to JAR 25 is that the maximum ice crystal content is given, although the minimum altitude considered is 10,000 ft.

Defence Standard 00-970 Icing Atmosphere: United Kingdom, Military

The Defence Standard 00-970 is shown in Annex 5. Two icing conditions are specified, continuous maximum and periodic maximum. For each, the LWC, horizontal extent, and altitude range are given for a single value of median droplet size, for air temperatures of +5°C, 0°C, -10°C, and -20°C. Reduced values of LWC are specified at altitudes below 4,000 ft. A graphical presentation of the LWC values is given in Annex 5. As well as specifying the LWC, etc., for pure supercooled water, definitions of mixed conditions, freezing fog, and freezing rain are also included.

This atmosphere is included in the U.K. military design requirements and was derived in the mid-1970s when it became clear that the full rigor of App C was not realistic for helicopters. The App C data were reexamined after removing all data for altitudes above 10,000 ft and some U.K. data were included in the analysis. It was found that the App C continuous maximum was valid except that some alleviation was possible at altitudes below 4,000 ft, and some higher values occurred for short distances from time to time. To cover this latter point the periodic maximum condition was introduced. No evidence was found of App C intermittent maximum conditions below 10,000 ft and so this case was not included. The droplet size specified was chosen to give, together with the LWC values, the worst design cases. The other icing cases included in 970 (mixed conditions, freezing fog, and rain) were based on the best evidence available, but it was recognized that the numerical values given might be in error, particularly for mixed conditions.

This atmosphere was intended to be a comprehensive guide for design purposes, using the best data available. The uncertainty in some areas was acknowledged and was to be taken into account when formulating clearances for operation within those areas.

FAA New Characterization of Supercooled Clouds below 10,000 Feet AGL

The characterization of the 10,000-ft atmosphere is shown in Annex 6. A curve of LWC versus median drop diameter is shown for each of three temperature ranges, 0°C to -15°C, -15°C to -20°C, and -20°C to -25°C. The distance for which any particular LWC may occur is also shown.

This atmosphere is based on the relevant data of those used for the App C atmosphere, together with about the same number of modern observations. In all, this amounts to some 6,700 data miles (of flight) with 1,400 icing events. An account of the data analysis (using an improved statistical method to that in Ref. 6) and results is contained in Ref. 3. As is well known, this work was undertaken to provide a more realistic icing atmosphere for helicopters, using the best available information.

Two main results came from the analysis. First, it was found that all the results, whether from layer or convective clouds, could be combined without any objectional discontinuities. Secondly, the results in the temperature bands 0°C to -5°C, -5°C to -10°C, and -10°C to -15°C were quite similar and it was, therefore, concluded that the one band 0°C to -15°C could be used. Results for temperatures of -15°C to -20°C and -20°C to -25C are also shown.

The overall atmosphere was then presented as a plot of LWC versus droplet diameter for the three bands of temperature already mentioned. On each curve the maximum duration of the icing condition in nautical miles is shown. The LWC results are calculated such that they will not be exceeded more than once in 1,000 icing encounters; similarly, the icing encounter distances, at various values of LWC, will not be exceeded more than once in 1,000 icing encounters.

Because this atmosphere represents new work based in part on new data, and because of its possible adoption as a new standard, a more thorough appraisal will be attempted later in this section.

The 10,000-ft atmosphere is not as comprehensive as the App C atmosphere in that the variation of LWC with distance is not defined in as much detail and, of course, if required, the distinction between LWC in layer and convective clouds has disappeared. The results on which the 10,000-ft atmosphere are based are presented in more detail in Ref. 2, which provides much valuable data on the variation of LWC horizontally and vertically, as well as a complete list of the results on which the analysis was based, in a form which should allow further analysis if required. In addition, previously unpublished curves, equivalent to the 10,000-ft LWC-versus-droplet-size plot but for varying encounter probabilities down to 80% as opposed to the 99.9% probability used in the 10,000-ft, have been developed by the FAA from their data base. These plots have been combined and are shown in Fig. 1.

As with the App C atmosphere, no account is taken of conditions outside the United States, or of mixed conditions, freezing rain, etc. However, this is recognized in Ref. 3 and further work is planned.

2.3 COMPARISON OF SIGNIFICANT FEATURES OF THE ICING ATMOSPHERES

Liquid Water Content

All six icing atmospheres, except the 10,000-ft atmosphere, distinguish between what LWC may be experienced continuously and what may be found intermittently. Where the distinction is made, "continuous" generally relates to stratiform clouds and intermittent to cumuliform clouds. The 10,000-ft atmosphere shows the distance for which a particular LWC may be experienced (in discrete steps). A difficulty in

making comparisons is that in some atmospheres the maximum LWC is given for only one droplet size, whereas in others it varies depending on droplet size.

The maximum values of LWC (versus air temperatures) are shown in Fig. 2 for the continuous conditions of the various atmospheres regardless of droplet size. The curve shown for the App C atmosphere is that for the standard distance of 17.4 n. mi. The CAA, 970, and JAR 25 values are stated to be continuous and lie on the App C line. The U.S. Army data were also stated to be continuous and show LWCs some 20% higher than those of App C, although they are similar for the same droplet size to those of the App C maximum LWC (15 μm). The 10,000-ft values, for a horizontal extent of 20 n. mi. show a value of LWC at 0°C, which is similar to that of App C, but at lower temperatures the LWCs are considerably higher.

Comparisons at distances other than 17 to 20 n. mi. are not possible since only the App C atmosphere gives values for continuous conditions. The 10,000-ft data for shorter distances are probably largely governed by cumuliform cloud cases and will be discussed below as intermittent conditions. However, it should be pointed out that for the shortest distance considered (5 n. mi.) the App C LWC is 1.34 times that of the standard distance (17.4 n. mi.), and this may be of significance as a possible "worst case" in stratiform clouds. The other atmospheres do not consider this except that the 970 periodic maximum (for a distance of 6 km) shows values of 1.5 times the App C standard value. In the 970 and CAA atmospheres, the maximum LWC reduces at altitudes below 4,000 ft (presumably AGL). This feature is not present in any of the other atmospheres for intermittent conditions.

Figure 3 shows some representative examples of the maximum LWCs given for the various atmospheres. None can be directly compared without qualification but certainly there is a wide variation between them. The App C line is that for a distance of 5.2 n. mi. (the longest for which data are provided) and gives therefore the lowest LWCs. .It is stated to apply only for altitudes above 4,000 ft. This case was chosen to provide a comparison with the 10,000-ft atmosphere, which shows a minimum distance of 6 n. mi. As would be expected taking into account the derivation of the two atmospheres, the maximum LWCs of the 10,000-ft atmosphere are, in general, considerably lower than those of the App C, although the reduction is quite small at temperatures of -10°C to -15°C. The U.S. Army line is in the main between the App C and 10,000-ft lines, but the LWCs may exist for up to 15 min. Such a time at normal flying speeds would give a distance far in excess of that considered in the App C; on the other hand, the appropriate LWCs from the 10,000-ft atmosphere for such a distance would be much lower, say 0.75 instead of approximately 2.0 at temperatures between 0°C and -10°C.

Water-Droplet Size

The European Atmospheres quote only the droplet size(s) which are to be taken into account as critical points, and the validity of these will not be discussed here, except to note that for water droplets a value of 20 μm is used and that in the new 10,000-ft atmosphere this value is approximately that for maximum LWC at air temperatures above -15°C but that at lower temperatures the maximum LWCs occur at smaller droplet sizes.

The App C atmosphere shows the LWC increasing as water droplet size decreases, down to the smallest droplet shown of 15 μm, and the U.S. Army atmosphere shows this trend continuing to lower sizes. This characteristic has been criticized as being unrealistic, and several explanations have been advanced to explain it. However, the recent analysis for the 10,000-ft atmosphere shows the variation of LWC down to droplet sizes of well below 10 μm with the expected decrease of LWC at the lower values.

Horizontal Extent of Icing Encounters

All icing atmospheres recognize that the highest values of LWC will only occur over limited distances or time. Where specific values are quoted, they are generally between 5 km and 6 n. mi., although the U.S. Army specifies 15 min. The App C atmosphere and the supporting analysis for the 10,000-ft atmosphere show the variation of LWC with distance, and this may be of considerable value although, as noted above, the decrease of maximum LWC with increasing distance does not imply that the higher LWCs appropriate to shorter distances will not be encountered. Also, in circling flight it may be possible to stay in a region of high LWC longer than would be indicated by flying over a particular distance in a straight line.

Variation of Maximum LWC with Altitude

The U.K. atmospheres show an alleviation of the maximum LWC below certain altitudes and the evidence in Ref. 2, although not conclusive, appears to support this feature. Such an alleviation might be of value in justifying clearances at low altitudes, and this might be particularly useful for helicopters that are not fitted with rotor protection. However, care is needed because there are indications that freezing fog containing only supercooled water droplets may cause significant icing problems.

Probability of Encountering Particular Icing Conditions

The European atmospheres make no mention of probability. It is stated in Refs. 1 and 6 that the values used in App C are such that the probability of exceeding the LWC, air temperature, and droplet size, at the same time, during any random icing encounter is 0.001, that is, 1 in 1000. The U.S. Army atmosphere uses values chosen for a probability of 1 in 100. The 10,000-ft atmosphere values relate to a probability of 1

in 1000, the same as App C, but in this case the probability is based on the chance of exceeding any partic-
ular parameter (e.g., LWC) and not the App C concept of exceeding all three relevant parameters together.

In the App C atmosphere (from Ref. 6), the chance of exceeding a set of values (LWC, temperature,
droplet size) is the chance of exceeding the temperature, multiplied by the chance of exceeding the LWC when
the temperature has been exceeded, multiplied by the chance of exceeding the droplet size when both the
temperature and the LWC have been exceeded. Thus, it would seem that the chance of exceeding, say, the
maximum LWC, is greater than the chance of exceeding all three variables. If this is correct, then the risk
of exceeding the LWC in the 10,000-ft atmosphere is less than in the App C atmosphere. The size of the
difference is not obvious, but Lewis (Ref. 1) in discussing the App C atmosphere stated that "it was deter-
mined that the condition that 99% of cases lie within the envelopes was roughly equivalent to a probability
of 1/1000 that all three variables represented by a single point would be exceeded simultaneously." As a
point of reference, it is noted that from Fig. 1, the 10,000-ft data at a level of probability of 99% give
maximum LWCs that are quite similar to those of the "periodic" values in the 970 atmosphere.

That the maximum LWC is significantly affected by the probability of exceedance is clear from the
various plots in Fig. 1, all derived from the same body of data, and from the preceding discussion it seems
that a higher level of probability is inherent in the 10,000-ft atmosphere than was used for the App C.
This raises the question of what level of probability should be used for military helicopters. No discus-
sion of this has been found in the literature for either military or civil helicopters, and it is recom-
mended that this omission be rectified.

## Other Atmospheric Conditions Conducive to Icing

These cases include mixed conditions, freezing fog, drizzle and rain, ice crystals, and snow. All are
addressed in the 970 atmosphere, although the values given are tentative; nonetheless, they have not been
covered elsewhere except that the case of snow is included in the CAA atmosphere (and qualitatively in the
JAR and FAR requirements), and ice crystals are covered in JAR. It is noted in Ref. 3 that more work is
needed in these areas, and that statement was endorsed in AR 166 and is repeated again here.


## 2.4 APPRAISAL OF ICING ATMOSPHERES

All the atmospheres were derived using the same, original NACA data except that the 10,000-ft atmo-
sphere also included about the same amount of new data.

### APP C Atmosphere

This was the first icing atmosphere and although certain features of it are open to criticism and
misinterpretation it has been widely used in the design and certification of large fixed-wing aircraft, and
also for the Puma and Super Puma helicopters with heated rotor blades. The App C atmosphere, together with
the fuller data contained in Ref. 6, gives much relevant information on LWC, although the variation with
altitude is not addressed. Care is needed in interpreting App C because of the definition of probability
used in establishing the data, and this may be of relevance to the apparently improbable high values of LWC
shown for small water droplet sizes.

This atmosphere was reviewed in 1969 in Ref. 1, which concluded that "although these standards are now
20 years old, they are generally consistent with data that have become available since their adoption.
Since these criteria have stood the test of use, and since the total of experience with existing aircraft is
more comprehensive than any data collecting program, it is suggested that future changes in criteria be
based primarily on operating experiences rather than on meteorological data." How this was to be achieved
was not discussed.

However, it became clear that a less demanding atmosphere could be safely used for helicopters operat-
ing at relatively low altitudes, and this has led to the definition of later atmospheres specifically for
helicopters. This work has shown that with more data and the latest methods of analysis it should be possi-
ble to improve the App C atmosphere. It is recommended that this work be carried out if an atmosphere
extending to high altitude is required for helicopters. Such work is in progress by the FAA for fixed-wing
aircraft and if completed would apply to helicopters.

### U.S. Army Atmosphere

The U.S. Army atmosphere was derived from App C data but with a probability of exceedance of 1 in 100
instead of 1 in 1,000. However, an examination of the LWC values obtained shows that particularly for
stratiform clouds, they are higher than might have been expected. Figure 2 shows a comparison of maximum
LWC with App C (regardless of drop size); for a 20 μm diam drop in stratiform clouds, the LWCs are virtually
identical to the App C values. From Ref. 6, it seems that a reduction of at least one third occurs when
changing from a probability of 0.1% to 1%, for a 20 μm drop, over the temperature range in question.
Another feature of this atmosphere is that the intermittent maximum is shown as existing for 15 min maxi-
mum. This time is considerably longer than would be expected from Ref. 6, and was selected for operational
reasons.

It is understood that this atmosphere has been used for design purposes, but for testing and clearance the "light" and "moderate" icing concept has governed the maximum LWC which is required. The U.S. Army is now giving consideration to changing to the 10,000-ft atmosphere.

## 970 Atmosphere

The 970 atmosphere is part of the U.K. Military Design Requirements for helicopters and was derived largely from the original NACA data for altitudes up to 10,000 ft and for ambient temperatures down to -20°C. It has been used as a reference for U.K. military testing in natural icing conditions, and has been generally found to be realistic for U.K. military operations although there is some test evidence that suggests that the maximum LWCs quoted may be somewhat exceeded at altitudes below 4,000 ft.

## CAA Atmosphere

The CAA atmosphere forms part of the CAA Draft Design Requirements for helicopters that are to operate in icing. Nothing is known as to whether its provisions have been related to testing for clearance purposes.

## JAR Atmosphere

For design purposes the JAR atmosphere is identical to the App C; for testing, the associated ACJ allows the App C procedure to be used (taking into account all possible combinations of maximum LWC versus droplet size) or, alternatively, compliance at specified test conditions. The latter give maximum values of LWC for a specific droplet size and, in addition, details of maximum ice crystal content, and freezing fog.

## 10,000 Ft Atmosphere

It is stated in Ref. 3 that the 10,000-ft characterization is intended to serve as a basis for the establishment of design criteria and regulations that pertain to ice-protection systems and equipments for low-performance aircraft which typically operate below 10,000 ft. Strictly, it should be judged only against its intended use for civil helicopters, but because new characterization results from a new analysis of the largest body of data yet available, it is bound also to be considered as a basis for design, testing, and acceptance criteria for all helicopters, protected or unprotected, civil or military. Hence, the comments below are wideranging, but some are not relevant to the stated purpose of the 10,000-ft atmosphere.

The Working Group has received two appraisals of the new atmosphere from outside sources (Refs. 8 and 9) and use has been made of them where they have been considered pertinent.

Comments on the 10,000 Ft Atmosphere. In most of the "modern" measurements, LWC values were often recorded from J-W and PMC probes. Neither set of readings was systematically higher than the other, and for the analysis the lower values were discarded. To illustrate the possible error, 35 events contained in the data base show LWC values from both the JW and the PMC probes where one value at least showed an LWC greater or equal to 1.0. Of these, the ratio of the PMC value divided by that from the JW varied from 2.27 to 0.64, with a mean of 1.28, and in 27 of the 35 cases the JW showed the lower value. Of the 35 comparison, 9 were within approximately ±10% of the appropriate mean value, 12 within ±20%, and the remaining 14 showed a greater variation. These errors were within the instrument errors of the devices used and since no universally accepted standard exists for any averaging process, the conservative method of using the higher value in each case was adopted.

Some doubt initially existed as to the maximum LWC (1.74) given by the characterization and more particularly the distance over which it can exist (6 n. mi.). For example, the actual maximum LWC of 1.7 used in the analysis was not a single data point but was an average of a number of 6-sec samples with LWCs ranging from over 2 to about 1. However, the maximum LWC of the characterization is justifiable in that it arises from the statistical analysis using all the data. The validity of the distance over which the high values of LWC may occur is less certain, and more detailed analysis performed since the characterization was established indicates that the duration of encounters may be reduced to 2 n. mi. for LWCs greater than 1.5. The FAA is considering such a reduction.

It must be accepted that high values of LWC can occur, but it is important to know for how long and with what probability. This leads to consideration of how far the data base is biased because many of the measurements may have been obtained by deliberately flying in areas where the highest values of LWC, for the atmospheric conditions in question, might be found. As an absurd extreme, if all the data points were obtained in this manner then the stated probability of encountering the extreme LWC would only be true if routine flying was conducted on the basis of seeking out the highest possible LWC. Obviously this is not the case, but some indication of the possible distortion of the probabilities due to nonrandom sampling would be most valuable.

The highest values of LWC included in the data base were found in certain areas with uncommon meteorological characteristics. If higher values were found over America (or elsewhere in the world), which is perfectly possible, it is understood that consideration would be given to changing the atmosphere to include them. A difficulty could arise if the higher values did not fit comfortably into the statistical distribution of LWC based on the total body of data.

Given that very high LWCs exist, perhaps the practical point at issue is what is the chance of actually encountering them during military flying, taking into account icing forecasts and the normal practice of avoiding areas of severe turbulence, and if a severe condition were encountered, how long would it last and how easy would it be to vacate the condition. It may be of interest that (from Ref. 2) when the LWC of 1.7 was measured, the next data point, a minute later, at an altitude of 100 ft lower, showed an LWC of 0.25. The next LWC, 8 min later and 600 ft higher, was 0.27. Efforts have been initiated by the FAA to address these considerations, and the results to date, which are preliminary, are shown in Fig. 1. These data, when supplemented by horizontal extents, might be the ultimate basis for selection of the appropriate design and qualification criteria.

Returning to the characterization, it is derived on the assumption of a mono-modal distribution of maximum LWC with droplet size, as in App C. This hypothesis was not accepted in earlier U.K. work on the NACA data. In Ref. 8, it is argued that if a flat top distribution were used, the maximum values of LWC might be reduced. Some further work on this question is being carried out by the FAA and will be reported in due course.

The maximum values of LWC for continuous conditions in layer cloud for the 10,000 ft atmosphere are not easily compared with those of other atmospheres, but for a distance of about 20 n. mi. it appears from Fig. 2 that those in the 10,000-ft atmosphere are, except near 0°C, significantly higher than those of the App C and most other atmospheres. Again making a comparison with the Russian results for layer clouds given in Ref. 3 shows that the 10,000-ft values are some 30% higher in the -10°C to -15°C region. The last comparison is not, though, entirely fair because it relates to evidence obtained from a different geographical area. These differences arise because the 10,000-ft atmosphere allows no reduction of LWC as the temperature falls from 0°C to -15°C. It is not clear how far this is a true reflection of continuous conditions or whether the statistical "mix" of convective and layer clouds biases the result. However, it has also been argued that in nature, below 10,000 ft, stratiform and cumuloform clouds exist in close proximity and should be combined to achieve a more realistic characterization.

Experience suggests that to obtain the 10,000-ft maximum LWC of 0.75 for 20 n. mi. at -15°C would be unlikely and an examination of the modern part of the data base in Ref. 2 showed that for a distance of about 20 n. mi., at air temperatures below -10°C, the maximum LWC was 0.34 at -12.7°C. Higher values of LWC occurred at below -10°C but for distances that were never more than 5 n. mi. and in about 80% of the cases, 1 n. mi. or less. The older NACA data do show one or two more severe cases, for example an LWC of 0.61 for 21 n. mi. with air temperatures varying between -8°C and -16°C. These results are plotted and discussed in Ref. 2 and it is recommended that they should be carefully considered before being accepted as valid. The statistical analysis will lead to the prediction of higher values of LWC and of horizontal extents than those in the data base, with the increases depending on the chosen probability. The FAA is currently reviewing the evidence in this area, particularly with regard to horizontal extent.

The horizontal extent has been simplified in the characterization by presenting a stepped variation of distance with LWC. This means that within the upper portion of each step the distance for the maximum LWC is likely to be higher than it should be. This may be particularly significant for high values of LWC; for example, using only the data for which the LWC values from the JW and PMC probes agree within ±20%, the longest distance for a mean LWC greater than 1.0 is 2 n. mi. and the distance for the highest LWC (1.7) is 0.6 n. mi. The FAA is currently considering the alternative approach of a smooth variation of horizontal extent as a function of LWC for future applications and it is suggested that this should also be applied to the present characterization.

The 10,000-ft characterization combines layer and convective clouds. The implications of this approach were not clearly understood by the Working Group as a whole and in view of the differing characteristics of these clouds and the different philosophies that currently exist between countries and between military and civil agencies, it would have been preferable to have presented the data for the two types separately as well as combined. The FAA is considering this approach in future analyses.

It was also felt by some that the variation of MVD with LWC from the single presentation of the characterization could be misinterpreted. It has been confirmed by the FAA that the correct interpretation is the same as that for the App C curves, that is, for a particular LWC the MVD can take any value which exists between the outer envelope of the characterization at that LWC. Some additional guidance is desirable to ensure uniform interpretation.

The 10,000-ft characterization does not include the variation of icing parameters as a function of altitude. It assumes that LWC extremes can be encountered at any altitude and the FAA considers this adequate and conservative for present civil helicopters. For military applications, or if considered appropriate for civil machines in the future, any relevant relationships could be established. If this were done, reductions of LWC below, say, 4,000 ft might become apparent (similar to those shown in Figs. 7 to 9 of Ref. 2), however, the effect of ground fog is not known. The FAA has identified a need to characterize the icing atmosphere at all altitudes including the effect of ground fog.

It is argued in Ref. 2 that although the LWC may be lower at low altitudes, the probable horizontal extent of icing encounters is longer and therefore the maximum ice accretion does not vary very much with altitude. This is a valid point where maximum ice accretion is the important parameter, but for the rotor the ice accretion per unit time, and therefore the LWC, is most important.

As already discussed, no justification is given for the choice of the probability of exceeding particular conditions, and there is doubt whether the same standard as App C is being used. However, preliminary information is available about the variation of maximum LWC with different levels of probability (Fig. 1) and the associated horizontal extent of icing encounters for varying probabilities has been produced from the data base by the FAA but not yet published. Raw data are however included in Table 1 of Ref. 3. It is considered desirable that the rationale for the adoption of particular exceedance probability standards, accepting that they may not be the same for military and civil helicopters, should be known.

The LWC values on which the new characterization is based have been correctly obtained from the best test instruments available. However, the LWC instruments commonly fitted to helicopters for clearance testing and in service use have differing characteristics, and in practice it may be necessary to establish the relationship between these different measurements.

The new characterization clearly represents an important step in establishing the icing conditions that a helicopter may meet in supercooled clouds. In particular, the establishment of the relatively large data base from which it was derived is very valuable. It is based on a systematic and sensible approach which should allow further data to be readily added as they become available. Also, the use of the data base for deriving additional information related to helicopter icing conditions should be relatively straightforward.

The analysis of the data has been performed using an improved statistical approach, but the actual form of the characterization is perhaps more controversial in that although it is an elegant way of presenting simply a large amount of information, the act of compression inevitably removes some of the detail which might for some purposes be valuable. This in itself need not be of special concern in that as already indicated, the data base exists to allow any interested party to use it as he sees fit. The possible problem is that the characterization will be used as it stands for various purposes including those for which it was not intended, without the benefit of the background information and the discussion contained in Refs. 2 and 3. Many readers will recognize that App C has been widely misunderstood even though the supporting NACA Technical Notes, which usually anticipated and explained the areas in which difficulties have occurred, have been readily available.

In relation to the declared objective of the new atmosphere, that is, to serve as a basis for the establishment of design requirements, it is felt that the characterization may be somewhat overcautious for military applications and does not necessarily provide enough detailed information to allow design points to be selected with confidence. Much useful background material is presented in Ref. 2, but it is not all analyzed in the same way as that used for the new characterization.

As explained earlier, the various comments on the 10,000-ft atmosphere relate to the usefulness of the new atmosphere in the widest possible context and it should also be said that they have been made without the benefit of detailed discussion with the originators of the 10,000-ft atmosphere; they should not, therefore, be necessarily considered as definitive. Perhaps the general theme is that every advantage should be taken of the new knowledge that is now available, or potentially available, to develop thinking about standards for design, testing, and clearance, without, if possible, creating any hard boundaries which might make it difficult to exploit the possibilities of helicopters flying in icing conditions, with, where necessary, restricted clearances.

The new characterization is restricted to supercooled clouds below 10,000-ft AGL. More work is promised for higher altitudes, which may be relevant to some helicopters, for other conditions conducive to icing, and for icing conditions in areas outside the United States. All this work will be of great interest and is supported by the Working Group.

## 2.5 QUESTIONS AND CONCLUSIONS

The six icing atmospheres examined here show different features as explained earlier in this section, but most lack any information on icing conditions other than those associated with supercooled clouds, and all are very largely based on measurements made over the United States.

With the exception of the 10,000-ft atmosphere, there is broad agreement between the atmospheres for the maximum LWC in continuous conditions in layer clouds but there is, with one or two exceptions, no consideration of transient peaks of LWC in these conditions or of reduced values of LWC at altitudes relatively close to the ground. Certain anomalies exist concerning droplet size, but these can probably be explained in the light of current knowledge.

There is less agreement for convective clouds, in particular for the maximum values of LWC and for how far they may exist. This question is further complicated by the fact that the probability of encountering severe conditions varies considerably, depending on geographic location.

A prerequisite to allow adequate information to be available, whether it be for design or certification, is an adequate data base. The one drawn up in Ref. 3 and used for the 10,000-ft atmosphere provides a sound beginning for supercooled clouds and should be expanded to include more data for the types of clouds that are not well represented at present, more data from ouside the United States, and, if there is a demand for it, data for higher altitudes. Similar work is needed for other icing conditions including mixed conditions, freezing fog, drizzle, and rain.

The use of helicopters in icing is a developing area and much remains to be learned about the design of protection systems, about testing in flight and in simulators, and about certification, for protected and unprotected machines, civil and military. It follows that there is a need for as much basic information to be obtained from the data bases as possible and for it to be widely disseminated. This should allow the best possible consideration to be given to how best to formulate criteria for design, clearance, etc. It should be recognized that such standards should at this stage be tentative, and provision should be made for them to be changed as knowledge increases. It is considered particularly important that the reasoning behind any criteria is stated in relation to safety standards.

It is not within the scope of this section to discuss design and certification standards except where they are governed by the use of icing atmospheres. From that point of view, any atmosphere should be sufficiently detailed to allow safe standards to be set for any type of operation ranging from an unprotected machine operating in the ASW role, close to the sea, where anything other than light icing is improbable, to a fully protected helicopter regularly operating in an area where severe icing conditions are common. None of the icing atmospheres considered meet these requirements and it is recommended that this question be reviewed with the objective of developing a framework, internationally agreed, within which the needs of all parties can eventually be met.

## 2.6. RECOMMENDATIONS

1. The data base for supercooled clouds up to 10,000 ft which has been established for the FAA should be expanded to include more data relating to convective clouds and conditions worldwide.

2. If there is a requirement, it should also be extended to cover higher altitudes.

3. Separate icing atmosphere characterizations for layer and convective clouds should be formulated from the present FAA data base.

4. Data bases should be established covering all other atmospheric conditions conducive to icing and in particular ice crystals, mixed conditions, freezing fog, drizzle, and rain. In addition, although the effects on the helicopter are different, the characteristics of falling and blowing snow need to be defined and an appropriate data base established.

5. As much information as possible should be derived from the data bases to meet the needs of all parties and it should be disseminated as widely as possible.

6. The rationale for basing icing clearances on a particular probability of encountering icing conditions should be established.

7. When enough information is available in a particular area there should be discussion of how best an appropriate icing atmosphere could be expressed, and if necessary reviewed as knowledge increases, to allow design, testing, and certification criteria to be established for all helicopters, protected or unprotected. The objective is to achieve standards accepted by all nations.

8. To promote better understanding between the nations, all these recommendations should be carried out internationally and the criteria used to reach all decisions should be clearly stated and, where possible, agreed upon.
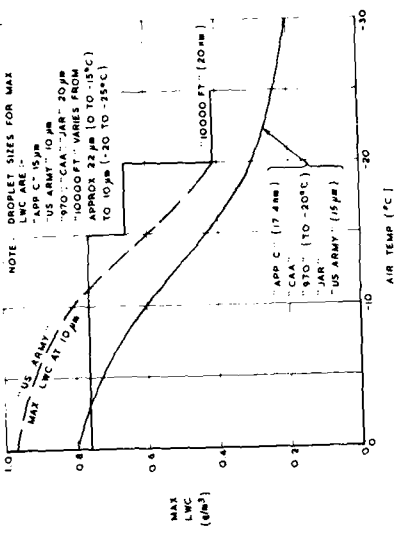
Fig. 2. Comparison of "continuous" conditions.
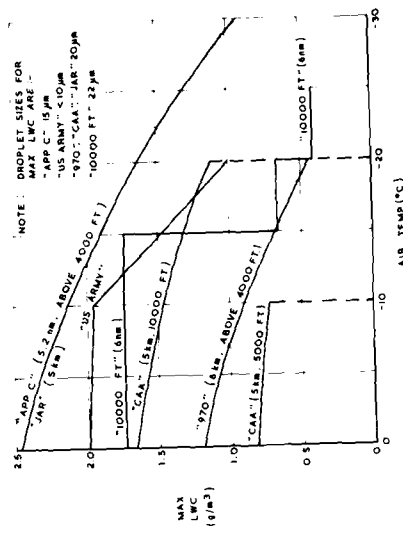


Fig. 3. Comparison of "intermittent" conditions.
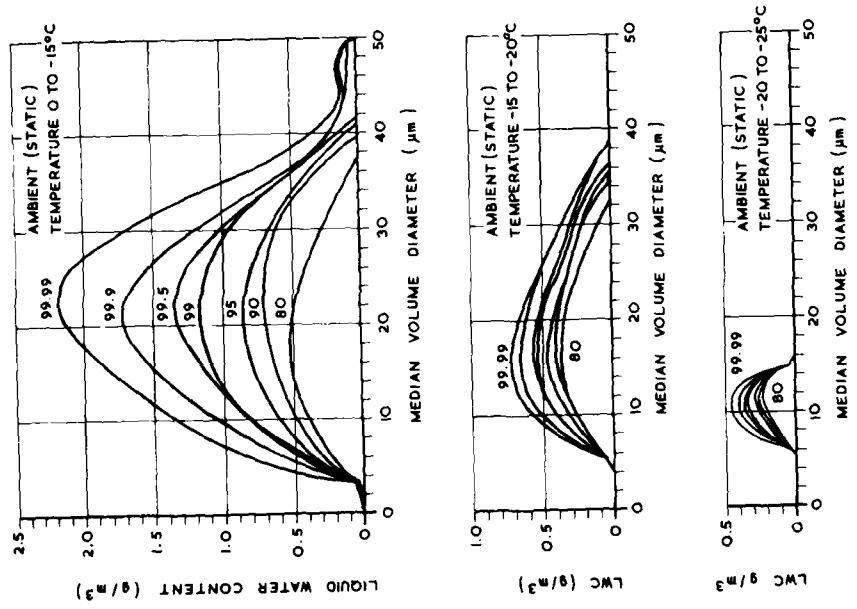


Fig. 1. Atmospheric icing conditions below 10,000 ft.

ANNEX 1

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a. _Continuous maximum icing_. The maximum continuous intensity of atmospheric icing conditions (continuous maximum icing) is defined by the variables of the cloud LWC, the mean effective diameter of the cloud droplets, the ambient air temperature, and the interrelationship of these three variables as shown in Fig. 1 of this Appendix. The limiting icing envelope in terms of altitude and temperature is given in Fig. 2 of this Appendix. The interrelationship of cloud LWC with drop diameter and altitude is determined from Figs. 1 and 2. The cloud LWC for continuous maximum icing conditions of a horizontal extent, other than 17.4 n. mi., is determined by the value of LWC of Fig. 1 multiplied by the appropriate factor from Fig. 3 of this Appendix.

b. _Intermittent maximum icing_. The intermittent maximum intensity of atmospheric icing conditions (intermittent maximum icing) is defined by the variables of the cloud LWC, the mean effective diameter of the cloud droplets, the ambient air temperature, and the interrelationship of these three variables as shown in Fig. 4 of this Appendix. The limiting icing envelope in terms of altitude and temperature is given in Fig. 5 of this Appendix. The interrelationship of cloud liquid water content with drop diameter and altitude is determined from Figs. 4 and 5. The cloud LWC for intermittent maximum icing conditions of a horizontal extent, other than 2.6 n. mi., is determined by the value of cloud LWC of Fig. 4 multiplied by the appropriate factor in Fig. 6 of this Appendix.
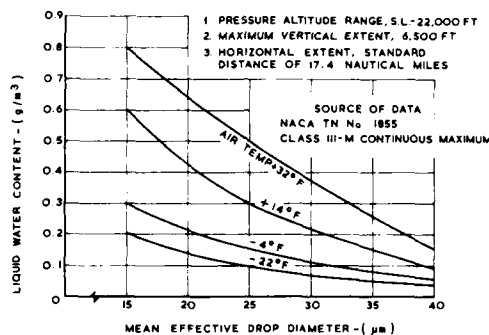


Annex 1 Fig. 1. Continuous maximum (stratiform clouds) atmospheric icing conditions. Liquid content vs mean effective drop diameter.
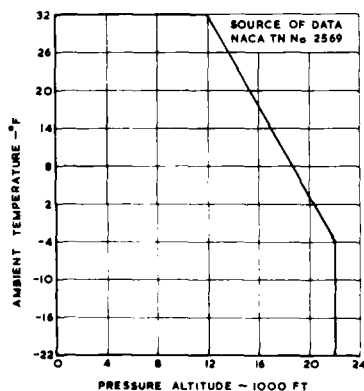


Annex 1 Fig. 2. Continuous maximum (stratiform clouds) atmospheric icing conditions. Ambient water temperature vs pressure altitude.
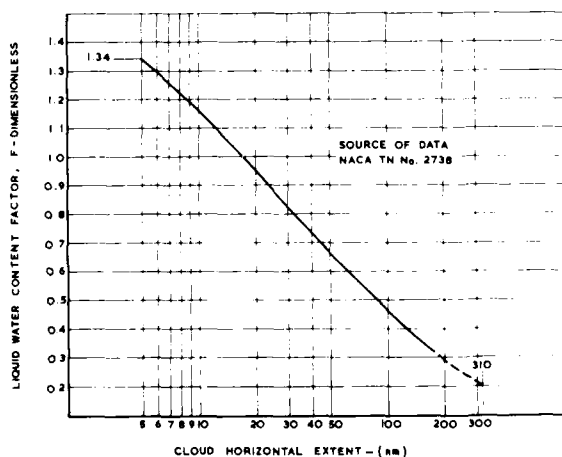
Annex 1 Fig. 3. Continuous maximum (stratiform clouds) atmospheric icing conditions. Liquid water content factor vs cloud horizontal distance.
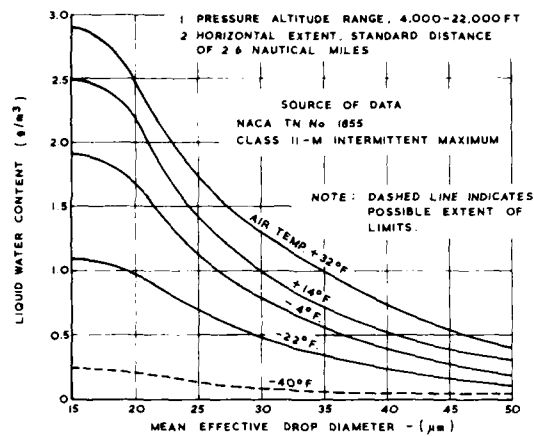
Annex 1 Fig. 4. Intermittent maximum (cumuliform clouds) atmospheric icing conditions. Liquid water content *vs mean effective drop diameter*.
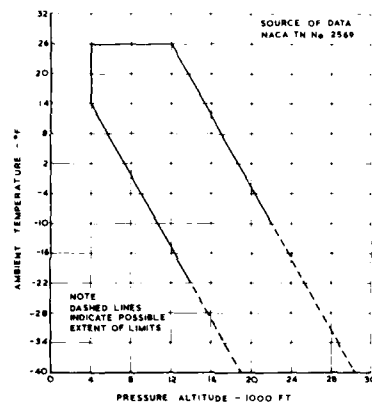


Annex 1 Fig. 5. Intermittent maximum (cumuliform clouds) atmospheric icing conditions. Ambient temperature vs pressure altitude.
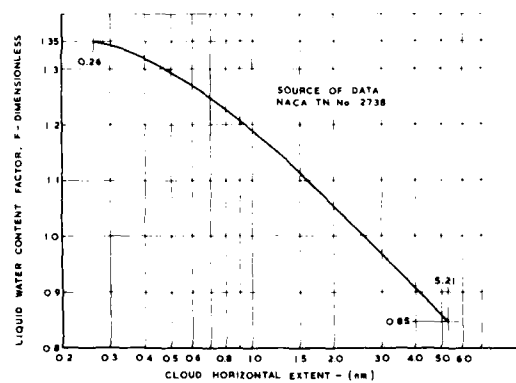


Annex 1 Fig. 6. Intermittent maximum (cumuliform clouds) atmospheric icing conditions. Liquid water content factor vs cloud horizontal distance.

ANNEX 2

U.S. ARMY ATMOSPHERIC ICING CRITERION
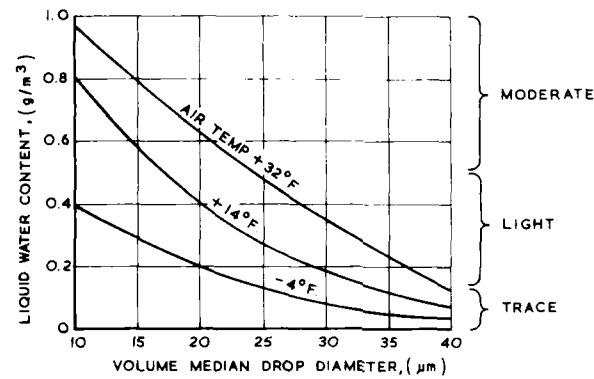
(A) CONTINUOUS MAXIMUM (STRATIFORM CLOUDS).
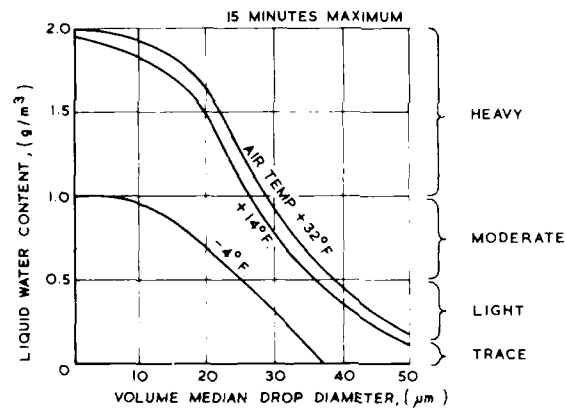


(B) INTERMITTENT MAXIMUM (CUMULIFORM CLOUDS).

Annex 2 Fig. 1  U.S. Army atmospheric icing criterion.

ANNEX 3

CAA DRAFT ICING ATMOSPHERE FOR HELICOPTERS (U.K. CIVIL)

CHAPTER G1-2 DEFINITIONS   Add a *new paragraph X* as follows:

X.    ATMOSPHERIC CONDITIONS

NOTE:   The definitions of this paragraph X are not necessarily an accurate representation of
meteorological data.  The defined conditions are intended to provide an acceptable basis for the
purposes of design for flight in atmospheric icing and snow conditions.

X.1.   SUPERCOOLED LIQUID CONTENT OF CLOUDS

a.   CONTINUOUS ICING CONDITIONS   The conditions in respect of supercooled liquid
water tabulated in Table 2(G1-2) which are assumed to be encountered for an unlimited
horizontal distance.

| AIR TEMP (°C) | ALTITUDE RANGE | | MAX LIQUID WATER CONTENT ABOVE 1200 m (4000 ft) (g/m$^3$) | MEAN DROPLET DIAMETER (μm) |
|---|---|---|---|---|
| | (m x 10$^3$) | (ft x 10$^3$) | | |
| 0 | 0-6.0 | 0-20.0 | 0.8 | |
| -10 | 0-7.5 | 0-25.0 | 0.6 | 20 |
| -20 | 0-9.0 | 0-30.0 | 0.3 | |
| -30 | 0-9.0 | 0-30.0 | 0.2 | |

TABLE 2 (G1-2)

NOTES:   1.  At altitudes less than 1200 m (4000 ft) there is a linear variation of maximum liquid
water content with altitude to zero content at sea-level except that below 300 m (1000 ft) the
content for 300 m (1000 ft) applies.

2.  The conditions are normally assumed to prevail for a vertical distance of 3000 m
(10,000 ft).

b.   INTERMITTENT ICING CONDITIONS   The conditions in respect of supercooled liquid
water tabulated in Table 3 (G1-2) assumed to be encountered for a horizontal distance
of 5 km (2½n miles) alternating with the conditions tabulated in Table 2 (G1-2) for a
horizontal distance of 28 km (15 n miles).

| AIR TEMP (°C) | ALTITUDE RANGE | | MAX LIQUID WATER CONTENT (g/m$^3$) | MEAN DROPLET DIAMETER (μm) |
|---|---|---|---|---|
| | (m x 10$^3$) | (ft x 10$^3$) | | |
| 0 | 1.5-6.0 | 5.0-20.0 | 2.5 | |
| -10 | 1.5-7.5 | 5.0-25.0 | 2.2 | |
| -20 | 3.0-9.0 | 10.0-30.0 | 1.7 | 20 |
| -30 | 4.5-10.5 | 15.0-35.0 | 1.0 | |

TABLE 3 (G1-2)

NOTE:   At altitudes less than 4500 m (15,000 ft) the maximum liquid water content appropriate to
the air temperature decreases linearly with reduction in altitude from 4500 m (15,000 ft) such that
if extrapolated to sea-level it would be zero.

X.2.   SNOW CONDITIONS   There are three conditions of snow occurence:  falling, blowing and
re-circulating.

The following concentrations are to be assumed:

X.2.1.   FALLING AND BLOWING

a.   Continuous 0.8 g/m$^3$ for unlimited duration.
b.   Periodic 1.5 g/m$^3$ for 8.0 Km duration.

X.2.2.   RECIRCULATING   1.5 g/m$^3$.
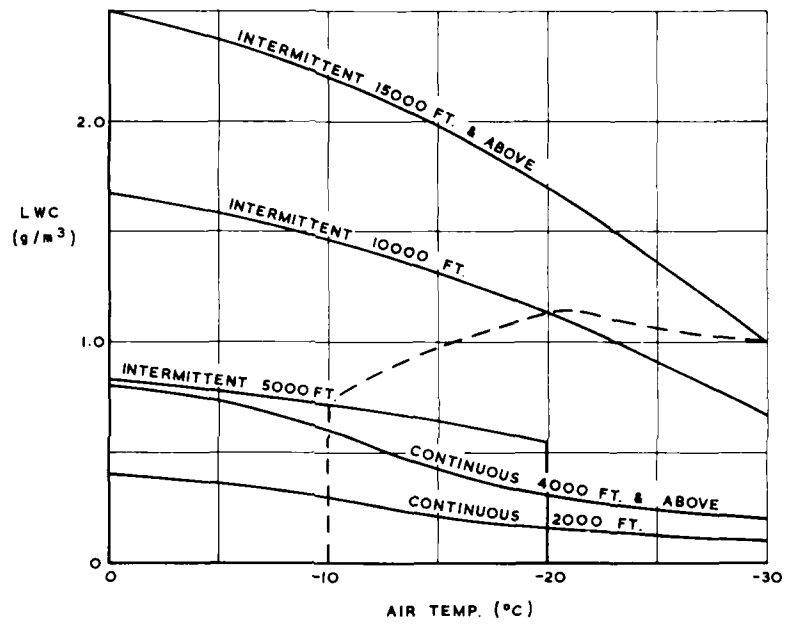
Annex 3 Fig. 1. Graphical representation of CAA draft icing atmosphere.

ANNEX 4

JOINT AIRWORTHINESS REQUIREMENTS 25 ATMOSPHERE

2.5.2.   TESTS IN CONTINUOUS MAXIMUM CONDITIONS

a.   Those parts of the airframe where the accretion of ice under the conditions of Appendix C is likely to have an adverse effect on the airworthiness of the aeroplane should be tested for a period of 30 minutes duration at each of the conditions specified in the following Table 1.

| ATMOSPHERIC TEMPERATURE (°C) | LIQUID WATER CONTENT (g/m³) | MEAN EFFECTIVE DROP DIAMETER (μm) |
|---|---|---|
| 0 | 0.8 | |
| -10 | 0.6 | |
| -20 | 0.3 | 20 |
| -30 | 0.2 | |

TABLE 1

2.5.3.   CHECK CONCERNING INTERMITTENT MAXIMUM CONDITIONS   It would be necessary to check that Intermittent Maximum icing conditions of Figures 4 and 5 of Appendix C do not hazard the aeroplane. The encounters considered should include three clouds of 5 km horizontal extent with Intermittent Maximum concentrations as in Table 2 separated by spaces of clear air of 5 km.

| ATMOSPHERIC TEMPERATURE (°C) | LIQUID WATER CONTENT (g/m³) | MEAN EFFECTIVE DROP DIAMETER (μm) |
|---|---|---|
| 0 | 2.5 | |
| -10 | 2.2 | |
| -20 | 1.7 | 20 |
| -30 | 1.0 | |

TABLE 2

4.   ICE CRYSTAL CONDITIONS   An assessment should be made into the vulnerability of the aeroplane and its systems to ice crystal conditions.

4.3.   Where any doubt exists as to the safe operation in ice crystal conditions appropriate tests should be conducted to establish the proper functioning of the system likely to be affected.

4.4.   For guidance Table 3 gives provisional details of the conditions likely to be encountered in service.

| AIR TEMPERATURE (°C) | ALTITUDE | | MAXIMUM ICE CRYSTAL CONTENT (g/m³) | HORIZONTAL EXTENT | | MEAN PARTICLE DIAMETER (mm) |
|---|---|---|---|---|---|---|
| | (ft) | (m) | | (km) | (n miles) | |
| 0 to -20 | 10,000 to 30,000 | 3000 to 9000 | 5.0 2.0 1.0 | 5 100 500 | (3) (50) (300) | 1.0 |
| -20 to -40 | 15,000 to 40,000 | 4500 to 12000 | 5.0 2.0 1.0 0.5 | 5 20 100 500 | (3) (10) (50) (300) | |

TABLE 3

NOTES:
1.   In the temperature range 0 to -10°C the ice crystals are likely to be mixed with water droplets (with a maximum diameter of 2 mm) up to a content of 1 g/m³ or half the total content whichever is the lesser, the total content remaining numerically the same.
2.   The source of information is RAE Tech Note Mech Eng 283 dated May 1959.

ANNEX 5

DEFENCE STANDARD 00-970 ICING ATMOSPHERE (U.K. MILITARY)

DEF STAN 00-970 ANNEX 5

## DEFINITION OF DESIGN ATMOSPHERIC ICING CONDITIONS

| CONDITION | AIR TEMP °C | WATER CONTENT g/m³ | HORIZONTAL EXTENT km | DROPLET SIZE MEDIAN VOL DIA MICRONS | ALTITUDE RANGE m(ft) | NOTES |
|---|---|---|---|---|---|---|
| I Continuous maximum icing | +5 0 -10 -20 | 0.90 0.80 0.60 0.30 | Continuous' | 20 | 1.5-3000 (4-10,000) | 1 |
| II Periodic maximum icing | +5 0 -10 -20 | 1.35 1.20 0.90 0.45 | 6 km every 100 km of Condition I | 20 | 1.5-3000 (4-10,000) | 1.2 |
| III Mixed conditions continuous | 0 -10 -20 | (0.20 LWC (0.60 ICE (0.15 LWC (0.45 ICE (0.10 LWC (0.20 ICE | Continuous | | 0-3000 (0-10,000) | 1 |
| IV Mixed conditions periodic | 0 -10 -20 | (0.30 LWC (0.90 ICE (0.20 LWC (0.70 ICE (0.15 LWC (0.30 ICE | 6 km every 100 km of Condition III | | 0-3000 (0-10,000) | 1.2 |
| V Falling snow continuous | +3 to -20 | 0.8 | Continuous | | 0-3000 (0-10,000) | |
| VI Falling snow periodic | +3 to -20 | 1.5 | 8 km every 100 km of Condition V | | 0-3000 (0-10,000) | 2 |
| VII Recirculating snow | 0 to -26 | 1.5 | | | Hover in ground effect | 2 |
| VIII Freezing fog | 0 to -20 | 0.3 | | 10 to 20 | 0-15(0-50) Above ground level | 2 |
| IX Freezing rain/drizzle | 0 to -15 0 to -10 | 0.3 at 0° to 0.0 at -15° 0.3 | ) 100 km ) | 200 1500 | 0-1500 (0-5000) | 2.3 |

TABLE 1

Note 1:  At altitudes below 1,200 m (4,000 ft) the maximum water concentration appropriate to the temperature decreases linearly with decrease in altitude to zero at sea level except that below 300 m (1,000 ft) the concentration for 300 m (1,000 ft) applies.

Note 2:  See Chapter 711 para 2.1.2.

Note 3:  See Chapter 711 para 2.7.4 and also Leaflet 711/2 para 6.

| DROPLET DIAMETER $d_F$ (MICRONS) | % BY WEIGHT OF TOTAL WATER CONTENT CONTAINED IN DROPLETS OF DIAMETER $d_F$ |
|---|---|
| 5.4  The droplet sizes quoted in | 3 |
| 11.1  Conditions I and II of Table 1 | 8 |
| 16.6  are the median volume droplet | 20 |
| 22.0  diameters ($d_V$) for the | 30 |
| 27.8  distribution shown in Table 2; | 20 |
| 33.4  $d_F$ is the particular drop | 10 |
| 39.0  diameter under consideration. | 5 |
| 44.4 | 4 |

TABLE 2

RANGE OF DROPLET SIZES
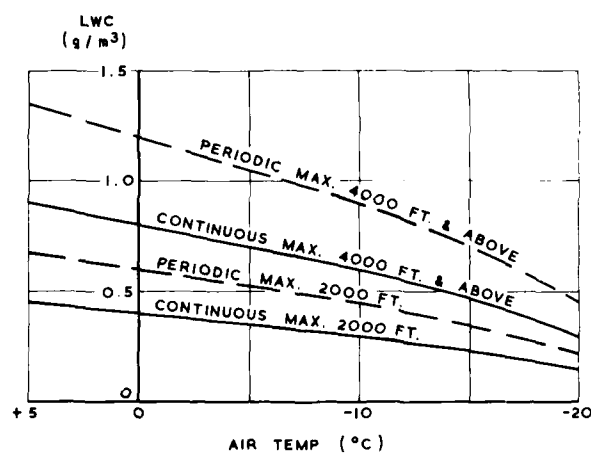


Annex 5 Fig. 1.  Graphical representation of DEF STAN 00-970 icing atmosphere.

ANNEX 6

FAA CHARACTERIZATION OF SUPERCOOLED CLOUDS BELOW AN ALTITUDE OF

10,000 FEET ABOVE GROUND LEVEL
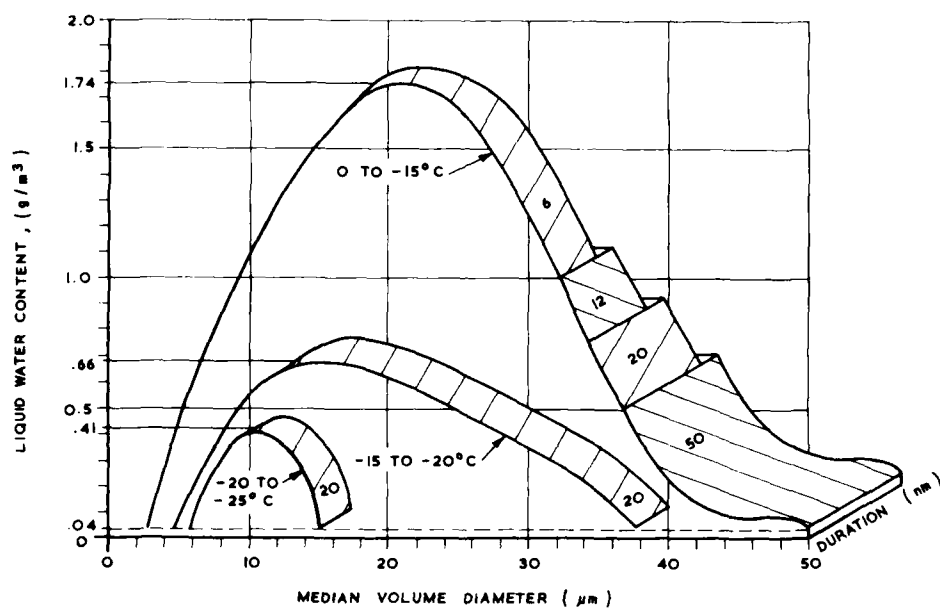
Annex 6 Fig. 1. A final depiction of the new characterization of supercooled clouds from ground level to 10,000 ft AGL.

# 3. FORECASTING

## 3.1 INTRODUCTION

AR 166 gave an extensive overview of the operational environment and meteorological conditions that affect the helicopter but presented only limited information on data collection and forecasting. One of the conclusions was that techniques then available were inadequate to allow the planning of unrestricted helicopter operations in icing conditions. Since that time, several meteorological agencies have studied the feasibility of improved forecasting techniques, and some promising schemes are emerging; however, it is too early to see any change at the level of the helicopter operator.

## 3.2 REQUIREMENTS FOR FORECASTING

### Climatology

During the past decade the increasing requirement to operate helicopters in adverse weather has led to a demand for a description of the icing atmosphere in probability terms for use in the design of icing-protection systems. While existing literature on fixed-wing icing forms a useful background, it does not provide adequate quantitative guidance in relation to the greater sensitivity of helicopters to icing. This is compounded by the smaller space and time scale within which they operate.

Reference 4 is an attempt to describe the climatology of some parameters relevant to icing, but specifically excludes prediction of effect on the vehicle as this can vary significantly from one helicopter to another. This aspect is covered further in Sec. 3.3. The availability of such a climatology, if it can be shown to correlate with actual helicopter icing experience, would be a significant element in the design process of a helicopter when attempting to put meaningful figures into system integrity calculations or assessment of the effects of failure.

### Flight Authorization

Whenever a sortie is authorized that is likely to operate in icing conditions, the authorizing officer makes an assessment based on the capabilities of the helicopter and its crew, weighed against the known weather conditions. If a reliable forecast of icing is available, that risk, or the need to plan an alternative mission, is easier to judge. Because such accurate forecasting is not available and environmental effects on the helicopter can vary significantly over a small geographic area, the onus has to be put on the pilot to avoid conditions outside the cleared flight envelope. It can be argued that once a fully protected helicopter is available the need for a forecast, as far as effect on the helicopter is concerned, is removed.

## 3.3 LEVELS OF FORECAST ICING INTENSITY

In order to provide a descriptive measure of forecast icing severity in preference to numerical values of the significant parameters (i.e., LWC, temperature, cloud type) there have been attempts to reduce forecast data to a level of icing severity. An example of the U.S. originated levels of forecast icing is shown in Table 1. However, the definitions used in this table are not endorsed by all authorities and are not universally used. Significant difficulties are apparent if an attempt is made to apply these descriptions simultaneously to different helicopter types.

Section 3.2 above identified that the effect of one set of environmental conditions can have a very different effect on different helicopter types. It has been shown that even an apparently slight change in one icing parameter can cause a significant and rapid change in the rate of ice accumulation. Icing research flights in the United Kingdom have shown this effect on several occasions, and from trials conducted over the last 10 years it has been shown that using criteria similar to those in Table 1, identical conditions can cause "light" icing on one type and "severe" icing on another.

## 3.4 RELEVANCE TO HELICOPTER OPERATING PARAMETERS

For an icing forecast to be useful to the helicopter operator it must include those factors which have been shown to be significant to the icing process (Table 2). Because the effect of such conditions varies significantly between one helicopter and another, then all the data (i.e., cloud type, level, temperature, LWC, droplet size) and the existence of mixed conditions, must be available for the user to make his own assessment of the potential operating hazard. It is the meteorologist's job to describe the atmosphere as accurately as is technically feasible, but not its effect on aircraft. To do so would be to make a judgment outside his professional competence (Ref. 10).

There would be advantages if a simple measure could be evolved which, for each helicopter, would show a relationship between specific icing parameters and the icing hazard. Current work in the United States

TABLE 1.- RECOGNIZED LEVELS OF ICING (U.S.)

---

TRACE

Ice becomes perceptible. The rate of accumulation slightly greater than the rate of sublimation. It is not hazardous even though deicing/anti-icing equipment is not utilized, unless encountered for an extended period of time--over 1 hr.

LIGHT

The rate of accumulation may create a problem if flight is prolonged in this environment (over 1 hr). Occasional use of deicing/anti-icing equipment removes/prevents accumulation. It does not present a problem if the de-icing/anti-icing equipment is used.

MODERATE

The rate of accumulation is such that even short encounters become potentially hazardous and use of deicing/anti-icing equipment or diversion is necessary.

SEVERE

The rate of accumulation is such that the deicing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary.

N.B. These descriptors do not take into account the significant variations in effect of similar conditions on different helicopter types.

---

TABLE 2.- ICING PARAMETER DEFINITION

---

Most used: Temperature, liquid water content, droplet size

Droplet size spectrum is important

LWC and temperature are main parameters for structural icing

Helicopter rotor icing: Drop size may be important

---

and United Kingdom goes some way to relating icing hazard to LWC, but other possibilities exist which may provide alternative means. An example is shown in Fig. 4.

3.5  DATA ACQUISITION METHODS

An icing forecast consists of an estimate of the freezing level, expected cloud-base and top (especially if stratocumulus), cloud type and amount, with a relative estimate of whether icing is expected to be light, moderate, or severe. It could be argued that cloud forecasting is so uncertain, let alone the distribution of LWC within clouds, that anything more sophisticated is not justified, but it is considered that some attempt to forecast LWC and temperature in whatever cloud is better than none.

The recently completed climatology, Ref. 4, identified that there are currently no routine observations of some parameters relevant to icing, of which the most important is LWC. The icing problems of fixed-wing aircraft during and after World War II gave some impetus to early measurements of LWC and led to the drafting of FAR 25, Appendix C (see Annex 1, Sec. 2). This impetus declined with the jet age but has now been revived by helicopter icing problems and has led to recent attempts to redefine the icing atmosphere. In spite of technical advances in LWC measurements, the amount of published LWC data remains disappointingly small, and the data are frequently divorced from simultaneous measurements of other relevant parameters (temperature, height above cloud-base, cloud type and location).

During recent research by the United Kingdom Meteorological Office it was realized that a unique data set of observations had been accumulated by military aircraft (e.g., Spitfire, Hurricane, Mosquito, Fortress) during meteorological reconnaissance flights on a routine daily or twice daily basis during and after World War II from up to 40 stations at a time. The original data were in manual form, but nearly 20,000 flights were put into machinable form to construct the cloud climatology of Ref. 4. The extent of these observations is illustrated in Table 3 and in Figs. 5 and 6. This cloud climatology was combined with more

CONCEPTUAL "ICING HAZARD RELATIONSHIP"

LWC,DS, TEMPERATURE LEVELS (CHARTS OR GRID POINTS)

ICING HAZARD RELATIONSHIP IS GIVEN IN A SERIES OF
CHARTS FOR EACH AIRCRAFT TYPE

IMPLIED MULTIPLICITY OF CHARTS MAY BE REDUCED
BY SIMPLE RELATIONSHIPS (eg VxT)
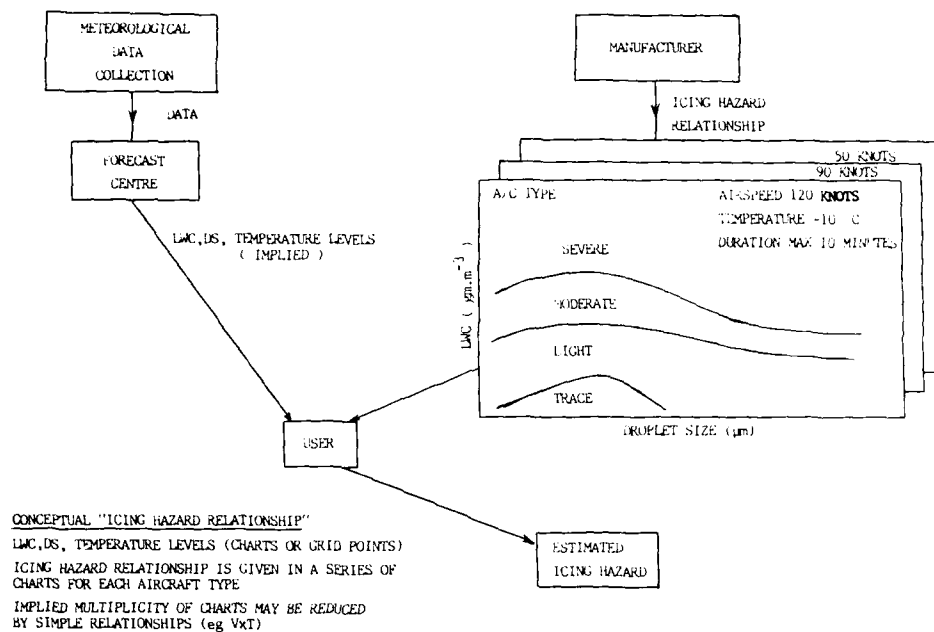
Fig. 4. Conceptual icing hazard and relationship.
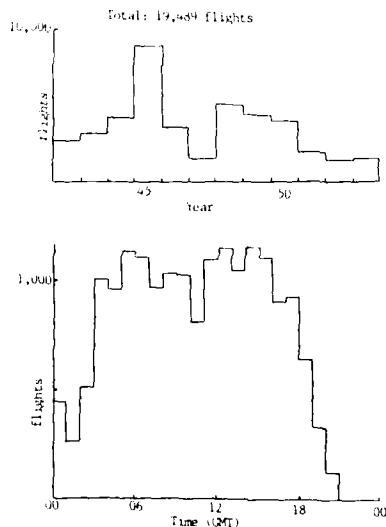


Fig. 5. Distribution of reconnaissance flights by
year and time of day.
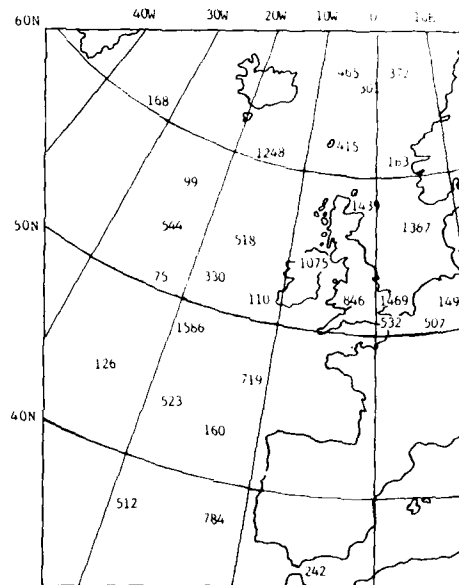
Fig. 6 Distribution of reconnaissance flights by
area.

TABLE 3.- MILITARY METEOROLOGICAL RECONNAISSANCE FLIGHTS (1942-1953)

Each flight contained most or all of the following parameters:
Position, date, time
Surface pressure or minimum height
Mean sea level pressure
0°C levels
Tropopause temperature and height (if attained)
Temperature and (sometimes) relative humidity at standard pressure levels
Cloud amount, type, levels of base and top
The heights of the 1000 mbars and other pressure surfaces

recent LWC data for the European area (Russian, Khrigian 1963; French, Gayet and Bain 1983; United Kingdom, Brown and McAdam 1982) to generate the LWC climatology of Ref. 4.

## New Tools for Data Collection and Analysis

Efforts are being made by meteorological agencies to increase the range of measured parameters, and suitable methods are now starting to come into operation (Refs. 11,12):

1. Automated collection, entry, processing and distribution of pilot reports

2. Automatic aircraft data collection: wind, temperature, humidity, LWC

3. Profiler for temperature, humidity, LWC, and wind

4. Advanced radar processing may deduce LWC, freezing level, and precipitable water

5. Satellite data for cloud top, deduction of type, temperature and humidity

It has been noted (Ref. 10) that there is a need for experiencing natural icing encounters through active involvement of operators, including the establishment of an effective encounter reporting system. Some military operators, notably in the United Kingdom, have had some form of subjective feedback which contributes in the long term to the assessment of risk associated with partial icing clearances. However, the basis for meeting the requirements of a more universal system is unlikely to exist until the new generation of ice-protected helicopters is in service and able to return quantitative measurements of some icing parameters on a regular basis from permanently installed sensors.

## Airborne Weather Radars

The current inability even of large and advanced ground based radars to accurately measure LWC is borne out by trials in icing conditions of aircraft weather radars. A particular example is a trial conducted by the French in 1981 when an extensively instrumented, radar-fitted Puma achieved some 27 hr in various icing conditions in order to assess the feasibility of making remote measurements of icing. The results showed that there was no possibility of good correlation between the radar returns and LWC (representative of icing severity) with this type of airborne radar, and (at the current state of knowledge) such equipment could not be used as the basis for a limited clearance.

## 3.4 IMPROVED FORECASTING TECHNIQUES

There is an ICAO requirement to generate digitized significant weather charts as operational numerical model output. This consists of the identification of areas of clear-air turbulence, deep convection, and icing. In the first instance, grid points at which the temperature is less than 0°C and the relative humidity greater than some high value will be identified as points of potential icing, particularly within convective clouds. There is much work to be done before such a model can be verified. The estimation of levels of supercooled water content at the subzero points represents another level of sophistication which should not be tackled until the cloud generation is completely satisfactory.

## Deduction of LWC and Droplet-Size Distribution

The USAF Environmental Technical Applications Center (Scott AFB) has begun to use computerized procedures for estimating LWC and droplet-size distributions over limited areas. The input on which these estimates are made is the three-dimensional nephanalysis data obtained by global satellite coverage. The accuracy of the LWC forecasts depends in part on the maximum LWC values which Smith and Feddes proposed for each cloud type as a function of temperature. Use of this model has potential for improving the forecasting of icing conditions and ties LWC and droplet size to temperature and position within a cloud.

It is hoped that measurement of actual conditions using tools such as vertical profilers, advanced radar and associated processing (NEXRAD, FRONTIERS, etc.) and sondes which include reliable LWC sensors, will eventually provide adequate verification for such models to be implemented.

32

## 3.7 DATA DISSEMINATION

The best forecast in the world is no use to the pilot if it is not available to him within the time for which it remains valid. With the small scale and changeability of significant icing parameters, this time-scale is likely to be relatively short. Promulgation through existing, well-established channels to air-fields is unlikely to cause problems, but ensuring that adequate data reach detached units operating under field conditions is likely to be more of a problem. The availability and response time of links with for-ward units in such a case will largely determine the effectiveness of any forecast. Although not confined to meteorological data, this element in the link between the forecaster and the user should not be ignored when assessing potential benefits of the forecasting system.

## 3.8 CONCLUSIONS

Forecasting techniques are currently inadequate to allow unrestricted helicopter operations in icing conditions; however, significant steps have been made since AR 166 was published. It is likely that protec-tion will be available for full clearance of helicopters in icing conditions before suitable forecasting techniques are validated and accepted. The need for a forecast is then theoretically, removed. There will, however, continue to be a significant number of partially protected or unprotected helicopters for the foreseeable future, which will still require improved forecasting facilities, as will the protected helicop-ter with system failure.

## 3.9 RECOMMENDATIONS

Ongoing efforts to improve forecasting capability with coordination between cloud physicists, forecas-ters, icing specialists, and operators should continue to be encouraged. The subject of icing forecasting is expanding and the brief study presented in this section barely scratches the surface. The WG concludes that the potential scope of such work justifies its own specialist working group and recommends that AGARD FMP consider conducting a deeper study of this topic.

## 4. PREDICTIVE METHODS AND SIMULATION

### 4.1 INTRODUCTION

In the past, the certification of helicopters for flight in icing conditions has been based primarily on the evidence of flight in natural clouds. The problems and limitations of this approach have long been realized; in particular, icing flight trials are very expensive and are dependent on nature to provide suitable weather. Although the aim is to clear the helicopter to extreme conditions, these will by definition occur very rarely, and some compromise has to be reached in terms of the level of experience which is acceptable as a basis for clearance. The philosophy of this was discussed in AR 166 and is discussed again in Sec. 6 of this report.

In recent years, much thought and effort have been given to the contribution that other techniques such as the use of prediction methods and simulation may make to design, development, and certification, so as to reduce the duration of natural icing trials (see, for instance, Ref. 13). Although it must be accepted that some natural testing will always be necessary, the use of other methods to interpolate and extrapolate from flight results to the extremes of the atmospheric and performance envelopes will be a major benefit.

In this section, a critical review is made of the available techniques, to assess their state of development, their limitations and their suitability for the various tasks to which they may be applicable. Recommendations are made for further development. The techniques considered cover the full range, from theoretical analysis and mathematical modeling, through laboratory and wind tunnel experiments at both model- and full-scale, to use of flight-test techniques other than the direct performance assessment in natural icing. The latter includes the use of artificially generated clouds and a brief review of the techniques that may be used to enhance the effectiveness of natural icing trials.

### 4.2 ANALYSIS

In this section, a review is made of the analytical methods that have been developed for various aspects of the ice accretion and protection problem. These include predictions of the accretion of ice, the behavior of deicing systems, the effects of ice on performance, and the trajectories of ice pieces shed from parts of the aircraft. Many of the analyses are aimed primarily at the rotor, although they often have a broader application to other parts of the aircraft (and even to fixed-wing aircraft). Although a few of the methods are purely analytical, most are mathematical models requiring input of empirical data. Main centers for this activity are in France (ONERA/Aerospatiale), the United Kingdom (RAE), the United States (NASA/contractors), and Canada (Alberta University/NRC).

In developing and assessing the analytical methods, it is important to consider the tasks to which they may be applied. Although these will obviously vary between the individual analyses, four broad applications may be identified:

    1. Understanding the observed behavior of helicopters in icing

    2. Design, particularly of protection systems

    3. Direct application to the certification process; for instance, for interpolation or extrapolation of flight-test results

    4. Assessment of the validity of test methods, both ground (laboratory and wind tunnel) and flight (e.g., Spray Rig, HISS), and for studies of the use of scaling

#### 4.2.1 Droplet Trajectories

**Description.** The first step in modeling the ice formation on any surface is the calculation of the impingement of the cloud particles (water droplets or ice particles) on the surface, involving computation of the trajectories through the local flow field. The impingement is normally expressed in terms of the catch efficiency $\beta$.

The calculation procedure involves two main stages, namely, the calculation of the aerodynamic flow field, and the computation of the particle trajectories, including the distribution of impacts on the surface and the calculation of local catch efficiency.

Although methods are available for computation of the full airflow through a helicopter rotor, including modeling of the vortex wakes, no attempt has been made to compute the trajectory of a particle within this flow field. In practice, a two-dimensional, steady-flow aerodynamic model is used to predict local velocity fields, at points along the blade span, for each position of azimuth.

**Applications.** The main applications of the calculated catch distributions are for use as input data to ice-accretion models and for the design of protection systems; in the latter case, the catch limits are of particular interest.

Development status and future plans. Codes have been developed by NACA and its contractors in the United States, by ONERA and Aerospatiale in France, by the RAE in the United Kingdom, and by Alberta University in Canada (Refs. 14-19). Although the codes are all fundamentally similar, they vary in detail, particularly in the methods used for the flow field. Table 4 summarizes the programs currently in use or under development.

It should be noted that in all these programs a general assumption is made that interception of the droplet trajectory with the surface (i.e., impingement) implies attachment of the droplet. The validity of this assumption is not fully established. Thought is now being given to the problems of droplet entrainment in the boundary layer and the minimum impact energy required for attachment.

Validation status. Validation of the programs is difficult since very few direct experimental results are available. Even when tunnel measurements are made on rime ice (where the water freezes on impact and thus the growth rate is a direct function of the impingement), the derivation of $\beta$ values requires assumptions about the accretion process, in particular concerning the local ice density; significant errors in this are likely, particularly in the low catch regions where impacts are highly oblique to the surface. These doubts are supported by French measurements of chordwise icing limits during tunnel tests at CEPr, Saclay (Fig. 7), which show differences between theory and experiment, with a significant overestimate of the lower surface limit. In the United States, it is planned to run tests on modern airfoils using the long established "blotter" technique to assess impingement characteristics (Ref. 20). An alternative approach to validation is the comparison of results from different codes for ranges of test cases, as has been done by NACA and RAE for both the NACA 0012 and a modern, cambered rotor airfoil (Ref. 18). A full range of chord, drop size, and Mach number was covered, the latter extending up to $M = 0.8$ to search for differences between the U.K. compressible and the U.S. incompressible methods. Typical results are shown in Figs. 8 and 9. Figure 9 also includes results from the two ONERA two-dimensional programs (see Table 4).

Limitations. The present codes address impingement only. They assume that the intersection of a trajectory with the surface implies that the cloud particle will attach. Experimental observations suggest that this may not be true for highly oblique impacts. Thus the model may be acceptable for producing input data for accretion models, where the leading edge is the main consideration, but may give an overestimate of catch limits, especially on the airfoil lower surface, and may therefore be more limited in their usefulness for system design.

All the codes developed specifically for rotors assume two-dimensional, steady flow. The effects of three-dimensional flow and turbulence are unknown, as is the effect of the rotor inflow on the cloud. For forward flight, with cyclic variation of velocity and incidence, the assumption that instantaneous catch is governed by instantaneous flow is probably acceptable and transient effects may be ignored. Viscous effects need further investigation. The applicability of the three-dimensional codes to rotors is unknown. The codes allow for most atmospheric parameters. Currently however, they can only cope with spherical drops, although ice crystals could be allowed for by use of a suitable drag coefficient law. The methods can deal with any droplet-size distribution, provided that the longer computing time is acceptable.

Because of the computation times required, some of the codes are unsuited to repeated time-stepping calculations in which the airfoil shape is changed by successive accretion layers. Furthermore, most codes fail to work if the accretion becomes too irregular, so that some smoothing of the shape becomes necessary, defeating the object of the modeling process.

4.7.2 Accretion

The requirements of an ice accretion code are that it should predict adequately the extent, the shape, and the rate of ice growth on a surface. In the case of a rotor blade, these outputs will not only depend on the atmospheric and flight conditions, but will also vary with the blade span. The model will also predict the chordwise and spanwise variation of temperature of the blade surface.

Applications. Applications for the codes include improving the overall understanding of the physics of rotor ice accretion; explaining flight-test results; predicting ice shapes for input to performance prediction programs; and defining initial conditions for deicing models, that is, initial ice coverage, thickness, temperature, etc.

Development status and future plans. The development of accretion theories goes back many years, to the work of Hardy (Ref. 21) and Messinger (Ref. 22). In principle, all the current models are still based on the method proposed by Messinger, namely, the solution of the quasi-steady icing energy-balance equation. Many codes (Refs. 15, 17, 23-30) have been developed to model airfoil icing and have been applied to both fixed-wing aircraft and to helicopters. For the most part, the codes have been based on two-dimensional steady flow, the conditions at a point on the helicopter rotor being described by steady (mean) values of V and α. The only transient accretion models so far attempted are the RAE model (Ref. 29), which computes the full heat balance on a conducting blade while varying V and α with azimuth, and the Texas A&M University code (Ref. 30), which calculates rime ice in forward flight by allowing for variations in catch rate and distribution with V and α. In both cases, the azimuthal and spanwise distributions of V and α are derived from rotor flow-field models.

The prediction of ice shape is based on calculations of the local rates of ice growth at points around the airfoil. For rime ice (dry growth), the accretion is purely a function of the catch distribution, LWC,

TABLE 4.- DROPLET TRAJECTORY PROGRAMS

| Agency and country | Flowfield method | Local velocity evaluation | Incompr or compr | Boundary layer | 2-D or 3-D | Droplet integration scheme | Derivation of $\beta$ | Comments |
|---|---|---|---|---|---|---|---|---|
| RAE UK Ref. 19 | Viscous Garabedian and Korn/VGK Potential flow + viscous | Grid interpolation | Comp | Optional | 2-D | 4th order Runge-Kutta | $\Delta y_o/\Delta s$ (Secondary trajectories) | B.L. effects on flowfield represented, but actual bl velocity gradient not included. |
| ONERA France Ref. 18 | Singularity panel method | Single point calculation | Incomp | Inviscid | 2-D | | $\Delta y_o/\Delta s$ | |
| | Finite element -potential flow | | Comp | Inviscid | 2-D | | Cubic spline fit to $y_o$ vs. s | |
| | Singularities method | | Incomp | No | 3-D | | | Primarily for aircraft nose region. Plans for swept wing use. |
| Aerospatiale France | Singularity panel method | Single point calculation | Incomp | Inviscid | 2-D | | $\Delta y_o/\Delta s$ | |
| Ohio S.U. USA Ref. 16 | Modified Theodorsen-potential | Single point | Incomp | No | 2-D | Variable step predictor/corrector | Cubic spline fit to $y_o$ vs. s | |
| NASA USA Ref. 15 | Hess Smith potential | Single point | Incomp | No | 2-D | Variable step predictor/corrector | Cubic spline or least sq. polynomial fit | |
| NASA/ASA. USA Ref. 17 | Modified Hess-Smith potential | Single point | Incomp | No | 3-D | Variable time step | None | Impact points and tangential limits only |
| Boeing USA | PANAIR potential or 3-D full potential | Grid interpolation | Incomp / Comp | No / No | 3-D / 3-D | Predictor/corrector | Area ratio | |
| Alberta University Canada Ref. 20 | Kennedy and Marsden potential flow | Single point | Incomp | No | 2-D | 4th order Runge-Kutta Fehlberg | Cubic spline fit to $y_o$ vs. s | |
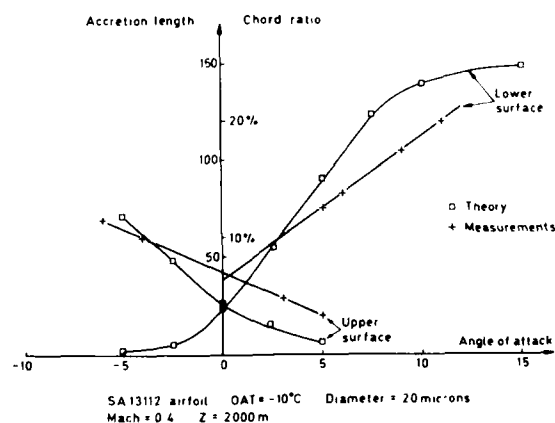


Fig. 7.   Impingement limits--comparison between theory and wind tunnel measurements.

and free-stream velocity; the only role of the heat-balance equation is to predict the variation of surface temperature, which may be of importance as an initial condition for a deicing system model.  Even for the apparently simple problem of predicting rime ice shape from local growth rates, a number of methods have been proposed.  To be rigorous, a time-stepping procedure should be employed, with successive thin layers
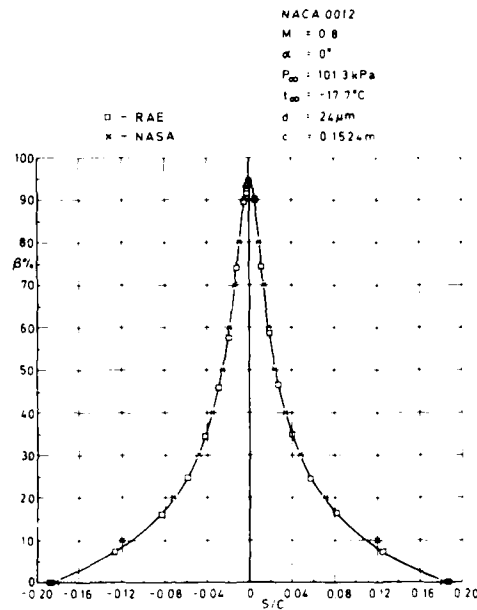
Fig. 8. Catch efficiency--comparison of RAE and NASA predictions.
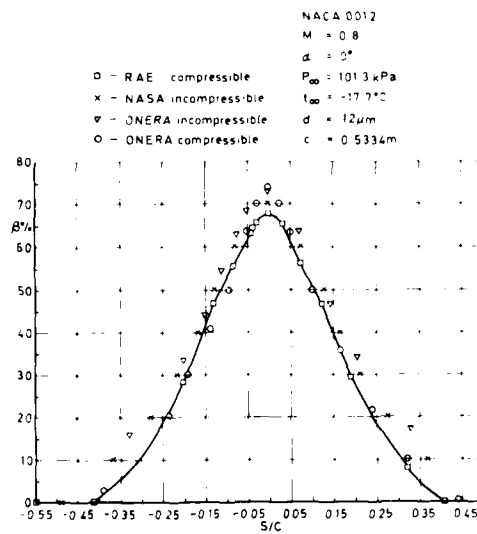


Fig. 9. Catch efficiency--comparison of RAE, NASA, and ONERA predictions.

being applied to the surface, each followed by recalculation of the flow field and impingement. It has been suggested that by applying the growth parallel to the nominal free-stream airflow, rather than normal to the local surface, larger time-steps may be made. Variable ice density is included in some models (Ref. 31).

For glaze ice, the energy-balance equation is needed to predict locally the fraction of the impinging water which freezes (freezing fraction, $n_f$). In all models, the unfrozen fraction is allowed to run back,

to enter the calculation for the next chordwise zone. Solution of the heat balance will yield local growth rates, and as with the rime, these may be applied to the surface to produce the overall ice shape. For small accretions, a single step applied normal to the surface can produce valid shapes, as shown in Fig. 10. For larger accretions, a time-step procedure produces better results (Figs. 11 and 12).
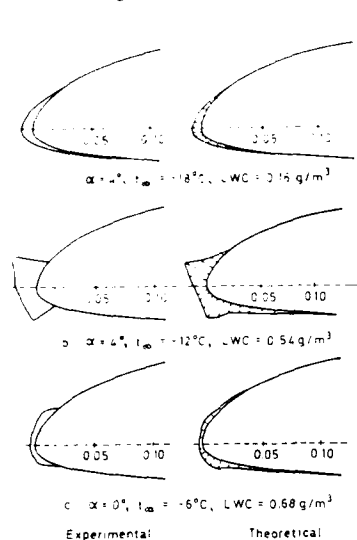


Fig. 10. Comparison of experimental and theoretical ice shapes on a 0.68 m chord, cambered airfoil, M = 0.4, after 5 min.
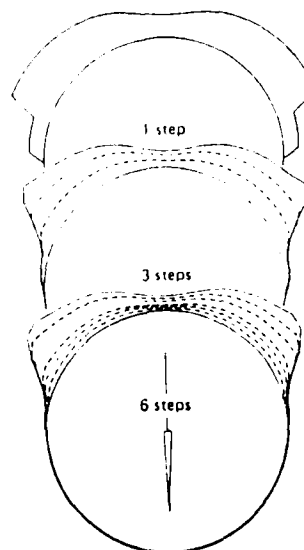
Fig. 11. Influence of number and size of time steps on predicted accretion shapes

Some attention is currently being given to the validity of the runback model for glaze ice. High-speed movies by NASA have shown that in the initial stages of the accretion in glaze icing conditions, runback water formed and refroze, but after a few seconds of the ice growth this runback was no longer visible. Based on visual observations, both the United Kingdom and France maintain their belief in the runback model. At present, the United States also continues to use a runback model pending further clarification of the true physical processes.

Primary inputs to the models are free-stream velocity, pressure, and temperature, together with incidence, airfoil section and chordwise distributions of catch efficiency, static pressure, and convective heat-transfer coefficient ($h_c$). The pressure distribution is important, particularly at the higher Mach numbers associated with the outboard part of the blade, since compressibility will affect both the local kinetic heating and the evaporative cooling. The acquisition of accurate $h_c$ data, either by experiment or theory, particularly for airfoil surfaces roughened or deformed by ice, is the major stumbling block of all current accretion models, and is the subject of many studies. These include theoretical work in France and in the United States on solution of the Navier-Stokes equations for the boundary layer around the iced airfoil (Refs. 17 and 32); the French study includes consideration of free-stream turbulence and surface roughness. Experimental heat-transfer measurements are being made in France and in the United States on moulded accretion shapes (Refs. 17, 33, 34). In the United Kingdom, indirect deductions of heat transfer are being made by matching of predictions with experimental measurements of accretion shapes; the chordwise array of $h_c$ is adjusted until a good match is obtained. By carrying out this process for a full range of accretion types, it is hoped to establish a data base and hence a generalized empirical correlation for $h_c$ (Refs. 28 and 29).

Other extensions to the basic models include an allowance for conduction within the blade structure (a nonconducting surface is assumed in most models) and in the latest RAE model now under development, modeling of transient effects owing to cyclic V and α (Ref. 29). The latter will enable estimates to be made of the difference in accretion shape/extent between hover and forward flight (important in assessing the validity of rig test methods, such as the NRC Spray Rig) and also the effect of incomplete immersion of the rotor, as in the limited cloud produced by tankers such as the HISS.

Future developments will include further developments of models, toward a full forward flight model with structural conduction and possibly including a time-stepping procedure; further validation work; and further experimental and theoretical studies on aerodynamics of iced airfoils, aimed in particular at improving the quality of input data.

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TIME STEP 4.50 sec
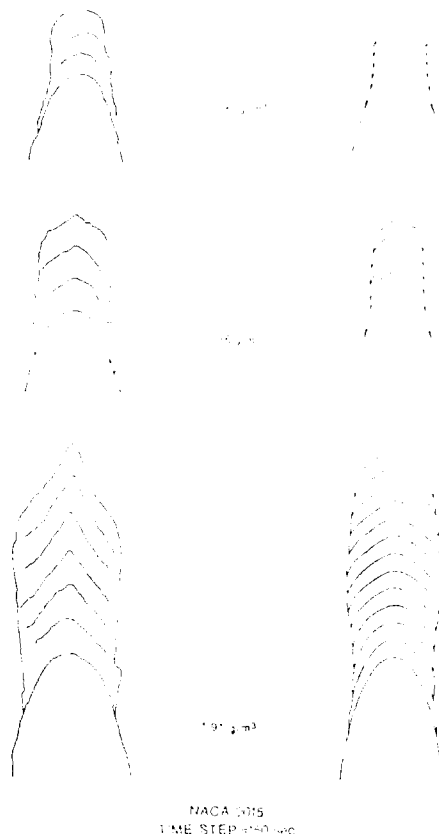
Fig. 12. Comparison of experimental profiles (left) with variable density profiles (right).
Chord = 0.175 m, free stream velocity = 11 m/sec.

Validation status. Validation of models has been attempted for the most part by direct comparison of ice accretions from tunnel tests with corresponding theoretical predictions. In France, much effort has gone into comparisons between accretions on full-size and model-scale airfoils; the scaling laws used are based on the thermal equilibrium theory and, therefore, by inference the results of such tests may be used for validation. In the United Kingdom, a systematic approach has been used, involving comparison of theoretical predictions with experimental results not only for accretion shapes, but also for surface temperature distributions in both wet and icing conditions, and threshold conditions for ice formation in the stagnation and suction regions.

Validation becomes increasingly difficult as the models become more complex, particularly for the forward-flight case where experimental evidence of the accretions relies on photographic results (at least for warmer OATs).

Limitations. Limitations of the current models are as follows:

1. Two-dimensional flow only; no allowance for three-dimensional effects at the tip or those owing to skewed flow

2. Turbulence effects are unknown

3. Quality of input data is inadequate; in particular, the data base for $h_c$ is inadequate because of the unquantified effects of surface irregularities and roughness

4. No best method has been established for "growing" the ice shape from the calculated local growth rates

5. The accuracy of shape predictions is inadequate for accurate estimation of the aerodynamic characteristics of the iced airfoils; this is particularly true of drag for which surface roughness is significant

6. Allowance for liquid water cloud only; attempts at ice phase and mixed conditions have been made but are of doubtful validity (Refs. 35 and 36)

### 4.2.3 Electrothermal Deicing Systems

The primary aim of analytical codes for electrothermal rotor deicing systems is the prediction of temperature transients resulting from cycling of the deicing heaters. To calculate these, the models must represent the thermal characteristics of the blade structure itself and of any attached ice layer; depending on the complexity, the model may also include iced surface heat-transfer boundary conditions and representations of ice melting, ice shedding, and the formation of new ice on the surface during cool down between heater cycles. Some analysis of the iced-shedding process itself, under the influence of aerodynamic, centrifugal, and other forces, may also be considered. The model output of most interest is the temperature of the ice-to-blade interface, since this has the major influence on the shedding process; in addition, the ability to predict temperatures within the internal structure of the blade is important. Although primarily concerned with main-rotor blades, most models are readily applicable to any deiced structure, and may be used to predict the behavior of electrically anti-iced surfaces.

Applications. The main applications of the codes are (1) to assist in the design of systems, both from the point of view of the deicing mat and the adjacent blade structure, and also from the control aspect (optimization of on-times, etc.); (2) prediction of temperatures within the blade structure, to ensure material integrity; (3) interpretation of flight-test observations; and (4) as an aid to certification, by enhancing confidence in results of natural icing trials and extending limits to conditions not encountered.

Development status. Since the early work at NRC Canada (Ref. 37), numerous codes have been developed in the United Kingdom (Refs. 29 and 38), the United States (Refs. 39-41), and France (Ref. 17). In all cases, the codes use finite-difference techniques to describe the thermal characteristics of the blade structure, including the basic spar, the heater mat with its discrete elements, the erosion shield, and the various adhesive layers. In addition, most of the models include an ice layer. The numerical method used for solution of the finite-difference equations varies, with the United Kingdom using an explicit method and the United States opting for an implicit scheme.

Various levels of complexity may be included in the models, as summarized below:

1. One-dimensional flat-plate structure, with uniform ice layer and simple convective external boundaries

2. Two-dimensional flat-plate structure, with finite-width heater elements

3. Two-dimensional flat-plate structure with nonuniform thickness of ice

4. Correct geometry for the blade structure and ice layer

5. Moving interface phase change modeling to predict the progress of the water/ice interface through the ice layer

6. Full icing heat balance on the external boundary, including accretion of new ice during cool down

7. Allowance for anisotropic thermal conductivity of composite structural layers

Ice-shedding criteria are a major consideration. Most simply, ice may be shed after the blade/ice interface has been above 0°C for a set time (typically 0.5 sec), or may be shed at a specific temperature above zero, based on experience. More refined methods based not only on surface temperature but also on the thickness of the melted water layer or the remaining unmelted ice layer or both are being considered. Centrifugal, aerodynamic, and structural loads will all assist in shedding ice and should therefore be included in a complete deicing model. To date, only the French have approached this aspect, with inclusion in their model of shedding criteria based on centrifugal loading.

No analyses have yet been developed specifically for tail rotors, for which modeling is complicated by the complex flow field and the possible effects of engine exhaust. Tail rotors are most often anti-iced, the heater design being a compromise between the power density requirement for the lowest OAT and the need to respect material limits.

Validation. Validation of the models has been achieved primarily through measurements of temperatures during heater cycling on a range of test specimens in the laboratory, in wind-tunnel experiments on stationary and oscillating sections of blade and on scale-model rotors, and on actual blades during flight trials (see Sec. 4.2). A reasonably adequate collection of experimental data is now available for evaluation of the temperature prediction capabilities. In addition, U.K. and U.S. programs have been run on common sets of physical data to compare their mathematical techniques; excellent agreement has been obtained for simple one-dimensional cases (see Fig. 13, which also shows comparable experimental results).

Experimental evidence with which to formulate and validate ice shedding criteria is much less adequate and may inhibit the development of this aspect of the modeling.
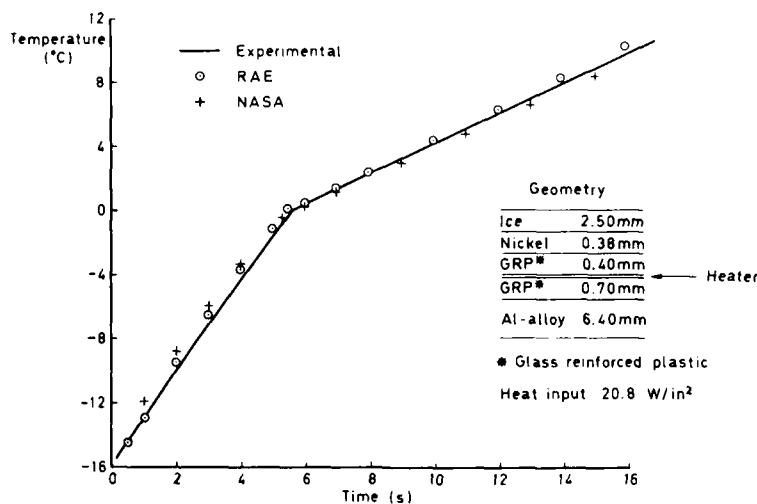
Fig. 13.  Comparison of NASA and RAE 1-D electrothermal deicer code predictions
with experimental results.

Limitations.  As with the accretion models, account must be taken both of those limitations inherent in the mathematics themselves and of limitations in the quality of the input data.  The main specific considerations are as follows:

1.  For models to produce accurate results, the physical properties of the system must be known accurately.  This includes the dimensions and thermal characteristics of all the structural layers, adhesive layers, heaters, etc.  These may be difficult to define, particularly for composites (glass or carbon reinforced plastics) which may have significantly anisotropic properties.

2.  The realism of the criteria used currently for ice shedding is not well established.  For instance, blade dynamics have an unknown influence on ice shedding.

3.  Ideally a complete model would address the formation, flow, and refreezing of runback water. However, to model this is difficult.  Although it is seen as having secondary importance since in the design of a deicing system runback problems can be corrected by changes in cycle options and do not affect mat coverage decisions, ultimately we should attempt to develop such a model to reduce development time during flight test.

Future developments.  Future developments will likely cover the following:  (1) modeling of the cool-down and re-accretion process; (2) correlation of experimental observations of shedding with surface temperature and ice loading in order to refine the criteria for shedding; and (3) improvements to the two-dimensional melting modeling.

4.2.4  Performance

An ultimate aim of model development must be the prediction of the actual performance of the helicopter rotor in icing conditions, covering all aspects of the aerodynamic and dynamic behavior, including overall thrust and drag, torque, vibration levels, loads (particularly in controls), and autorotative capability. For the unprotected rotor, the main concerns are the primary accretion on the blade leading edge, which may lead to a direct degradation of performance, and asymmetric shedding, giving problems of imbalance and hence vibration.  For the protected rotor, performance degradation should be contained, but may not be totally eliminated, by the deicing system, since with cyclic deicing some leading-edge ice will always be present. Over long periods in icing conditions, secondary accretions aft of the heater mats may cause performance degradation.

Applications.  The main applications are for prediction of the response of different rotor designs to icing, for explanation of in-flight observations, and eventually as an input to the certification process.

Development status.  The development of the icing performance prediction capability involves two aspects:  first, the rotor performance models themselves, which are under development for the analysis of rotor systems performance independently of any icing considerations; and second, the determination of the effect of the ice on basic rotor characteristics to provide data for input to these performance models.  The latter includes both the aerodynamic performance of airfoils spoiled by ice and the effects of ice on blade dynamics.

The development of rotor-performance models is a continuing high priority task throughout the helicopter community (Ref. 42), and has achieved a state where the models are adequate for use for icing studies where steady flight is the prime consideration. Loads and performance models for maneuvering flight are less well established. This work will continue, regardless of icing considerations.

Although methods for predicting the effects of ice on rotor airfoil characteristics are less well established, several programs of experimental and theoretical research are now in hand. In the United Kingdom, a preliminary experimental study has been made of the relative sensitivity of the NACA 0012 and a modern cambered airfoil to a small stylized protruberance on the upper surface (Ref. 43). In the United States, three different approaches to the analysis of iced airfoils are being investigated: (1) data correlations, (2) conventional airfoil performance codes, and (3) Reynolds-averaged Navier-Stokes codes. In a test program using 6-in.-chord models in the NRC Icing Tunnel (Ref. 44), NASA has acquired an aerodynamic data base for a number of modern helicopter airfoils and is now developing performance correlations based on these data (Ref. 45). Other tunnel data using replicated (moulded) and stylized ice are also being incorporated into these correlations (Ref. 46). In applying conventional airfoil prediction methods to icing, a major problem is underestimation of drag, owing to the inability to treat roughness effects. Work on modification of the integral boundary-layer formulation of Ref. 47 to allow for roughness is described in Ref. 48. For glaze ice shapes, flow separation is a further major factor. Various existing flow codes are being evaluated for use in analyzing this aspect; in parallel, experiments are being conducted to build up a detailed data base on representative flow fields around glaze-iced airfoils (Ref. 49). NASA has recently initiated an effort to evaluate the present capabilities of a Navier-Stoke  code to handle the airfoil icing problem.

A problem in much of this work, particularly that using a theoretical approach, is in predicting and describing in adequate detail the form of the accretion. The present accretion models (Sec. 4.1) are unable to predict accurately the precise shape and roughness of glaze ice and the form of rime feathers on the flanks of the accretion.

Studies of rotor performance, using degraded airfoil data in performance models, have been done by Texas A&M University (Ref. 30) and supported by experimental work at model-scale in a wind tunnel (Ref. 50). In France, a model has been used for the deiced Puma rotor to study the effect of ice on the blade lower surface outside the heated area; modified values of $C_d$ were calculated for a small step at 20% chord and were used to estimate the increase in rotor profile power. In the worst instance, a 10% increase was predicted, corresponding to a 5% increase in overall flying power.

To date, very little work has been done on the effects of ice on rotor dynamics, although it is generally felt that they will be less severe than the aerodynamic problems. Changes to vibration modes owing to mass and stiffness increases will be small and the addition of mass at the leading edge will have a favorable effect on the c.g. Once data on the mechanical properties of ice have been obtained (see Sec. 4.2), theoretical studies can be carried out using existing modal and loads prediction programs.

No attempts have been made to predict the effect of ice on rotors featuring advanced concepts, such as novel tip configurations (swept tips, UK BERP tip, anhedral tip, etc.). Computational fluid dynamic analyses of the three-dimensional flow around rotor tips are under development, but it seems unlikely that they can be applied with any degree of confidence to this icing problem.

Validation. The general rotor-performance prediction models used by the helicopter community have been well validated by comparison with flight and wind-tunnel data. However, very little has been done to validate their use in icing, where the primary doubt must be in the validity of the input aerodynamic data. No attempt has yet been made to predict the performance of a particular helicopter in a particular icing condition, and to compare the results with actual flight experience.

Limitations. The primary limitations are the following:

1. The inability to predict in sufficient detail the form of the ice on the blades. This applies to short-term leading-edge ice, to the longer-term icing state of an unprotected blade on which significant self-shedding may have occurred, and to the deiced rotor on which small residual and secondary accretions may be present.

2. The general lack of data on the aerodynamic characteristics of iced airfoils, covering the full range of ice forms and aerodynamic conditions.

## 4.2.5  Ice-Shedding Trajectories

Ice chunks can be shed from the main rotor, from the tail rotor, and from various accretion regions on the fuselage, and may impact and cause damage to main or tail rotors or be ingested by engines. So far as is known, the only attempt to analyze the trajectories of shed ice has been by France as an aid to the Puma certification. The trajectories of ice chunks shed from the fuselage were predicted theoretically. The method was based on solving the nonlinear differential equations relating the aerodynamic and inertial forces on the ice as it moved through the flow field around the aircraft. The technique was used to predict impacts on the main and tail rotors during level flight at various speeds and during descent at 1500 ft/min.

No validation work has yet been undertaken. The main limitations are the following:

1. Ice trajectory is assumed to proceed in a plane surface; ice paths are in a vertical plane crossing the reference point (accretion area).

2. Effective flow in the vicinity of the fuselage is not modeled; only the downwash speed induced by the main rotor is considered.

3. The Mejer-Drees induced flow model is used in forward flight.

4. The ice chunks are modeled by their weight and aerodynamic coefficients $C_d$ and $C_l$. A parametric scan is necessary whenever these data are not well known.

5. Movement around the center of gravity (ice chunks of any shape) are not modeled; the aerodynamic coefficients are considered constant over the complete path.

Because of these numerous hypotheses and simplifications, the accuracy of this method is quite limited. The results must therefore be handled cautiously and errors evaluated with a parametric scan. However, it is felt that despite these restrictions, the technique can be used as a flight testing, development, and certification aid.

4.2.6  Conclusions and Recommendations

The overall conclusions and recommendations for further work on each of the aspects of analysis reviewed are presented below.

Droplet trajectories. A number of codes are now available and are being put to practical use. The main deficiency at present lies in validation, for which more experimental evidence is needed. This validation process will help to indicate the level of complexity needed, particularly for the flow field computation (two-dimensional vs three-dimensional, compressible vs incompressible).

Further development is needed to make the codes more generally applicable, particularly to the irregular shapes of iced airfoils. Comparisons of different codes should be made for common sets of input data, and a data base should be established of both theoretical and experimental results for general use in validation. Experimental and theoretical studies are needed to clarify the conditions for droplet attachment to the surface. In particular, experimental studies should be made of the impact and subsequent attachment or bouncing of droplets on surfaces at very shallow angles of impingement; and the effects of boundary layers should be studied theoretically.

Accretion. The present models allow qualitative interpretation of experimental results and some fundamental understanding of parametric effects. The models will be adequate for defining deicing system initial conditions. However, modeling of sufficient accuracy for performance prediction will be the most difficult task. Outstanding problems requiring further effort are (1) the physical process of accretion, in particular the reality of the assumed runback process, and (2) the heat transfer from rough and irregular surfaces.

Experiments should continue with the aim of clarifying the physical processes of accretion and improving the data base on heat-transfer coefficient. Comparisons of different codes should be made for common sets of input data. Experimental results should be exchanged.

Electrothermal deicing systems. Overall conclusions on the current models are that they are acceptable for assistance in design; acceptable for structural temperature prediction; probably adequate for qualitative (but not quantitative) interpretation of flight-test observations; but not sufficient for certification use because the correlation between surface temperature and ice shedding may not be sufficiently clear.

It is recommended that continuing efforts be applied to the development and validation of the models, since this can lead to great potential benefits to the certification process in terms of cost, time saving, and added confidence. Specifically, attention should be given to correlation of surface temperature with ice shedding, and to runback formation. Experimental data will be vital to both these studies.

Performance. The predictive methods for rotor performance in icing are not yet well established, and are certainly not validated. At present, their effect on the certification process is very small.

It is recommended that continuing efforts be applied to establishing a comprehensive data base on the aerodynamics of airfoils over the full range of icing conditions and to correlate these data to simplify their use in standard performance and loads prediction models. A further requirement is a data base on the performance of rotors with known accretions (natural, artificial, or replicated).

Ice shedding trajectories. Because of the numerous hypotheses and simplifications incorporated in the present methods, their accuracy is quite limited. The results must, therefore, be used cautiously and errors evaluated with a parametric scan. However, it is felt that despite these restrictions, the technique can be used as a flight testing, development, and certification aid.

Existing methods must be substantiated by comprehensive in-flight tests in order to reinforce the confidence in them as a means of compliance. However, at this time, because of the complications involved in this type of analysis, it is not considered worthwhile to pursue such studies in depth, and protection of

helicopters against ice shedding should be achieved through good engineering design and substantiated by
test.


## 4.3 SIMULATION AND EXPERIMENTATION

### 4.3.1 Laboratory

Laboratory tests cover a broad spectrum of activities, including fundamental experiments on the icing
phenomenon and the accreted ice itself; basic studies of materials associated with ice protection; and
substantiation of protection systems or their components. Attention was given in AR 166 to the various
aspects of the environmental testing required for systems, such as lightning, erosion, vibration, and
impact. The present review considers the adequacy of the current test techniques and highlights areas for
further research and development.

Thermal properties. The properties of ice and constructional materials must be known accurately for
use in mathematical models of deicing systems. Relevant parameters include thermal conductivity, specific
heat, density and thermal diffusivity.

Experimental methods for the determination of these properties are well established, although the
increasing use of fiber-reinforced composites is a complication. These materials have anisotropic proper-
ties, particularly thermal conductivity (the conductivity of carbon-fiber-reinforced plastics can be orders
of magnitude higher along the fibers than across them). The present need is not for the development of
techniques, but for the creation of a data base on new materials, including not only composites but also new
metallic materials such as the titanium alloys being used for erosion shields. A further important consid-
eration is the thermal effect of voids or delamination within a laminated heater mat; there is no current
information on this.

Adhesion. Knowledge of the adhesive strength of ice to typical helicopter materials has several appli-
cations. It is relevant to the shedding of ice from main and tail rotors under the influence of centrifugal
and aerodynamic forces; random self-shedding from unprotected rotors can cause dynamic and aerodynamic
imbalance with consequent overstress, vibration, and hazardous projection of pieces of ice. Adhesive
strength is also of interest in considering the functioning of mechanisms such as weapon releases. Experi-
mental techniques are required in order to measure ice adhesion under controlled and representative condi-
tions.

Applications: Data on ice adhesion are needed for the prediction of shedding from components and for
comparing the adhesion of ice to different materials. A particular recent application has been by the
French as part of the Puma certification to determine the maximum imbalance that could occur on the tail
rotor; to substantiate the self shedding of ice on the unprotected main-rotor tip cap; and to complement the
ONERA program for validation of the efficiency of the rotor-blade deicing system at very low temperatures.

Current development: Experience has shown that the measurement of ice adhesion is difficult. In
particular, consistent results are difficult to obtain. It is important to grow the ice in a representative
manner, to ensure that the surface to which the ice is attached is representative, and to apply loading to
the ice correctly. Factors to be considered include:

1. The conditions of ice formation: airspeed, OAT, LWC, droplet diameter, etc.

2. The conditions of strength testing, which should ideally be those under which the ice is formed,
since large changes may cause thermal stresses

3. The structural configuration: surface finish and texture, material, rigidity of the surface, etc.

4. The application of the load; this should represent as closely as possible the actual situation

It is particularly important in considering adhesion to rotors that erosion damage to the surface
should be properly represented. Adhesion to a newly manufactured blade may be quite different (and mislead-
ingly lower) than that to a blade which has suffered typical in-service erosion.

Numerous test rig configurations have been tried over the years. Much of the past work has been with
bulk frozen water rather than accreted ice. The best (most consistent) results have come from rigs in which
the loading is applied centrifugally, usually by use of a test specimen at the end of a rotating arm.

Results have shown the adhesion to be a function of the attachment surface, the type of ice, and, most
important, the temperature of the ice. The apparent adhesive shear strength may also be a function of the
area of adhesion; this implies that the adhesive failure may not be as a result of pure uniform shear but
may originate at an edge and propagate across the surface. In France, small-scale results have been extrap-
olated to large areas, relevant to large surfaces such as rotors; Fig 14 shows shedding stress values as a
function of temperature and iced area.

Very few new studies have been initiated in recent years. In the United Kingdom, a technique has been
developed recently by QMC for studying the basic physics of ice adhesion, particularly to flexible sub-
strates such as polyurethane elastomer (Ref. 51). The method involves pressurization to failure of an
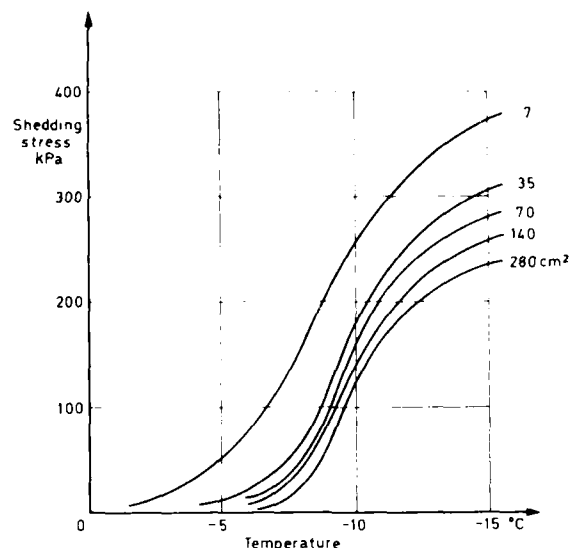
Fig. 14. Variation of shedding stress values with temperature and attachment area.

enclosed interfacial crack. The effects of ice thickness, loading rate, temperature, and material properties on the apparent failure energy have been explored.

Limitations: The accuracy and reproducibility of results is limited by the difficulty of accreting representative ice, loading the ice in pure shear, and preparing repeatable samples.

Ice mechanical properties. Knowledge of the mechanical properties of ice is required for consideration of the loading on the aircraft under dynamic conditions, such as that resulting from blade flexing or during the operation of mechanical de-icing systems such as pneumatic boots or EIDI. It is also relevant to the operation of mechanical systems such as weight release and droop stops. Properties of relevance include tensile and compressive strengths, shear and flexural modulus.

It is essential that the measurement of mechanical properties be made on ice accreted under representative conditions rather than from ice frozen from pure water. The mechanical properties are governed by the structure and type of the ice and again depend on the conditions of accretion—OAT, LWC, velocity, etc. and it is important in making such measurements that the temperature of the test specimen is closely controlled to that to which it would normally have been subjected.

... in the United States, ... a cylindrical test piece formed by ... with increasing strength with temperature ... of 3 MPa, compared with ...

... the blades, they are not ... provide protection with a minimum ... the materials used for ... and provide an ... must have a minimum thickness. Damaging factors can be classified as ... for example, water and hail; and (2) factors causing ... ice, stones, birds.

Current methods: Well established test methods ... of materials and structures under the following conditions:

1. Water (rain): normally by water ...

2. Hail: air-blast guns ...

3. Hail: air guns ... available to test with hail up to ... diameter at airspeeds ...

4. Birds: ...

Conditions  LWC = 1 g/m³,  $d_d$ = 30 μm,  V = 40 m/s
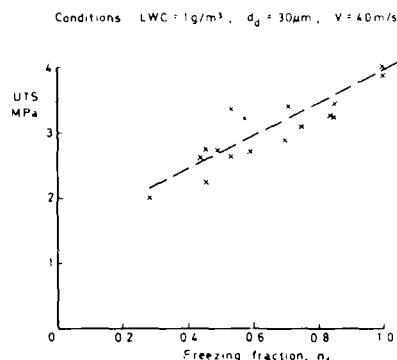


Fig. 15.  Variation of ultimate tensile strength of accreted ice with freezing fraction.

Test requirements vary between nations and may vary between aircraft according to their operational requirements.  Some attempts are being made to standardize tests; for instance the U.S. Army is working toward a standard rain test for helicopters (6 hr at 1 in./hr with 2- to 2.5-mm drops).

Validation:  General evidence suggests that rotor-blade erosion characteristics predicted by rig tests are experienced in practice, that is, rain causes erosion of the leading-edge, and sand erodes the upper and lower flanks of the blade.  Impact testing is well established for aircraft components.

Other aspects.  Other laboratory tests applicable to deicers and their associated systems include EMC, resistance to lightning, chemical compatibility, and overall substantiation of deicing mats in association with the blade or other structure.  No outstanding deficiencies have been highlighted in these test techniques, which are believed to be adequate for future clearance requirements.  In the case of blade substantiation, the need for simultaneous heater cycling and fatigue loading has yet to be established; if required, techniques for such tests could be developed, although it is felt that this complication should be avoided if possible.

4.3.2  Two-Dimensional Wind Tunnel

Two-dimensional wind-tunnel testing can be utilized to study icing phenomena at several different levels.  The most fundamental aspect is that of droplet trajectory and accretion.

Trajectories.  Trajectory information would be used for the substantiation of analytical predictions, and for the determination of the required deicing system chordwise coverage.

Status:  Up to this point, the only useful data bearing on trajectories is limited to approximations of impingement limits.  No attempts at the documentation of liquid-particle trajectories, using two-dimensional wind-tunnel tests, have yet been conducted.  Airfoil collection efficiency data were acquired by NACA before 1955, but no data are available for modern technology airfoils.  A joint FAA/NASA program is being initiated to measure local catch using ink-blotter techniques to correlate trajectory codes.  Correlation of accretion implies trajectory correlation.

Cloud physics investigations have used double-pulsed light photographs to obtain droplet velocity.  Information obtained in a mono-dispersed stream and a student project at the Massachusetts Institute of Technology (MIT) is reported to be using pulsed-flash techniques to correlate trajectory codes.  Collection efficiency data exist only for low Mach numbers.  Impingement limits as a function of airfoil angle of attack for both steady and oscillating airfoils have been defined experimentally, as shown in Fig. 16 (see Ref. 52).

In addition, Aerometrics, Inc., in the U.S., is developing a laser velocimeter optimized to track water droplets; the device is currently being used to characterize fuel and icing cloud sprays.  This technology has not yet been appplied to trajectories as influenced by the presence of a body, but, expecially if combined with a mono-dispersed stream, might offer an enhanced means for acquiring trajectory data and in particular, to try to understand the apparent difference between theory and experiment discussed under Droplet Trajectories in Sec. 4.2, in which catchment does not appear to correlate with trajectory predicitions.

Conclusions:  Impingement limits can be determined using two-dimensional test techniques, but the complete trajectory determination is not yet possible.  Tests have not successfully resolved individual droplets, nor provided the necessary measurement tools to study the apparent anomaly between trajectory predictions and observed catchment limits.

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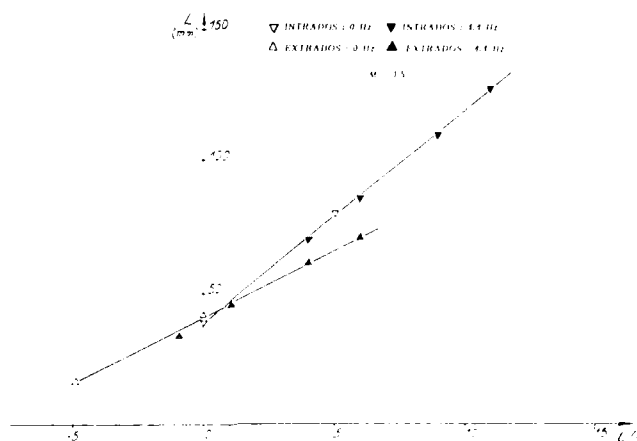


Fig. 16. Accretion length versus angle of attack, M = 0.5.

Recommendations: A cooperative effort to develop a data base, possibly by combining mono-dispersed stream technology with two-dimensional laser velocimetry, should be instituted. This program should focus on providing a general data base for trajectory code correlation, but in particular, for understanding the anomaly which currently limits the usefulness of trajectory codes for deicing system design.

Accretion. The measurement and photography of accreted ice in the artificial icing environment of wind tunnels have been accomplished by many research organizations. Recent progress has been made for rotorcraft airfoils, expanding the volume of available data, and extending the data base to include the effects of Mach number, temperature, and airfoil oscillation. Tests have been conducted by NASA in the Icing Research Tunnel and on behalf of NASA in the NRC High Speed Icing Wind Tunnel, by ONERA/Aerospatiale at CEPr and by RAE/WHL at Pyestock and Artington. (See Sec. 5.2 for a description of these facilities.) This work is intended to provide correlation information for analysis methods, to provide impingement limits for deicing system design, and to provide data for use in the interpretation of full- and model-scale icing tests.

Development status and future plans: Numerous tests have been conducted to expand the available data base. Following the systematic application of this information to determine the areas of disagreement, concern, and unanswered questions, a plan for further tests can be developed. NASA tests using dye-burst techniques to observe accretion have raised questions on the collection efficiency in the buildup process.

ONERA proposes to conduct fundamental research on accretion on cylinders and RAE plans further tests on model- and full-scale airfoils. NASA plans to test accretion on simulated ice shapes to investigate the ability of trajectory codes to predict collection efficiency.

Airfoil tests in two-dimensional wind tunnels provide data that appear to fit trends predicted by available analyses and trends available from model and full-scale rotorcraft data. Tests conducted during the past 5 years have greatly expanded the airfoil icing data base and have provided information for the effects of primary icing and rotorcraft variables. These tests have allowed the quantification of the ice shape and extent of chordwise coverage, have determined the parameters that have an influence on the ice accretion, and have provided data on the aerodynamic increments resulting from the ice. The tests have shown that the accretion limits on the upper and lower surfaces of the airfoil are a linear function of the maximum angle of the attack.

The French data available suggests that amplitude of oscillation has little effect on the ice accretion limits of impingement, but does affect the ice shape, especially at warmer temperatures. Increasing Mach number increases the size of the ice growth because of the increase in the mass of water impinging on the airfoil, and may alter the shape of the ice due to the increased kinetic heating caused by the higher speed. Two-dimensional wind-tunnel tests have provided information to define the boundary temperatures between ice types and indicate the maximum temperature for the formation of ice as a function of Mach number, LWC, and incidence. Typical results are shown in Figs. 17 through 21. Tests covering the subject of ice accretion have been documented in Refs. 28, 45, 52, and 53. Figure 20 shows the regions of ice types from Ref. 45.

Tests to date to verify the rules of similitude with regard to ice accretion on airfoils are contradictory. Some tests conducted by NASA in the IRT have provided movie documentation of the accretion process and have provided airflow data with simulated ice for comparison with prediction codes. Recent French and
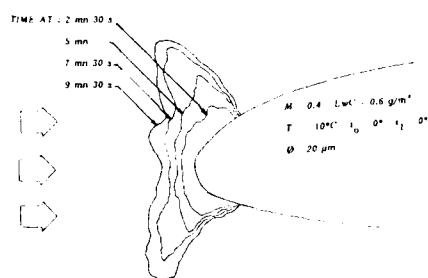
Fig. 17. Ice growth vs time, M = 0.4.
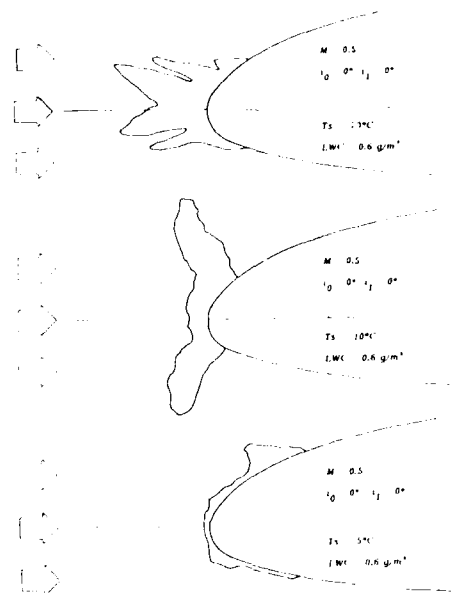


Fig. 18. Influence of ambient temperature on ice shape, M = 0.5.
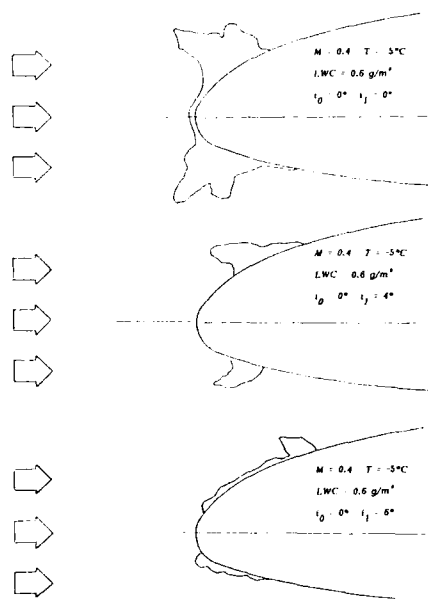


Fig. 19. Influence of oscillation amplitude on ice shape, T = -5°C.
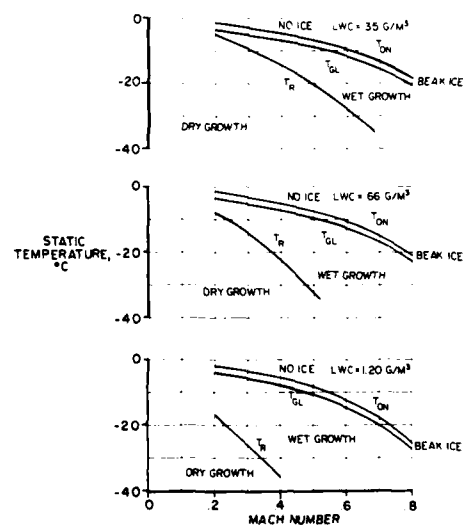


Fig. 20. Ice type boundaries, angle of attack = 6°.
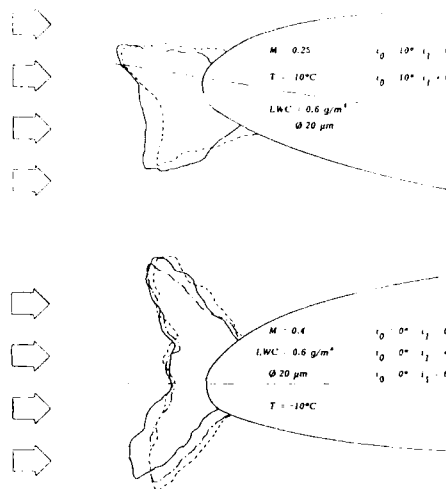
Fig. 21.   Influence of oscillation amplitude on ice shape, T = -10°C.

early U.K. tests have provided encouraging confirmation of similitude laws with regard to the major elements
of shape, but recent NASA work has raised a question about the ability of current similitude laws to ade-
quately deal with the larger buildups.  The RAE has made further surface-temperature measurements in icing
conditions on various airfoils, for use in validating computer models and for derivation of heat-transfer
parameters.

Validation status and other limitations:  The data acquired in these test programs are available to
correlate with other data, and with analysis.  Through a cross-correlation between data, confidence in the
data can be established.  However, sufficient dynamic data to validate icing buildup mechanisms in the
dynamic sense are not available and such data (NASA movies) suggest that this is an area that deserves more
attention.

Conclusions:  In short, this technology seems to be well in hand, and it has generated some of the most
interesting data on ice-accretion shapes and the influence of physical parameters, with the exception of
data necessary to resolve questions about the physics of the accretion process and to provide the data base
necessary to confirm the heat-transfer models assumed (see Sec. 4.2).

Recommendation:  It is recommended that research be focused on the dynamic ice buildup process.  See
recommendation for experimental and theoretical studies under Droplet Trajectories in Sec. 4.5.

Anti-icing/deicing.  Data are needed to obtain transient effects of models during deicing system
cycling, to validate prediction methods, to optimize deicing systems, and to provide substantiating data for
system qualification and certification.

Development status and future plans:  Several tests have been conducted, including tests by
RAE/Westland at Pyestock using full-chord sections of a deiced blade, and at Artington on an unanti-iced
cylinder.  ONERA/Aerospatiale at CEPr has conducted two-dimensional airfoil deicing tests.  RAE plans to
continue to conduct fundamental research on a deiced cylinder and to continue work with Westland in support
of aircraft projects.

Validation status and limitations:  Tests to date have shown that the models represent actual blades,
and that although the ice shedding is not fully representative of the dynamic and centrifugal effects,
useful information can be obtained on icing-system design parameters.  Tests on airfoils at reduced scale
have shown evidence of runback not observed during flight tests.  Tests must be conducted at as large a
scale as possible, and when reduced-scale models are used, similitude relations must be employed to repre-
sent scaled droplet diameter, liquid water content, and icing time, and to use the same velocity.  Even with
these variables matched, the runback water will not follow full-scale patterns.

Conclusions:  Full-scale anti-icing and deicing tests can be used to simulate in-flight characteristics
(see Ref. 54).  Smaller-scale models can be used to define trends, but further research must be conducted to
validate the use of subscale models in wind tunnels before their use as certification tools.  Runback water
tends to be a greater problem for subscale models (see Fig. 22).

Recommendation:  If it is desired to develop a capability to investigate thermal deicing systems in
model scale, two-dimensional tests to understand the size effect on runback phenomena will be required.
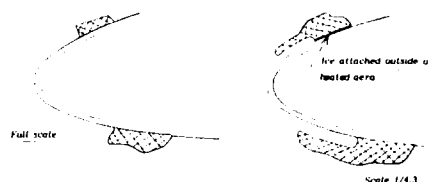
Fig. 22.  Effect of scale on deicer performance.

**Performance.**  Tests to evaluate the degraded performance of iced airfoils have been conducted in many facilities, using both artificial ice and simulated ice.  Lift, drag, and pitching moments increments can be determined (some facilities can provide only limited data; see Sec. 5.2) for variation in Mach number, LWC, droplet diameter, temperature, angle of attack (both steady and oscillating), and airfoil geometry.

Data resulting from two-dimensional tests can be used to predict the performance degradation of rotor sections and to provide a data base for the development of analytical airfoil and rotorcraft control load, stress, and torque rise prediction methods.  The results of the tests might be used to predict potential iced airfoil performance for airfoil trade-off studies, as well as for unprotected aircraft hazard analysis and clearance.

Development status and future plans:  Tests have been conducted on a multitude of blade sections and models.  Recent work has included NASA supported artificial icing tests in the NRC High Speed Icing Wind Tunnel and simulated ice tests in the Texas A&M University, Ohio State University, and FluiDyne wind tunnels.  Tests of small ridges installed at several chordwise locations on airfoils to represent ice have also been conducted by RAE in tests in the ARA 8 in. x 18 in. tunnel to compare relative increments for the NACA 0012 and the RAE 9645 modern cambered airfoil.  The analysis of normal force coefficient data show that at Mach-number incidence conditions appropriate to the forward and aft areas of the rotor disk, the RAE 9645 airfoil was less sensitive than the NACA 0012 to the presence of the upper surface spoilers, agreeing with results obtained in NASA/Sikorsky tests.  The RAE tests showed that the cambered RAE 9645 airfoil was more sensitive to stall and pitching moment break than the NACA 0012 airfoil in the region from 5% to 30% chord.  Maximum sensitivity for NACA 0012 was at 2% chord (see Refs. 43 and 55).  Several of the simulated ice models tested in the United States represent artificial ice from two-dimensional wind-tunnel tests and rotorcraft flight tests (Refs. 46,50,53,56-58).

Plans for the immediate future include the documentation of recent tests and comparing the results with prior data.

Validation status and limitations:  The determination of the validity of artificial icing two-dimensional tests is the subject of industry, university, and government research in the United States, and of researchers in the United Kingdom and France.  Simulated ice research is also receiving a significant amount of validation work.  Reference 59 concluded that simulated ice shape can be used to investigate the performance effect measured in icing tunnels and as predicted by the Ref. 45 icing relationships, provided that grit is added to rime ice shapes and that the corner radius of glaze ice is properly modeled.

The limitations of these tests are not clear at this time.  Their validity will be confirmed by comparisons with flight-test data, but even those data have significant quality and quantity limitations.  The turbulence in the flow caused by the spray system installation is a concern, as is the ability to replicate results in repeat artificial icing encounters.  Beyond this, the question of unsteady-flow effects also remains.

4.3.3  Three-Dimensional Wind Tunnel Tests (Model Rotor Testing)

This section deals with testing of rotating rotors in wind tunnels, which to date has only been carried out at model scale.  Such tests allow assessment to be made of the particular effects of centrifugal force, and of cyclic pitch and velocity.

The use of a spray nozzle array in a low-temperature wind tunnel allows simulation of icing conditions.  An alternative possibility is to stick simulated ice shapes onto the airfoil to measure the aerodynamic characteristics of the iced model.  The following tests are possible:  (1) determination of the extent and shape of ice accretions on models or actual parts of helicopters, along with their effect on aerodynamic characteristics; (2) study of the efficiency of deicing or anti-icing devices; and (3) alteration of aerodynamic characteristics in simulated ice shape conditions.

Applications.  Applications of icing tunnel tests of model rotors are as follows.

1.  Evaluation of the sensitivity of rotor design options to icing environments

2.  Investigations of the efficiency of anti-icing and deicing systems

3. Validation of computer models for accretion or deicing conditions by comparison of test results with those given by the numerical codes in the same aerodynamic and icing conditions (without the use of similitude laws)

4. Certification of helicopters in icing conditions with application of similitude laws by comparing the wind-tunnel results with the in-flight test results, for equivalent aerodynamic and icing conditions

5. Comparative studies of aerodynamic and performance parameters according to different ice shapes in order to specify the parts of the operational envelope where protection is not necessary

6. Systematic exploration of cloud parameters (LWC, OAT, droplet diameter, velocity) in order to bring out the general trends; in particular, tasks of immediate interest are studies of the effect on rotor accretion, of advance ratio and partial immersion of the rotor in cloud (i.e., cloud width less than rotor diameter)

Development status. While wind-tunnel testing of rotors at model scale is a well-developed art for aerodynamic and dynamic studies, the testing techniques for icing phenomena have only been studied to a limited extent. Although NASA has plans to initiate some small-scale work in the IRT, the only really significant work to date has been accomplished by the French in the S1 tunnel at Modane. Descriptions of the installation of the icing test facilities and the model rotor rig used in this tunnel are given in Refs. 60 and 61. The similitude laws used for this testing are described in Ref. 61.

The test technique consists of setting up the rotor and tunnel to their nominal running conditions before injection of the icing cloud. As soon as these settings are obtained, the cloud is injected. The rotor rotation speed is then maintained constant throughout the duration of the test. During the whole icing test, aerodynamic force measurements and video recordings are made. At the end of the test, photographs of ice accretions are taken in the test section.

The dimensions of the artificial cloud can be adapted by increasing or decreasing the number of nozzles of the spray array. The injected water and air are preheated, to prevent nozzle freezing. The cloud is homogeneous 1 min after the start of injection. The fitting of the spray bar array requires 1 day of work. The dismantling of an ordinary test, then the fitting of an icing test requires 2 days work.

Accretion on a three-bladed rotor model. The first similitude icing tests on a helicopter rotor were performed during the 1973-1974 winter on a 4-m-diam, 3-bladed rotor, supplied by Aerospatiale (scale 1/3). These results are documented in Refs. 61 and 62.

Accretion on a four-bladed rotor model. The tests were performed during the 1980-1981 winter. The report on this work has not been released publicly yet, although a summary of these tests is contained in Ref. 17. The main rotor characteristics were as follows: diameter, 4.2 m; chord, 0.14 m; airfoil, NACA 12/SA 1306; and scale, 1/4.3. For full scale, $V = 63$ m/sec, $d = 25$ $\mu$m, LWC = 0.6 g/m$^3$, and T = 10 mn; for reduced scale, $V = 63$ m/sec, $d = 10$ $\mu$m, LWC = 0.8 g/m$^3$, T = 1.75 mn.

The primary observations in respect of the aerodynamic coefficients were (Fig. 23):

1. Reduction of the free-stream temperature increased very strongly the aerodynamic coefficients

2. Increasing the water droplet diameter increased the aerodynamic coefficients

3. Increasing the LWC increased the drag and decreased the lift.

These results are similar to those obtained on a fixed blade element (Ref. 44), but centrifugal forces on the ice are more important than aerodynamic, so that the comparison is only valid for short accretion times.

Because of shedding, the ice accretion observed upon shutdown represents an indeterminate accretion period. However, analysis of the ice shapes has identified the following general conclusions:

1. No significant deposit exists if the static temperature is greater than -3°C; for the lowest temperatures (-11°C), the deposit is significant and can reach 100% of the blade span (M > 0.5); we then note the "horn" shape.

2. The influence of velocity is very important to the shape of the ice; the shape is massive near the blade root, where the velocity is lower, but is characterized by horns further outboard (where M is greater than 0.4); (Fig. 24).

3. When the droplet diameter increases, the shape is more massive and the deposit extends further on the lower surface.

4. LWC did not significantly modify the ice-accretion shape during the tests.

5. Ice accretion shapes appeared to be very similar to those obtained by two-dimensional tests at the same mean Mach and Reynolds numbers and the same icing conditions except that at the warmer temperatures, local runback ice was produced by the action of centrifugal forces.

| COMPONENT SIKORSKY | ROTOR MODANE |
|---|---|

PROFILE : SC1018R8
LWC : 1.0 g.m$^{-3}$
DIAMETER : 20 μm
MACH : 0.29
TIME : 60 s

PROFILE : SC1095
LWC : 0.66 g.m$^{-3}$
DIAMETER : 20 μm
MACH : 0.58
TIME : 45 s

■ DIAMETER : 10 μm
LWC : 0.6 g.m$^{-3}$
TIME : 60 s
□ DIAMETER : 10 μm
LWC : 3.8 g.m$^{-3}$
TIME : 60 s
○ DIAMETER : 15 μm
LWC : 0.6 g.m$^{-3}$
TIME : 60 s
● DIAMETER : 15 μm
LWC : 3.8 g.m$^{-3}$
TIME : 60 s
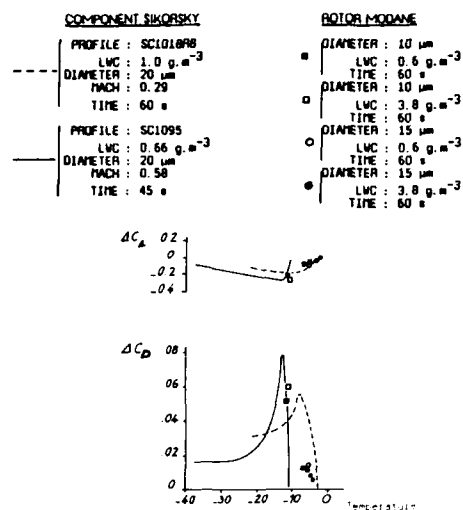
Fig. 23. Effect of temperature on lift and drag.
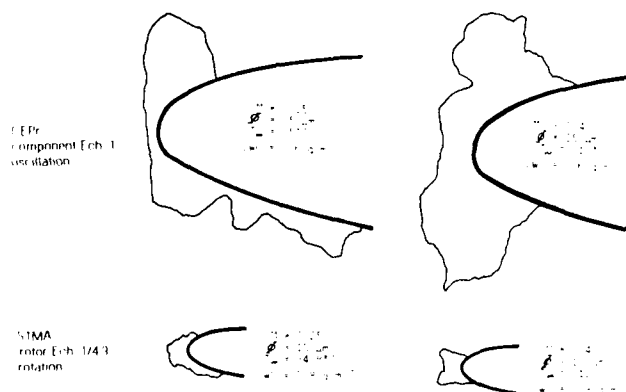
Fig. 24. Effect of velocity and droplet diameter on ice accretion shapes.

**Deicing on a four-bladed rotor model.** The tests were performed during the 1981-1982 winter. The heating power was adjusted to account for the inability to scale the heater mats, so as to achieve the correct heat flux at the ice/blade interface.

Deicing was obtained, but the aerodynamic parameters were significantly affected by a refreezing outside the protected area; this phenomenon has not been observed during flight trials. This appears to be a fundamental limitation in the use of a deiced, reduced-scale rotor to simulate a deiced, full-scale rotor, since it is impossible to scale the runback phenomenon. However, results of this type of test, particularly temperature measurements, have been of value in validation of computer codes and for comparison with in-flight temperature measurements.

**Validation status.** There are a number of fundamental issues that the model-rotor icing tests to date have only partially addressed. First and foremost is the question of whether or for what situations icing phenomena can be scaled. It is difficult to foresee the availability of any ground-based facility that simulates high-speed forward flight which will not require scaling for most of the situations of interest. It is therefore crucial to know under what circumstances scaling laws can be relied upon. While smaller tunnels can investigate scaling phenomena to some degree, only the S1 tunnel allows the testing of rotors at a sufficiently large scale to achieve a reasonable Reynolds number with model blades approaching structural dynamic similitude.

As reported above, S1 ice accretion studies to date have focused primarily on comparisons of icing phenomena on model rotors with those seen in two-dimensional tests. However, to validate truly the ability of the model tests to represent ice accretion and performance effects, the model tests must be correlated with full-scale, free-flight icing data. It is notable that model- to full-scale comparisons for fixed-wing aircraft have been encouraging and that basic scaling studies on cylinders have demonstrated the validity of the similitude law (Ref. 61).

With regard to rotor icing, the question breaks down into a number of subquestions that an in-depth study would answer. For example,

Can icing-accretion shapes and types of icing be replicated in scale models?

Can performance deterioration (e.g., torque rise) be predicted by model tests?

Can control load buildup or vibration thresholds and magnitude be predicted by models?

Can ice shedding and the effect of blade flexibility thereon be predicted by models?

Can thermal deicing systems be evaluated in model scale? Do heat-induced shedding and runback scale?

Limitations. Apart from the limitations implied in the foregoing discussions of validity, the S1 tunnel itself is limited in its use for icing. Such tests must be done during winter, from November to March. During this time, a statistical study based on a 15-year period gave the following results:

| t | -5°C | -7.5°C | -10°C | -12.5°C | -15°C |
|---|---|---|---|---|---|
| N2 | 53 | 30 | 17 | 7 | 4 |
| N4 | 47 | 27 | 14 | 6 | 3 |

N: Number of days during which the temperature was less than or equal to t (at least 2 hr, N2; at least 4 hr, N4).

The static temperature in the wind tunnel is very close to the external temperature, whatever the test speed.

## 4.3.4 Flight Test

In this section, a number of flight-test techniques are reviewed, covering artificial icing, replicated ice, and natural icing conditions, and having applications ranging from development and certification to basic research.

Artificial icing. Artifical icing tests are conducted by discharging a cloud of water into ambient cold air to produce a supercooled cloud. Two primary examples of such systems, the U.S. Army Helicopter Icing Spray System (HISS) and the Ottawa Spray Rig (OSR), are described in Sec. 5.2. The HISS can discharge into the atmosphere behind a helicopter flying at speeds from 90 to 120 knots, while the OSR is fixed and relies on ambient wind.

Applications: Applications include assessment of both unprotected and protected helicopters, primarily as an aid to system development; basic research studies; simulation of freezing fog conditions for investigation of ground running problems (Ottawa Spray Rig); and evaluatic of deicing and anti-icing systems and development of initial icing envelope prior to final testing in the natural icing environment.

Development status/limitations/validation: Although the HISS is a useful icing test tool, it does not in all cases produce a spray cloud representative of a natural icing cloud. This can be seen by the operating characteristics given in Sec. 5.2. Additionally, the HISS does not have the capability to immerse completely most vehicles, to produce a variable VMD independent of LWC, and to produce LWC to the requirements of FAR 25 Appendix C. The form of ice shapes generated on test articles has not always been representative of the natural environment and has caused some variations in test results. However, these anomalies are known and natural tests fill in the test voids to obtain valid test data. Performance measurements are not taken in the HISS cloud because of the effects of turbulence from the HISS aircraft, but are made immediately outside the cloud where it is believed they are still valid.

Significant differences have been found between helicopter behavior in the OSR and in natural conditions, but it is unclear whether these are due to the different flight conditions (hover versus forward flight) or differences in the process of ice accretion. This is a key question that needs to be resolved, since it has a major effect on the degree to which data from the Spray Rig can eventually be used in the certification process. Another major limitation of the OSR is the variability and imprecision of the cloud,

resulting from the effects of variation in the outside atmospheric parameters such as wind speed, gustiness, humidity, solar effects, and snow recirculation. The main effect is on LWC and to a lesser extent on droplet size.

Better measurement of accretion shapes in flight is urgently needed in order to make possible the rigorous correction of analysis and two- and three-dimensional test results with flight test. The necessity of waiting until castings can be made after landing significantly degrades confidence in the shapes recorded. An in-flight means of measuring ice-accretion shapes on a rotor would offer a major breakthrough in icing flight testing. A U.S. approach, utilizing photogrammetric analysis of stereo photographs, appears to offer promise. Exploratory tests have successfully documented ice shapes on a UH-1H helicopter following hover tests and on a Twin Otter in flight. Feasibility investigations to determine the techniques necessary to extend this photogrammetric approach to a helicopter in flight are under way (Ref. 63).

Replicated ice: Replicated ice accretions, that is accretions of representative shape or mass or both made from substances other than frozen water, may be used in place of real ice for various purposes; for instance, on rotor blades or other aerodynamic surfaces (e.g., tailplanes) to simulate the aerodynamic degradation caused by ice, and for simulated ice shedding studies.

Applications: Applications of replicated ice include its use as an aid to certification, for fundamental research studies, and for development and proving of test methods.

Development status/limitations/validation: The technique has found little use to date for the direct assessment of rotor-performance degradation, primarily because of the difficulty in defining and replicating the form of the accretion with sufficient accuracy for the results to be useful for certification. The use of stylized ice on rotors may have some value for research studies and to validate predictive methods, but to date very few experiments have been conducted.

Stylized ice has been used in the United Kingdom to degrade individual blade performance as part of the development and proving of the 2 × 2 technique for testing heated-rotor-blade systems. This method involves using different heating cycles on different blades (for instance on opposite pairs on a four-bladed rotor) and relies on the ability of instrumentation to measure changes in individual blade characteristics. Stylized ice was used to establish the sensitivity of the method.

The use of replicated ice on fixed surfaces, such as tailplanes, is common practice for fixed-wing aircraft. It has been used by the French for the Puma certification and on the Super Puma to confirm the need for protection of the tailplane. For this type of test, the shape of the ice may be established with sufficient accuracy by theoretical prediction, by wind-tunnel test, or from observations during flight test in natural or simulated icing conditions. The use of replicated ice allows the full flight envelope to be explored.

Simulated ice shedding has been used in the United Kingdom on the Lynx. Wax blocks of representative size, shape, and mass were released from critical accretion points such as aerials in order to determine ice trajectories in various flight conditions.

Natural icing. Despite the advances made in analytical and simulation techniques, considerable flight testing in natural icing conditions is still essential for both development and certification.

In order to maximize the effectiveness of natural icing flight tests, a number of factors must be considered, including the particular aims of the trial, the instrumentation of the helicopter, the choice of test site, and provision of supporting facilities.

Applications: Natural icing flights have two main areas of application: development and certification. Development applications include (1) development of control systems, including final setting up of deicing cycles; (2) functioning of the whole helicopter in icing conditions, including assessment of vibration, torque increment, stresses, blade temperatures, and overall protection system performance; and (3) assessment of subjective aspects, such as crew work load and vibration.

Certification applications include evidence of problems or absence of problems in real conditions sufficiently representative of those to be encountered in operational use; and assessment of levels of safety and safety margins, including failure cases. For both these aspects, natural icing tests provide the data required for the ultimate validation and correlation of analysis and simulation.

Development status: The effectiveness of natural icing flight tests has been improved by the use of a number of techniques, including the following:

1. On-board instrumentation, including real-time analysis, to measure both cause and effect, that is, both the atmospheric conditions and the corresponding behavior of the helicopter. In particular, instantaneous display of LWC has proved of great value in finding the best icing.

2. Improved ground analysis facilities

3. Use of different heating cycles on individual sets of rotor blades, for the direct comparison of deicing efficiency (the so-called 2 × 2 method)

4.   Improved cameras: rotor head for blade upper surface; fuselage-mounted for blade leading edge and lower surface; and video cameras with optic fibers for monitoring intake and engine icing

5.   Temperature instrumentation for anti-icing and deicing systems

6.   The ability to reprogram deicing system cycles in flight

7.   Increase in aircraft fuel capacity (e.g., by fitting with long-range tanks) to enable flights of longer range and duration to be made to search more widely for the best icing conditions and make maximum use of them once found

The effectiveness of the trials relies not only on these aircraft systems and the associated trials equipment, but is also dependent on having a clear understanding of the test evidence required to achieve the overall trial objectives. In particular, criteria must be defined (1) to judge the adequacy of each particular flight-test point and (2) to judge from the overall results of the program whether sufficient evidence is available to justify both safety (including airworthiness aspects) and a proper definition of performance penalties. Some progress has been made, but more rigorous and generally agreed definitions of these criteria are still required.

Validation:   The validity of test evidence acquired during natural icing flight is strongly dependent on the ability to measure accurately both the conditions encountered and their effect of the helicopter. At present, techniques may not be adequate to give the unique relationship that one wants between cause and effect. In particular, it is felt that reliable measurement of total water content and the ratio of liquid water to ice crystals would greatly enhance the validity of the demonstration against a given test program.

Flight in cumulus clouds may form a significant proportion of the overall icing experience for certification, depending on the requirements of the particular authority. However, tests in cumulus clouds involve special difficulties, particularly in resolving the specific effects of the icing from the overall performance changes. It is notable that flight in cumulus clouds is the only way of assessing the overall effects of turbulence.

For icing flight evidence to be valid for certification, there must be confidence that any special equipment or operational procedures used for the trial do not alter the basic performance of the helicopter or its sensitivity to the effects of icing. If necessary, some repeat tests should be made with a "clean" aircraft to confirm the validity of the use of the data for certification.

Limitations:   Major limitations are:

1.   Reliance on nature to provide adequate test conditions

2.   Difficulty in finding extreme conditions

3.   Time and expense

4.   Difficulties in accurate measurement of the atmospheric conditions, notably doubts about the accuracy of measurement of LWC, particularly at high values and in rapidly changing conditions; the inability of simple devices to measure solid water content (it may be necessary to know this in order to study the thermal behavior of the protection system and the whole helicopter); and the fact that equipment to measure continuously the droplet size is bulky and difficult to calibrate

5.   Operation in snow or ice crystals must be explored, but conditions sometimes take a long time to find

6.   The VMD and droplet-size distribution vary widely within and between clouds. Such variations may cause possible inconsistencies in test results, but must be accepted as a basic characteristic of the natural environment.

4.3.5  Conclusions and Recommendations

Laboratory test.  Conclusions and recommendations from the review of laboratory test methods are as follows.

Thermal properties:  Experimental methods are well established. The need is for a data base on the thermal properties of new materials. It is recommended that available data should be shared, and that further measurements should be made on composites, on new alloys, and on the thermal effects on delamination.

Adhesion:  Available data show large scatter. Some present methods are adequate for comparison of materials. Further work is needed to develop better test methods and to produce a more reliable data base on ice adhesion to different materials over the full range of icing conditions. The effects of erosion damage on adhesion to blades should be considered.

Ice mechanical properties:  The work is all at an early stage, but it is important to obtain an understanding and a reliable data base in order that structural models for deicing may be used. It is recommended that present studies should continue.

Erosion/impact: Satisfactory test methods are available. Some test standards exist, and others are still being formulated.

Other aspects: Adequate techniques are available for testing deicers and their associated systems in terms of other aspects such as EMC, lightning, chemical compatibility, and structural substantiation. The necessity for simultaneous heater cycling and fatigue loading on blades has yet to be established.

Two-dimensional wind-tunnel test. The conclusions and recommendations for two-dimensional simulation and experimentation are as follows. In spite of the limited amount of data that can be used to substantiate the performance data acquired from artificial and simulated ice tests, it is believed that the information can be used as input to formulate analytical prediction methods for the prediction of rotor performance with iced airfoils. These test data will be the foundation that will provide the basis for future research and are likely to lead to more cost-effective approaches to rotorcraft certification. The Gray correlation (Ref. 64) has failed to provide the necessary accuracy over a wide range of conditions, as shown in Fig. 25. Improved correlation for rime ice was achieved by Bragg (Ref. 15), and recently Flemming and Lednicer have offered a correlation for rime and glaze ice (Ref. 45) as shown in Figs. 26 and 27.
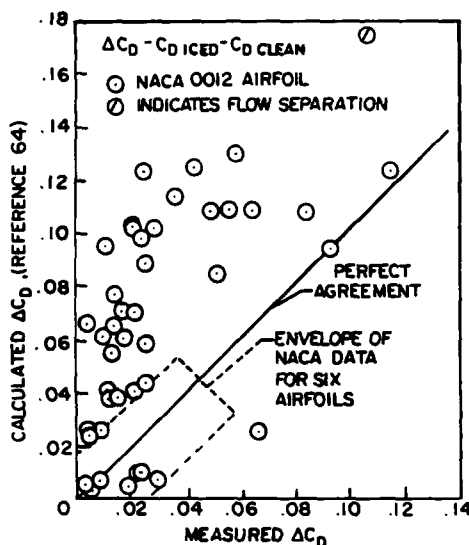


Fig. 25. Comparison of measured drag coefficient with values predicted by Gray Correlation for the NACA 0012 airfoil.
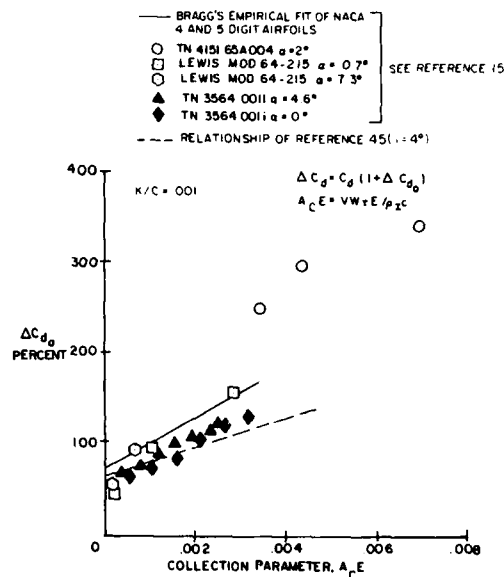
Fig. 26. Rime ice drag coefficient correlation.

Although the effect of advance ratio is not established, an important observation by ONERA is that limited tests to date have shown that the shapes on a fixed blade element and on a model rotor are similar and the general trends observed are the same. The rotating movement has only a small influence on the ice accretion shape.

Future efforts should focus on the examination of existing two-dimensional and rotorcraft icing data to first determine which data provides the most accurate correlation information, and then to use this information to upgrade prediction methods. At that point, efforts should focus on the examination of existing two-dimensional and rotorcraft icing data to first determine which data provide the most accurate correlation information, and then to use that information to upgrade prediction methods. In addition, attention should also be given to accumulating some similar data on deiced blades.

Three-dimensional wind-tunnel tests (model rotors). The conclusions and recommendations on the testing of model rotors in wind tunnels are as follows. The very useful, though limited, tests in the S1 tunnel to date suggest that there is a significant role for model-rotor testing to investigate important aspects of the rotor icing problem and particularly to provide controlled and documented data for analytical code validation. Although the role of model testing in the development and certification process is less clear, model tests can certainly be used to understand more thoroughly the limitations of other simulation techniques, as discussed in Secs. 4.6 and 6.4.
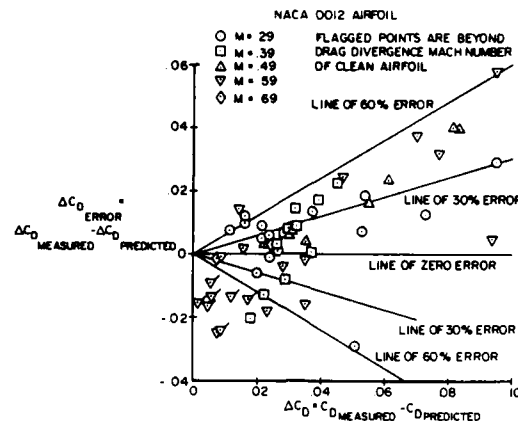
Fig. 27. Correlation of reference 45 incremental drag relationship with NACA 0012
data acquired in the NRC High Speed Icing Wind Tunnel.

It is recommended that an internationally supported program be conducted to accumulate coordinated data on model-scale and full-scale flight tests in icing conditions to address the questions raised under Validation Status in Sec. 4.5. As a first step, an ad-hoc group should be convened to define the most efficient means of accomplishing this recommendation and those of Secs. 4.6 and 6.4 in a single, coordinated program.

Flight test. The conclusions and recommendations on the various aspects of flight test reviewed are as follows.

HISS: The HISS has been an excellent flight-test facility for generating an artificial icing environment for test vehicles. It has provided rapid accumulation of test data throughout the U.S. Army moderate icing envelope when natural icing conditions were not available. After 10 years of use, the HISS has proven effective in significantly reducing calendar test time, providing the highest margin of safety, and evaluating icing envelope extremes difficult to obtain under natural icing conditions. However, the system requires further development to make it more representative of the natural icing environment. Studies, including flight testing, are continuing in order to understand the effects of differences between the artificial and natural conditions.

Ottawa Spray Rig: The OSR has been useful as a "first look" technique, for instance for the initial proving of new deicing systems (such as the pneumatic boots for rotor blades). However, efforts to take advantage of it to assist in setting up electrothermal deicing system cycles have produced mixed results. The United Kingdom and France have found it misleading, whereas the U.S. and German development teams feel that they have obtained useful results. Thus, its potential to assist in the certification process is even less clear at this time. To establish the ultimate usefulness of a low-speed spray rig it is essential that the source of the problems encountered be understood. In particular, it must be established whether icing shapes and extent observed in the Ottawa Spray Rig are sufficiently similar to those encountered in forward flight so as to provide the shape information required to use replicated ice to investigate forward flight effects.

Replicated ice: The use of replicated ice is a useful technique for fixed surfaces which can provide valuable evidence for certification and in some cases may be the only method for gaining the necessary justification. To date there has been little application to rotor blades. The future role of the use of replicated ice on rotors in the certification process has yet to be established; this is discussed further in Sec. 6.4.

Natural icing: Flight testing in natural icing conditions is, for the moment, the only method covering most of the certification demonstrations, and provides the ultimate means for validation and correlation of many of the analysis and simulation methods. But it has to be extensive, of en intensive, and it is therefore expensive. This position will continue until significant improvements are made in simulated icing test methods or in other techniques for justification.

Potential improvements in natural icing test methods include the following:

1. Improved test program

2. Better forecasting of icing conditions and good airborne information

3. Lighter and more reliable instrumentation

4. Use of production rather than prototype aircraft, if available, so that the test team can be smaller and more flexible

5. Use of increased fuel capacity for enhanced range and endurance

6. Further improvements to ground analysis

7. Although only in its early stages of development, there appears to be considerable potential in the use of video cameras for the observation of ice on rotor blades

Furthermore, full advantage should be taken of all natural icing tests, including those for certification, to accumulate the data base required for correlation and validation of analytical and simulation techniques. This may have implications for the instrumentation requirements and also the way in which the trials are conducted.

## 5.  INSTRUMENTATION AND FACILITIES

### 5.1  INSTRUMENTATION

Several discrete instrumentation topics, submitted by various members of WG 14, are covered in this section.  The first topic presents comparisons of measurements from the most common liquid-water-content instruments and also similar comparisons from droplet-sizing instruments.  Next is presented a new high-speed video camera technique for documenting ice coverage and ice shedding on both the rotors and fixed components.  The next two sections describe the development status of two new systems that monitor critical helicopter parameters and feed them into on-board computers which provide an icing status display and assess the severity of the icing encounter.  Finally, the last section presents the status of a new LWC probe developed in the United Kingdom.

#### 5.1.1  Icing Instrument Comparisons

Description.  NASA Lewis Research Center has equipped a twin-engine aircraft with many of the most commonly used instruments for measuring LWC and water droplet sizes in natural icing clouds.  For LWC, data from a Johnson-Williams (J-W) hot-wire probe, a Rosemount ice detector, and a Leigh ice detector were compared with simultaneous measurements from rotating multicylinders (RMC).  For water droplet size, data from a forward scattering spectrometer probe (FSSP-Knollenberg) were compared with simultaneous measurements from sooted slides and RMC.  Similar measurements were made in the U.K. programs on the PUMA and Chinook (Sec. 6.5).  NASA has also conducted a comparison of icing cloud instruments in their Icing Research Tunnel (IRT) (Ref. 65).

Discussion.  Figure 28a shows that the J-W and RMC agreed quite well up to 0.4 g/m$^3$.  The larger scatter above this level is assumed to be due to partial water runoff from the cylinders at relatively high temperatures.  In Fig. 28b, considerable scatter is seen in the comparison of the Rosemount and the RMC at the lower LWC levels; little data were acquired at LWC levels above 0.5 g/m$^3$.

Although the data are not shown, the Leigh ice detector indicated LWC levels about 60%-70% of the RMC values.  A recalibration by Leigh Instruments Ltd. confirmed that this unit experienced a calibration shift to approximately 75% of the correct level.  Unfortunately, there was no way to detect this shift during the icing season except by comparing its results with those of other instruments.

Figure 28c compares the LWC calculated from the FSSP with that from the RMC.  As can be seen the FSSP often does not agree with the RMC.  In Ref. 65 it was shown that a ±20% variation in LWC causes about a ±20% variation in drag on a UH-1H airfoil section.

Figure 28d compares the median-volume droplet diameter (MVD) from the FSSP and the RMC.  The FSSP generally indicated MVD values from 2 to 6 μm higher than the RMC.  Figure 28e shows a comparison of the FSSP MVD and the sooted slide MVD.  As with the RMC comparison, the FSSP generally indicated larger MVD values than the sooted slide, although the data scatter is quite large.  Similar results obtained by the A&AEE in the United Kingdom are shown in Figs. 28f through 28i.  Tests in the NASA IRT (Ref. 65) showed that a ±30% variation in droplet size (near 16 microns) had a surprisingly large effect on the ice shapes and a corresponding +70/-62% change in measured drag on a UH-1H airfoil section.

Limitations.  The data shown in the instrument comparisons for natural icing have not been corrected for flow-field effects caused by instrument location on the NASA aircraft.  The effects of local particle concentration on droplet size and LWC measurements is currently being examined at NASA with a 3-D particle trajectory code.

Future plans.  NASA plans further IRT tests to investigate the causes of data scatter seen in the instrument comparisons for natural icing.  Effects of different air velocities, droplet sizes, air temperatures, and the LWC levels will be determined for each instrument.  The effects of instrument location on local particle concentration will be established by three-dimensional particle trajectory analyses.  Flight data will then be reanalyzed taking any quantifiable effects into account to determine if the data scatter seen in the original instrument comparisons is reduced.  Additional flight data will be acquired to improve the statistical significance of the instrument comparisons.

Acceptability.  Internationally accepted calibration standards currently do not exist for LWC and droplet-sizing instruments.  This means that the accuracy and limitations of these instruments cannot be readily established.  A standard test facility, such as an icing wind tunnel, would be of great benefit in quantifying and comparing instrument accuracy.  Finally, it should be mentioned that at this time there are no absolute calibration standards for either the LWC instruments or the MVD instruments.

#### 5.1.2  Operating Experience with Icing Cloud Instruments

Liquid water content measurement (NASA, U.S.A.).  It has been found that the Johnson-Williams sensor head's response can change for unknown reasons.  The net result of these changes is that the measured LWC values may be underestimated by 50% or more.  The only known way to determine if such sensor changes have occurred is to periodically check the sensor head using a water spray of constant, repeatable LWC.
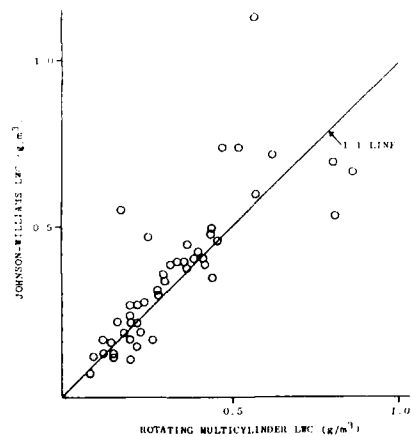
(a) Johnson-Williams vs the rotating
multicylinders.
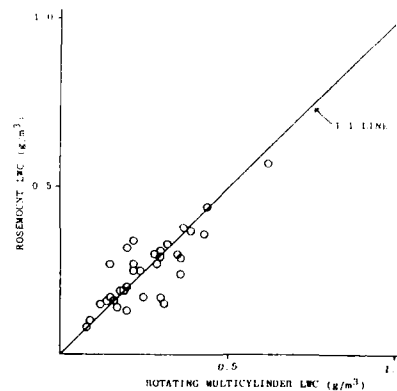
(b) Rosemount ice detector vs the rotating
multicylinders.
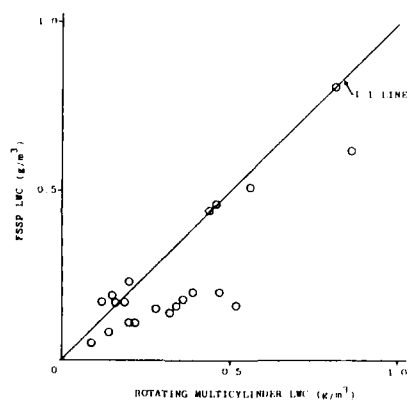
(c) FSSP LWC vs the rotating multicylinders.
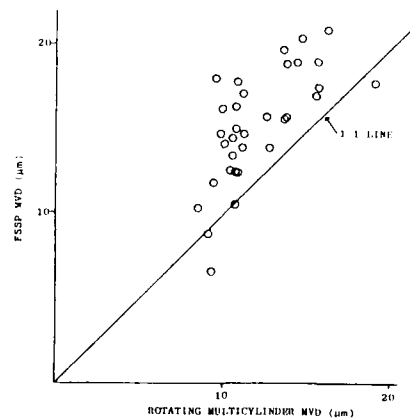
(d) FSSP MVD vs the rotating multicylinders.
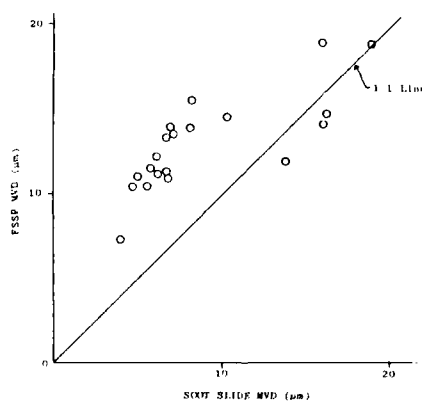
(e) FSSP MVD vs the sooted-slide.

Fig. 28. Scatter plots of in-flight icing instrument comparisons.
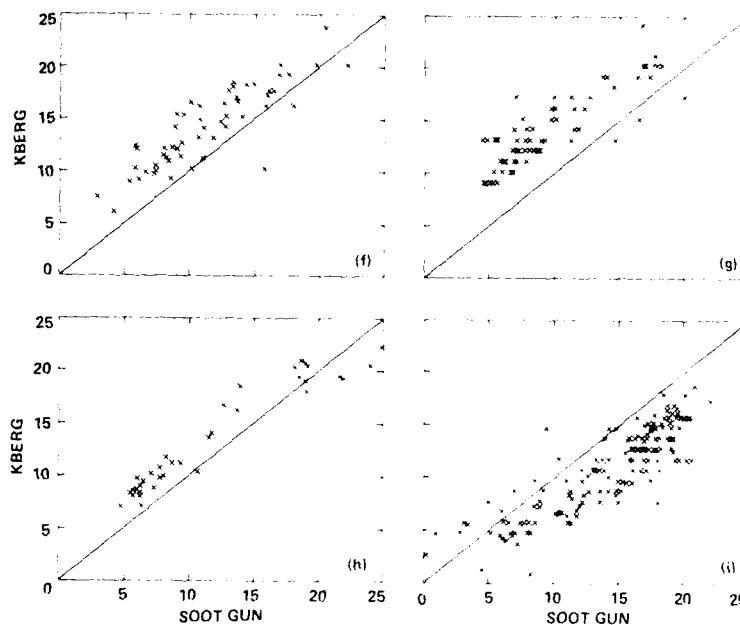
Figure 28.- Concluded. Comparison of soot slide and Knollenberg results: (f) for Chinook and Puma Denmark 1982/83; (g) for Chinook ZA708 winter 1983/84; (h) for Chinook ZA708 winter 1984/85; (i) for all points.

Tests of several Johnson-Williams sensor heads in an icing tunnel at NASA Lewis Research Center have shown that at temperatures below -15°C (5°F), ice may form on the front post that holds the compensating wire. As the ice forms, the indicated LWC decreases. After some time, the i.. sheds and the indicated LWC rises rapidly to a value above the actual LWC before it returns to the correct value. This ice buildup and shedding results in the indicated LWC being very erratic and unreliable. For example, for a LWC of 0.6 g/m³, the indicated LWC from one Johnson-Williams fluctuated between 0.10 and 0.8 g/m³.

Droplet diameter measurement (NASA, U.S.A.). It has been found that when the forward scattering spectrometer probe (FSSP) is used in icing for an extended period of time (i.e., 45 min), ice may form on the interior of the sampling cylinder in addition to the hemispherical head of the instrument pod. These ice accumulations can cause the indicated particle concentrations (and LWC) to decrease and the indicated median volume diameter (MVD) to increase. Reduction in indicated LWC of up to 80% accompanied by a MVD increase of 5 µm has been observed in natural icing conditions. In most cases the effects of ice buildup on the probe can be discovered if the LWC from the FSSP is compared with the LWC from another instrument.

Liquid water content measurement (Aerospatiale-France). In the course of the various flight programs, four types of sensors have been used to measure LWC: Johnson-Williams hot-wire probe; Leigh ice detector; Rosemount ice detector; and fixed-icing indicator (CEV TT6100 indicator). Sometimes, the results from these various instruments were somewhat different, and the major conclusions reached are as follows.

The sensor taken as reference was the Johnson-Williams. This instrument of the hot-wire type, is capable of detecting not only the supercooled water, but also the ice crystals, and indicates a total water content. Owing to its principle, it gives an instantaneous value that is rapidly variable in unstable clouds. Leigh and Rosemount sensors are instruments that detect ice accumulation on a sensitive element that is exposed to the airflow. Generally, these instruments only measure the supercooled water content. With regard to these two sensors, the following remarks can be made.

The mean indications are generally rather close to one another in continuous icing conditions up to 0.6 g/m³; the values obtained by both instruments may be lower than those indicated by the J-W sensor, in mixed conditions in particular. Generally speaking, the behavior of both these sensors is coherent and generally satisfactory in continuous icing conditions, which makes them acceptable as a system for monitoring the severity limits, even if the values indicated are not always representative of the actual water content.

Apparently, the Leigh detector sensitivity is greater for the small drops (median volume diameter: 15 to 20 µm), and it indicates lower values than those given by the Rosemount sensor for larger drops. In

intermittent icing conditions, the Rosemount indications more closely follow the values given by the J-W sensor than those of the Leigh sensor which gives markedly underestimated values (up to 2-3 times). The deicing periods of the vibrating strip on the Rosemount sensor (30 to 90 sec) lead to indications that are temporarily erroneous.

The CEV indicator gives ice accretion rate values, consistent with the mean values given by the Johnson-Williams sensor in continuous icing conditions. On the other hand, in intermittent icing conditions, the use of the CEV indicator leads to an overestimation of the ice accretion time and an underestimation of the water concentration, compared with the J-W sensor.

The severity limits recommended, therefore, are effective for a given sensor, in the configuration (location in particular) experimented during these tests.

Droplet-diameter measurement (Aerospatiale-France). The FSSP Knollenberg probe has been used for flight tests. This instrument, whose calibration and utilization are delicate, is required when a relation with calculations and wind-tunnel tests is to be made. The Johnson-Williams and Knollenberg sensors are necessary for accurate flight measurements. The instruments are fragile and must be used with caution. They are not adequate for operational use. However, although Leigh and Rosemount sensors are inaccurate in some configurations, they can be considered as reliable and used in operational conditions in case of icing limitations.

5.1.3  Video Tape Documentation Techniques

Description. High-speed video cameras are installed on helicopter rotor hubs to document ice coverage and shedding characteristics of rotor blades in icing conditions. Video cameras are also used to document icing on fixed objects such as antennas, sections of the fuselage, and other remote areas during flight testing. The basic video system consists of a high-speed video camera, a video monitor, and a video tape recorder. This equipment is relatively inexpensive, readily available, and simple to install and use. When a camera is mounted on the rotor hub, slip rings are required to transmit the electronic signal from the video camera to the video tape recorder.

Potential applications. Video systems can be mounted on rotor hubs and used to document extent of icing on rotors and ice-shedding characteristics in flight. Video cameras can be mounted in remote areas and used to document icing on fuselage areas, antennas, and external stores. One of the chief advantages of video over photographic methods is that a video monitor can be used to view what is being recorded or to replay a test sequence immediately after the test. This significantly improves test efficiency since results can be evaluated without having to wait for photographic documentation to be developed.

Development status. High-speed video cameras have been mounted on rotor hubs and used by the U.S. Army to document rotor icing on two UH-1H helicopters. Figure 29a shows a video camera installation on the rotor hub of a UH-1H. Video cameras were also used to document antenna icing on a UH-60 helicopter. All tests were judged highly successful.

Validation status. Validation of the use of hub-mounted video cameras to document rotor icing is complete. The use of very small (2- by 2-in.) cameras to document icing on antennas and other objects has also been successful. Figures 29b through 29f show an example of a hardcopy of five frames of a series showing the ice shedding caused by a pneumatic boot on a UH-1H helicopter.

Limitations. Video camera resolution is inferior to photographs, although it is sufficient for most icing documentation work. The video manufacturing industry is actively pursuing the development of higher-resolution video cameras.

Future plans. The U.S. Army has made great strides in the application of high-speed video camera techniques to document ice-accretion and ice-shedding characteristics on rotors and fixed components. The Army's future plans include the development of small, lightweight, self-contained (internal power supplies), high-resolution color video cameras. Data will be telemetered from the rotorhead cameras, thereby eliminating electrical and mechanical interference with video recorders. Resolution will be further improved by going from 350 to at least 525 lines and by use of imagery enhancement techniques. This effort has the potential for substantially improving documentation of ice shapes and characteristics on rotors and fixed components, and it should be continued.

A nonintrusive means of measuring ice-accretion shapes on a rotor in flight would offer a major breakthrough in icing flight testing. A U.S. approach, utilizing photogrammetric analysis of stereo photographs, appears to offer promise. Exploratory tests have successfully documented ice shapes on a UH-1H helicopter following hover tests and on a Twin Otter in flight. Feasibility investigation to determine the techniques necessary to extend this photogrammetric approach to a helicopter in flight (Ref. 63) are under way.

Acceptability. Video systems allow on-line monitoring of events. Unlike photographic methods, video systems permit immediate replay of a recording, allowing evaluation of test results, thereby greatly increasing test efficiency.

62



(a)
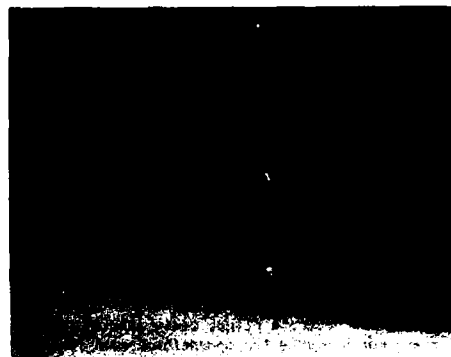
(b)

(c)

(d)

(e)
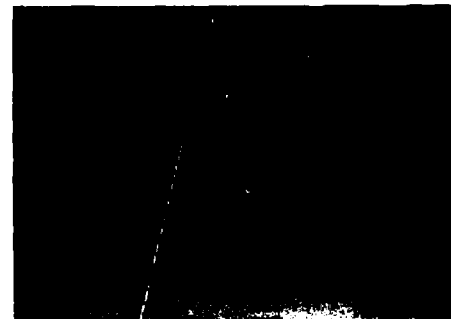
(f)

Fig. 29. High speed video camera installation and ice-shedding pictures.

### 5.1.4 Advanced Icing Severity Level Indicating System (AISLIS)

Description. The U.S. Army is evaluating the AISLIS concept, which is used to provide an aircrew with an icing status display. Leigh Instruments Ltd. is developing this system through a contract with the U.S. Army. The system will sense rotor speed, vibration level, engine torque, fuel content, static and dynamic pressure, air temperature, and LWC. The number of persons aboard, cargo weight, and aircraft configuration will be entered manually by the crew. These inputs will be processed by the AISLIS unit. A meter then displays the degree of severity of a particular limiting condition which can be either delta torque, power margin, air temperature, or LWC. Another section of the display may illuminate one or more warning legends, such as unit fault, ice crystals, engine delta P, autorotation, asymmetric shedding or vibration.

Potential applications. The AISLIS system could be applied to any helicopter. Analysis of the characteristics of the particular helicopter is required in order to program the unit for that helicopter.

Development status. The basic AISLIS hardware has been built up and tested in a wind tunnel. The next step required to check out the complete system, including external sensors, requires that the complete system be installed on a helicopter. The system must then be flown in clear air to complete adjustments of input signals and software for proper warning levels, etc. Flights in icing conditions would then be required to determine if the installed system works as intended.

Validation status. Testing of the AISLIS system on a helicopter has not yet been done.

Limitations. Before the AISLIS system can be used on a helicopter, the performance algorithms for that particular helicopter model must be established. It is anticipated that as more actual flight experience is gained with this system, performance algorithms for other helicopters can be more easily established.

Future plans. Installation of the AISLIS system on a UH-1H helicopter for ground, clear air and icing flight testing is planned as funds become available.

### 5.1.5 Torque-Increment Systems

Description. Several systems have now been developed in the United Kingdom and in the United States for the continuous computation, in flight, of the excess power requirement of the rotor system due to the degradation of its performance by ice. This power (torque) increment may arise directly from additional profile drag caused by the ice, or may result from increased collective pitch to compensate for loss of blade lift. In all the present systems, the torque increment is found by comparing the actual rotor or engine torque with a datum value calculated from other parameters such as speed, altitude, temperature, and rotor speed. The main differences between systems arise in their method of calculating the datum torque. The systems may be self-contained, with their own cockpit display, or may exist primarily as software in a multipurpose, on-board computer, with the output available to the pilot on a multiparameter display.

Potential applications. The potential applications of torque-increment systems include the following: (1) to enable pilots to make full use of clearances which include torque increment as a limiting parameter; (2) for use as a possible control input to a blade deicing system; and (3) for indication of degradation of rotor performance by means other than ice, for example, sea salt accretion, erosion damage, battle damage.

Development status. In the United Kingdom, two systems have been tried. The original, developed by A&AEE and tested in natural icing on a Lynx helicopter, used collective pitch as a primary input; consequently, although it readily identified profile drag rise, it failed to register fully the effects due to lift loss. More recently, a self-contained system by Marconi (now GEC) Avionics has been developed and tested in clear air (not icing) on a Lynx. This system uses a more fundamental approach for computation of the base-line torque, summing the total from computed values of induced power, parasite power, KE and PE changes, etc. In the United States, Boeing-Vertol included a torque increment routine in the on-board computer facility for the RAF Chinook HRB trial. This in effect works with the standard aircraft nondimensional performance curves which it keeps stored in memory. Lastly, a torque-increment system was included in the AISLIS package discussed earlier in this section.

Validation status. For full validation, the system must be shown to give an accurate output of torque increment for all flight conditions, both in and out of icing. To date, none of the systems has been subjected to this rigorous proving. As a first step, the Marconi system was tested under a wide range of controlled clear-air conditions to examine its ability to maintain a zero output with an undergraded rotor. The Marconi method has also been applied, postflight, to other icing-trials data, primarily for the Chinook, and comparisons will be made with torque increments derived by traditional long-hand methods. Similar analysis has been used for the B-V system.

Limitations. Most of the techniques deal well with steady flight. The limitations tend to be defined by their ability to cope with acceleration, deceleration, climbs, descents, turns, etc. Their accuracy in these maneuvers will depend not only on the software but also on the quality of the input signals. Filtering, needed to dampen the effects of spurious transients, particularly in turbulent conditions, may cause significant deadening of the response.

6.1.6   RAE Element Thermal LWC Probe

Description.   A thermal-type LWC probe has been developed, using a cylindrical probe 40 mm long by 8 mm diameter, made from a positive temperature coefficient ceramic (PTC) semiconducting material.  The probe self-controls at approximately 70°C.  Unlike earlier thermal probes such as the Teddington and the Johnson-Williams, no reference probe is used; instead, the power dissipation from the probe is compared with a calculated reference power, based on flight speed, altitude, and OAT.  Any excess power dissipation above this reference is assumed to be due to evaporation of impacting water, and hence cloud LWC may be calcu-lated.  The PTC material ensures a very accurate surface temperature, virtually eliminates control electron-ics, and gives a very rapid response to changes in atmospheric conditions.  Unlike accretion-type LWC instruments, the response time of the PTC is unaffected by OAT.

Applications.   The primary application is for LWC measurement.  The probe responds also in some snow/ice and fog conditions (see text).

Development status.   Most of the development effort has been on the probe itself.  To date, the signal processing to derive LWC has been either with an existing on-board computer, or postflight.  Development of the probe has provided units adequate for icing trials use, but unacceptable as a production standard (see Limitations below).

Validation status.   Good comparisons have been made with other LWC instruments in natural icing.  Every opportunity will be taken to continue such comparisons.  Use in icing tunnels is troublesome because convective power dissipation from the probe is affected by turbulence from the water spray system and the probe is responsive to fluctuation in the supposedly stable tunnel cloud.

Limitations.   The probes are relatively fragile; improvement schemes are being considered.  The maximum power dissipation from the probe sets an upper limit to the intercepted water that can be evaporated; at present this limit is about 1.8 g/m at 100 knots, although there is a possibility of future improvement.  No dedicated real-time computation/display system is available yet.  Accuracy depends on the quality of the available air data.

6.1.7   Instrumentation Conclusions and Recommendations

Icing instrument comparisons.   Liquid water content sensors, when operated over their proper range, are probably accurate to ±20%.  This accuracy currently has to be accepted for qualification and certification flight testing.  It is probably not acceptable for obtaining comparisons between natural icing test results and icing simulation facilities (i.e., icing tunnels and spray tankers), and for computer code validation, improvements are necessary.

Droplet sizes obtained from the FSSP (Knollenberg) average about 2 to 10 μm higher than that obtained from the sooted slides and rotating multicylinders.  In an icing tunnel test at NASA, a variation of several microns in drop size caused a wide variation in ice shapes on a UH-1H airfoil section and a corresponding wide variation in drag increment.  Thus, an uncertainty of several microns in drop size would make it very difficult to obtain comparisons between test results in natural icing and in icing simulation facilities, or to validate computer codes.  But for qualification and certification flight testing, the uncertainties might be less important so long as the aircraft is tested over a sufficiently wide range of natural icing conditions, provided the LWC is known.

Operating experience with icing cloud instruments.   It is very important that the operating problems of the commonly used cloud instruments be understood and documented.  This section documents only a few of the idiosyncracies of these instruments, and should serve only as a precaution to the potential user that their proper use is both an art and a science.

Some important issues that should be addressed in future research include (1) the development of inter-national calibration facilities and standards for these instruments; (2) the development of a capability to produce mixed conditions in icing wind tunnels to evaluate the response of the various instruments to mix-tures of snow and supercooled water droplets; and (3) a systematic study of the sensitivity of the various instruments to airspeed, outside air temperature, LWC levels, droplet sizes and distributions, length of exposure to icing conditions, etc.

Finally, the effects of instrument location on cloud concentration, particle separation, and shadowing should be accounted for when interpreting the instrumentation results.  An empirical approach, or three-dimensional droplet trajectory codes should be used to assess the effects of instrument location.

Video tape documentation techniques.   The U.S. Army has made great strides in the application of high-speed video camera techniques to document ice-accretion and ice-shedding characteristics on rotors and fixed components.  This method has the potential for substantially improving documentation of ice shapes and characteristics on rotors and fixed components, and it should be continued.

Advanced icing severity level indicating systems (AISLID).   The AISLIS concept is attractive for heli-copters since it will give the quickest possible warning of danger due to icing problems and will also indicate the cause of the difficulty.  This should give the flight crew sufficient information to remedy the problem or to take evasive measures.  The objectives of this program justify a continuation of the effort when funds become available.

Torque increment systems. The ability of the U.K. torque-increment systems to register real torque increments in icing has been demonstrated. Further work is needed to improve accuracy in maneuvers and in turbulence, in particular to eliminate false warnings in clear air. The application of the systems for possible enhancement of clearances or optimization of HRB control should be studied.

RAE/Plessey thermal LWC probe. The RAE/Plessey thermal probe has proved more responsive than accretion systems in natural icing conditions. Dead time during deicing and loss of response at temperatures close to 0°C are eliminated. Accuracy is high providing the input air data are of good quality. Development is recommended of (1) a less fragile probe, and (2) a complete self-contained system including cockpit display.

## 5.2 FACILITIES

In AGARD Advisory Report No. 166, Rotorcraft Icing--Status and Prospects, published in August 1981, the European and North American icing facilities that were known to exist were listed in Chapter 3. During the interval since then, some of the facilities have been modified and an additional number of facilities have been placed in operation. The tables of facilities as originally listed have therefore been amended to delete those facilities removed from service and to add new facilities developed within the last four to five years. Figure 30 provides sketches of the various types of icing facilities and defines the dimensions provided in Tables 5-11.

Two new U.S. Army facilities, the improved HISS, and the JU-21A Airfoil Section Array are described below.

### 5.2.1  U.S. Army Helicopter Icing Spray System (HISS)

Description. The HISS is installed in a modified CH-47C helicopter and consists of an internally mounted 1,800-gal water tank and an external spray boom assembly suspended 19 ft beneath the aircraft from a cross-tube through the cargo compartment. Hydraulic actuators rotate the cross-tube to raise and lower the boom assembly. The spray boom consists of two 27-ft center sections, vertically separated by 5 ft and two 17.6-ft outriggers. The outriggers are swept back 20° and angled downward 10° giving a tip-to-tip boom width of 60 ft. A total of 97 Sonic Development Corporation Sonicore Model 12-HB nozzles are installed on the two center sections. The spray cloud is generated by pumping water at known flow rates from the tank to the nozzles in the boom assembly, using bleed air from the aircraft engines and an auxiliary power unit to atomize the water. A calibrated outside air temperature probe and a dew-point hygrometer provide accurate temperature and humidity measurement. A radar altimeter with aft-facing antenna is mounted on the CH-47 to allow positioning the test aircraft at a known standoff distance. The facilitate photographic documentation during icing tests, a chemical is added to the water to impart a yellow color to the ice.

Future plans. The U.S. Army has initiated action to design, fabricate, install, and qualify through flight testing an improved HISS which will be palletized and installed in a JCH-47D helicopter. Basically, the width and depth of the HISS cloud needs to be increased to allow complete immersion of a test helicopter and the generation and control of the cloud needs to be improved to more closely approximate the natural icing cloud. Additionally, the HISS needs to be a palletized system easily removed and installed in another aircraft to preclude lost test time in the event of a major mechanical failure of the aircraft. The improved HISS will have the operating characteristics listed in Table 8.

### 5.2.2  JU-21A Airfoil Section Array (ASA)

Description. The U.S. Army has designed, fabricated, and installed a research and development airfoil section array (ASA) for use on the JU-21A aircraft with the cloud sampling equipment. The ASA consists of a structural mounting on the left wing of the JU-21A and is designed to accept two 18-in.-span airfoil sections. Airfoil sections fabricated and to be tested include the full-scale and scale 0.0012 and SC 1095R8 chords. The airfoils have full span leading-edge heating for deicing and are adjustable through 20° angle of attack. Continuous video and photographic coverage of the upper and lower surfaces of the leading edges of the airfoils are provided.

Future plans. Comparative evaluations of ice-accretion characteristics on airfoil sections caused by artificial and natural icing are planned.
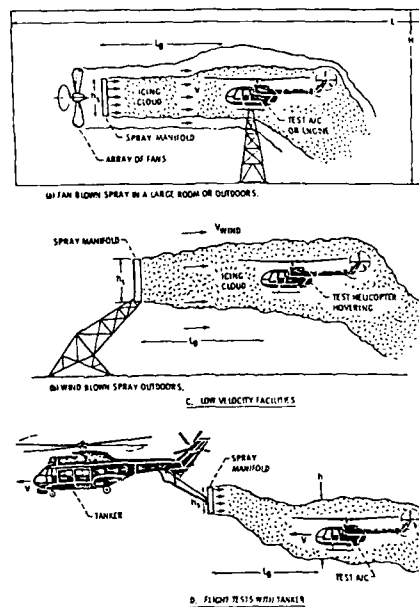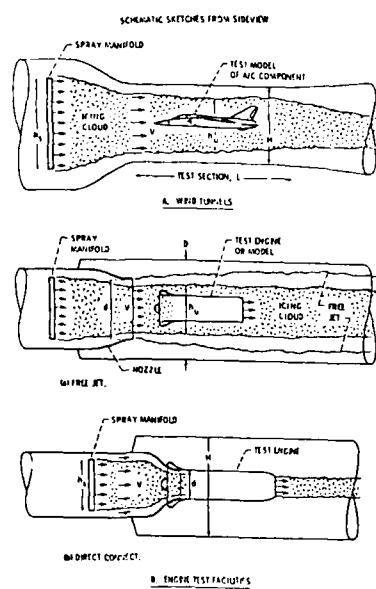
Fig. 30. Types of icing simulation facilities.

## TABLE 5.- WIND TUNNELS--NORTH AMERICA.

See Table 8 for Notes

| FAC-ILITY NO. | FACILITY NAME (LOCATION) | TYPES OF ICING TESTS RUN (a) | WEATHER SIMULATED (b) | TYPE OF FACILITY | SIZE (SEE SKETCHES), m TEST CHAMBER | UNIFORM ICING CLOUD | RANGE OF PARAMETERS USED IN ICING TESTS (c) AIRSPEED KM/HR | MINIMUM AIR TEMP-ATURE °C | ALTITUDE m | LWC g/m³ | VOL. MED. DROP SIZE um | INSTRUMENTS USED FOR LOCAL DROP SIZE AND LWC | TECHNICAL PERSON TO CONTACT | TEST SEASON | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A-1 | NASA-Lewis Research Centre Cleveland, OH) e. IRT | FSC, I MS, R IA, P(d) | ICE, FR (d) | Wind Tunnel | H = 1.8 W = 2.7 L = 6 | $h_u = 1.2$ $w_u = 1.5$ | 10 to 470 | -30 | 0 | (e) 0.5 to 3.0 | (e) 5 to 50 | Rot. cyls & various modern instruments (rot.cyl.) | J. Reinmann (216)433-4000 | All Year | Modernization to be completed in 1986 |
| | b. ANT-Rehabilitation | FSC, I, MS, R, CPU, G, P, | ICE, FR, SI | Wind Tunnel | D = 6 | $d_u = 4.5$ | 10 to M = 1.0 | -30 | 0 to 15,000 | 0.2 to 3 | 5 to 50+ (nozzles changed) | Various modern instruments | J. Reinmann (216)433-4000 | All Year | Proposed for 1988 to 1990 |
| A-2 | Lockheed, (Burbank, CA) | MS, FSC, I | ICE | Wind Tunnel | H = 1.2 W = 0.8 | $h_u = 0.5$ $w_u = 0.3$ | 90 to 340 | -20 | 0 | 0.7 to 4.0 | 10 to 25 | Rot. Cyls., (rot. cyl.) | B. Robinson (213)847-6121 | All Year | --- |
| A-3 | Boeing (Seattle, WA) | MS, FSC, I | ICE | Wind Tunnel | H = 0.5 W = 0.4 L = 0.9 | $h_u = 0.4$ $w_u = 0.3$ | 180 to 370 | -30 | 0 | 0.3 to 5.0 | 10 to 50 (nozzles changed) | Rot. Cyls., oil slide (sm. cyl.) | R. Wilder (206)342-4776 | All Year | --- |
| A-4 | NRC (Ottawa, Canada) | MD, FSC | ICE | Wind Tunnel | H = .55 W = .55 | $h_u = 0.5$ $w_u = 0.5$ | 90 to M = 0.3 | -30 | 0 to 9,000 | 0.2 to 2 | 10 to 30 | Oil slide (rot. cyl) & modern | Section Head (613)993-2439 | All Year | --- |
| A-5 | AEDC Research Cell (Arnold AFS, TN) | FSC, MS | ICE | Free Jet d = 0.3 | D = 0.9 | $d_u = 0.3$ | 150 to Mjet = 0.7 | -30 | 0 to 15,000 | 0.2 to 3+ | 15 to 30 | Various modern instruments | J. Hunt (615)455-2611 | All Year | --- |
| A-6 | Rosemount (Minneapolis MN) e. Low Speed | MC | ICE | Wind Tunnel | H = 0.15 W = 0.1 L = 0.3 | $h_u = 0.1$ $w_u = 0.07$ | 90 to 170 | -30 | 0 | 0.2 to 1.5 | 20 to 40 | Oil slide (rot. cyl.) | R. DeLeo (612)941-5560 | All Year | Rosemount use only |
| | b. High Speed | MS | ICE | Wind Tunnel | H = 0.15 W = 0.3 L = 0.8 | $h_u = w_u = 0.1$ | 90 to 740 | -25 | 0 to 3,000 | 0.1 to 3.0 | 10 to 40 | Oil slide (rot. cyl.) | R. DeLeo (612)941-5560 | All Year | Rosemount use only |

TABLE 5.- CONCLUDED.

See Table 8 for Notes

| FAC- ILITY NO. | FACILITY NAME (LOCATION) | TYPES OF ICING TESTS RUN (a) | WEATHER SIMULATED (b) | TYPE OF FACILITY | SIZE (SEE SKETCHES), m | | RANGE OF PARAMETERS USED IN ICING TESTS (c) | | | | | INSTRUMENTS USED FOR LOCAL DROP SIZE AND LWC | TECHNICAL PERSON TO CONTACT | TEST SEASON | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | TEST CHAMBER | UNIFORM ICING CLOUD | AIRSPEED KM/HR | MINIMUM AIR TEMP- ATURE °C | ALTITUDE m | LWC g/m 3 | VOL. MED. DROP SIZE um | | | | |
| A-7 | Frost Tunnel (Univ. of Alberta Can.) | MS, LA | ICE, | Wind Tunnel | D = 0.5 Octagonal L = 0.9 | $d_u$ = 0.3 | 10 to 240 | -20 | 0 | 0.4 to 3.0 | 20 to 50 (nozzles changed) | Oil slide (rot. cyl.) | E. Gates (403)432-5180 | All Year | --- |
| A-8 | UCLA Cloud Tunnel | MS, OP | ICE, R | Vertical Wind Tunnel | H = 0.15 W = 0.15 L = 0.5 | $h_u$ = 0.1 $w_u$ = 0.? | 0 to 55 | -30 | 0 | 0.1 to 3 | 2 to 50 | Various modern instruments | H. Pruppacher (213)825-1038 | All Year | Free particle suspension |
| A-9 | Fluidyne Engineering (Minneapolis, MN) | MS, FSC | ICE | Wind Tunnel | H = 0.55 W = 0.55 L = 0.4 | $h_u$ = 0.4 $w_u$ = 0.4 | M=0.8(10min) M=0.25(40min) and lower | -20 and lower | 0 | 0.1 to 2.0 | 20 | Oil slide blade | J. Idzorek (612)544-2721 | Winter | --- |

TABLE 6.— ENGINE TEST FACILITIES—NORTH AMERICA.
(Note that most free jets can do wind tunnel types of tests)

See Table 8 for Notes

| FAC-ILITY NO. | FACILITY NAME (LOCATION) | TYPES OF ICING TESTS RUN (a) | WEATHER SIMULATED (b) | TYPE OF FACILITY | SIZE (SEE SKETCHES), m TEST CHAMBER | UNIFORM ICING CLOUD | RANGE OF PARAMETERS USED IN ICING TESTS (c) AIRSPEED KM/HR | MINIMUM AIR TEMP-ATURE °C | ALTITUDE m | LWC g/m³ | VOL. MED. DROP SIZE um | INSTRUMENTS USED FOR LOCAL DROP SIZE AND LWC | TECHNICAL PERSON TO CONTACT | TEST SEASON | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B-1 | AEDC (Arnold AFS, TN) a. ETF | EDC | ICE | Direct connect d = 1.5 | D = 3.7 or 4.5 L = 11 | Spray bars sized to engine | 0 to M = 0.7+ | -30 | 0 to 15,000 | 0.2 to 3+ | 15 to 30 | Various modern instruments | J. Hunt (615)455-2611 | All Year | -- |
| | b. Free jet | CPU, FSC, I, MS | ICE | Free jet d = 1.5 | D = 3.7 or 4.5 L = 11 | Spray bars sized to engine | 0 to M = 0.7+ | -30 and lower | 0 to 15,000 | 0.2 to 3+ | 15 to 30 | Various modern Instruments | As Above | All Year | -- |
| | c. ASTF | CPU, FSC, I | ICE | Free jet d + 2.7 | D = 8 L = 18 | Spray bars sized to engine | 0 to M = 0.7+ | -30 and lower | 0 to 15,000 | 0.2 to 3+ | 15 to 30 | Various modern Instruments | W. Bates (615)455-2611 | All Year | -- |
| B-2 | Detroit Diesel Allison Inlet & compressor stage (Indianapolis, IN) a. Comp. Test Facility | | ICE | Free jet Direct connect d = 0.5 | D = 2.3 L = 9 | Spray bars sized to engine | 0 to M = 0.7+ | -30 and lower | 0 to 6,000 | 0.2 to 3.5 | 15 to 40 | Rotating cylinders | W. Stiefel (317)243-4066 | All Year | -- |
| | b. Small Engine Facility | EDC | ICE | Direct connect | D = 0.45 L = 1.2 | Spray bars sized to engine | 0 to M = 0.7+ | -30 and lower | 0 to 6,000 | 0.2 to 3.5 | 15 to 40 | Rotating cylinders | As Above | All Year | -- |
| B-3 | GE Cross-wind Facility (Peebles, OH) | CPU, P(d) R(d) | ICE | Free jet Outdoors d = 7.0 | Outdoors | d_u = 4.5 | 90 | Ambient air to -20 | 0 | 0.4 to 3.5 | 15 to 50 | Knollenberg spectrometer (rot. cyl.) | R. Keller (513)243-4483 | Winter | -- |
| B-4 | P&W Altitude Facilities (E. Hartford, CT) a. Large | EDC, I | ICE | Direct connect | D = 5.5 L = 10 | Spray bars sized to engine | 0 to M = 0.5 | -25 | 0 to 6,700 | 0.2 to 9 | 15 to 40 | Oil slide | J. Berlock (203)565-2091 | All Year | -- |
| | b. Smaller | EDC, I | ICE | Direct connect | D = 3.7 | Spray bars sized to engine | 0 to M = 0.5 | -30 and lower | 0 to 6,700 | 0.2 to 9 | 15 to 40 | Oil slide | As Above | All Year | -- |

TABLE 6.- CONTINUED.

(Note that most free jets can do wind tunnel types of tests)

See Table 8 for Notes

| FAC- ILITY NO. | FACILITY NAME (LOCATION) | TYPES OF ICING TESTS RUN (a) | WEATHER SIMULATED (b) | TYPE OF FACILITY | SIZE (SEE SKETCHES), m TEST CHAMBER | UNIFORM ICING CLOUD | RANGE OF PARAMETERS USED IN ICING TESTS (c) | | | | | INSTRUMENTS USED FOR LOCAL DROP SIZE AND LWC | TECHNICAL PERSON TO CONTACT | TEST SEASON | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | AIRSPEED KM/HR | MINIMUM AIR TEMP- ATURE °C | ALTITUDE m | LWC g/m 3 | VOL. MED. DROP SIZE um | | | | |
| B-4 | P&W Altitude Facilities (E. Hartford, CT) c. P&W Sea Level Facility | EDC | ICE | Direct connect | Varies with test cell | Spray bars sized to engine | 0 to M = 0.5 | -20 (Ambient?) | 0 | 0.2 to 9 | 15 to 40 | Oil slide | J. Barlock (203)565-2091 | Winter | --- |
| B-5 | McKinley Climatic Lab. Engine Test Cell (Eglin AFB, FL) | OPU, FSC | ICE, SI, FR, R | Fan blows spray indoors | H = 7.5 W = 9 L = 40 | h_u = 3 w_u = 6 | 0 to (30 to 75) | -30 and lower | 0 | 0.1 to 3 | 12 to 60 800 to 1500 (nozzles changed) | Particle Interferometer (rot, cyl.) | R. Toliver (904)882-3626 | All Year | --- |
| B-6 | Naval Air Propulsion Facility (Trenton, NJ) a. Five small engine cells | EDC, OPU, I, FSC, MS | ICE, SI, FR, R | Free jet d = 0.6 | H = 3 W = 3 L = 6 | Spray bars sized to engine | 0 to M = 0.7+ | -30 and lower | 0 to 15,000 | 0.1 to 2 | 15 to 50 (nozzles changed) | Knollenberg spectrometer and OAP (rot, cyl.) | Resource Manager (609)896-5655 | All Year | --- |
| | b. Two large sea level cells | EDC, OPU, I, FSC, MS | ICE, SI, FR, R | Free jet d = 1.2 | H = 4.5 W = 7 L = 17 | Spray bars sized to engine | 0 to M = 0.7+ | -30 and lower | 0 | 0.1 to 2 | 15 to 50 (nozzles changed) | Knollenberg spectrometer and OAP (rot, cyl.) | As Above | All Year | --- |
| | c. Three large altitude cells | EDC, OPU, I, FCS, MS | ICE, SI, FR, R | Free jet d = 1.2 | D = 5 L = 9 | Spray bars sized to engine | 0 to M = 0.7+ | -30 and lower | 0 to 15,000 | 0.1 to 2 | 15 to 50 (nozzles changed) | Knollenberg spectrometer and OAP (rot, cyl.) | As Above | All Year | --- |
| B-7 | Teledyne Altitude Cells (Toledo, OH) a. Chamber 1 | OPU, EDC | ICE, SI, FR, R | Free jet or direct connect | D = 2.7 L = 5 | Spray bars sized to engine | 0 to M = 0.7+ | -30 and lower | 0 to 15,000 | Up to 3 | 15 to 25 | Oil slide | R. Treuth (419)470-3236 | All Year | --- |
| | b. Chamber 2 | OPU, EDC | ICE, SI, FR, R | Free jet d = 0.2 | H = 2.5 W = 2.5 L = 4 | Spray bars sized to engines | 0 to M = 0.7+ | -30 and lower | 0 to 15,000 | Up to 3 | 15 to 25 | Rotating Cylinders | As Above | All Year | --- |

TABLE 6.- CONCLUDED.

(Note that most free jets can do wind tunnel types of tests)

See Table 8 for Notes

| FAC-ILITY NO. | FACILITY NAME (LOCATION) | TYPES OF ICING TESTS RUN (a) | WEATHER SIMULATED (b) | TYPE OF FACILITY | SIZE (SEE SKETCHES), m TEST CHAMBER | UNIFORM ICING CLOUD | AIRSPEED KM/HR | MINIMUM AIR TEMP-ATURE °C | ALTITUDE m | LWC g/m 3 | VOL. MED. DROP SIZE um | INSTRUMENTS USED FOR LOCAL DROP SIZE AND LWC | TECHNICAL PERSON TO CONTACT | TEST SEASON | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B-8 | Avco Lycoming (Stratford, CT) B. Component Facility | EDC | ICE, FR | Direct connect d = 0.4 | ------ | Spray bars sized to engine | 0 to 370 | -30 and lower | 0 | 0.1 to 3 | 15 to 40 | Oil slide (rot. cyl.) | R. Norris (203)385-2667 | All Year | --- |
| | b. Engine Test Facility | EDC | ICE, FR | d = 0.4 / d = 1.2 | W = 3.7 H = 2.7 Outdoors | Spray bars sized to engine | 0 to 200 | -30 and lower / -20 | 0 | 0.1 to 3 | 15 to 40 | Oil slide (rot. cyl.) | As Above | All Year / Winter | --- |
| B-9 | NRC, Cell #4 (Ottawa, Canada) | EDC, CPU | ICE, SI | Free jet or direct connect d = 0.75 / d = 2.0 | H = 7.5 W = 7.5 | Spray bars sized to engine | 0 to 650 | -20 and lower | 0 | 0.2 to 2 | 15 to 40 | Oil slide cylinders | Section Head (613)993-2425 | Winter | --- |
| | | CPU, P | | | | | 0 to 93 | Ambient | | | | | | | |

TABLE 7.- LOW VELOCITY FACILITIES--NORTH AMERICA.

See Table 8 for Notes

| FAC-ILITY NO. | FACILITY NAME (LOCATION) | TYPES OF ICING TESTS RUN (a) | WEATHER SIMULATED (b) | TYPE OF FACILITY | SIZE (SEE SKETCHES), m TEST CHAMBER | UNIFORM ICING CLOUD | AIRSPEED KM/HR | MINIMUM AIR TEMPERATURE °C | ALTITUDE m | LWC g/m³ | VOL. MED. DROP SIZE um | INSTRUMENTS USED FOR LOCAL DROP SIZE AND LWC | TECHNICAL PERSON TO CONTACT | TEST SEASON | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C-1 | NRC Helicopter Spray Rig (Ottawa, Canada) | FLT (helicopters in hover) | ICE, FR | Wind blown spray outdoors | D = ∞ | Spray manifold $h_s = 4.5$ $w_s = 23$ | Ambient wind, 20 to 45 (gusty) | -20 ambient | 0 | 0.1 to 0.8 | 30 to 60 | Oil slide (rot. cyl.) | Section Head (613)995-2439 | Winter | --- |
| C-2 | G.E. Cross Wind Facility (Peebles, OH) | CPU, P(d), R(d) | ICE, FR | Free jet outdoors | D = 6 | $d_u = 4.5$ | 90 | -20 ambient | 0 | 0.4 to 3.6 | 15 to 50 | Knollenberg spectrometer (rot. cyl.) | R. Keller (513)243-4483 | Winter | --- |
| C-3 | McKinley Climactic Lab (Eglin AFB, FL) a. Main Chamber | FS, R(d) | ICE, SI / FR, R | Fan blown spray indoors | H = 21 W = 76 L = 76 | Spray Manifold $h_s = 3$ $w_s = 9$ | 0 to (30 to 75)(e) (depending on $L_B$) | -30 and lower | 0 | 0.1 to 3 | 12 to 60 800 to 1,500 (nozzles changed) | Particle Interferometer (rot. cyl.) | R. Tolliver (904)882-3626 | All Year | Largest cold room |
| | b. Engine Test Cell | CPU, FSC | ICE, SI / FR, R | Fan blown | H = 7.5 W = 9 L = 4.0 | Manifold $h_s = 3$ $w_s = 6$ | 0 to (30 to 75)(depending on $L_B$) | -30 and lower | 0 | 0.1 to 3 | 12 to 60 800 to 1,500 (nozzles changed) | Particle Interferometer (rot. cyl.) | As Above | All Year | --- |
| | c. All Weather Room | FSC | ICE, SI / FR, R | Fan blown spray Indoors | H = 4.5 W = 6.5 L = 12 | Manifold $h_s = 3$ $w_s = 3$ | 0 to (30 to 75)(depending on $L_B$) | -30 and lower | 0 | 0.1 to 3 | 12 to 60 800 to 1,500 (nozzles changed) | Particle Interferometer (rot. cyl.) | R. Tolliver (904)882-3626 | All Year | Largest cold room |
| C-4 | US Army CRREL Cold Room (Hanover, NH) | FSC, MS R, LA | ICE, SI / FR, R | Fan blown spray Indoors | H = 1.1 W = 0.7 L = 1.5 | -------- | 0 to 20 | -50 and lower | 0 | 1 to 2.5 | 10 to 50 | Cascade Impactor | G. Ashton (603)643-3200 | All Year | --- |

TABLE 7.- CONCLUDED.

See Table 8 for Notes

| FAC-ILITY NO. | FACILITY NAME (LOCATION) | TYPES OF ICING TESTS RUN (a) | WEATHER SIMULATED (b) | TYPE OF FACILITY | SIZE (SEE SKETCHES), m TEST CHAMBER | SIZE (SEE SKETCHES), m UNIFORM ICING CLOUD | RANGE OF PARAMETERS USED IN ICING TESTS (c) AIRSPEED KM/HR | RANGE OF PARAMETERS USED IN ICING TESTS (c) MINIMUM AIR TEMPERATURE °C | RANGE OF PARAMETERS USED IN ICING TESTS (c) ALTITUDE m | RANGE OF PARAMETERS USED IN ICING TESTS (c) LWC g/m³ | RANGE OF PARAMETERS USED IN ICING TESTS (c) VOL. MED. DROP SIZE um | INSTRUMENTS USED FOR LOCAL DROP SIZE AND LWC | TECHNICAL PERSON TO CONTACT | TEST SEASON | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C-5 | Mt Washington Observatory (Gorham, NH) | FS, CP, MS | Natural icing of mountain | Natural icing of tied down equipment on top | | | 0 to 80 (gusty) | -20 and lower | 1800 | Generally severe natural conditions | | Rotating cylinders | J. Howe (603)466-3388 | Fall to Spring | --- |
| C-6 | US Navy FMTC (Pt Mugu) Climatic Hanger | FSC, FS G | R, FR | Fan blown spray Indoors | H = 7.6 W = 18 L = 18 | h_s = 1.2 w_s = 1.2 | 0 to 75 | -30 and lower | 0 | 30 cm rain/hr 5 cm snow/hr | 500 to 4,500 50 to 100 | Oil slide (rain gauge) | D. Everett (805)982-8011 | All Year | --- |
| C-7 | Acton Environmental Test Corp. (Acton, MA) | G | R, FR S(d) | Fan blown spray Indoors | H = 6 W = 4.5 L = 7.5 | d_s = 2.5 | 0 to 45 | -30 and lower | 0 | 10 cm rain/hr | 1,000 to 4,000 | Not measured (rain gauge) | R. Gilroy (617)263-2933 | All Year | --- |
| C-8 | NRC (Ottawa, Canada) Climatic Eng's Facility | G, FS | FR, S(d) | Fan blown spray Indoors | H = 6.1 W = 6.1 L = 30.5 | d_s = 1.2 to 2.5 | 0 to 55 | -30 and lower | 0 | 0.3 cm rain/hr | 500 to 1,000 | Screen method (accumulation rate) | D.B. Conveney (613)998-5979 | All Year | --- |
| | Cold Chamber #2 | G, FS | FR | Fan blow spray Indoors | H = 5 W = 5 L = 7 | d_s = 1.8 | 0 to 55 | -30 and lower | 0 | 0.3_d cm rain/hr | 500 to 1,000 | Screen method (accumulation rate) | As Above | All Year | --- |
| C-9 | Wyle Labs (Norco, CA) Cold Room | G, FSC | FR | Fan blown spray Indoors | H = 5 W = 4.5 L = 11 | -------- | 0 to 35 | -30 and lower | 0 | 12 cm rain/hr | -------- | ------------ | M. Clark (714)737-0871 | All Year | --- |
| C-10 | Arctec Canada Ltd (Ottawa, Canada) Cold Room | G, IA | FR(d) S(d) | Fan blown spray Indoors | H = 3.7 W = 5.5 L = 9 | -------- | 0 to 35 | -30 and lower | 0 | -------- | -------- | ------------ | A. Newver (613)592-2830 | All Year | --- |

TABLE 8.- TANKERS FOR FLIGHT TESTS--NORTH AMERICA.
(In addition, most airframe companies can test aircraft in natural icing)

| FAC-ILITY NO. | FACILITY NAME (LOCATION) | TYPES OF ICING TESTS RUN (a) | WEATHER SIMULATED (b) | TIME IN ICING AT HIGH LWC (min) | SIZE OF SPRAY, m AT NOMINAL DISTANCE L, B | MANIFOLD | RANGE OF PARAMETERS USED IN ICING TESTS (c) | | | | | INSTRUMENTS USED FOR LOCAL DROP SIZE AND LWC | TECHNICAL PERSON TO CONTACT | TEST SEASON | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | AIRSPEED KM/HR | MINIMUM AIR TEMP-ATURE °C | ALTITUDE m | LWC g/m³ | VOL. MED. DROP SIZE um | | | | |
| D-1 | US Air Force (Edwards AFB, CA) a. KC 135 Tanker | Flt | ICE, N R, FR | 60 | At L_B = 60 d = 3 | $d_s$ = 1.2 | 300 to 650 (370 nom) | -20 (ambient) | 1,200 to 8,000 | 0.05 to 1.5 0.5 to 32 | 28 to 35 200 to 800 | Knollenberg spectrometer ( " ) | R. Morrison (805)277-3068 | All Year | Final calibration in 1981 |
| | b. C 130 Tanker | Flt | ICE, N R, FR | 60 | At L_B = 60 d = 5 | $d_s$ = 1.2 | 190 to 390 (280 nom.) | -20 (ambient) | 1,200 to 8,000 | 0.05 to 1.5 0.5 to 32 | 28 to 35 desired 200 to 800 | Knollenberg spectrometer ( " ) | As Above | All Year | Planned for 1981 |
| D-2 | a. US Army MISS Helicopter Tanker (Edwards AFB, CA) | Flt | ICE, N | 30 | At L_B = 50 h = 2.4 w = 11 | $h_s$ = 1.6 $w_s$ = 12 | 130 to 220 | -20 (ambient) | 0 to 3,050 | .1 to 1.0 | 17 to 30 and 20 to 65 | Knollenberg spectrometer (Leigh) | Mr Blaha (805)277-2271 | Normally Winter | --- |
| | b. Improved US Army MISS | Flt | ICE, N | 30 | At L_B = 50 h = 4.6 w = 16.3 | $h_s$ = TBD $w_s$ = TBD | 110 to 240 (240 nom.) | -20 (ambient) | 0 to 3,660 | 0.1 to 2.0 | 15 to 50 | Knollenberg spectrometer | As Above | Normally Planned for Winter 1988 | |
| D-3 | Cessna 404 Tracker (Wichita, KS) | Flt | ICE, R FR, N | 60 | At L_B = 150 d = 6 | $d_s$ = 0.6 (V-bar) | 165 to 530 (260 nom.) | -20 (ambient) | 300 to 8,000 | 0.05 to 4.0 | 20 to 49 (water nozzles) | Gelatin slide (J&M) | D. Hazelwood (316)946-6606 | All Year | --- |
| D-4 | Piper Cheyenne Tanker (Lock Haven, PA) | Flt | ICE, FR R, N | 14 | At L_B = 30 h = 3 w = 5 | $h_s$ = 1.2 $w_s$ = 1.8 | 200 to 300 (240 nom.) | -20 (ambient) | 300 to 8,000 | 0.1 to 1.7 | 30 to 50 | Gelatin slide (J&M) | J. Bryerton (717)748-6711 | Not Summer | --- |
| D-5 | Flight Systems T-33 Tanker (Mojave, CA) | Flt | ICE, R FR, N | 45 | At L_B = 60 d = 2.5 | $h_s$ = 0.3 $w_s$ = 0.9 | 230 to 420 (370 nom.) | -20 (ambient) | 300 to 8,000 | 0.1 to 1.0 | 17 to 50 | Knollenberg spectrometer ( " ) | J. Ligon (805)824-4601 | All Year | --- |

(a) Types of icing and anti-deicing tests run: CPU = complete propulsion unit; EDC = engine direct connect; FSC = full-scale aircraft component (including wing, tail, fuselage, windshield, stores, gear, etc.); MS = model scale tests and instrumentation; LA = ice adhesion; CP = cloud physics; R = rotating experiments (e.g. helicopter rotor models and propellors); G = ground transport and installations in freezing rain; FS = full scale aircraft; Flt = flight tests of aircraft; I = inlets with suction; P = complete propellor engines; H = human physiological experiments.

(b) Weather simulated: ICE = icing cloud environment; S) = solid ice particles; FR = freezing rain; R = rain; N = natural icing; S = snow.

(c) Parameter ranges vary with conditions; request operating envelope from contact person.

(d) Modification to do this has been seriously proposed.

(e) Tests are in progress to extend these limits.

## TABLE 9.- WIND TUNNELS--EUROPE.

See Table 10 for Notes

| FAC-ILITY NO. | FACILITY NAME (LOCATION) | TYPES OF ICING TESTS RUN (a) | WEATHER SIMULATED (b) | TYPE OF FACILITY | SIZE (SEE SKETCHES), m | | RANGE OF PARAMETERS USED IN ICING TESTS (c) | | | | | INSTRUMENTS USED FOR LOCAL DROP SIZE AND LWC | TECHNICAL PERSON TO CONTACT | TEST SEASON | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | TEST CHAMBER | UNIFORM ICING CLOUD | AIRSPEED KM/HR | MINIMUM AIR TEMP-ATURE °C | ALTITUDE m | LWC $g/m^3$ | VOL. MED. DROP SIZE um | | | | |
| **Austria** | | | | | | | | | | | | | | | |
| E-1 | Ground Vehicles Test Station Vienne | | ICE | Wind Tunnel | H = 4.9 W = 4.9 | | 115 | -18 | 0 | | | | | | To date tests on cars & railway vehicles |
| **Federal Republic of Germany** | | | | | | | | | | | | | | | |
| E-2 | Volkswagen Wolfsburg | MS | N | Wind Tunnel | H = 5 W = 7 | | 180 | -30 | 0 | | | | Hr Schwabe 05361-925130 | All Year | To date with priority tests on cars |
| E-3 | IFVLR | MS | N | Wind Tunnel | H = 2.4 W = 2.4 | | 260 | -173 | 0 | | | | Dr Viehweger 02203-6012295 | | |
| E-4 | Porsche | MS | N | Wind Tunnel | H = 1.5 W = 1.0 | | 170 | -40 | | | | | | | |
| **France** | | | | | | | | | | | | | | | |
| E-5 | Ett Technique Bourges | FS, MS | ICE, FR | Wind Tunnel | H = 4.1 W = 5.5 L = 15 | $h_u = 3$ $w_u = 4$ | 145 | -40 | 0 | | | A, B | IPETA Chestagnol (48) 70 52 75 | All Year | |
| E-6 | LAMP | | | Open Wind Tunnel | H = 0.3 W = 0.2 | $d_u = 0.2$ | 200 | -10* | 1,500 | 0-2* | 10-20* | D | J.F. Gayet (73) 26 41 10 | Winter | *Depends on ambient conditions |
| E-7 | ONERA Modane | FS, MS, R | ICE | Wind Tunnel | 0 = 8 | $h_u = 2$ $w_u = 2$ or $h_u = 1$ $w_u = 4$ | 540 | -25* | 1,000 to 2,500 | 0.4 to 10 | 10-30 | Various | C. Armand (79) 05 00 55 | Winter | *Depends on ambient conditions |

TABLE 9.- CONCLUDED.

| FAC-ILITY NO. | FACILITY NAME (LOCATION) | TYPES OF ICING TESTS RUN (a) | WEATHER SIMULATED (b) | TYPE OF FACILITY | SIZE (SEE SKETCHES), m | | RANGE OF PARAMETERS USED IN ICING TESTS (c) | | | | | INSTRUMENTS USED FOR LOCAL DROP SIZE AND LWC | TECHNICAL PERSON TO CONTACT | TEST SEASON | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | TEST CHAMBER | UNIFORM ICING CLOUD | AIRSPEED KM/HR | MINIMUM AIR TEMP-ATURE °C | ALTITUDE m | LWC g/m³ | VOL. MED. DROP SIZE um | | | | |
| **Italy** | | | | | | | | | | | | | | | |
| E-8 | Fiat Research Centre Turin | R | SI, FR | Wind Tunnel | H = 3 W = 4.2 L = 11.6 | | 140 | -50 | 0 | | | | A. Garrone (011) 9012777 Ext 139 | All Year | |
| **Sweden** | | | | | | | | | | | | | | | |
| E-9 | Aeronautical Research Institute | | | Wind Tunnel | D = 3.6 | | 145 | | 0 | | | | | | Tests on simulated ice accretion shapes |
| **United Kingdom** | | | | | | | | | | | | | | | |
| E-10 | A&AEE Blower Tunnel Boscombe Down | FS, MS | ICE | Wind Tunnel | Open Bed | d = 1.2 d = 1.8 | 500 400 | -30 | 0 | 0 to 3 | 20 to 1,000 | A, C | Supt of Engineering (0980) 23351 | Winter | LN$_2$ injection for cooling |
| E-11 | Lucas Aerospace Artington | MS, FSC | ICE, SI, FR | Wind Tunnel | H = 0.2 W = 0.3 to H = 0.5 W = 0.5 | 80% of cross-section | 660 215 | -40 | 0 | 0.1-5 0.2-10 ICE | 12-40 lmm ICE | A, D | G. Howard (0483) 66876 | All Year | |
| E-12 | RAE Farnborough | MF | ICE | Wind Tunnel | H = 0.1 W = 0.1 | $h_u = w_u = 1$ | 50 | -15 | 0 | 0-2.0 | 12-30 | Blade | R.W. Gent 0252-24461 Ext 5126/2722 | All Year | |
| E-13 | Hucknall | MS | ICE | Wind Tunnel | D = 0.4 | | 500 | -30 | 0 | 0-1.1 | | | B.R. Leivers 633111 | | |
| **Norway** | | | | | | | | | | | | | | | |
| E-14 | VHL Sea Spray Icing Tunnel Trondheim | | ICE | Wind Tunnel | D = 1.4 L = 9 | | 108 | | 0 | | | | T. Carstens (47) 7-592364 | Winter | |
| E-15 | Aero- and Gas Dynamics NTH/SINTEF Trondheim | | | Wind Tunnel | H = 1.8 W = 2.7 L = 12.5 | | 97 | | 0 | | | | A. Kyrkjeelde (47) 7-593715 | All | Tests on simulated ice accretion shapes |

See Table 10 for Notes

TABLE 10.- ENGINE TEST FACILITIES--EUROPE.

| FAC-ILITY NO. | FACILITY NAME (LOCATION) | TYPES OF ICING TESTS RUN (a) | WEATHER SIMULATED (b) | TYPE OF FACILITY | SIZE (SEE SKETCHES), m | | RANGE OF PARAMETERS USED IN ICING TESTS (c) | | | | | INSTRUMENTS USED FOR LOCAL DROP SIZE AND LWC | TECHNICAL PERSON TO CONTACT | TEST SEASON | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | TEST CHAMBER | UNIFORM ICING CLOUD | AIRSPEED KM/HR | MINIMUM AIR TEMP-ATURE °C | ALTITUDE m | LWC g/m³ | VOL. MED. DROP SIZE um | | | | |
| **France** | | | | | | | | | | | | | | | |
| F-1 | CEPr Saclay R2 Cell | CPU, FS | ICE | Free Jet | D = 3.5 | $d_u = 1.15$ | 540 | -60 | 0 | 0-6 | 15-30 | A | M. Dufour (6) 941-81-50 | All Year | |
| F-2 | CEPr Saclay R4 Cells | CPU, FS | ICE | Free Jet | D = 3.5 | $d_u = 1.30$ | 500 | -60 | 0 | 0-6 | 15-30 | A | M. Dufour (6) 941-81-50 | All Year | |
| F-3 | CEPr Saclay R5 Cell | CPU, FS | ICE | Free Jet | D = 5 | $d_u = 3$ | 260 | -60 | 0 | 0-10 | 15-30 | A | M. Dufour (6) 941-81-50 | All Year | |
| **United Kingdom** | | | | | | | | | | | | | | | |
| F-4 | NGTE Pyestock Cell 3 | EDC, CPU | ICE, SI | Direct Connect or Free Jet | D = 6.1 | Engine dia or $d_u = 1$ | To suit engine or 820 | -70 | 0 to 15,000 | 0.2-10 | 15-30 | D | Head Engine Test Dept (0252) 44411 | All Year | |
| F-5 | NGTE Pyestock Cell 3 West | EDC, CPU, FS, MS | ICE, SI, FR | Direct Connect or Free Jet | D = 7.6 | Engine dia or $d_u = 2.5$ | To suit engine or 770 | -40 | 0 to 15,000 | 0.2-10 | 15-30 | D | Head Engine Test Dept (0252) 44411 | All Year | Solid ice available 1981 |
| F-6 | Lucas Aerospace Burnley | EDC, MS | ICE, SI | Direct Connect or Free Jet | D = 4 | | To suit engine or 250 | -55 | 0 to 15,000 | 0.2-10 | 15-30 | A | S. Greenwood (0282) 25051 | All Year | |

a. Types of Icing Test Run

CPU = complete propulsion unit; EDC = engine direct connect; FSC = full scale aircraft components; MS = model scale tests; R = rotating experiments; FS = full scale aircraft; FLT = flight tests of aircraft.

b. Weather Simulated

ICE = icing cloud environment; SI = solid ice particles; FR = freezing rain; N = natural icing.

c. Instruments used for Drop Size and LWC

A = oiled slide; B = Rogeo spectrometer; C = Johnson and Williams moisture concentration meter; D = other devices (eg Knollenberg).

TABLE 11.- SITES FOR NATURAL ICING TESTS.

| | | OTTAWA Canada | SHEARWATER Canada | BRETIGNY France | TIRSTRUP Denmark | MANCHING Germany | ST. PAUL U.S. | SYRACUSE U.S. | DULUTH U.S. |
|---|---|---|---|---|---|---|---|---|---|
| ATMOSPHERE | Cloud Temp & LWC Data | Known Temp. & Dew Pt. | Known Temp & Dew Pt. and some LWC | Known Temp. & Dew Pt. | Known Temp. & Dew Pt. | Known Temp. & Dew Pt. | Known Temp. & Dew Pt. | Known Temp. & Dew Pt. | Known Temp. & Dew Pt. |
| | Snowfall | Known | Known | Known | Known | Known App 1 | Known | Known | Known |
| | Snow Cover | Known | Known | Known | Known | Known App 1 | Known | Known | Known |
| | Hours of Daylight | Known | Known | Known | Known | Known App 1 | Known | Known | Known |
| AIRSPACE | Allocation | Defined & Limited | Defined, may be Limited | Unlimited (ATC) | Unlimited (ATC) | Limited | Normal ATC | Normal ATC | Normal ATC, Special within 35 NM |
| | ATC Liaison | Special | Available | Special & IFR | Special & IFR | Good | IFR | IFR | IFR, MARSA |
| | Navigation Aids | TACAN, VOR, ILS | TACAN, PAR, ADF (Halifax Int'l 18 NM, ILS, VOR, DME) | VOR, ILS | TACAN, VOR, ILS | Sufficient | TACAN, VOR, ILS | TACAN, VOR, ILS | TACAN, VORTAC, ILS (2) |
| | Radar Coverage | Altitude, Limited | Terminal at Halifax Available Int'l (18 NM) | Available | Altitude, Limited | Good | Altitude Limited | Altitude Limited | Altitude Limited |
| | Communications | VHF, UHF | VHF, UHF, HF | VHF, UHF | VHF, UHF | | VHF, UHF Minn/St Paul Airport | UHF, VHF | VHF, UHF |
| | Meteorology | Available | Available (good) | Available | Available | Good | | Available | Hibbing FSS |
| | Traffic Density | Constraint | Light | No Constraint | No Constraint | High | Constraint | Constraint | Low |
| | Population Density | Light | Light | Light | High | | Moderately high | High | Low to North |
| SEARCH AND RESCUE | Topography | Flat 180° | Flat (Ocean-South) | Flat 360° | Flat 360° | Better than Alps | Rolling & Streams 180° | Flat 360° | Rolling & Streams & Lakes |
| | Services | Normal & Local AF Helicopters | Normal & Local Mil, Helicopters, Buffalo | Normal & Local AF Helicopters | Normal & Local AF Helicopters | Available | Air Nat'l Guard Helicopters | Army Reserve Helicopters | None |
| | Equipment | Helicopters | Helicopters | Helicopters | Helicopters | Available | | | None |

TABLE 11.- CONCLUDED.

| | | OTTAWA Canada | SHEARWATER Canada | BRETIGNY France | TIRSTRUP Denmark | MANCHING Germany | ST. PAUL U.S. | SYRACUSE U.S. | DULUTH U.S. |
|---|---|---|---|---|---|---|---|---|---|
| TEST SUPPORT | Aircraft Shelter | Heated | Heated | Heated | Heated | Heated | Heated | Scarce, Heated | Heated |
| | Engineering | Known | Known | Known | Known | Available | None | None | None |
| | Office Space | Adequate | Adequate | Adequate | Adequate | Adequate | Adequate | Poor | Adequate |
| | Power Supplies | Known | Known & Adequate | Known | Known | Available | Limited | Limited | Available |
| | Data Processing | Known | Known (commercial) | Known | Known | Available | Commercial | Commercial | Commercial |
| | Logistics | Known | Known, Adequate | Known | Known | Some Available | Minimal | Photo Processing None | Adequate (Commercial/MN ANG) |
| | TELEX Facilities | Available | Available | Available | Available | Available | Available | Commercial | Available |
| | POL | Available | Available | Available | Available | | | | |
| SECURITY CLEARANCE | Military Aircraft | Required | Required | Required | Civil Registration | NATO Base | Local, Civil & Mil. Authority | Airport Authority | Local, Civil & Mil. Authority |
| | Crew | Required | Required | Required | Special Authorization | NATO Base | Local, Civil & Mil. Authority | No Restriction | Local, Civil & Mil. Authority |
| | Civil Aircraft | Required | Required | Required | Danish Civil Authority | NATO Base | Local, Civil & Mil. Authority | Airpor Authority | Local, Civil & Mil. Authority |
| | Special Instr. | Required | Required (PPR) | Required | Special | NATO Base | No Restriction | No Restriction | No Restriction |
| DOMESTIC | Accommodations | Adequate | Adequate | Adequate | Adequate | Ingolstadt Adequate | Adequate | Motels | Adequate |
| | Catering | Adequate | Adequate | Adequate | Adequate | Adequate | Adequate | Adequate | Adequate |
| | Transportation | Rental | Rental | Rental | Rental | | Rental & GSA | Rental | Rental & GSA |
| | Entertainment | Adequate | Adequate | Adequate | Poor | Good | Adequate | Adequate | Adequate |

AIRSPACE ACRONYMS

AIC - Air Traffic Control
IFR - Instrument Flight Rules
TACAN - Tactical Aid to Navigation
DME - Distance Measuring Equipment
VOR - Very High Frequency Omni-directional Range
VORTAC - Combined VOR AND TACAN
ILS - Instrument Landing System
PAR - Precision Approach Radar

ADF - Automatic Direction Finder
UHF - Ultra High Frequency (Radio Communication)
VHF - Very High Frequency (Radio Communication)
HF - High Frequency (Radio Communication)
FSS - Flight Services Station
PPR - Prior Permission Required
MARSA - Military Accepts Responsibility for Separation of Aircraft

# 6. FLIGHT CLEARANCES AND REQUIREMENTS

## 6.1 INTRODUCTION

General standard requirements for helicopter flight clearance in icing conditions and associated procedures for compliance have been used for both full and limited clearances. Little operational experience has been gained from helicopters with full icing clearances, much more has been gained from those with limited clearances. In the latter category some clearances are based on limited liquid water content and some rely on other limitations reflecting the effects on the helicopter, e.g., increase of power required. In either case the clearance may also be restricted in terms of ambient temperature and altitude and although not well documented, no significant difficulties have been reported in respecting the relevant limitations, and the accident safety record has been excellent. Nevertheless, feedback of information from operators on icing encounters is most important and may ultimately lead to improved icing clearances.

This section discusses those requirements which must be incorporated in the case of full and limited clearances and sets out the means by which compliance may be demonstrated. Section 6.4 speculates on possible ways in which the high cost and lengthy time-scales of icing certification might be reduced by incorporating more features from the predictive techniques described in Sec. 4. The need to correlate natural icing results with this simulated icing and analysis is identified as important for such future goals. A synopsis of both experimental and operational flight experience, gained since AR 166, is given, and in order to complete the operational scenario, preparation of aircraft for flight in ice-forming conditions is also considered.

Because of the cost of icing certification programs that rely mainly on natural icing conditions, it s forecast that analysis substantiation will be developed; consequently, the need to correlate natural icing results with artificial icing, and simulated ice, and analysis will become important for the future.

## 6.2 DEFINITIONS

### 6.2.1 Icing Atmosphere

Several icing atmospheres and atmospheric conditions are under consideration in 1985. Refer to Sec. 2 for the details of the list below:

- Atmosphere FAR 29, Appendix C

- U.S. Army atmosphere derived from Appendix C

- Atmospheric icing conditions of CAA draft paper 610

- European JAR 25 (App. C) atmosphere and atmospheric icing conditions of the associated ACJ

- Atmospheric icing conditions of U.K. Defence Standard 970

- "New characterization of supercooled cloud below 10,000 ft AGL" FAA atmosphere

The icing atmosphere FAR 29, APP.C (same as FAR 25. APP.C) is the most widely known. It is not limited to 10,000 ft and furthermore it is often used for engine, windshield, sensors, rotors, and airframe. Consequently, Secs. 6.2.1, 6.3.1, and 6.4.1 of the present document use it as reference in an homogenous manner. Every time alternative atmosphere will be chosen, standards requirements and the adequacy of the associated procedures for compliance must be established and agreed with the authorities.

### 6.2.2 Operational Icing Envelope

The operational icing envelope is that portion of the FAR 29. APPC. envelope within which the helicopter will be cleared to operate. This envelope may be the whole helicopter flight envelope or only a part of it. The manufacturer or user must ask for a clearance to fly in the defined operational icing envelope.

## 6.3 GENERAL STANDARD REQUIREMENTS FOR HELICOPTERS

Whatever icing clearance is desired, a defined icing atmosphere must be declared and approved by the authorities. If not included, the following atmospheric conditions, frequently associated with icing must be considered:

- Falling and blowing snow

- Ice crystals

- Mixed crystal and water conditions

- Hail

- Freezing fog

- Freezing rain

- Slush, lightning

6.3.1  Full Clearances

(a) If certification for flight in icing conditions is desired, the operational icing envelope shall be defined to the certification authority and applicable paragraphs of this document must be demonstrated.

(b) The helicopter must be able to operate safely in the continuous and intermittent icing conditions defined by FAR 29 Appendix C as prescribed in par. 6.3.1(a).  An analysis must be performed to establish, on the basis of the helicopter's operational needs, the adequacy of the ice protection provisions for the various components of the helicopter.

(c) In addition to the analysis and ground testing, the effectiveness of the ice protection system and its components must be shown by flight tests of the helicopter in measured natural atmospheric icing conditions.  In addition, the adequacy of the ice-protection system must be determined by one or more of the following tests:

(1) Laboratory clear air or simulated icing tests or a combination of both, of the components or adequate model of the components.

(2) Clear-air flight tests of the ice-protection system as a whole, or of its individual components.

(3) Flight testing of the helicopter or its components in measured natural and/or properly calibrated simulated icing conditions.

(d) Each engine, complete with its air intake systems, duct and icing guard, with all its icing-protection systems operating, must operate throughout its flight power range from flight idle to maximum rated power, to include any contingency/emergency power ratings:

- In continuous maximum and intermittent maximum icing conditions of FAR 29 APP.C

- In snow both falling, blowing and recirculating

- In freezing fog

without unacceptable:

- Immediate or ultimate reduction of engine performance

- Increase of engine operating temperature

- Deterioration of engine control characteristics, and

- Mechanical damage

(e) Pilot external view

The helicopter must have a means to maintain a clear portion of the windshield, during the following conditions, sufficient for both pilots to have a sufficiently extensive view along the flight path in the operational flight envelope of the helicopter.  This means must be designed to function, without continuous attention on the part of the crew,

- In snow both falling and blowing

- In heavy and freezing rain

- In continuous maximum and intermittent maximum icing conditions of FAR 29 APP.C within the helicopter's operational icing envelope.

(f) Airspeed indicating system

Each airspeed indicator system must have an ice-protected pitot tube or an equivalent means of preventing malfunction due to icing, in continuous maximum and intermittent maximum icing conditions of FAR 29 APP.C.

(g) Static pressure system

Each static port must be designed and located in such a manner that the static pressure system performance is not impaired by icing in continuous maximum and intermittent maximum icing conditions of FAR 29 APP.C., or by liquid water running and refreezing.

(h) Ice formation indication

The helicopter flight manual must describe the means of determining potential ice formation and must contain information necessary for safe operation of the helicopter in icing conditions. Unless otherwise restricted, this means must be available for nighttime as well as daytime operation.

(i) Lightning

Ice protection systems and equipments must meet the basic requirement for the whole helicopter.

6.3.2 Limited Clearances

The requirements of par. 6.3.1 for full clearances are applicable to limited clearances taking into account any relaxations which are permissible because of the reduced operational icing envelope and, if appropriate, the time which is spent in icing and the degree of risk acceptable to the operator and/or certifying authority.

NOTE: Refer to par. 6.4.2 for various national views and policy.


6.4 PROCEDURES FOR COMPLIANCE

6.4.1 Full Clearances

6.4.1.1 Items to be considered during acceptance process. As part of the whole substantiation for full certification, as a minimum, each of the following shall be adequately taken into account:

- Engine with its helicopter air intake or, if the intake is separately qualified, engine alone

- Rotor systems including droop stops, flap restraints, and external vibration dampers

- Flight controls

- Necessary probes or sensors: pitot heads, statics, angle of attack, ice accretion, ice detector, etc., and their qualification status

- Windshields and wipers

- Unprotected surfaces

- All vents and exhaust ports

- Emergency access/exit

- Antennas, radome

- External stores and systems

- Landing gear

- Ice shedding trajectories from the whole helicopter

- Minimum instrumentation required for operation within the operational icing envelope (navigation instruments included)

- Following natural icing tests, including measurements, an approved extrapolation analysis for the operational icing envelope for which clearance is permissible

- Failure analysis and tests

- Safety during embarkation and disembarkation, rotors turning

- Cleaning the helicopter before takeoff when ice or frost formations are present, taking into account the safety of the following flight

- Lightning, electromagnetic compatibility

6.4.1.2 Recommended procedures for icing clearance for engine and air intake system. The helicopter's air intake system includes the air intake itself, any duct, guard or specific engine intake-related icing-protection device fitted on the helicopter.

In order to obtain an icing clearance the following ground tests are required. Furthermore adequate testing in natural icing with proper instrumentation is required (Par. 6.3.1(c)), for which the use of closed-circuit television (CCTV) or photography is often necessary.

Especially for helicopters, engine behavior depends on the ability of the air intake system to protect against ice and/or slush shed from any part of the helicopter. Where appropriate testing facilities are available, it is recommended that testing be conducted on a fully representative engine installation, taking into account the absence of rotor downwash and the various flight attitudes by adjustment of the inflow angle. Separate assessment and/or testing of the intake system and engine are not excluded; in this case the precise details of the tested intake system will be defined in the engine approval documents. It will be finally the responsibility of the helicopter manufacturer with the concurrence of the engine manufacturer) to show that the engine tests are valid for his particular installation.

Nonaltitude testing is permissible where appropriate substantiation can be presented, but this could involve modifications to the other test conditions of the method and could also necessitate confirmatory tests in natural icing conditions.

Where ice or slush could enter an engine, tests to determine the amount of ice or slush the engine can tolerate are necessary.

These following alternative methods shall take into account the helicopter's flight envelope:

Method 1 is an arbitrary empirical method based on the French practice for engine and helicopter air intake system icing protection. These tests are conducted in an altitude facility in accordance with Table 12. A separate test should be conducted at each temperature condition of Table 12, the test being made up of repetitions of the following cycle:

- 32 km in the conditions of Table 12, column (a) appropriate to the temperature, followed by 5 km in the conditions of Table 12, column (b) appropriate to the temperature, for a duration of 30 min (or less if a steady state can be established, or until the engine will no longer operate satisfactorily)

- Cruise conditions shall be established to both maximum and minimum helicopter speed for -5°C and -10°C

- Cruise conditions shall be established at maximum speed for -30°C

- Takeoff power setting test shall be conducted only if clearance for takeoff under icing conditions is desired

- The minimum engine power shall be established for the critical conditions

- Larger droplet sizes available in the test facility shall be investigated to show that test results are not significantly different from those for 20-μm droplets

- The combination of altitude and temperature to be tested will be agreed for each installation

- Due to the diversity of helicopter air intake ice-protection systems, the test program shall be adapted to take account of particular features of engine, engine intake and protection systems to be tested

- During or at the end of some tests it will be useful to examine the possible ice accretion on and behind the air intake or on the engine

At the conclusion of each test the engine should be run up to maximum power conditions for a sufficient period during which the air temperature should be raised above 0°C to ensure that all ice has shed

- A test should be conducted for a duration of 30 min, with the engine set to the minimum ground idle conditions approved for use in icing, with the air bleed available for engine icing protection at its critical condition without adverse effect, in an atmosphere that is at a temperature between 15° and 30°F (between -9°C and -1°C) and has a LWC not less than 0.3 $g/m^3$ in the form of drops having a mean effective diameter not less than 20 μm. At the end of the period, the engine should be accelerated to maximum takeoff power (in a manner approved for inclusion in the operating instructions) without suffering unacceptable damage or power loss. During the 30 min of idle operation, the engine may be run up periodically to a moderate power setting in a manner acceptable to the authorities.

TABLE 12.- ENGINE AND INLET ICING TEST CONDITIONS

| Ambient air temperature, °C | Altitude | | Liquid water content, $g/m^3$ | | Mean effective droplet size diameter, μm |
|---|---|---|---|---|---|
| | m | ft | a | b | |
| -5 | 1,200 | 4,000 | 0.7 | 2.4 | |
| -10 | | | 0.6 | 2.2 | |
| -20 | to | to | 0.3 | 1.7 | 20 |
| -30 | 4,500 | 15,000 | 0.2 | 1.0 | |

Method 2 is the U.S. practice based on their own experience of the Military Specifications' named Conditions 1-2-3 (see advisory circular AC20-73 dated 21 April 1971, pages 26-27).

(a) The engine should be capable of operating acceptably under the meteorological conditions of Appendix C of FAR 29 over the engine operating envelope and under conditions of ground fog.

(b) Experience has indicated that testing to the points set forth in Table 13 and the following schedule has been considered a successful means of showing compliance if used in conjunction with the critical conditions determined in the design analysis:

(1) Operate the engine steadily under icing conditions 1 and 2 for at least 10 min each at takeoff setting, 75% and 50% of maximum continuous power and at flight idle setting, then accelerate from flight idle to takeoff. If ice is still building up at the end of 10 min, continue running until the ice begins to shed or until the engine will no longer operate satisfactorily.

(2) Operate steadily at ground idle setting for at least 30 min under icing condition 3 followed by acceleration to takeoff setting.

(3) While at cruise and flight idle, for engines with icing-protection systems, operate for at least 1 min in the icing atmosphere prior to turning on the icing protection system.

(c) Engine operation in these icing conditions should be reliable, uninterrupted, without any significant adverse effects, and should include the ability to continue in operation and to accelerate. Some power reduction is acceptable at idle power settings but all other operation should be unaffected.

(d) Special consideration and tests should be conducted to adequately substantiate:

(1) Engine with inlet screens

(2) Engines with air passages which might accumulate snow or ice due to restrictions or contours

(3) Unprotected surfaces upon which ice may build up significantly during exposures longer than specified above

TABLE 13.- ENGINE AND INLET TEST CONDITIONS

| Icing condition | 1 | 2 | 3 |
|---|---|---|---|
| Liquid water content, g/m$^3$ | 2 | 1 | 2 |
| Atmospheric temperature, °C | -5 | -20 | -1 |
| Mean effective water droplet diameter, μm | 25 | 15 | 40 (minimum) |

6.4.1.3  Recommended procedures for icing clearance of rotor systems. At the present time, all certifying authorities require testing in natural atmospheric conditions.

The icing clearance shall be based on the test results obtained in natural icing conditions with a properly instrumented test helicopter. Supplementary substantiation from analysis, ground tests and simulated in-flight or wind-tunnel icing tests may be useful in evaluating the amount of natural icing testing required and in assisting in extrapolation of natural icing test results.

The overall level of safety during flight in icing shall be acceptable taking into account any failures which may occur, including those of ice-protection systems.

A.  Instrumentation

The following instrumentation will be required for acquisition of rotor systems icing clearance data, taking into account that deficiencies are likely to give an inadequate understanding of the behavior in icing and thus make extrapolation hazardous, extend the testing necessary for a given standard of safety in service and prolong the development of the systems:

(a) Cameras fitted in such a manner as to record ice accretion, ice shedding and residual ice

(b) Instruments to measure outside air temperature (OAT), liquid water content (LWC), droplet size, ice-accretion rate, and, when available, solid particle content

(c) Rotor torque and stresses, and airframe vibration levels

(d) The appropriate performance and characteristics of the rotor icing protection system (if provided), both in icing and in clear air

(e) Flight-test instrumentation to measure helicopter performance and flying qualities parameters

B. Test scope

In order to achieve full clearance, tests must be performed as follows:

(a) Throughout the minimum required temperature range of 0°C to -20°C, but any opportunity to investigate lower temperatures should be taken

(b) Over the altitude range for which clearance is required

(c) As far as practicable for liquid water contents specified by the continuous and intermittent maximum conditions for FAR 29 APP.C (without application of the attenuation factor)

(d) For:
Protected rotors, in any configuration or conditions, to establish the effect of failure or partial failure of the protection system, or the accumulation of run-back ice
- Unprotected rotors, in any conditions such as partial or asymmetric shedding, which could degrade the handling, performance and vibration level of the helicopter or its engine(s)

(e) When rotor systems are designed to function under snow conditions, test must be made in snow with the heating on in order to see if any problems may occur when flying in snow conditions

C. Qualification criteria

- Protected and unprotected components of the rotor systems shall funciton properly throughout the operational icing envelope.

- Icing conditions shall not induce excessive pilot work load, unacceptable helicopter vibration, blockage of vents/exhaust ports, improper functioning of rotor droop stops/ flap restraint systems, or physical damage due to shed ice.

- After failure of any one portion of the ice-protection system, the level of safety shall remain acceptable for continued operation in icing conditions.

-Stress levels of the rotor system and other critical dynamic components during flight in icing conditions shall not unacceptably reduce the fatigue lives established for non-icing flight. Retirement lives shall include appropriate reduction for operation in icing conditions.

- Torque increases and fluctuations (during ice shedding) shall not exceed limits established for maximum torque and torsional stability of the drive system and shall not unacceptably impair helicopter performance. Rotor speed control within normal operating limits shall be possible during ice shedding or accumulation under autorotational conditions.

- Analysis of test data obtained in natural i_ng conditions, together with any other test data which are valid, and accepted analytical methods may be used to extend the temperature range of the clearance below -20°C and the values of LWC above those encountered and to allow for other conditions which cannot be covered adequately by natural icing testing at this time.

The resulting clearance may then be limited compared with that which is desired. Further extrapolation is permissible only if the degree of risk involved is determined and accepted.

D. Simulated icing tests

Method 1. At the present time no agreed test method with existing icing simulation facilities is satisfactory enough to give the basic substantiation that can be obtained for fixed-wing aircraft elements. When artificial icing tests are envisaged, the French propose the following test program:

(a) Tests in continuous maximum conditions for a period of 30 min duration at each of the conditions specified in Table 14.

- At the end of the tests any residual ice shall be shown to be acceptable.

- The duration of the above tests can be reduced if it can be demonstrated that the surface is completely ice-free or that self-shedding is repetitive naturally or enforced by cyclic operation of the protective system. However, at least one of the test conditions shall be investigated for a longer period in order to evaluate the margins of the system.

TABLE 14.- CONTINUOUS ICING TEST CONDITIONS

| Atmospheric temperature, °C | LWC, g/m³ | Mean effective drop diameter, μm |
|---|---|---|
| -5 | 0.7 | |
| -10 | 0.6 | |
| -20 | 0.3 | 20 |
| -30 | 0.2 | |

(b) **Tests in intermittent maximum conditions**. The following conditions must be considered. Above 1200 m intermittent conditions exist. The icing encounters considered include three clouds of 5-km horizontal extent with intermittent maximum concentrations as in Table 15 separated by spaces of clear air of 5 km.

TABLE 15.- INTERMITTENT MAXIMUM ICING TEST CONDITIONS

| Atmospheric temperature, °C | LWC, g/m³ | Mean effective drop diameter, μm |
|---|---|---|
| -5 | 2.4 | |
| -10 | 2.2 | |
| -20 | 1.7 | 20 |
| -30 | 1.0 | |

Note 1. When the above tests (a) and (b) are conducted in non-altitude conditions, appropriate justification or amended program test conditions can be presented for approval.

Note 2. When considering simulated icing tests, the flight conditions selected for testing at each temperature should be the most critical, taking into account the operational icing envelope requested by the applicant.

Method 2. The U.S. Army has developed a Helicopter Icing Spray System (HISS) which is capable of producing a simulated icing cloud which approximates to limited natural icing conditions. The HISS can reasonably duplicate LWCs up to 1 g/m³ with a mean effective water droplet size of 28 μm, at temperature down to -20°C and pressure altitude up to 10,000 ft. The capability is limited by the size of the cloud and the droplet size distribution. It has been of considerable value for development and airworthiness substantiation purposes but it cannot presently be considered alone for the purposes of certification.

The icing testing is conducted to fill the following range of conditions, each for a 30-min duration.

| Temperature, °C | Liquid water content, g/m³ | | | |
|---|---|---|---|---|
| | 0.25 | 0.50 | 0.75 | 1.0 |
| -5 | X | X | X | X |
| -10 | X | X | X | X |
| -15 | X | X | X | X |
| -20 | X | X | | |

In the event the helicopter cannot be completely immersed in the cloud, reimmersion will be performed in order that each part of the aircraft will have experienced the 30-min required exposure time at each condition. The liquid water content will be mechanically regulated based on the current calibration of the spray system. Temperature will be selected from the available atmosphere in the range from 1500 ft above ground level to 10,000 ft pressure altitude and any altitude at which the desired temperature exists will be accepted. The cloud dimensions are approximately 8 ft vertical and 36 ft in width at a standoff distance of 150 ft for the test aircraft.

6.4.1.4 Recommended guidance for windshield anti-icing heating. For windshields protected by electrical heating, Table 16 could be adequate for design purposes (MIL-T-5842A).

TABLE 16.- WINDSHIELD ICING TEST REQUIREMENTS

| Normal cruise speed | | Heat requirement, W/m$^2$ |
|---|---|---|
| Knots | Km/hr | |
| 100 | 185 | 3800 |
| 150 | 278 | 5800 |
| 200 | 370 | 6000 |
| 250 | 463 | 6300 |

Note: This heat requirement gives generally an exterior windshield temperature not less than +2°C.

5  Recommended procedures for icing clearance of probes. Tests could be derived from the
.B.

ng and anti-icing: The tube shall be tested in an icing wind tunnel at an indicated airspeed of
nots and ambient temperature of -30° ±5°C. The water droplet size shall be regulated to provide a
iter content of 1.25 ±0.15 g/m$^3$. Tests shall be made at angles of attack of 0° and 20°. The proce-
each test run shall be as follows: Ice shall be allowed to form on the tube until either the pitot
a opening has been sealed or the ice cap has extended 0.50 in. in front of the tube tip. Power shall
: applied to the heater(s) at rated voltage. The total time required to achieve correct pressure
gs shall not exceed 1 min and to remove all accumulated ice shall not exceed 1.5 min. The icing test
be continued for 15 min after the ice cap is removed and no ice shall collect on the tube that will
t the pressure measurement.

If these previous tests are conducted in non-altitude conditions it shall be demonstrated that results
iin valid at altitude.

6.4.1.6  Unprotected surfaces. Where ice can accrete on unprotected parts it should be established
at such ice will not critically affect the characteristics of the helicopter as regards safety (e.g.,
.ight, structure, flutter) and shall not unacceptably degrade handling. An adequate means of substantia-
.ion for flight surfaces consists of testing the helicopter fitted with artificial ice shapes. These shapes
will be the most critical ones determined by agreed methods (analysis or test).

Note. This method has not yet been shown to be valid for rotors.

As an indication from fixed-wing aircraft service experience, the amount of ice on the most critical
unprotected main airfoil surface need not exceed a pinnacle height of 75 mm (3 in.) in a plane in the direc-
tion of flight. In the absence of an acceptable analysis a uniform pinnacle height of 75 mm could be
assumed, or any other maximum ice accretion height agreed by the certification authority.

The critical ice shape on unprotected parts will normally occur during the cruise at a total tempera-
ture near 0°C.

The subsequent proper operation of retractable devices shall be demonstrated with representative ice
accretion.

6.4.1.7  Ice-shedding trajectories from the whole helicopter. Ice shedding trajectories from protected
or unprotected parts of the whole helicopter throughout the flight envelope should be analyzed. If such
shedding could interfere with the continuous safe operation of the helicopter, it would be required to
demonstrate that the trajectories of such ice are not critical. Furthermore, consideration must be given to
minimizing the risk of ice shed from the helicopter causing injury to persons on the ground.

6.4.1.8  Instruments required for operational flights. A need exists for some instruments or equipment
for identifying icing severity within the operational icing envelope for full or limited clearance. Such
instruments would be specified by the manufacturer and agreed by the certification authority. Required
instruments could be, but not necessarily be limited to:

- OAT

- Ice accretion device (a means for determining the formation of ice and accretion rate on critical
parts of the helicopter)

END

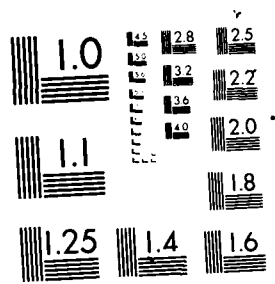DATE
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- Ice severity meter

- Weather radar

- Torque meter

- Any suitable instrument which indicates changes in power necessary for flight.

<u>Note</u>.  Navigation subsystems such as antennas and radomes must not be unacceptably impaired by icing.

<u>6.4.1.9  Tests in natural icing atmospheric conditions</u>.

A.  Tests in icing conditions

Flight tests of the helicopter in measured natural atmospheric icing conditions are mandatory.  At the present time such tests are the main substantiation for certification purposes.  The helicopter shall be fully instrumented for ea_ specific component subject to icing, for measurement of icing parameters and for engine parameters.  The natural icing tests carried out on the helicopter will be judged for their acceptability by the evaluation of the icing conditions through which the helicopter has flown in relation to the operational icing envelope wanted within the conditions of FAR 25 Appendix C.

B.  Tests in falling, blowing, and recirculating snow

Taking into account the lack of an approved definition, the fact that the horizontal visibility is not necessarily related to snowfall sever!' , the variability and difficulty in identifying the worst conditons, quite extensive tests are necessar'    natural snow to support a snow clearance.  Some realistic conditions are proposed as a minimum to allow unrestricted operation in snow:

1.  Visibility 0.4 km or less as limited by snow provided this low visibility is due only to falling snow (<u>no fog</u>); this value corresponds approximately to 1 g/m$^3$.

2.  Temperature:  -3°C to +2°C (26.6°F to 33.8°F) wet snow; -9°C to -2°C (16°F to 28°F) dry snow, unless other temperatures are found to be critical.

<u>Note</u>.  (i) Lower temperatures (dry snow) will present no additional problems if the above condition is satisfactory.

(ii) Care is needed with dry snow impinging on a heated surface (forming slush) at any lower temperature.

3.  In blowing snow the density has been reported to increase to 3 to 4 g/m$^3$.

4.  Recirculating snow is lying snow which is lifted and recirculated by the rotor downwash.

5.  Test configuration.  See Table 18.

In testing the relevant snow factors, the following are to be taken into account:

- Ambient air temperature including particularly temperatures about 0°C

- The severity of the snow

- The exposure time

- Whether the snow is falling, blowing, or recirculating snow

Clearance is normally recommended for the temperature range which has been adequately covered by the tests that have been made except that tests at about -8°C are considered tc clear all lower temperatures (except for heated surfaces or surfaces wetted by anti-icing fluid).  Snow severity and the exposure times which have been experienced during the testing must also be taken into account.  Consideration must be given to the possibility of protective screens and other particle separation tubes or deflection devices becoming blocked, or snow/slush concentrations shedding from the airframe into unprotected engine inlets.  In the latter case knowledge of how much slush an engine can tolerate is important.

C.  Tests in ice crystal and mixed crystal and water conditions

Ice crystal conditions can seldom be measured and their effects on the helicopter are, so far as is known, covered by the testing in snow and some natural icing test conditions referred to above.  Such conditions must be investigated during flight test especially for helicopters equipped with thermal protective systems because the energy balance is significantly different from supercooled droplet to solid ice particle (1 cal/g to heat liquid water by 1°C; 80 cal/g to melt ice).

D.  Tests in freezing fog, freezing rain and slush

- Freezing fog is defined in par. 6.4.1.2, Method 1.

- Freezing rain and slush, which are not defined, shall be evaluated in the natural atmosphere.

6.4.1.10 Failure analysis and tests. Failure analysis of the ice-protection system shall be performed to establish the adequacy of the helicopter to fly safely in icing conditions. Such analysis must include a detailed review of single failures, taking into account any dormant failures and summarized failure cases. An acceptable level of airworthiness must exist taking into account all these failures and subsequent crew actions.

Failure cases of any critical protected part shall be evaluated during natural icing atmosphere tests or by an acceptable analysis.

Table 17 is given as example of presentation of summarized failure case. ACJ No. 1 to European requirement JAR 25.1309 gives an example of definitions (ACJ = Joint Airworthiness Compliance; JAR = Joint Airworthiness Requirement).

TABLE 17.- SAFETY ANALYSIS - SUMMARIZED FAILURE

| DEFINITION OF THE SUMMARIZED FAILURE : | | REFERENCE OF THE SUMMARIZED FAILURE |
|---|---|---|
| IMMEDIATE EFFECTS OF FAILURE : | PHASES OF FLIGHT CONCERNED : | REFERENCE OF BASIC FAILURES LEADING TO SUMMARIZED FAILURE |
| DETECTION BY CREW : CORRECTIVE ACTION BY CREW : | MOST CRITICAL PHASES OF FLIGHT : | |
| CONFIGURATION AFTER POSSIBLE ACTION BY CREW : | MOST ADVERSE EXTERNAL FEATURES : | |
| SITUATION AFTER FAILURE : EFFECT ON HELICOPTER AIRWORTHINESS : | REFERENCE OF SUBSTANTIATING FILES : | |
| ESTIMATED PROBABILITY : $X$ $10^Y$ per hour | CLASSIFICATION OF SITUATION AFTER FAILURE : | |
| PROBABLE / REMOTE / EXTREMELY REMOTE | NON CRITICAL / CRITICAL / CATASTROPHIC | |

6.4.1.11 Safety during embarkation and disembarkation. Rotors must be completely stopped unless it has been demonstrated that no danger could result from rotors in rotation either after a flight in icing conditions or on the ground if ice can be accreted and shed.

6.4.1.12 Cleaning the helicopter before takeoff when ice formations or snow are present. The helicopter must be completely cleaned before takeoff when ice, snow, or frost formations are present, unless it has been demonstrated that any ice accreted on the blades, the structure and the air intake system of the engine cannot impair the safety of the helicopter during takeoff and the following flight.

For flight clearances, it is necessary to substantiate the flight safety of the helicopter following de/anti-icing ground operation when aqueous fluid solutions are used. Helicopter performance and flight characteristics will be shown.

6.4.1.13 Lightning. When helicopters are cleared to fly in icir; conditions, they will be flying more frequently into clouds at levels where temperatures are between 0°C and -10°C. This temperature range is where lightning strikes are the most frequent. The icing protection systems and equipment must comply with the same basic helicopter standard as other essential systems and equipment, fitted on board.

6.4.1.14 French proposal, as ar example of a table of general conditions to be tested for an icing clearance for helicopters. Table 18 gives the complete flight configurations to be demonstrated, for times appropriate to each helicopter, in natural icing and associated conditions. These tests must be performed with regard to:

1. _Temperature range_. The temperature ranges are based on the different effects of icing observed during previous experience; they are shown in Table 18.

TABLE 18.- ICING CLEARANCE TEST CONDITIONS

| Conditions | Temperature ranges, °C | Main effects |
|---|---|---|
| a | 0 to -2 | Runback |
| b | -2 to -5 | Large ice shapes |
| c | -5 to -10 | Transition range between large and well-stuck ice |
| d | -10 to -15 | Well-stuck ice |
| e | -15 to -20 | Cold ice, possibility of insufficient protection power |

Any opportunity to fly in icing at temperatures lower than -20°C should be taken.

2. _Altitude range_. The whole altitude range for which clearance is required has to be explored, with particular attention to high altitudes at which the flight power margin is reduced.

3. _Water content_. To demonstrate LWC values as close as possible to the maximum conditions of the defined atmosphere, it is advisable to fly many times in cumulus and strato-cumulus-type clouds. In fact such flights will also provide experience in mixed crystal and water conditions.

4. _Helicopter weight_. Due to the fact that gross weight has a great effect on performance, handling qualities and vibration levels, it is important to test different weights in icing conditions, and in particular gross weights close to the maximum.

5. _Night flights_. Several icing flights must be performed at night in order to identify and specific problem, mainly associated with crew judgment and behavior, which may be different from those of daytime flight.

6. _Configurations to be demonstrated_ for helicopter natural icing tests; see Table 19.

6.4.2  Limited Clearances--National Views and Policy

6.4.2.1  _Limited clearances_.  The procedures used to obtain limited clearance should follow the recommendations for full clearance given in paragraph 6.4.1, except where any relaxation of the Standard Requirements in accordance with paragraph 6.3.2 permits less stringent procedures to be used. In all cases, the level of risk associated with such clearances should be estimated and accepted by the certifying authorities and the users.

6.4.2.2  _U.S. Army and U.K. view on limited clearances_.  Changes in procedures to obtain limited clearances arise mainly from the methods adopted to permit the limited operation of the helicopter in icing. An account of the various possibilities and the methods used by the U.S. Army and the U.K. for military aircraft was given in paragraph 5.3 of AGARD-AR-166. These methods have been used since 1980 for limited clearances by the U.S. Army for the UH-1, CH-47, and UG-60 helicopters, and by the U.K. for the Chinook and Puma helicopters. The U.S. Army requires that helicopters qualified for flight into icing conditions to operate in light (0.5 gm/m$^3$) or moderate (1.0 gm/m$^3$) ice depending on operational requirements. Full clearance procedures are followed and the helicopter must demonstrate the capability to operate in the level of icing intensity to which cleared. Limited clearances have been invaluable for the extension of military operations and have proven to be a safe procedure. Since 1974 the U.S. Army has operated witn limited clearances; there have been no fatalities or injuries associated with operating in icing conditions and only minor incidents have occurred. This safety record is attributed to the stringent limited clearance procedures, good operating procedures, and well-trained, experienced aviation personnel.

6.4.2.3  _French view on limited clearances_.  For the following reasons, the French certifying authority has not issue limited clearances:

- First, results of research flights made on helicopter behavior in icing conditions without icing protection on rotor systems

- Second, evidences gained during icing protective system "failure cases" test flights in natural icing conditions

This leads to the following concepts:

- Small helicopters are much more sensitive to icing than larger ones (comparison Gazelle/Super Frelon)

TABLE 19.- NATURAL ICING TEST CONFIGURATIONS TO BE DEMONSTRATED

| Configuration | A<br>Icing | B<br>Snow | C<br>Mixed<br>conditions | D<br>Freezing<br>rain | E<br>Gust,<br>lightning,<br>hail |
|---|---|---|---|---|---|
| **Normal flight** | | | | | |
| 1.1 Taxi + ground holding | Yes<br>10 + 30 min<br>a b c d e | Yes<br>10 + 15 min<br>a b | No | Yes<br>15 min<br>a b | No |
| 1.2 Hovering | Yes<br>30 min<br>a b c d e | Yes<br>30 min<br>a b | No | No | No |
| 1.3 Low-speed forward flight | No | Yes<br>30 min<br>a b c | No | Yes<br>30 min<br>a b | No |
| 1.4 Takeoff - acceleration | Yes<br>a b c d | Yes<br>a b | No | Yes<br>a b | No |
| 1.5 Climb | Yes*<br>a b c d e | Yes*<br>a b | Yes*<br>b c d e | No | Yes*<br>b c |
| Level flights<br>1.6 Terrain following, speed to be determined | Yes 1 hr | Yes 1 hr | No | No | No |
| 1.7 Long-range cruise | Yes 1 hr | Yes 1 hr | Yes 30 min | No | Yes 30 min |
| 1.8 Cruise at maximum collective pitch allowed in icing | Yes 1 hr<br>a b c d e | No<br>a b c | Yes 10 min<br>b c d e | No | Yes 30 min<br>b c |
| Descent<br>1.9 Normal | Yes* | Yes* | Yes* | No | Yes* |
| 1.10 High rate | Yes*<br>a b c d e | No<br>a b c | No<br>b c d e | Yes*<br>a b | Yes*<br>b c |
| 1.11 Approach and speed reduction | Yes<br>with<br>10 mm of ice<br>b c | Yes<br>with<br>6 mm of ice<br>a b | No | Yes<br>with<br>6 mm of ice<br>a b | No |
| 1.12 Go-around with landing gear retraction (if movable L.G.) | Yes<br>with<br>10 mm of ice<br>b c | Yes<br>a b | No | No | No |
| **Failure Cases** | | | | | |
| 2.1 One-engine failure during takeoff | Yes<br>b c | No | No | Yes<br>a b | No |
| 2.2 One-engine failure in cruise | Yes<br>45 min<br>b c | No | Yes<br>10 min<br>b c | No | No |
| 2.3 One-engine failure during approach | Yes<br>with<br>10 mm of ice<br>b c | No | No | No | No |
| 2.4 Delay for rotor protection system energizing | Yes<br>b c d | No | Yes<br>c d | Yes<br>a b | No |
| 2.5 Rotors protection partial failure | Yes<br>b c d | No | Yes<br>c d | Yes<br>a b | No |
| 2.6 Rotors protection total failure | Yes†<br>b c d | No | Yes†<br>c d | Yes†<br>a b | Yes†<br>b c |

*Time to be determined for each type of helicopter.
†Torque limit to be determined prior to or during tests.
 a, b, c, d, e refer to Conditions of Table 18.

- Even a large helicopter can suffer quite rapidly unpleasant or unsafe behavior in light to moderate icing conditions (blade stall 25 knots before VNE on Super Frelon)

Furthermore, remote measurement of icing conditions by airborne radar led to very poor results due to present technology for meteorological radars.

Consequently, helicopters can rapidly encounter far more severe icing conditions than those for which they could have been qualified, and losses in performances and handling qualities (virtually instantaneous) can be unacceptable before leaving icing conditions.

From these considerations, it is impossible to set a figure to give a sufficient safety margin associated with drills written in the flight manual.

The "escape route" concept cannot be envisaged as it places too much responsibility on the pilot, who would not have sufficient information to judge if the escape route actually exists when it is needed and whether it would save the situation if it did exist.

Furthermore, it appears that, if it is easy to follow an altitude limitation, it is less easy to follow a temperature limitation, and it is very difficult to follow a limitation in terms of LWC or icing severity, due to the fact that:

- Measuring devices are not good enough

- LWC changes rapidly in unstable clouds

- It is quite impossible to demonstrate an available safety margin

6.4.2.4  Canadian policy for helicopter clearances.  The Canadian Armed Forces policy is to derive the clearance criteria from individual weapons systems requirements.  The Aerospace Engineering and Test Establishment (AETE) would be the recommending authority for clearan    and would conduct the required evaluation and assessment as well as conducting the required flight testing.  A clearance granted by National Defence Headquarters Director General Aerospace Engineering and Maintenance (NDHQ/DGAEM) would be for a specified flight envelope limited by temperature and altitude.

Transport Canada is the clearance authority for civil certification.  A certification will be granted upon a successful evaluation of aircraft data against Federal Aviation Regulations.  It is not intended to grant limited clearances.

6.4.2.5  Norwegian policy for helicopter clearances.  The Royal Norwegian Armed Forces policy is to follow whatever icing clearance is recommended by the helicopter manufacturer or by another military operator of that vehicle.  In certain cases additional restrictions, within that clearance, may be imposed due to special risks associated with Norwegian geography and weather conditions.  The Norwegian CAA is not involved in clearing Norwegian military helicopters.

6.5  INTEGRATION OF ANALYSIS, SIMULATION, AND FLIGHT TESTING TECHNIQUES INTO THE CERTIFICATION PROCESS

6.5.1  Introduction

It has often been pointed out that the development and clearance of helicopters and their systems for flight in snow and icing conditions is a very protracted and expensive exercise. Although it is believed that adequate ice-protection systems can be, and indeed have been designed, adequate demonstration of compliance with certification authorities requirements has been a major stumbling block, preventing widespread adoption of these systems and their capabilities despite increasing demand. This has also tended to stifle development of advanced and more efficient systems and generally slowed the advent of truly "all weather" helicopters.

The basic problem is the difficulty involved in finding the extreme conditions in which the system must be validated. The analysis and simulation techniques discussed in Sec. 4 provide an invaluable set of tools to assist in the design and development of helicopter ice protection systems. It is also apparent that these same tools, suitably adapted, can greatly assist in the certification process, primarily by providing the means of extrapolating to extreme conditions by methods that have been correlated under more available conditions. It is the intention in this section to give an example of a method in which these techniques can be effectively integrated into the certification process resulting in improved release confidence levels, and reduced time and cost penalties.

In doing this it is intended to briefly highlight areas where techniques may be deficient or even nonexistent (or believed so) such that efforts can be directed to those areas for the benefit of all. It is also hoped that it will provoke deeper consideration of this matter and stimulate ideas which could uncover other techniques and/or result in alternative and possibly better strategies.

6.5.2  Basic Procedure

The objective of icing certification is to verify that the helicopter can operate safely throughout the approved operational icing envelope. This entails either determining that no limitations due to icing exist, or if limitations do exist, defining precisely what these limitations are and establishing acceptable operational procedures to accept these limits. Such areas where limiting conditions may manifest themselves include handling qualities, autorotation, increases in power requirements, vibration due to asymmetric shedding from rotors, and visibility through windscreens.

In general, compliance can be established when there is sufficient evidence to show that in the most critical conditions the helicopter can operate safely. Failure cases must also be taken into account based on flight test evidence and a risk/hazard analysis (including a full F.M.E.A.). To meet this requirement there are two fundamental steps which could be adopted in a certification procedure:

1. Determination and definition of all critical design points. This can best be achieved by formulation of hypotheses largely based on past flight experience, together with analysis and rig tests. As a general guide, Table 20 highlights the basic helicopter components/atmospheric conditions that have been found most likely to give rise to a limiting condition. It must be emphasized that some critical conditions/design points may well exist within the atmospheric icing envelope not necessarily at or near the edges or corners of the envelope.

TABLE 20.- HELICOPTER COMPONENTS AND ATMOSPHERIC CONDITIONS MOST LIKELY TO GIVE RISE TO
LIMITING CONDITION

| Condition | Component | | | | | |
| | Rotors | | Engine installations | | | Airframe/systems |
| | Heated | Unheated | Engine anti-icing | Flame-out | Damage from ingestion | |
|---|---|---|---|---|---|---|
| Supercooled water (icing cloud, freezing fog) | ✓ | ✓ | ✓ | | ✓ | ✓ |
| Freezing rain | ✓ | ✓ | ✓ | | ✓ | ✓ |
| Snow/ice crystals: | | | | | | |
| Precipitation (slush) | | | | ✓ | | ✓ |
| Recirculation (refrozen) | ✓ | (impact damage) | | | ✓ | ✓ |
| Crystals (dry) | ✓ | | | ✓ | | |
| Mixed conditions | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

Note:  Components and conditions found most likely to give rise to a limiting condition
indicated thus: ✓.

... A quantity ... analysis and test data ... provide reasonable assurance that the helicop-
ter ... operate safely within design limits. The key limitation with this step is being
... carry out ... system ... flight tests that comprise the
... the use of, and show sufficient correla-
tion with ... techniques.

... development of a strategy to meet the requirements of a basic procedure

... fundamental ... step in the strategy such as this is to establish the main
parameters that need to be demonstrated satisfactory. The second step is then to identify the basic
... all the influencing factors
... evaluate ... and select those which
... a strategy which uses those techniques in
... way that ... demonstration ... possible at all the established
... design points.

... areas of the airframe and propulsion system where the loads, droplet trajectories and heat balance
are essentially well known or easily established, and the nature of ... a quasi-static
nature e.g., windscreen, engine, and air intake anti-icing, demonstration of compliance with the
currently available test methods and analysis techniques ... is a common and well known procedure.

This, however, is not the case for rotor systems where the loads, droplet trajectory patterns, and
transient nature of accretion, shedding, and thermal cycling (in an electrothermal de-icing system) are so
complex that no analysis or simulation method yet exists which is able to adequately satisfy the full
range of requirements for certification. In this case, however, the strategy is far more difficult and
needs to incorporate a considerable amount of ... of the methods
used.

**6.5.3.2 Application of principles to clearance of an electrothermal system.** The following example
illustrates these basic principles and suggests the way in which ... to obtain a full icing
clearance for rotor systems.

**Note.** This example is not intended to cover every aspect of a system's operation but rather to
give a broad outline of the fundamental principles ... which might be addressed using current
techniques.

For a helicopter rotor system there are four main parameters which must be shown to be acceptable
within the proposed atmospheric and flight envelopes. These are:

1. Stresses. In general this involves the rotor loads, stress ... and propulsion system power
cycles. It must be established that there is a margin within the substantial fatigue and other stress
spectra limitations, in flight, and along the covering ... by either extensive fatigue substantia-
tion, over and above that carried out in flight in any case, and/or cutting back the flight enve-
lope to restrict areas ... when operating within ice.

2. Aircraft performance. Any reduction in aircraft performance due to icing must be established such
that reduced performance areas and limitations can be provided where appropriate.

3. Handling qualities. Adequate handling qualities must be maintained throughout the flight enve-
lopes.

4. Vibration. Vibration must be kept within acceptable limits through the flight envelope.

During the operation of an electrothermal rotor de-icing system these four parameters are likely to
be influenced by location in the flight and atmospheric envelopes, and state of de-icing system operation.
These will influence primarily the accretion, shedding, and runback ice accretion, thus causing changes in
aerodynamic characteristics, structural dynamic characteristics, and aeroelastic characteristics, and
affecting the four parameters: stress, performance, handling qualities, and vibration.

The following summarizes the basic activities most appropriate for achieving the objectives of this
task:

- Assessment of prior experience

- Analysis and prediction (computer codes for modeling accretion, de-icing system operation (including
shedding) and rotor performance)

- Laboratory and ground tests (dry air, simulated and artificial icing)

- Flight trials (dry air, simulated, artificial and natural icing)

In order to identify opportunities for research which could alleviate the problems of icing certifica-
tion, consider Fig. 31, which compares three possible strategies.

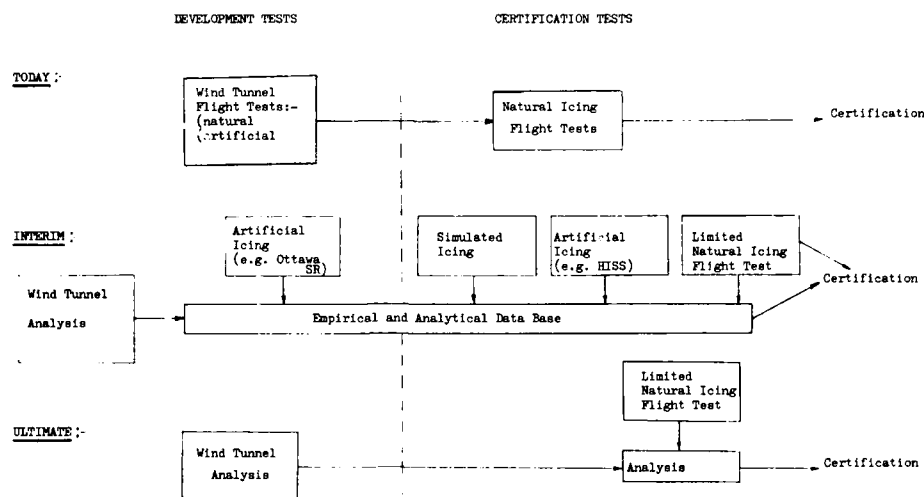DEVELOPMENT TESTS                    CERTIFICATION TESTS



Fig. 31.   Proposed certification procedures.

(a) The current approach to rotorcraft icing certification which, although not insisted on, generally results in heavy reliance on natural icing tests, which are extremely expensive to achieve the necessary confidence levels in the ability of the protection systems to cope with extreme conditions.  This approach usually results in a lengthy "trial and error" iterative process in the development cycle, as well as the expensive search for extreme atmospheric conditions during certification.

(b) An interim approach utilizing a number of simulated and artificial techniques (discussed below).

(c) The eventual goal in which major reliance can be placed on analysis and/or simulated/artificial icing tests (whichever is simpler and cheaper) using natural icing tests to spot check conditions of adequate ice protection system performance.

Since the ultimate solution will take a long time to mature, and is likely to evolve out of interim solutions, the immediate research focus should be on technology for implementing a hybrid (test and analysis) approach.  It should not be necessary to use all the elements of the "interim" approach on any specific certification, although all these elements may contribute to a generic data base that could be drawn on to increase confidence in any extrapolation of data in a given program.  In its most simple form, the following scenario represents a reasonable and economical approach at which to aim:

- Based on two-dimensional testing and analysis, the extent and probable cycle time for an (electro-thermal) deicing system would be hypothesized.

- Tests in static spray rigs (e.g., Ottawa) would be used to establish the deicing cycle necessary to avoid runback ice and limit accretion to a level which two-dimensional tests indicate should not produce intolerable torque rise or control load buildup in forward flight.

- From castings made for the critical accretions allowed in the deice cycles, make replicated ice shapes for forward flight testing under dry air conditions.  Such shapes could be obtained from computer codes or tests conducted in artificial conditions (e.g., Ottawa spray rig) representative of both typical natural icing conditions and for the extreme event/critical conditions.

- Correlate the replicated icing shape effects on forward flight characteristics for the frequently encountered conditions with tests in natural icing.

- Possibly, and only if it is shown to provide valid and useful results, increase confidence in prediction of extreme event characteristics with artificial icing flight testing (e.g., HISS).

- Certification would then be based on limited tests in natural icing conditions and on flight tests with replicated ice in the worst conditions.  Analysis methods would be used primarily to get the best "first cut" on deicing system design and assist in the correlation of all the tests and techniques used.

Eventually it should be possible to base certification solely on:

- Analysis correlated by flight tests of the specific design in natural icing conditions

- Analytical extrapolation/interpolation to the extreme event/critical conditions

6.5.4 Conclusions

While sufficient data do not yet exist to prove clearly the extent to which analysis, model and full-scale artificial and simulated ice testing could expedite the clearance procedure, available evidence suggests that with a more complete technical base, a far more reliable, thorough and less-expensive clearance procedure could be evolved. However, to do this, certain key areas of research must be undertaken to confirm that certain key assumptions implicit in the approach suggested above are valid and to provide a data base for correlation of discrete elements of the analysis. These assumptions are:

1. There is no significant difference between the shapes and extents found at the low speeds achievable in ground based spray rigs and the speeds of interest for the flight envelope to be cleared which would invalidate dry air forward flight testing of shapes obtained for hover rigs. This assumption is fundamental to the approach suggested above and is not yet being addressed by any research program.

2. Rotor deice cycles and coverage allow essentially the same shape and extent of ice buildup at both low and high speeds. This assumption could be relatively easily checked by rotor camera documentation of in-flight shedding at low and high speeds.

3. Replicated ice shapes derived from ice shapes observed in icing ground rig tests, can adequately replicate the aerodynamic effect of natural ice. This assumption is already under thorough examination using two-dimensional testing techniques by NASA in the U.S.

To confirm the first assumption, a model program should be instituted which uses a facility (such as the S-1 tunnel at Modane) to produce reasonable replication of rotor icing phenomena. From this it should be possible to obtain data on the shape and extent of accreted rotor ice at typical forward flight conditions. Scale effects can be accounted for by supporting analysis work at both full- and sub-scale.

These data could then be compared with similar data accumulated on the same rotor utilizing the same model spray rig in the same facility at low speeds. If aerodynamic wall effect phenomena are found to be limiting at low speeds by using this facility, similar data could be acquired by using an outdoor model hover stand (such as the Sikorsky facility in Connecticut) where ambient temperatures during the winter would also allow icing tests to simulate, say, the Ottawa facility in model scale.

Such an international program would be an excellent opportunity to address a question of considerable importance to the rotorcraft icing community at large.

As well as answering the specific question above, data from such a test would also provide a valuable data bank of rotor ice accretion shapes, accretion extent, performance and loads data, which will be necessary to correlate the discrete modules of analytical codes which model the whole range of icing accretion and system effect phenomena.

The approach here is attractive but, because several important assumptions are as yet unsupported it represents, at the present level of knowledge, a high risk. Nevertheless, should success be achieved by this means the potential benefits would be considerable.


6.6  CERTIFICATION/QUALIFICATION FLIGHT TEST AND OPERATIONAL EXPERIENCE

6.6.1  Introduction

This section summarizes the flight experience of France, the United Kingdom, and the United States since 1980 relative to certification/qualification of helicopters for flight into icing conditions, as well as the operational experience under icing conditions. The French experience consisted of certification and operational efforts for full clearance of the Aerospatiale 332 Super Puma. The U.K. experience consisted of certification and operational efforts for limited clearance for the Puma HC Mk 1 and the Chinook HC Mk 1 helicopters without rotor blade deicing and certification program for the Chinook with rotor blade deicing.

United Kingdom experience also consisted of rotor ice-protection system development on the Wessex MK 5 for application to the Westland/Agusta EH 101 for future certification efforts. The U.S. military qualification (which is equivalent to the FAA, French, and U.K. "certification" terminology) experience was extensive and consisted of the AH-64A, UH-60A, EH-60A, CH-53E, and the SH-60B helicopters. The BHT 412, BHT 214ST, and the S-76 were flight tested under FAA certification requirements. Due to contractor proprietary rights and other reasons, the complete flight experience is not presented on some of the U.S. helicopters: however, as much information as is available is provided. Table 21 summarizes the certification/qualification flight-test experience for the helicopters discussed in this section. Operational experience is discussed separately under par. 6.6.4. A summary consisting of conclusions and recommendations is contained in par. 6.6.5.

6.6.2  Certification/Qualification Flight-Test Experience

6.6.2.1  French AS 332 Super Puma (Ref. 66). Certification flight tests were conducted in dry air and natural icing conditions during 1981/1982/1983 to support a full clearance per the certification requirements of FAR, Part 25, Appendix C. Additionally, tests were conducted to determine the capability for flight into icing conditions without ice protection.

TABLE 21.- SUMMARY OF ICING CERTIFICATION FLIGHT TEST EXPERIENCE FOR HELICOPTERS



| | | | | FLYING QUALITIES TIME (HR-MIN) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | DRY AIR | SIMULATED ICING | NAT ICING | | REMARKS |
| | | | | | | | | STANDARD U.S. NAVY CONFIGURATION. RELEASE NOT ISSUED DUE TO BLADE DAMAGE. TEST SUSPENDED. | |
| | | | | | | | | STANDARD COMMERCIAL CONFIGURATION. TESTING CONDUCTED TO OBTAIN DATA TO SUBSTANTIATE FAA CERTIFICATION REQUIREMENT. | |
| | | | | NONE | | 11 HOURS BEHIND OTTAWA SPRAY RIG | 12 | STANDARD COMMERCIAL CONFIGURATION. TESTING CONDUCTED TO OBTAIN DATA TO SUBSTANTIATE FAA CERTIFICATION REQUIREMENT. | |
| | | YEAR | NONE | | | 11 OF HOURS BEHIND OTTAWA SPRAY RIG | 0 | STANDARD COMMERCIAL CONFIGURATION. TESTING CONDUCTED TO OBTAIN DATA TO SUBSTANTIATE FAA CERTIFICATION REQUIREMENT. | |

The helicopter was a standard Super Puma configured with electrically deiced composite main-rotor blades, electrically anti-iced composite tail-rotor blades, lightning protection for the complete deicing system, pneumatic deicing of the horizontal stabilizer, weather radar, ice detector, and various fairings. *Figure 82* depicts a front view of the Super Puma following a natural icing encounter. Instrumentation/test equipment consisted of a Leigh detector, rosemount detector, Johnson-Williams hot-wire probe, fixed probe fitted with a graduated plate, and a Knollenberg FSSP, in addition to recording 24 basic helicopter parameters, 4 icing parameters, 12 deicing parameters, and 23 stress and vibration parameters.

Icing tests were conducted within the instrument flight envelope and gross weight and airspeed limitations, pressure altitudes to approximately 10,000 ft, OAT from -2°C to -20°C and LWC from 0.2 $g/m^3$ to 2.5 $g/m^3$.

The main effect of flight into icing conditions was a temporary increase in the four-per-rev vibrations in level flight as blade heating goes off. This hindrance disappears as the blade leading-edge strip is heated during the leading-edge "d" strip deicing cycle. *The transient vibration increase was acceptable for every icing encounter* and the severe function operation was not required to augment the number of deicing cycles. Main-rotor blade stall was approached in level flight while flying in icing conditions and it was recommended not to increase collective pitch over 15.5° while in such conditions. Whenever a deicing strip failed, the vibration levels became irregular as a result of assymetric deicing.

The most significant engine parameter variations occurred in intermittent icing conditions where the effects of icing were amplified by turbulence and temporary increases to maximum engine continuous power. The variations were exceptional and decreased as soon as the leading-edge "d" strip was heated. The variations in continuous icing conditions were much lower and posed no problems. The variations were cyclic and related to the main-rotor deicing system operation. Partial clogging of the air intakes resulted in a decrease of 7% for the power available under the most significant clogging. This caused a performance penalty both in and out of the icing conditions so long as the intakes were iced.

Depending on the icing severity, the average decrease in airspeed was 5 to 10 knots in continuous icing conditions. Ice accretions noted on the aircraft during landing was estimated by extrapolation to represent approximately 50 kg.

Handling qualities under icing conditions resulted in pilot work load being insignificantly higher than experienced in IMC flight in turbulence. Yaw/roll interference occurred during torque variations on some flights which resulted in heading deviations of approximately 10°. These interferences were evidenced in continuous icing conditions, calm air, and were often confused with turbulence effects. The preceding occurs during torque increases associated with the deicing system off followed by a rapid torque decrease as the "d" strip is heated. There were no other unusual characteristics during flight into icing conditions. Critical stress values on dynamic components were never reached during any icing encounter.

Based on test results, the Super Puma was certified by the French Aviation Authorities and the U.S. Federal Aviation Administration (FAA) for flight into forecast icing conditions without restriction. Additionally, based on flight tests, it appears possible to operate the Super Puma without full ice protection up to 8,000 ft altitude, minimum temperature of -6°C to -10°C (depending on icing severity), and in light to moderate icing.

6.6.2.2  U.K. Chinook (unheated main-rotor blades) (Ref. 67). Certification flight tests were conducted in natural icing conditions during 1982/1983 to support a limited icing envelope clearance down to -10°C. Additionally, the performance capability of different instruments to measure LWC was compared and different methods of obtaining water droplet sizes were used.

The trials helicopter was a standard Chinook configured with fiber composite main-rotor blades, engine anti-icing with engine intake all weather screens, electrically heated windscreen, and rear rotor droop stop covers. Instrumentation/test equipment included an A&AEE OAT sensor, Leigh Mk12, Rosemount 871 FFI, RAE thermal probe, A&AEE vernier device ("hot" rod), Knollenberg FSSP-100, ARL Soot Gun, video cameras to visualize engine "D" rings and recording system.

Icing tests were conducted within the instrument flight envelope, with takeoff gross weights up to 22,220 kg, pressure altitude to 9,000 ft, airspeed to 130 KIAS, OAT to -10°C, and mean LWC to 0.47 $g/m^3$.

The Chinook could typically continue flight at 100 to 120 KIAS with increased CGI readings and power increases of between 5% and 20%. Below -9°C high CGI readings, large power increases and increased vibration due to asymmetric ice shedding occurred. Minor blade damage resulted from shed ice. No engine damage occurred during the trials. No ice developed inside the fixed intake screens. Blockage of screens was observed but with the bypass screens removed there was no significant reductions in engine power available.

Based on test results, a limited clearance was established for the Chinook with unheated fiber composite main-rotor blades. The clearance basically includes operational limitations (non-icing conditions up to at least 1,000 ft above the surface and others), maximum airspeed of 130 KIAS, maximum pressure altitude of 7,000 ft, not less than -6°C true temperature, limits on the maximum torque, and increase of torque due to icing, no marked increase in vibration levels, and flight into mixed snow and icing conditions as well as

Figure 32. AS 332 Super Puma following natural icing encounter.

freezing rain is prohibited. The restriction on "mixed" conditions was due to a lack of test experience in snow.

    6.6.2.3 U.K. Chinook (heated rotor blades) (Ref. 68). Certification flight tests conducted in dry air and natural icing conditions started during 1983/1984 to support a limited icing envelope clearance down to -20°C. Test objectives were the same as for the U.K. Chinook with the unheated blades and additionally also to develop the ice protection systems and assess the need for engine anti-icing.

The trials helicopter was a standard Chinook as discussed in par. 6.6.2.2 except that the electrically heated fiber composite rotor blades were installed. Instrumentation/test equipment installed was the same as for the Chinook with the unheated rotor blades. Additional instrumentation included two A&AEE rotor head cameras, hand-held 35-mm camera, rotor-blade temperature sensors, critical dynamic component strain gauges, video cameras with inputs via fiber optic cables to monitor the engine intakes, an extensive, on-board real-time computing facility for displaying selected parameters including performance, handling qualities, atmospheric conditions and stress.

Icing tests were conducted within the instrument flight envelope, with takeoff gross weights up to 50,570 lb, pressure altitude to 10,000 ft, airspeed to 130 KIAS OAT to -18.5 C°, and mean LWC to 0.42 $g/m^3$.

Considerable testing was conducted; however, test results are still being analyzed and future tests are planned. In temperatures of 0°C to -4°C, there was little loss of performance experienced. Blade deicing was not needed except in freezing rain. Ice shed satisfactorily from the heated blade portion but before optimization of the heating cycle run-back occurred. Heavy airframe icing occurred. Between -4°C and -8°C performance degradation was acceptable. Heavy airframe icing occurred. At -8°C to -14°C, high values of LWC were encountered and significant performance degradation occurred. At -14°C to -20°C, LWC was relatively low, there was no significant performance degradation, and ice buildup was a "streamlined" extension to the leading edge of the airfoil. In all icing encounters, there were no aircraft handling problems, and vibration increases were mild. Simulated failures of the rotor-blade mats were induced. The consequences appeared acceptable in the short term. Extended flight with failed mats needs to be evlauated. It was determined engine bleed air was not needed, which results in increased power available. The Rosemount nonaspirated detector was very reliable and was used to initiate blade heating.

The control laws for the rotor-blade electrical deicing system were established and will be used for future testing. Additional certification flight testing is required, particularly at higher LWCs below -15°C. The type of test instrumentation/equipment used resulted in highly successful test results. However, there were significant discrepancies in LWC measurements during nonsteady-state icing conditions. This aspect needs further attention, as does the comparison of water droplet sizes encountered during tests as compared to the sizes used for design and certification purposes.

6.6.2.4 U.K. Puma (Ref. 69). Certification flight tests were conducted in natural icing conditions during 1982/1983 to provide evidence for a clearance in icing conditions in service operation to temperatures down to -10°C. Additionally, the performance capability of different instruments to measure LWC was compared and different methods of obtaining water droplet sizes were used.

The trials helicopter was a standard Puma configured with fiber composite main-rotor blades, multipurpose engine air intakes, and an electrically heated windscreen. Droop stop covers and a tail-rotor servo fairing were installed. Instrumentation/test equipment consisted of an A&AEE OAT sensor, Leigh Mk 12, Rosemount 871 FFI, RAE thermal probe, A&AEE vernier device ("hot rod"), Knollenberg FSSP-100, ARL soot gun, 35-mm camera mounted on the main-rotor hub, hand-held camera, strain-gauge torquemeter for main-rotor gear box, and strain gauges fitted to critical dynamic components.

Icing tests were conducted within the instrument flight envelope with takeoff gross weights up to 7,000 kg, pressure altitudes up to 9,800 ft, airspeed to 128 KIAS, OAT to -12°C and LWC to 0.63 $g/m^3$. Special transmission torque limits were necessary since RAF Pumas are not fitted with torquemeters, and are flown to collective pitch limitations.

Limiting conditions, due to increased power required, vibration or stress levels were reached on a number of occasions. It was often necessary to reduce airspeed during icing encounters to 80 KIAS and it was rarely possible to continue flight above 120 KIAS. Ice accretion on a pitot mast caused one airspeed indicator to read incorrectly. Minor blade damage from shed ice occurred on three occasions on the main rotor and twice on the tail rotor. The Rosemount and Leigh detectors gave early warnings on ice conditions and LWC readings were in good agreement in stable LWCs. In variable icing conditions, the Rosemount gave higher values of LWC. Both systems were initially unreliable. Irregularities still occurred after manufacturer's corrections. The RAE probe gave excellent results up to 0.5 $g/m^3$ and above this value underread. This probe has considerable potential. Water droplet size measured by the Knollenberg were generally 2 to 5 μm larger than those measured by the soot slides. The mean diameter of the water droplets was lower than anticipated (between 10 and 15 μm). Further analysis is planned to relate water droplet size to ambient temperature.

Based on test results, a limited clearance was established subject to incorporation of certain modifications including a torquemeter, and a satisfactory analysis of stress data to establish the effects on fatigue lives due to blade icing. The clearance includes operational limitations (nonicing conditions up to at least 1,000 ft above the surface and others), maximum airspeed of 120 KIAS, maximum pressure altitude of 5,000 ft, not less than -6°C true temperature, (-10°C is permitted within 1,000 ft AGL for pressure altitudes up to 2,000 ft), limits on the maximum torque rise allowed above a normal torque, no marked increase in vibration levels, bank-angle limitations, maximum gross weight of 7,000 kg, and rate of descent restrictions of 1,500 ft/min after an icing encounter. Flight into mixed snow and icing conditions is permitted provided the condition is vacated if slush builds at temperatures of -4°C or higher. Of the three LWC instruments, the aspirated ones, the Leigh Mk 12, and the Rosemount 871 FFT were unreliable and not suitable for service use. The RAE probe appeared to show promise for both test and service use. The water droplet

size measurements of the Knollenberg FSSP-100 and ARL soot gun were not in agreement. Both instruments gave droplet sizes lower than those given in the various icing atmospheres.

6.6.2.5 U.K. Wessex HU MK5 (ice-protection system development) (Refs. 70-72). Development trials to substantiate future certification of a rotor ice-protection system were conducted on a Wessex MK 5 during the winters of 1979/1980, 1981/1982, and 1983/1984. Specific tests were conducted to extend experience below -10°C to -20°C on high LWCs and optimize heating "on time" for ice shedding; investigate comparative effects from incorporating heating mats in composite and alloy spars; and assess the proven cycle heating concepts as applied to even and odd number of main-rotor blades. Results are to be applied to the Westland/Agusta EH 101. Secondary test objectives included gathering blade temperature data; gaining exper- ience on a range of ice detectors and severity systems; and gathering general atmospheric data relevant to icing conditions.

The trials helicopter was a standard Royal Navy Wessex HU MK5 modified with an alternator to power an electrothermal rotor blade deicing system and windscreen anti-icing system. A special heated and fluid- anti-iced intake was incorporated but not part of the trials assessment. Instrumentation/test equipment consisted of Tinsley OAT, Rosemount aspirated probe, Leigh MK 10 and 12a aspirated unit, RAE/Plessey thermal probe, A&AEE vernier device ("hot rod"), ARL soot gun, Lucas MK 30 ice detector, Rosemount 871 FA ice detec- tor, engine and helicopter performance and handling-qualities parameters, two 70-mm cameras, one mounted on the main-rotor head and one mounted on the tail cone, main-rotor-blade internal and external temperature measurements, strain gauges installed on the main- and tail-rotor blades and transmission, and rotor-blade current and voltage transducers.

Icing tests were conducted within the instrument flight envelope with gross weights, pressure altitudes and airspeeds within the allowable flight envelope, OAT to -22°C and mean LWC to 0.83 $g/m^3$.

The developed heated rotor blade system functioned satisfactorily in icing conditions to -22°C. No helicopter handling qualities or vibration problems were encountered. The effects of icing on the helicop- ter fell into three distinct groups related to temperatures as follows.

(a) 0°C to -5°C. Acceptable performance was maintained with operative and inoperative blade deicing system. Control loads increased slowly in high LWCs between -4°C and -5°C with the blade deicing system inoperative.

(b) -5°C to -15°C. Significant performance degradation (torque rises) and increased blade and control loads occurred. Without blade deicing in moderate to high LWCs, limitations in stress, performance handling qualities or vibration were reached within seconds. This required immediate vacation of the icing condi- tions. Use of the deicing system allowed prolonged icing encounters without exceeding limitations.

(c) -15°C to -22°C. Performance or rotor loads degradation occurred slowly due to the conformal rime ice accretion characteristics. Ice formed on the blades was very tenacious and difficult to shed. Poten- tial problems stem from asymmetric shedding rather than from performance loss.

The operation of the Lucas heater mat in the helicopter rotor blades was not significantly affected by the use of spar material. Material thickness and composition between the elements and blade surface affected surface temperatures and ice-shedding characteristics.

The Wessex HU MK 5 deicing system provided significant protection down to -20°C. Substantial advances in the optimization of ice-shedding efficiency were made. The successful development achieved can be attributed to the considerable amount of icing experience and the very comprehensive instrumentation/test equipment package.

6.6.2.6 U.S. YCH-47D (Ref. 73). Qualification flight tests were conducted in artificial and natural icing conditions during 1980 to establish a light icing envelope and a 30-min moderate icing envelope for the CH-47D without heated rotor blades. Additionally, an icing envelope with heated blades was to be deter- mined, as well as the usefulness of the Leigh Mk XII LWC display, production FAT probes, windshield wipers, and other modifications.

The test YCH-47D was a prototype helicopter representative of a production aircraft. The helicopter incorporated production fiberglass rotor blades (modified with nonstandard heating elements), auxiliary 40 kVA generator, and equipment modifications. Instrumentation/test equipment consisted of two Rosemount 871 FA detectors, one Leign Mk XII IDU-3, two visual ice detectors, still camera, high-speed movie camera, and two fiber-optic television cameras in the right engine inlet.

Icing tests were conducted in two phases: (1) protected (the deice system operated automatically) in an artificial icing environment and (2) unprotected (the deicing system in a standby status), both in the artificial and natural icing environments. Tests were conducted at gross weights from 34,030 lb to 47,000 lb, pressure altitudes from 1,600 ft to 8,500 ft, airspeeds from 63 KIAS to 136 KIAS, OAT from -2°C to -19°C, and LWC from 0.3 $g/m^3$ to 1.5 $g/m^3$.

The YCH-47D demonstrated an operational capability with the rotor blades unheated to -5°C and LWC up to 0.5 $g/m^3$ without incurring significant blade damage or asymmetric ice sheds. This was demonstrated both in the artificial and natural icing conditions. Below temperatures of -5°C and LWCs greater than 0.5 $g/m^3$ blade damage from shed ice increased significantly and vibration levels from asymmetric ice sheds from the rotor blades caused significant vibration increases. The engines operated satisfactorily down to -15°C

under icing conditons with engine anti-ice OFF. The iced-detector cockpit indications of the icing environ-
ment were unreliable and did not provide accurate ice-accretion rates. No noticeable degradation in han-
dling qualities or performance was encountered.

Based on test results, a light icing envelope clearance to -5°C was established. A moderate icing
envelope for 30 min of -20°C and LWC of 1.0 g/m$^3$ was not feasible due to blade damage from shed ice and high
vibrations from asymmetric blade ice shedding. Insufficient testing was conducted to establish the icing
envelope with heated rotor blades due to additional engineering efforts required to optimize the blade deice
system for satisfactory operation.

6.6.2.7  U.S. UH-60A (Ref. 74).  Qualification flight tests were conducted in artificial and natural
icing conditions during 1980 to establish a moderate icing envelope of -20°C and 1.0 g/m$^3$, determine the
effectiveness of the ice detection subsystem and obtain data for inclusion in the Operator's Manual.

The test UH-60A was a production helicopter incorporating standard deicing/anti-icing systems and an IR
countermeasures suit including the IR suppressor kit. Figure 33 depicts the UH-60A undergoing artificial
icing tests behind the JCH-47C Helicopter icing spray system. Instrumentation/ test equipment was standard
and included still- and high-speed-camera photography and standard calibrated instruments for handling
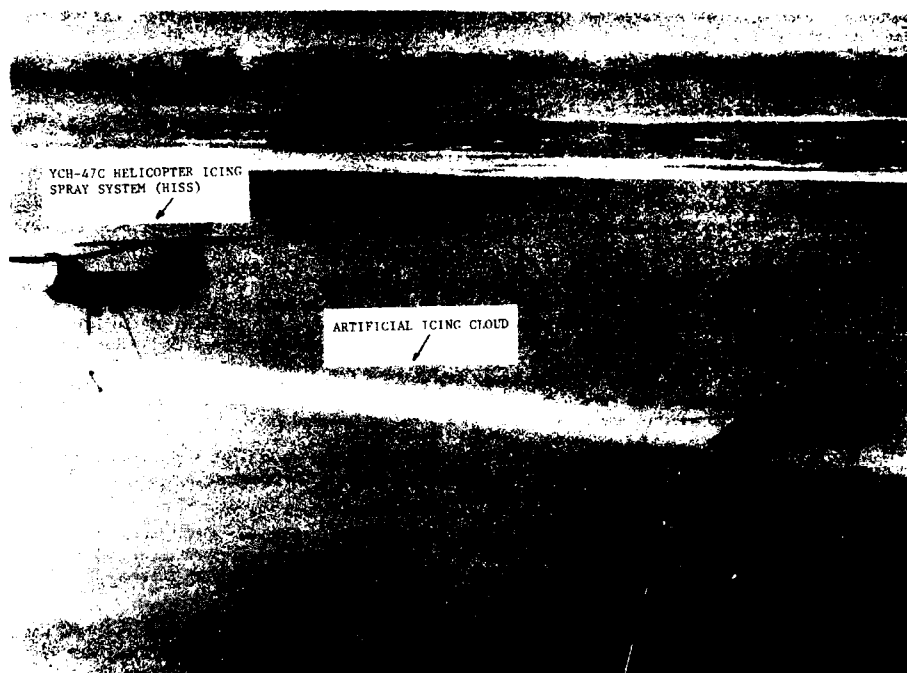qualities and performance.



Fig. 33.  UH-60A artificial icing test behind HISS.

Icing tests were conducted in artificial and natural icing conditions. Tests were conducted with test
gross weights from 16,000 lb to 16,760 lb, pressure altitudes 1,700 ft to 10,000 ft, airspeed from 82 KIAS
to 138 KIAS, OAT from -4°C to -21.5°C, and LWC from 0.01 g/m$^3$ to 1.0 g/m$^3$.

The test UH-60A demonstrated the potential to operate in a moderate icing envelope based on correcting
problem areas. A major problem area was accretion on the rotor-blade drop stops and flap restrainers. The
accreted ice prevented the stops and restrainers from returning to the static positions, thereby causing a
blade hazard during shutdown. At the lower temperature (down to -20°C) ice remained on the rotor blades aft
of the protected areas and in the reverse flow regions. Shed ice caused indiscriminate minor damage and
skin dents to rotor blades, fuselage, and stabilator. Damage appeared acceptable. Shed ice also was
observed by high-speed photography to be ingested into the engines; however, no FOD to the engines was
detected. Ice accreted over numerous areas of the helicopter. Vibration levels did not increase markedly
during the ice-accretion phase, but did increase noticeably for a short period during the deice cycle.
Large increases in "power required" occurred (up to 22% increase over noniced helicopter) during deicing
cycles. There was no noticeable degradation in handling qualities during icing encounters.

Based on test results, the UH-60A demonstrated a moderate icing envelope capability; however, release of a moderate icing envelope was deferred until correction of problem areas, the most significant being the droop stops failing to return to the static position. Other problems requiring correction included the improvement in the deice system "off time" schedule, icing rate meter calibration, and an updated engine inlet modulating valve installation. The degradation of performance during icing encounters was noted in the Operator's Manual. The Rosemount ice detector system appeared to operate satisfactorily and compared favorably with other methods of determining LWC and icing severity. One method was the cloud parameter measurement equipment on the JU-21A SIIDS aircraft, and another, the visual rate indicator.

6.6.2.8  U.S. UH-60A reevaluation (Ref. 75). Qualification flight tests were conducted in artificial and natural icing conditions during 1981 to evaluate the correction of problem areas exhibited during the UH-60A qualification in 1980.

The test UH-60A was the same production UH-60A and in the same configuration as the one that was used in 1980 qualification tests except it had incorporated droop stop anti-ice protection, updated engine inlet modulating valve installation, revised deice system of time schedule, and an updated icing rate meter calibration. Instrumentation/test equipment was the same as that in the 1980 qualification tests.

Tests were conducted at test gross weights averaging 16,300 lb pressure altitudes from 2,800 ft to 7,000 ft, airspeed from 97 KIAS to 125 KIAS, OAT from -4°C to -15°C, and LWC from 0.15 g/m$^3$ to 0.5 g/m$^3$.

The test UH-60A experienced considerable unpredictable ice shedding from the main-rotor blades with random assymetric ice sheds occurring anywhere from 17 to 52 min after entering the icing environments. Frequency of sheds were a function of LWC and OAT. Increased vibration occurred when blade ice shed and airframe and blade damage occurred from shed ice. Performance degradation occurred as previously reported. There were no indications (visual or performance) which would indicate the icing severity.

Based on test results, the UH-60A helicopter demonstrated an unprotected icing envelope (no blade deicing system) of 0.3 g/m$^3$ at temperatures to -20°C. This resulted in acceptable vibration levels and tolerable blade and airframe damage. Unacceptable damage occurs at LWCs of 0.5 g/m$^3$ and greater. As in prior tests, the droop stops (unheated) would not reseat after icing encounters. Any operation anticipated in icing environments of greater than 0.3 g/m$^3$ would require an LWC indication.

6.6.2.9  U.S. UH-60A Icing envelope evaluation with blade deicing system inoperative (Ref. 76). Qualification flight tests were conducted in artificial and natural icing conditions during 1982 to establish an icing envelope for the UH-60A with the blade deicing system inoperative.

The test UH-60A was a production UH-60A in the same configuration as the one used in 1981 qualification tests in which configuration improvements were incorporated. However, the blade deicing system was used as a safety backup only since an icing envelope without blade deicing capability was defined. Instrumentation/ test equipment was standard with the addition of a visual ice probe.

Tests were conducted at test gross weights averaging 16,300 lb, pressure altitudes from 2,800 ft to 7,000 ft, airspeed from 97 KIAS to 125 KIAS, OAT from -4°C to -15°C, and LWC from 0.15 g/m$^3$ to 0.5 g/m$^3$.

The test UH-60A experienced considerable unpredictable ice shedding from the main-rotor blades with random asymmetric ice sheds occurring anywhere from 17 to 52 min after entering the icing environments. Frequency of sheds was a function of LWC and OAT. Increased vibration occurred when blade ice shed and airframe and blade damage occurred from shed ice. Performance degradation occurred as previously reported. There were no indications (visual or performance) which would indicate the icing severity.

Based on test results, the UH-60A helicopter demonstrated an unprotected icing envelope (no blade deicing system) of 0.3 g/m$^3$ at temperatures to -20°C. This resulted in acceptable vibration levels and tolerable blade and airframe damage. Unacceptable damage occurs at LWC's of 0.5 g/m$^3$ and greater. As in prior tests, the droop stops (unheated) would not reseat after icing encounters. Any operation anticipated in icing environments of greater than 0.3 g/m$^3$ would require a LWC indication.

6.6.2.10  U.S.-YEH-60A Quick Fix (Ref. 77). Qualification flight tests were conducted in artificial and natural icing conditions during 1984 to establish a moderate icing envelope of the UH-60A with the prototype Quick Fix installation (the installation results in the redesignation of YEH-60A).

The test YEH-60A was a production UH-60A with the prototype Quick Fix installation. Figure 34 shows a standard UH-60A with the installation in which the main external differences are the four FM DF dipole antennas and the one retractable ECM antenna shown in the retracted position. Instrumentation/test equipment was standard and included still and high-speed-camera photography as well as color video cameras monitoring the FM DF antennas.

Icing tests were conducted in artificial and natural icing conditions at an average gross weight of 15,700 lb, pressure altitudes from 830 ft to 7,630 ft, airspeed from 93 KTAS to 131 KTAS, OAT from -4°C to -22.5°C, and LWC from 0.15 g/m$^3$ to 1.16 g/m$^3$.
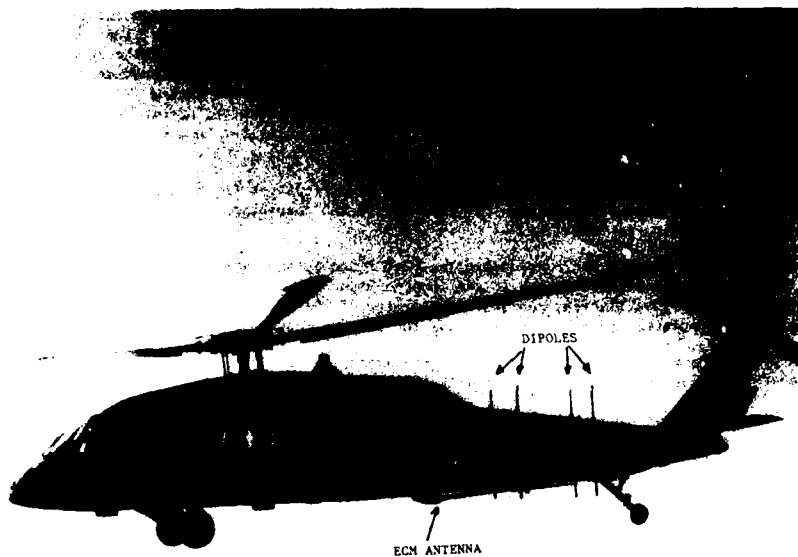
Fig. 34. YEH-60 quick fix.

The basic ice-accretion, ice-shedding, vibration, performance and handling qualities of the YEH-60A were similar to the qualified UH-60A; however, ice-accretion and shedding characteristics of the FM dipole antennas and ECM antenna caused serious problems. These characteristics were similar under artificial and natural icing conditions. Ice accreting on the dipoles caused antenna vibrations resulting in structural failure of the mounting systems. The shed ice caused tail-rotor blade damage. Anti-icing heating elements were designed and incorporated during tests which eliminated ice buildup on the FM dipole antennas; however, they caused EMC problems. Ice buildup on the ECM antenna when extended resulted in vibrations; however, the ice was self-shedding before unacceptable antenna oscillations occurred.

Based on test results, the YEH-60A configuration was satisfactory for operation in a moderate icing envelope provided anti-icing heating elements are incorporated in the FM dipole antennas. The ECM antenna ice accretion and shedding characteristics were satisfactory. Further tests are required to optimize the heating element wattage for proper power density.

6.6.2.11  U.S. UH-60A with external stores support system (ESSS) (Ref. 78). Qualification flight tests were conducted in artificial and natural icing conditions during 1984 to substantiate the moderate icing envelope of the UH-60A with the ESSS installed.

The test UH-60A was a production UH-60A with the standard deicing/anti-icing systems and the ESSS. The ESSS consists of two 450-gal and two 200-gal auxiliary fuel tanks mounted externally on a wing support structure. Additionally, the UH-60A was configured with a wire strike protection system (WSPS) and reoriented pitot static tube (Fig. 35).

Tests were conducted at gross weights from 12,180 lb to 18,530 lb, pressure altitudes from 80 ft to 7,960 ft, airspeed from 100 KIAS to 135 KIAS, OAT from -3°C to -21°C, and LWC from 0.05 g/m$^3$ to 1.05 g/m$^3$.

The basic ice-accretion, ice-shedding, vibration, performance and handling qualities of the UH-60A with the ESSS were similar to the qualified UH-60A; however, ice-accretion and shedding characteristics of the WSPS and the pitot-static tube support structs and fairings caused serious problems. Ice buildup and shedding on the WSPS components (wire cutter and deflectors) caused FOD to the airframe. Ice accretion on the anti-iced pitot-static tube support resulted in runback behind the supports and large ice buildups in front of the engines. This increased the potential for engine FOD in the event the ice were to shed. Ice also accreted on the fairings where it was not anticipated. The icing environments, both artificial and natural, resulted in similar ice shapes and accretion characteristics on the helicopter and good comparison was obtained between the artificial icing produced by the HISS and natural icing.

Fig. 35. UH-60A with external stores support system (ESSS)

Based on test results, the UH-60A helicopter with the ESSS installation demonstrated a marginal capability to operate in the moderate icing envelope of temperatures to -20°C and LWC to 1.0 g/m$^3$. Efforts are under way to correct the ice-accretion and shedding problems with the WSPS, pitot-static tube support and the fairings.

6.6.2.12  U.S. YAH-64 (Ref. 79).  Qualification flight tests were conducted in artificial icing conditions during 1982 to determine the ice-protection and detection systems effectiveness, the effect of ice accumulation on performance and handling qualities, and the capability of the YAH-64 and associated subsystems to operate in moderate icing conditions.  The tests conducted were the first in a series over a period of two or three icing seasons to substantiate airworthiness qualification for flight in moderate icing conditions.

The test YAH-64 was a prototype helicopter configured with a main- and tail-rotor deice system and complete anti-ice systems for the windscreens, pitot-static tubes, air data sensor, engines, engine inlets, nose gearbox and cross shaft fairings, the target acquisition and designation system (TADS) and the pilot night vision system (PNVS).  Deice capability was provided for the Hellfire missiles.  Figure 36 depicts the YAH-64 with accreted ice following an icing encounter.  Instrumentation/test equipment was standard with the addition of three on-board high speed cameras.  Hand-held cameras were used in the cockpit to document ice accretion.

Tests were conducted at gross weights from 16,280 lb to 16,700 lb, pressure altitudes from -400 ft to 9,800 ft, airspeed from 90 KIAS to 120 KIAS, OAT from -5°C to -21.5°C, and LWC from 0.17 g/m$^3$ to 1.1 g/m$^3$.

The test YAH-64 main and tail-rotor deicing systems worked exceptionally well in the artificial icing environment; however, there was evidence of shed-ice damage to the rotor blades, which in one case (high LWC) resulted in a blade change.  The canopy frames accreted large amounts of ice as did the TADS, PNVS, Hellfire system, and other subsystems on the helicopter.  In some cases, ice was observed to shed and pass through the rotor systems or enter the engines.  Engine inspections after icing encounters revealed no evidence of FOD; however, rotor-blade damage occurred.  While the helicopter accreted considerable ice on the exposed areas of the helicopter and subsystems, there was no apparent degradation in performance or handling qualities.  At temperatures below -15°C and at LWC of 0.75 g/m$^3$ or greater, there was a noticeable increase in vibration levels, which was not annoying.

Based on test results, several system concepts were successfully demonstrated including effective main and tail-rotor blade ice-shedding characteristics, satisfactory Hellfire missile deicing, engine anti-ice,

TARGET ACQUISITION
DESIGNATION AND PILOT
NIGHT VISION SENSOR
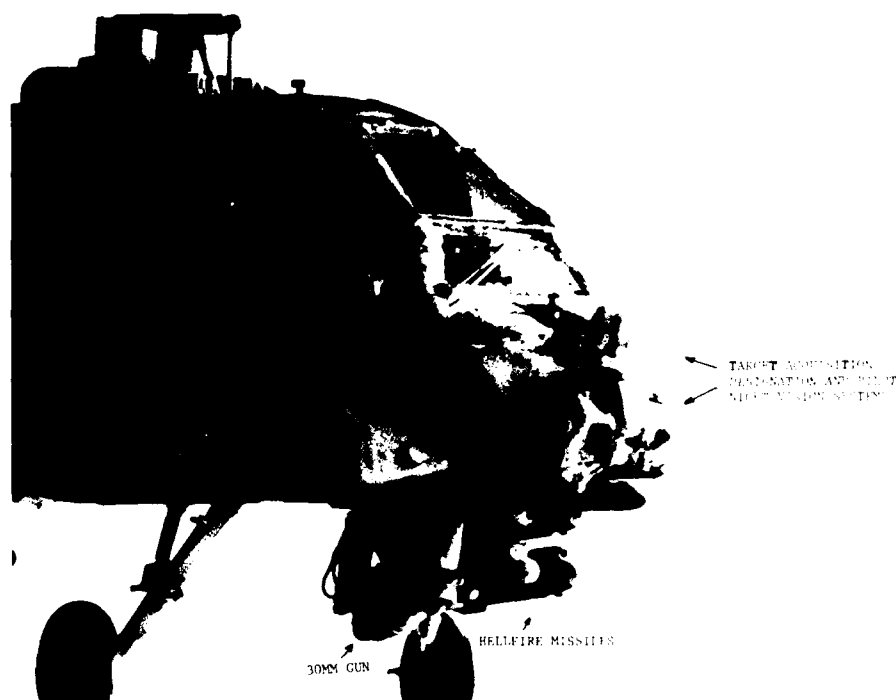
HELLFIRE MISSILES

30MM GUN

Fig. 36. YAH-64 following artificial icing encounter.

pitot-static, air-data sensor, wing-pylon articulation, and mechanical operation of the gun. Overall, the icing tests were very successful.

6.6.2.13 U.S. CH-53E (report reference not available). Qualification flight tests were conducted during 1984 to evaluate the CH-53E helicopter for IFR cruise flight in icing conditions up to and including moderate icing.

The helicopter was a standard U.S. Marine Corps CH-53E, configured with windshield anti-icing, engine and engine inlet anti-icing, and pitot-static anti-icing. Instrumentation/test equipment consisted of engine air particle separators (EAPS), inlet pressure loss sensors, video cameras in the No. 2 EAPS area, and the tail-rotor hub, vibration sensors on the pilot's seat, main-gear box, tail-rotor gear box and horizontal stabilizer, and a Rosemount detector.

Tests were conducted in artificial and natural icing at gross weights from 43,000 lb to 52,500 lb, pressure altitude from 2,000 ft to 10,000 ft, airspeeds from 120 KIAS to cruise speeds, OAT from -5°C to -20°C, and LWC from 0.2 g/m$^3$ to 1.1 g/m$^3$.

Ice accreted on the pitot tube and pitot mount above trace icing conditions and resulted in significant unreliable and erratic airspeed indications (airspeed error up to 50 KIAS). Engine shutdowns, when ice was still accreted on the rotor blades, resulted in the ice shedding, causing hazards to ground personnel. Asymmetric blade ice sheds at the high LWCs (0.7 g/m$^3$) and high-time icing exposure (over 30 min) resulted in high vibration levels which were unacceptable. Vibration levels at LWCs 0.5 g/m$^3$ or less were acceptable. Flight under light icing conditions (less than 0.5 g/m$^3$) resulted in 6% to 8% increases in power required. Flight under moderate icing conditions (above 0.5 g/m$^3$) resulted in 12% to 17% increases in power required. Fuselage and rotating components ice accretion resulted in minor performance degradation (estimated at less than 5 KIAS), even with significant ice of up to 5.5-in. thick on some locations. Little shedding was observed from fuselage icing. Significant rotor-blade damage from shed ice occurred at LWCs greater than light icing. The ice-detection system was unreliable in icing conditions and was not accurate as an indication of icing severity. Handling qualities were similar to those experienced in nonicing environments; however, the unreliability of the pitot-static system in the icing environment could result in uncommanded inputs to the automatic flight control system (AFCS), which seriously affects the helicopter response.

Based on test results, the CH-53E demonstrated the capability for flight into light icing conditions of 0.5 g/m$^3$ LWC or less, to an OAT of -10°C or higher, and exposure in icing conditions of 30 min or less. It

was recommended that a release of an envelope be based on correction of the problem areas associated with the pitot-static system.

6.6.2.14 U.S. SH-60B (report reference not available). Qualification flight tests were conducted during 1985 to evaluate ice accretion and shedding characteristics of the helicopter with extensive mission equipment and avionics changes which modified the external configuration. Qualification was conducted to verify the helicopter with the preceding modification to ensure a moderate icing envelope capability.

The helicopter was a standard U.S. Navy SH-60B, configured with the U.S. Army UH-60A deicing/anti-icing systems except for LWC indication and droop stop heaters. Instrumentation/test equipment consisted of vibration pickups at the pilot, copilot, and sensor operator stations. Video cameras were used to monitor the hoist. Additional photographs and video coverage was provided by the U.S. Army JU-21A with the cloud parameter measurement equipment.

Tests were conducted in artificial icing at mission gross weights, pressure altitudes below 10,000 ft, cruise airspeeds, OAT from -7°C to -21°C, and LWC from 0.21 g/m$^3$ to 0.3 g/m$^3$.

Tests conducted were terminated after four flights due to significant blade damage caused by shed ice, which was unusual for the icing conditions. Indications are that the deice control panel may have been faulty. Significant ice accreted on the fuselage and mission equipment but did not cause shed-ice problems. The rotor system droop stops would not completely seat on shutdown causing safety problems. Handling qualities and performance were not adversely impacted. The ice detector was unreliable and failed on two occasions. Except for one case, vibration levels were low.

The test results were inconclusive; however, the SH-60B demonstrated a limited potential for flight into icing conditions. Additional testing was recommended following an evaluation of the limited test results.

6.6.2.15 U.S. Sikorsky S-76 (report reference not available). Certification flight tests were conducted during 1982 to substantiate an icing envelope to the (FAA).

The helicopter was a standard commercial version configured with main- and tail-rotor deice systems, windshield anti-icing, pitot anti-icing, and engine inlet and engine anti-icing. Instrumentation/flight equipment consisted of standard performance and handling qualities instrumentation, Rosemount and Leigh ice detectors, current and voltage measurements, cockpit accelerometers, and rotor-blade zone temperatures.

Icing tests were conducted in artificial and natural icing conditions. Test results are not documented or available for publication.

6.6.2.16 U.S. Bell Model 412 (Ref. 80). Certification flight tests were conducted during 1981 and concentrated primarily on obtaining development test data to substantiate an icing envelope to the FAA. The substantiation of an icing envelope was based on data obtained from artificial icing flight tests at the Ottawa spray rig, and analytical data.

The helicopter was a standard commercial version configured with a main- and tail-rotor deicing kit, 30 kV-alternator kit, windshield deicing system, and icing detector system. Instrumentation/test equipment consisted of standard type (including stress measurements), rotor-blade zone temperature measurements, current and voltage measurements, engine delta pressures, Leigh and Rosemount ice detectors, Bell Helicopter designed ice detector, cloud-particle spectrometer, forward-scattering spectrometer probe, and high-speed movie cameras mounted on the rotor mast and tailboom.

Icing tests were conducted at gross weights, altitudes, and airspeeds within the approved FAA flight envelope, OAT -5°C to -20°C, and LWCs 0.25 g/m$^3$ to 1.0 g/m$^3$.

The initial efforts of the icing tests were in optimizing the ice controller cycle time to obtain adequate ice-shedding and vibrational characteristics. Engine inlets operated satisfactorily and ice accretion on the elevator did not result in unacceptable loads or handling-qualities characteristics. Blade-ice shedding characteristics and increased power requirements in the artificial icing conditions presented problems associated with the deicing systems.

Based on test results, the objectives of the test program were achieved, and data obtained will be used to optimize the main- and tail-rotor icing systems and as a basis for conducting further evaluations of all helicopter deicing/anti-icing systems. The tests results were applicable to certification requirements; however, they mainly supported developmental efforts. Consequently, several recommendations relative to future certification flight tests resulted in major recommendations which included verifying main- and tail-rotor deicing capability in natural icing, further evaluation of all deicing/anti-icing systems, and leading-edge deicing on the horizontal elevators. Other recommendations included main-rotor-blade surface temperature measurements in all heater zones, mark helicopter with flight numbers for photographic identification, the helicopter should be a dark color for better identification of ice, rotor blades should be dark with heater zones marked in white, install mast-mounted camera, install still camera to take pictures of critical areas (such as inlets), and use a flight crew of three to reduce work load.

6.6.2.17 U.S. Bell Model 214ST (Ref. 81). Flight testing was conducted in artificial icing conditions at the Ottawa spray rig and behind the HISS to obtain data on the heated main and tail rotors, heated windshields, and a booted elevator in support of future FAA certification tests.

The helicopter was a standard commercial version configured with main- and tail-rotor deicing system, heated windshield, heated engine bellmouths, and booted elevators. Instrumentation/test equipment consisted of standard-type (including stress measurements), rotor-blade zone temperature measurements, current and voltage measurements, Leigh and Rosemount ice detectors, Teddington ice detector, and high-speed movie cameras on the main-rotor hub and cabin roof, and video recorders. Additionally, the test instrumentation on the U.S. Army JU-21A was used to provide cloud measurements to support the tests and included a cloud-particle spectrometer, forward-scattering probe, Rosemount and Leigh detectors, and hygrometer.

Icing tests were conducted at gross weights, altitudes, and airspeeds within the approved FAA flight envelope, OAT -5°C to -20°C, and LWCs 0.25 $g/m^3$ to 1.0 $g/m^3$.

Initial efforts in the icing tests were primarily in optimizing the ice controller cycle times, determine correct blade heating voltages and the character and rate of ice accretion to ensure acceptable ice accretion shedding and vibrational characteristics. Further developmental testing was conducted to substantiate the effectiveness of the preceeding in support of future FAA certification requirements.

Based on test results, the objectives of the test program were achieved. The main- and tail-rotor deicing systems final configuration operated satisfactorily and cycle times were correct. There were no significant increases in component loads resulting from ice accretion on the rotor blades. The windshield operated satisfactorily and maintained a suitable ice-free area. The engines require some form of air intake cowl protection. Additional testing is required to substantiate that protected (booted) elevators are required for handling-qualities purposes. The rotor deicing system was not operated in the automatic mode due to the HISS cloud (in some cases the HISS cloud water droplet size exceeds the capability of the detector to provide accurate and stable LWC inputs to the controller). Recommendations relative to future certification requirements included automatic shutdown of the main- and tail-rotor deice systems and master caution lights illumination, and disablement of the deice systems when OAT is greater than and rotors at a minimum operating speed.

### 6.6.3 Overview of Certification/Qualification Efforts

The French, U.K., and U.S. use different methods, techniques, and procedures to certify/qualify helicopters for flight into icing conditions; therefore, the test results and lessons learned vary dependent on application of the preceding. Other member countries generally accept the certification/qualification results of a particular helicopter based on the French, U.K., or U.S. certification/qualification testing. With respect to the methods used, the U.S. effort concentrates on artificial icing behind the HISS then expand an envelope to the extreme icing conditions. Natural icing tests are conducted flying mission profiles to substantiate the artificial icing tests and a final limited clearance. The United Kingdom carries out all testing in natural icing conditions. Additionally, the French and the FAA currently require full clearances per FAR 29, Appendix C, while the United Kingdom and the U.S. military require only limited clearances based on the operational user's requirements. The following discusses the individual country efforts.

#### 6.6.3.1 French efforts.
The certification efforts of the French on the AS 332 Super Puma was extensive and consisted mainly of flights into natural icing conditions with other substantiation efforts consisting of using the Ottawa Spray Rig, icing wind tunnels, and lightning strike simulation tests. Considerable expertise has developed from conducting icing tests since 1964 which ultimately resulted in certification of the SA 330 Puma and AS 332 Super Puma.

The French use conventional performance and flying-qualities measurements in addition to special instrumentation for measuring icing parameters. Parameters consist of LWC, droplet diameter, and static temperature. Extensive instrumentation would include 24 basic parameters, 4 icing parameters, 12 deicing parameters, and 23 stresses and vibrations recorded on magnetic tape.

The French concentrate on conducting icing tests in varied natural conditions in which all deicing/anti-icing systems are checked. The deicing and anti-icing systems have been designed to ensure protection to the FAR 29 icing envelopes. Substantiation of system effectiveness is based on in-flight measurements and observations on simulated or natural icing conditions and theoretical analyses by comparison with measurements taken in flight and in an icing wind tunnel.

#### 6.6.3.2 U.K. efforts.
This account is related to U.K. procedures for military aircraft. The same methods are used for the Army, Navy, and Air Force helicopters.

a. Service requirements: The requirement is specified for the helicopter in question. For helicopters with no blade deicing, this amounts to the best possible clearance within the existing instrument flight (IF) clearance, recognizing it is unlikely that any release below an air temperature of -10°C will be possible. For machines with heated rotor blades, it has been usual to require clearance within the IF envelope down to a temperature of -20°C accepting small penalties in speed and range if necessary.

b. Nature of trials: Most certification testing is carried out in natural icing conditions and the trials aircraft is detached to a suitable site for one or more icing seasons, as necessary. In general, it is accepted that it will not be possible to see the worst icing conditions during a reasonable period of time, usually 1 or 2 years, and in considering what release can be safely used, due account is taken of the scope of evidence that is available from the testing in natural icing together with, particularly for heated rotors, results from analyses and tests in ground-based icing facilities.

However, certain requirements have to be met prior to a clearance. For example, it must be well established that engine damage/flame-out will not occur, and it has sometimes been necessary to carry out additional testing in clear air to track the path of simulated ice shedding from different points of the airframe to ensure that they do not enter the engines. For the rotor, before certification, a specified minimum level of experience is required in natural icing at values of LWC of up to and including 60% of the Def Stan 00-970 maximum continuous value, and over the range of ambient temperatures and altitudes being considered. In recent trials of unheated rotors, it has required one season's testing to acquire the necessary evidence with some 20 hr actually accreting ice, out of approximately 40 hr total trials flying. However, to achieve this required a high standard of instrumentation (discussed below), some luck with the weather and even then the clearance did not cover the full range of altitude and temperature which might potentially be usable. Another aspect which must usually be examined is stress levels in dynamic components and enough evidence must be accumulated to allow an assessment of whether any additional fatigue damage is incurred during flight in icing.

c. Icing release for service use: The extent of the clearance will be governed by the results of the tests in natural icing and any unsatisfactory test points will be excluded. Since the worst conditions will not have been seen during testing safety for unprotected helicopters is ensured by first specifying when, in terms of increased vibration, increased power required and, where appropriate, increased stress levels the pilot must take action to vacate a severe icing environment. Secondly, flight in icing is prohibited (except at low level) unless it is believed that a layer of 1,000 ft of nonicing air exists above the surface. Thus, in most cases, an "escape route" exists as a last resort.

For helicopters with heated rotor blades, the same arguments will be used except that no "escape route" is likely to be necessary. Instead, more severe conditions than have been tested will be considered in relation to theoretical analyses and rig tests results. This approach, although less than ideal, is considered satisfactory provided that clear margins can be seen at critical conditions. The case of partial and complete failure of the heating systems also need to be considered and here a "risk analysis," based on flight-tests results and reliability data, must show an acceptable result.

Changes to helicopters subsequent to testing often occur and are considered on their merits. Changes to the external shape sometimes require further flight trials, but in some cases, such as carriage of additional stores, rig tests or even clearance by analogy can be considered. Increases in the maximum weight of the helicopters may again require new flight tests, but it may be possible to provide a more limited clearance, usually in terms of maximum speed, by preserving aerodynamic and dynamic margins in the critical cases.

d. Instrumentation: It has been found from experience that undue economy in the provision of adequate instrumentation is counterproductive. Apart from routine provisions to measure performance and handling qualities, and where necessary, engine and stress parameters, the following have been found most necessary for icing trials:

1. At least two and preferably three independent measurements of LWC with suitable displays for the pilot and test engineer.

2. On-board displays of relevant parameters for the test engineer with, if possible, some real-time computing facility to obtain derived parameters. It is particularly valuable to know the power which would be required in clear air during flight in icing.

3. Means of displaying what is occurring at critical points on the rotor and airframe. For the airframe and engine air intakes, video has been successfully employed, in conjunction with, where necessary, fiber optics. The display(s) may be used simply to monitor in-flight whether any dangerous accretions are occurring but in many cases, a recording facility is used as well for after flight analysis. It is often useful to be able to "see" what is happening to both the upper and lower surfaces of the rotor blades and during development of heated rotor-blade systems it is considered essential if rapid and systematic progress is to be made. A&AEE has developed camera systems to do this and has obtained excellent results for the upper surface and less good but usable results for the lower.

6.6.3.3 U.S. efforts. The qualification efforts of the U.S. Air Force, U.S. Navy, and U.S. Marines have been limited. The U.S. Air Force is developing the HH-60D, which is a derivative of the UH-60A, and except for mission equipment, it incorporates the same deicing/anti-icing systems. The U.S. Navy and the U.S. Marines conducted icing qualification testing on both the SH-60B and CH-53E and used the U.S. Army qualification methods, techniques, and procedures. Consequently, these efforts and experiences relative to lessons learned, and results are similar to those of the U.S. Army. While the commercial Sikorsky S-76, Bell Model 412, and the Bell Model 214ST were tested to FAA certification requirements, testing was accomplished using U.S. Army qualification methods, techniques, and procedures, as well as facilities and some instrumentation/test equipment support. Consequently, the lessons learned and results were similar to those of the U.S. Army. The U.S. Army icing qualification experience over the past 11 years has been extensive. It can be categorized into three areas: test facilities/instrumentation, qualification requirements and techniques, and qualification test results and lessons learned.

a. Test facilities/instrumentation: The U.S. Army uses the Helicopter Icing Spray System (HISS) installed in the CH-47C to provide an artificial icing environment through the U.S. Army moderate icing intensity requirements of from 0°C to -20°C OAT and 1.0 g/m$^3$ LWC. The icing cloud produced by the HISS is 8 by 36 ft and is calibrated by use of the JU-21A with cloud-sampling equipment. Improvements in the HISS

and JU-21A capabilities have been continuous since 1979 and have resulted in the artificial icing cloud approaching the characteristics of a natural icing cloud. The HISS and JU-21A have been invaluable in obtaining a wide matrix of qualification test points in a short period of time, with test results similar to those obtained in natural icing. The JU-21A is also used to characterize the natural icing environment when natural icing tests are conducted, as well as search for icing conditions. This method has been highly successful in obtaining accurate environment characterization, as well as saving test time and additional equipment on the test aircraft.

The HISS needs to be improved so as to produce a larger cloud, higher LWC, and better droplet distribution as does the capability of the JU-21A to measure water droplet sizes to 3,000 μm (currently 300-μm capability). The U.S. Army has a HISS improvement program which should result in an improved HISS by 1988 that will correct current problems, as well as completely immerse a medium size helicopter and have the capability to selectively immerse parts of the helicopter when required. The HISS has proven invaluable as an in-flight artificial icing facility.

The U.S. Army has developed and employed test instrumentation packages, video cameras, and recording systems, high-speed and still camera systems as part of the test helicopter or external to the test helicopter. Such equipment has been used for documenting ice-accretion and shedding characteristics of rotating and nonrotating systems, subsystems and components; handling qualities and performance; and also aerodynamic loads, vibration, and stress. New small, lightweight, low-cost, high-resolution video packages are being developed by the U.S. Army to provide accurate continuous documentation of ice-accretion and shedding characteristics. The new developments will result in significant improvements in documentation for determining fixes and adequacy of ice protection devices.

b. Qualification requirements and techniques: The qualification requirements are based on the operational users' required capability for operating in various icing conditions, such as light or moderate icing. Light icing is defined as up to 0.3 g/m³ LWC and down to -20°C OAT. Moderate is up to 1.0 g/m³ LWC and down to -20°C OAT. The U.S. Army procedures, to substantiate meeting the requirements, includes testing in the artificial environment at least 30 min at each selected combination of OAT and LWC. At least 10 hr of natural icing is normally required in flying mission profiles. The helicopter must demonstrate it can be operated safely under the preceding conditions prior to limited certification. The requirements and techniques employed have proven satisfactory, as evidenced by operational experience. Depending on the extent of qualification requirements (new development or verify configuration changes), qualification flight-test time on test helicopters has varied from 4 to 30 hr of combined artificial and natural icing flight testing (see Table 21).

c. Qualification test results and lessons learned: Results of qualification testing have shown that the helicopters tested can operate up to moderate icing conditions (0.5 g/m³ LWC or less and down to -20°C OAT) safely without rotor-blade protection. Rotor-blade protection is required when OAT and LWC are more than the preceding values and operation is conducted in moderate icing conditions.

Rotor-blade, fuselage, engine and mission equipment damage from accreted and shed ice can be expected under some conditions. Performance degradation and vibration level increases caused by accreted and shed ice also occur and must be accounted for in mission planning.

External configuration changes to previously qualified helicopters generally require requalification under icing conditions. Such changes include weapons, stores, antennas, fairings, and deicing/anti-icing systems. The magnitude of the change dictates the requirements for requalification.

The qualification techniques and procedures have proven to be satisfactory to ensure helicopters will operate safely under given icing conditions. The lessons learned since 1980 substantiate the U.S. Army method of qualification; however, refinements in the facilities and instrumentation use are required.

6.6.4 Operational Flight Experience

6.6.4.1 French experience. The civil Super Puma fleet existing at the beginning of 1985 included some 40 helicopters. Thirty of the helicopters were flying with limited icing clearances issued by the U.K. Civil Aviation Authority (CAA). ¨ of the helicopters where operating under trial unlimited clearances for civil operations in Norway. The operator's feedback on flights in icing conditions with limited clearance mention a good general behavior of the helicopter. Flights in icing conditions is a normal operation during winter and quite common. There is little experience available for helicopters with full clearances due to mechanical problems not related to icing. This prevented helicopter operations in icing conditions during the winter of 1984/1985. Nevertheless, the system's operational advantages have been confirmed. There were no registered operational disadvantages with the equipment serviceable.

6.6.4.2 U.K. experience. To date, all U.K. experience has been with helicopters without rotor protection. The first machine cleared for limited use in icing conditions was the Sea King in 1974, and since then, the Lynx in 1976 and, more recently, the Puma and Chinook. Considerable experience has been gained with the Sea King although much of it has been at relatively low altitudes over the sea where icing conditions would not be expected to be severe. Experience with the Lynx is less extensive for various reasons unconnected with the validity of the icing clearances. More detailed information is classified and cannot therefore be included; however, it can be stated that no flight safety problems have been encountered.

Overall, the U.K. Services have found limited icing clearances of considerable value for appropriate helicopters despite their inherent restrictions.

6.6.4.3 U.S. experience. The U.S. Air Force, U.S. Navy, U.S. Marines, and the U.S. helicopter manufacturers have not developed any operational experience on helicopters certified/qualified for flight into icing conditions since none have been certified/qualified to date. The U.S. Army experience is extensive, worldwide, and includes operational missions in icing conditions with helicopters qualified to operate under limited clearances. Since 1974, not one fatal/major accident occurred which was caused by flight into icing conditions. The U.S. Army helicopters qualified for flight into icing conditions include the UH-1, CH-47, and the UH-60A. The preceding represent approximately 5,200 helicopters cleared for and normally flown in icing conditions. In approximately 11 years, 78 mishaps occurred. The vast majority are associated with ice accumulations on the helicopter which occurred prior to flight (normally from water freezing) and not related to flight in the icing environment. Such ice accumulations resulted in binding flight controls, frozen fuel lines, binding flight control surfaces, iced over windshields, and binding servos. Other types of mishaps included failed deicing/anti-icing systems (windshields, pitot-static systems, engine inlet heat, etc.) and improper operating procedures. Less than five mishaps occurred which resulted from in-flight icing conditions. These mishaps resulted in aborting a mission because of degraded performance due to increased weight and drag from accreted ice or by increased vibration due to asymmetric ice shedding. Additionally, the flight was being conducted in more severe icing conditions than those to which the helicopter was cleared.

The demonstrated outstanding safety record of U.S. Army helicopters with limited clearances substantiates the limited clearance philosophy to their satisfaction. Helicopters which are adequately protected and flown by well-trained pilots can safely operate with limited clearances on a routine basis.

6.6.5 Summary

6.6.5.1 French summary. The methods used to certify the Super Puma for flight in icing conditions, with and without limitations have given good results. The methods used were analysis, icing wind-tunnel tests and mainly flight in natural icing conditions. Although flight in natural icing conditions appears the most accurate method of certifying a deicing system, it requires flying many hours to find sufficient varied icing conditions to substantiate certification.

Military operational and commercial flight in icing being something new, it is important for people working on helicopter icing to have as much information as possible from the operators to increase the knowledge and then the safety for flying in icing conditions.

Efforts are under way to develop simulated icing wind-tunnel tests and analysis as a major means of compliance.

6.6.5.2 U.K. summary. The philosophy and methods used by the United Kingdom to obtain icing releases for military helicopters have been found to be satisfactory, giving clearances which are useful operationally and safe. However, the trials required to obtain them are both expensive and time consuming. Also, it is possible that the clearances, particularly for machines without rotor protection, are overrestrictive.

Looking to the future, progress will probably be fairly slow. Improved theoretical methods and ground-based facilities should provide a sounder starting point for flight trials and reduce the development phase for heated rotors, but the need for flight data for qualification purposes will remain. Some improvement in clearance for unprotected helicopters might be possible if they were fitted with reliable LWC indicators, but this remains to be proved.

Since icing trials are expensive and the total international experience is limited, there would be some benefit in sharing detailed flight test results, particularly in cases where it would be possible to make a direct comparison between methods. For example, between results obtained behind the HISS and those in natural icing. However, for this to be achieved, it would probably be necessary to agree to a common method of presenting the results.

6.6.5.3 U.S. summary. The U.S. certification/qualification techniques, methods, and procedures to substantiate the issuance of limited clearances to U.S. Army requirements have worked exceptionally well. The use of the U.S. Army facilities/instrumentation for artificial icing tests, followed by natural icing tests, as a logical buildup for limited icing clearance has resulted in safe operational icing envelopes. When external configuration changes are made (to include deicing/anti-icing capabilities), it is generally necessary to requalify the helicopter for flight into icing conditions to which previously qualified.

Recommendations to improve the U.S. Army facilities/instrumentation for more efficient operations have been made. Efforts are under way to improve the JCH-47C HISS, the JU-21A cloud-sampling equipment package, instrumentation, and video cameras and recorders.

6.7 PREFLIGHT ANTI-ICING/DEICING

In low-temperature operations, ice can form on helicopter airframes when parked on the ground at open sites. This ice accumulates in several ways. For example, after landing in a snowstorm, snow may melt on the warm airframe and rotors to refreeze later as the structure cools, forming thick and rough ice

deposits. Another mechanism is sublimation of moist air to form hard ice deposits on a cold-soaked airframe. Although different in appearance from ice formed in flight, these deposits would have similar airworthiness penalties and must be removed before the next sortie.

Complete removal of such ice deposits is a difficult and time-consuming task which, in Arctic conditions, can take several hours per airframe and often has to be performed in the dark. It would be preferable if the formation of these deposits could be prevented.

Over the last 10 years, those countries which have continued to operate helicopters in Arctic field conditions have evolved various techniques for prevention or removal of such ice; however, there are few unclassified reports describing the actual methods used. The underlying principles are similar however, and delegates to WG 14 indicate general agreement of the principles outlined below.

6.7.1  Current Procedures

6.7.1.1  Deicing.  When a helicopter has built up ice deposits, two methods may be used to clear the surfaces before flight: deicing fluids and direct heat. The first requires large quantities of fluid and is not very efficient, requiring significant manual effort. The most effective method so far used is the application of heat. This may be achieved by applying hot air or liquid to the affected components. To supplement this it is also possible that rotors with heated blades could be energized. This application of heat still remains a time-consuming task, and requires special ground equipment which is a hindrance to mobile operations.

6.7.1.2  Anti-icing.  Because removal of ice deposits is such a difficult and slow process it is much better to prevent any ice forming in the first place. The use of a warm, weatherproof hangar is the ideal which solves the problem but, unfortunately, in the areas where detached helicopters will operate, they do not exist and other methods of protection have had to be evolved.

It has been past practice to protect exposed airframes against snow and ice by applying covers to the fuselage and rotor blades. Although this prevents the worst deposits forming, condensation freezes inside the covers effectively bonding them to the surface. This adhesion can be minimized by liberally spraying a freezing point depressant onto the surface when applying the covers. The disadvantage of this protection is that fitting and removing such covers is extremely time consuming and, because it affects aircraft reaction time and availability, must be weighed carefully against operational needs. The covers and the equipment to store and dispense the anti-ice fluid also form a heavy and bulky load which would have to be carried by the helicopter itself. This loss of payload can be a major consideration when deploying to forward operating bases and experience has shown that there are few occasions when full covers are necessary.

Most observed occasions of ice forming on helicopter surfaces happen when the temperature is near the freezing point and precipitation occurs. The most significant items affected are the airfoils and exposed primary controls. At temperatures below -10°C, precipitation is usually "dry," and any snow that collects on the structure is easily brushed off. Application of heat in this case can only make matters worse. For military purposes, when the risk of unexpected weather must be set against operational reaction times, Arctic protection may be considered in three different stages to cover differing weather conditions: full covers, limited covers, and no covers.

a.  Full covers:  These should be applied to unserviceable aircraft necessarily left in the open for prolonged periods; they should also be used on all aircraft in blizzard conditions. All surfaces should be treated with anti-icing fluid before fitting covers to minimize the effects of trapped condensation.

b.  Limited covers:  These should be used on serviceable aircraft only in the temperature range -10°C to +5°C when wet precipitation is present or when these conditions are expected before the next flying sortie. Limited covers would be applied to main- and tail-rotor blades and to primary flying controls. Aerodynamic stabilizing surfaces may also have to be considered. Engine blanks, gags, and tip socks would be fitted as normal. Anti-icing fluid should be applied with the covers as above.

c.  No covers:  Covers should not be fitted at temperatures below -10°C, above +5°C or when wet precipitation is not expected. The airframe is left clean with only blanks, gags, and tip socks fitted.

6.7.2  Icephobic Coatings

As discussed above, the use of fluids to remove accreted ice is inefficient and requires the storage of large quantities of fluid and its bulky application equipment. The alternative covering methods also have disadvantages. In the search for more lasting protection, research has been conducted in Europe and the United States to consider the use of icephobic coatings which could be applied to airframes either to prevent ice formation altogether or enable easy ice removal by reducing adhesion. Such a substance would possess the following characteristics:

- Must not degrade rotorcraft safety and reliability, performance and handling

- Easy to apply, without additional mixing or heating, by hand or spray

- Effective on oily as well as clean surfaces

- Remain effective on a helicopter after 24 hr parked in the open

- Able to survive flight conditions

- Noncorrosive

- Nonslippery

- Inert to aircraft materials

- Nontoxic

- Low cost

Investigations into the chemical or physical properties of candidate substances have been made with some success; however, the operational value of such methods is in doubt. So far, the short life when exposed to flight conditions and the manpower and support equipment required for application and reapplication to the airframe show no evidence of operational advantages over the covering methods described above. Enthusiasm for further research into such icephobics is dissipating.

### 6.7.3 Airworthiness Consideration of Applied Substances

If icephobics, in the form of pastes or viscous coatings, are brought into use, it is essential that certification authorities are satisfied that any adverse effects on rotorcraft performance and handling can be identified and shown to be acceptable. For example, if a viscous substance is applied to airfoils and not removed before flight it could flow under flight conditions causing changes to the airfoil shape resulting in performance degradation similar to the ice which it has prevented. Although there is little evidence for this concern, due to the lack of flight experience with such substances, it is a consideration which must not be overlooked.

### 6.8 CONCLUSIONS AND RECOMMENDATIONS

The proposed standard requirements and procedures for compliance for both full and limited clearances should be used to obtain more experience of flight in icing conditions. It is strongly recommended that such experience should be documented and made available to NATO countries.

It is necessary to identify any difficulties encountered, during operational experience in icing, in order to assess the level of safety of existing clearances for future improvements.

Meetings of icing specialists in working sessions should be held every 2 years to review experience gained on procedures for compliance, in order to achieve more rapid improvements. It is recommended that AGARD should invite the French delegation to organize the first such meeting. Civil certifying authorities should be encouraged to participate.

Conduct an international study to define criteria for judging the validity of each natural icing sortie.

Recognize the importance of correlation in order to increase the use of analysis and simulated icing tests to enhance clearance procedures.

Improve the HISS artificial icing cloud to more accurately duplicate the natural icing environment and increase its capability in LWC, duration, and cloud size to enhance certification testing. The United States should continue its HISS improvement program.

Improve test equipment and instrumentation to more accurately document certification icing test results. Specific needs are:

1. Light, small, high-definition video systems with self-contained power supplies and which can transmit data without electrical or mechanical slip rings.

2. Accurate devices for measuring all important icing environment parameters which are usable under all icing conditions and have traceable calibrations to recognized standards.

Establish documentation of operational experience to obtain data to substantiate the adequacy of certification procedures. Standardized data gathering is required to allow use by member nations.

Encourage continued development of analytical codes and ground-based tests and their correlation with general icing data banks, in particular, icing flight-test data.

In the light of the example and conclusions given in par. 6.5.3.2 and 6.2.4.4 above, conduct an internationally supported program to assess, by model tests in the S-1 tunnel and in other facilities (if necessary), the effect of advance ratio (speed) on rotor ice accretion and shapes.

Current techniques for preflight preparation in icing conditions contain significant shortcomings and remain a high-work-load task. The measures taken must be balanced between essential reaction time, payload,

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and the probability of adverse weather. Improved techniques are necessary. Development of icephobic coatings may alleviate some of the problems, but the economic use of such techniques, with savings in both time and manpower, has yet to be demonstrated.

## 7. PROTECTION METHODS

Reference 82 contains a comprehensive review of the ice-protection systems technology for helicopters as of 1981; this section provides an update of research and development efforts in ice protection since that time. Reference 82 recommended further research and development on six advanced ice-protection concepts as potential alternatives to the electrothermal system for rotors. Since 1981, only one of the recommended systems, pneumatic deicers, has been developed into a prototype system for rotors and successfully flight tested on a helicopter in icing conditions (Ref. 83).

Although it was not recommended for rotor systems in Ref. 82, the electromagnetic impulse deicer system (EIDI) has had R&D effort in France since 1976 and in the United States since mid-1982. To date the emphasis for EIDI has been on fixed-wing aircraft applications (Ref. 84). In principle, however, the EIDI system is also applicable to rotors, but many design issues remain to be resolved before it could be made practical. Two other methods are currently being examined for rotor ice protection: freezing-point depressant fluid systems (Ref. 85), and higher harmonic control (Ref. 86). These last two methods are in the conceptual stages of investigation.

In this section, a standardized format will be used to give an update for each of the above four ice protection systems.

### 7.1 PNEUMATIC DEICERS FOR ROTORS

Description

Deicer boots for rotors have two spanwise tubes on the leading edge of the blade and chordwise tubes on the upper and lower surfaces. The elastic polyurethane surface always self-shed the ice near the rotor tip during hover icing tests. Therefore, for forward flight tests the outboard 40 in. of the boot was made noninflatable. The noninflatable section should have less shape distortion and be less vulnerable to FOD and erosion damage.

The system weighed only 30 lb and consisted of only six major components: pneumatic deicer, regulator-reliever shutoff valve, timer, rotary union, hose and flap assembly, and ejector flow control valve to keep the deicers deflated.

Development Status

Pneumatic deicer systems for rotors are in the advanced prototype development stage. Current emphasis is to further reduce the drag penalty for a boot applied over an unprotected factory production blade. The polyurethane material was shown to be field repairable for both rain erosion and FOD damage. This has been a joint effort by NASA, the U.S. Army, and the B. F. Goodrich Company.

Validation Status

From 1981 to 1985, the system was flight tested by the U.S. Army on a JUH-1H. Tests included structural loads surveys, performance and handling-qualities tests, limited rain-erosion tests, artificial icing flight tests in hover and forward flight, and limited natural icing flight tests. The prototype pneumatic deicer system deiced satisfactorily under all test conditions. All deicer activations resulted in symmetrical ice sheds without increases in lateral vibrations. Because the polyurethane material promoted self-shedding, ice accumulations near the tips were never heavy enough to cause severe lateral vibrations during natural asymmetrical ice sheds. After asymmetrical sheds, cycling the deicers reduced the associated vibration within 2 sec. Handling qualities during deicer activation required only slight compensation.

Figure 37 compares level-flight performance of the installed deicer (boots deflated) with standard-blade hover data for an early YUH-1H.

Limitations

The primary limitation is a potential vulnerability to rain erosion and FOD damage. Drag of the over-layed boots might cause unacceptable performance penalties for some missions, but recessed boots should provide an acceptable drag penalty. To obtain adequate operational and maintenance data, a few helicopters should be operated with pneumatic deicers for at least a year. Newer aircraft, with advanced airfoils, should be flight tested with pneumatic deicers.

Future Plans

The U.S. Army will measure the performance of the actual test JUH-1H with the pneumatic deicers removed. Then a third-generation prototype deicer boot, with lower drag, will be installed on the test JUH-1H, and its installed drag penalty measured. The U.S. Army will equip a second UH-1H with pneumatic deicers and conduct a total of 50 hr of rain- and sand-erosion tests during 1985.
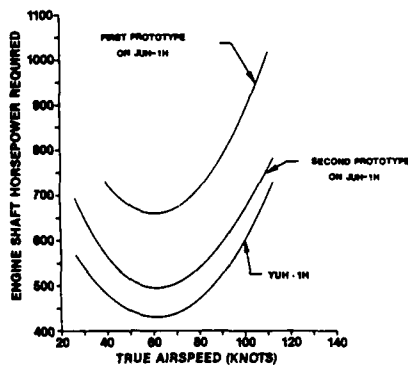
Fig. 37.  Level-flight performance with pneumatic deicers installed on JUH-1H compared to YUH-1H bare-blade
performance; pneumatic boots deflated; gross weight = 8510 lb; density altitude = 8600 ft.

Acceptability

The penumatic deicer system is relatively low cost, is lightweight (about 30 lb for the JUH-1H), uses
negligible engine bleed air, is easy to install, and is mechanically simple.  There is no runback.  Pneu-
matic deicers would not add to the blade's radar cross section.


7.2  ELECTROMAGNETIC IMPULSE DEICERS (EIDI)

Description

Flat-wound coils made of copper ribbon wire are placed just inside the leading edge of a wing's skin
with a small gap separating sk.n and coil.  An electro-impulse is initiated by triggering a thyristor, which
discharges a capacitor through the coil.  The current pulse in the coil creates a transient magnetic field
that induces eddy currents in the metal skin of the wing.  Opposing magnetic fields resulting from electric
currents in the coil and skin create a repulsive force of several hundred pounds magnitude, for a fraction
of a millisecond.  A small amplitude, high acceleration movement of the skin acts to shatter, debond, and
expel the ice.

Potential applications include fixed-flight airfoil surfaces, engine inlets and possibly rotor blades.

Development Status

The USSR's widebody aircraft, 11-86, has been cited as having been the first aircraft to be equipped in
production with the EIDI system.  During the 1970s, work was done on the FIDI method in Great Britain and in
the United States.  In 1976, DBA/Air Equipment (France) bought a Russian licence.  Since then, France has
conducted extensive performance testing of EIDI on aircraft components.  A French qualification of a redun-
dant system for a medium range aircraft is in progress.  Since mid-1982, NASA has funded a comprehensive R&D
effort on the EIDI.  Both the French and U.S. efforts are for the whole range of civil aircraft.  Work is
just beginning on th⁻ application of EIDI to rotor blades.  It is presumed that there will be no particular
difficulty to protect helicopter air intakes with EIDI.

Validation Status

The French have successfully flight tested EIDI systems on an Alpha Jet air intake in natural icing
conditions and on an Airbus 300 number 1 slat (50%) in clear air.  They have also successfully deiced the
following components in icing tunnels:  Caravelle vertical stabilizer; Mercure horizontal stabilizer; Alpha
Jet engine air intake (Larzac engine running); Fouga 90 engine air intake (Astafan engine running); and an
end piece of outer wing slat of a typical civil aircraft for 200 passengers.  NASA successfully conducted
21 natural icing flight tests of the EIDI system on a 50-in. wing span o. their Twin Otter.  Cessna Aircraft
Company conducted a total of 16 flight tests of the EIDI on a wing and a wing strut of the C-206 aircraft in
artificial and natural icing.  The following components were successfully deiced by EIDI in the NASA Icing
Research Tunnel:  an engine nacelle (Falcon 200); a stationary, composite rotor blade with an aluminum
"erosion" shield; and a wing made from composite materials.

In both the French and American programs, the EIDI system successfully cleared ice that was from about
2-25 mm thick.  The thicker the ice, the easier it was to remove.  Below 2 mm, the removal was not complete,
but it was acceptable.  Strain levels were not excessive; acoustical noise inside the aircraft was accept-
able; and electromagnetic interference was acceptable.

## Limitations

For helicopters, the power-and-sequencing box must be placed in the core of the rotating mechanism. The limited space inside the blades will force the thyristors to be in the rotating mechanism also. Thus, coils will be connected by a rather large number of wires to the central power box. It seems likely that EIDI can be used only with composite spars. EIDI coils would be recessed into a plastic leading-edge material. The abrasion shield must be free to move normal to its surface to expel ice, so bonding of the shield will have to be restricted to its upper and lower sides well downstream of the nose. These limitations mean that the blade will have to be redesigned to accommodate EIDI: it is not an add-on system for helicopter blades.

## Future Plans

Cessna Aircraft Company plans to install a complete pre-prototype EIDI system (wings, empennage, and struts) on the C-206 and flight test it in 1985. NASA will continue testing engine nacelles, but future emphasis will be on helicopter rotors. The French plan to test EIDI in a quarter section of an Airbus 310 engine inlet lip in a CEPR icing test cell at Saclay by the end of 1985.

## Acceptability

The EIDI system is lightweight and uses a trivial amount of electrical energy (about 200 J/ft). It has no aerodynamic penalty. For fixed-wing aircraft, system weights are comparable to those for pneumatic deicers, and the power used is about equal to the landing light power. The maximum power is about 1% of that used by a hot-gas anti-icing system, or about 10% that of an electrothermal deicing system. Furthermore, the EIDI system will become more economical if it is used for both airfoils and air intakes. It should be highly reliable and have low maintenance. Electromagnetic interference is negligible. Strain levels can be kept below critical levels. Air Equipment (France) has sufficient data to declare that this system can advantageously be used on any existing aircraft for ice protection.


## 7.3  FLUID FREEZING-POINT DEPRESSANTS FOR ROTORS

### Description

A freezing-point depressant (glycol-water) is pumped through a porous leading-edge distributor panel to prevent ice accretion on the wing or control surface. The distributor panels for fixed-wing aircraft are fabricated from sintered stainless steel mesh or from electron-beam-drilled porous titanium. Pumping power requirements are very low.

### Development Status

Liquid ice-protection systems have been in use on fixed-wing aircraft for several decades. Special features required to make the system practical for rotor blades are in the conceptual design stage. This will be a joint effort by Bell Helicopter Textron, TKS (Aircraft Deicing) Ltd., and Kohlman Aviation Corp.

### Validation Status

A test of a liquid ice-protection system was conducted by Bell Helicopter in 1960. Although results were generally favorable, the system was not developed further. Some U.K. tests of the Sycomore and Wessex in the early 1960s showed problems of nonuniform fluid distribution, and the method was not pursued. New means of fluid distribution and more effective liquids have not been tested on rotors.

### Limitations

A liquid ice-protection system has a finite endurance, limited by the quantity of fluid on board. The fluid distributor panel is potentially vulnerable to sand, rain, and FOD damage in the harsh environment where rotor blades must operate. Fleets of aircraft injecting ethylene-glycol into the atmosphere could significantly affect the environment.

### Future Plans

A program will be proposed to develop and test a prototype liquid ice-protection system on a modern helicopter. The tests will involve flight testing using the Ottawa hover spray rig and the HISS helicopter tanker.

### Acceptability

Since the fluid system functions in an anti-ice mode, it prevents asymmetric ice buildup, eliminates torque rises in icing conditions, and does not cause chunks of ice to be thrown off the blades. It prevents runback icing and uses very little power.

## 7.4 HIGHER HARMONIC CONTROL FOR ROTOR ICE PROTECTION

### Description

Higher harmonic control (HHC) has been demonstrated as a mechanism for reducing helicopter vibration levels. Deicing will be achieved by generating a moving wave in the blade. The resulting blade surface strain will crack the accreted ice which will be free to shed.

### Development Status

A preliminary analytical study has shown that the HHC mechanism can generate a moving wave in a helicopter rotor blade and that the resulting blade surface strain is sufficient to crack ice accreted on the blade.

### Validation Status

Program status is too rudimentary for concept evaluation.

### Future Plans

A research program is being planned that will include further analytical study and will culminate with flight testing at the NRC Ottawa hover spray rig.

### Acceptability

Compared to an electrothermal deicing system, an HHC rotor-blade deicing system would be lighter, require less power, and would not add to the radar cross section of composite blades.

## 7.5 CONCLUSIONS

This update on ice-protection technology for helicopters reveals that with the exception of the pneumatic deicer, almost no new R&D work has been done on the advanced ice-protection concepts recommended in Ref. 82 for the rotors. It appears that electrothermal deicing of rotors has become the de facto standard for the rotorcraft industry. Pneumatic deicers may prove to be a feasible alternative to electrothermal deicers, but the rotorcraft industry will have to take the initiative for its implementation and for acquiring operational experience with it. The main reasons for developing an alternative ice-protection system are lower initial costs, lower maintenance costs, lower weight, or lower power concumption. Other reasons would be vehicle specific requirements or special mission requirements. But there are three necessary requirements on any alternative system: (1) it must provide effective ice protection, (2) it must have acceptable resistance to erosion and FOD, and (3) it must have acceptable performance penalties (such as added installed drag or weight) at all times, including when the system is not in use.

Perhaps the only effective driving force for a new ice-protection system would be a major procurement for an all-weather rotorcraft that could not use electrothermal deicing for the rotors. One example is the tilt-rotor concept, where attempts to use deicers might possibly result in fuselage damage caused by ice chunks thrown from the rotors. If that were the case, it could force the development of the fluid system, which can operate in the anti-ice mode to prevent ice buildup. As another example, the requirement for an all-weather rotorcraft with low radar cross section could force the implementation of pneumatic deicers for the rotors.

## 7.6 RECOMMENDATIONS

Fundamental R&D should continue on the alternative ice-protection systems to determine if they offer advantages over the electrothermal system, and to form the design data base needed when an electrothermal system cannot meet the vehicle--or mission--specific requirements.

## 8. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the conclusions and recommendations which derive from the body of this report as contained in Secs. 2 to 7.

### 8.1 ICING ATMOSPHERES

The various icing atmospheres examined show different features, but most lack any information on icing conditions other than those associated with supercooled clouds, and all are very largely based on measurements made over the United States.

With the exception of the 10,000-ft atmosphere there is broad agreement between them for the maximum LWC in continuous conditions in layer clouds but there is, with one or two exceptions, no consideration of transient peaks of LWC in these conditions or reduced values of LWC at altitudes relatively close to the ground. Certain anomalies exist concerning droplet size, but these can probably be explained in the light of current knowledge.

There is less agreement for convective clouds, in particular over the maximum values of LWC and for how far they may exist. This question is further complicated by the fact that the probability of encountering severe conditions varies considerably depending on geographic location:

A prerequisite to allow adequate information to be available, whether it be for design or certification, is an adequate data base. The one drawn up in Ref. 3 and used for the 10,000-ft atmosphere provides a sound beginning for supercooled clouds and should be expanded to include more data in the types of cloud which are not well represented at present, more data from outside the United States, and, if there is a demand for it, data at higher altitudes. Similar work is needed for other icing conditions including mixed conditions, freezing fog, drizzle, and rain.

The use of helicopters in icing is a developing area and much remains to be learned about the design of protection systems, about testing in flight and in simulators, and about certification, for protected and unprotected machines, civil and military. It follows that there is a need for as much basic information to be obtained from the data bases as possible and it should be widely disseminated. This should allow the best possible consideration to be given to how best to formulate criteria for design, clearance, etc. It should be recognized that such standards should at this stage be tentative and provision should be made for them to be changed as knowledge increases. It is considered particularly important that the reasoning behind any criteria is stated in relation to safety standards.

It is not within the scope of this report to discuss design and certification standards except where they are governed by the use of icing atmospheres. From that point of view, any atmosphere should be sufficiently detailed to allow safe standards to be set for any type of operation ranging from an unprotected machine operating in the ASW role, close to the sea, where anything other than light icing is improbable, to a fully protected helicopter regularly operating in an area where severe icing conditions are common. None of the icing atmospheres considered meet these requirements and it is recommended that this question be reviewed with the objective of developing a framework, internationally agreed, within which the needs of all parties can eventually be met.

The data base for supercooled clouds up to 10,000 ft which has been established for the FAA should be expanded to include more data relating to convective cloud and conditions worldwide.

If there is a requirement it should also be extended to cover higher altitudes.

Separate icing atmosphere characterizations for layer and convective clouds should be formulated from the present FAA data base.

Data bases should be established covering all other atmospheric conditions conducive to icing and in particular ice crystals, mixed conditions, freezing fog, drizzle, and rain. In addition, although the effects on the helicopter are different, the characteristics of falling and blowing snow need to be defined and an appropriate data base established.

As much information as possible should be derived from the data bases to meet the needs of all parties and it should be disseminated as widely as possible.

The rationale for basing icing clearances on a particular probability of encountering icing conditions should be established.

When enough information is available in a particular area there should be discussion of how best an appropriate icing atmosphere could be expressed, and if necessary, reviewed as knowledge increases, to allow design, testing, and certification criteria to be established for all helicopters, protected or unprotected. The objective is to achieve standards accepted by all nations.

To promote better understanding between the nations, all these recommendations should be carried out internationally and the criteria used to reach all decisions should be clearly stated and where possible agreed upon.

## 8.2 FORECASTING

Ongoing efforts to improve forecasting capability with coordination between cloud physicists, forecasters, icing specialists and operators should continue to be encouraged.

The subject of icing forecasting is expanding and the brief study in this report barely scratches the surface. The potential scope of such work justifies its own specialist working group and AGARD FMP should consider conducting a deeper study of this topic.

## 8.3 PREDICTIVE METHODS AND SIMULATION

### Analysis

Droplet trajectories. A number of codes are now available and are being put to practical use. The main deficiency at present lies in validation, for which more experimental evidence is needed. This validation process will help to indicate the level of complexity needed, particularly for the flow-field computation (two-dimensional vs three-dimensional, compressible vs incompressible).

Further development is needed to make the codes more generally applicable, particularly to the irregular shapes of iced airfoils.

Comparisons of different codes should be made for common sets of input data, and a data base should be established of both theoretical and experimental results for general use in validation.

Experimental and theoretical studies are needed to clarify the conditions for droplet attachment to the surface. In particular, experimental studies should be made of the impact and subsequent attachment or bouncing of droplets on surfaces at very shallow angles of impingement; and the effects of boundary layers should be studied theoretically.

Accretion. The present models allow qualitative interpretation of experimental results and some fundamental understanding of parametric effects. The models will be adequate for defining deicing system initial conditions. However, modeling of sufficient accuracy for performance prediction will be the most difficult task.

Outstanding problems requiring further effort are (1) the physical process of accretion, in particular the reality of the assumed runback process; and (2) the heat transfer from rough and irregular surfaces.

Experiments should continue with the aim of clarifying the physical processes of accretion and improving the data base on heat-transfer coefficient. Comparisons of different codes should be made for common sets of input data. Experimental results should be exchanged.

Electrothermal deicing systems. Overall conclusions on the current models are that they are acceptable for assistance in design; acceptable for structural temperature prediction; probably adequate for qualitative (but not quantitative) interpretation of flight-test observations; but not sufficient for certification use because the correlation between surface temperature and ice shedding may not be sufficiently clear.

It is recommended that continuing efforts be applied to the development and validation of the models, since this can lead to great potential benefits to the certification process in terms of cost, time saving, and added confidence. Specifically, attention should be given to correlation of surface temperature with ice shedding, and to runback formation. Experimental data will be vital to both these studies.

Performance. The predictive methods for rotor performance in icing are not yet well established, and are certainly not validated. At present, their effect on the certification process is very small.

It is recommended that continuing efforts be applied to establishing a comprehensive data base on the aerodynamics of airfoils over the full range of icing conditions and to correlate these data to simplify their use in standard performance and loads prediction models. A further requirement is a data base on the performance of rotors with known accretions (natural, artificial or replicated).

Ice-shedding trajectories. Because of the numerous hypotheses and simplifications incorporated in the present methods, their accuracy is quite limited. The results must, therefore, be used cautiously and errors evaluated with a parametric scan. However it is felt that despite these restrictions, the technique can be used as a flight testing, development and certification aid.

Existing methods must be substantiated by comprehensive in-flight test in order to reinforce the confidence in them as a means of compliance. However, at this time, because of the complications involved in this type of analysis, it is not considered worthwhile to pursue such studies in depth, and protection of helicopters against ice shedding should be achieved through good engineering design and substantiated by test.

### Simulation and Experimentation

Laboratory test. Thermal properties: Experimental methods are well established. The need is for a data base on the thermal properties of new materials. It is recommended that that available data be shared.

and that further measurements should be made on composites, on new alloys, and on the thermal effects of delamination.

Adhesion: Available data show large scatter. Some present laboratory test methods are adequate for comparison of materials. Further work is needed to develop better test methods and to produce a more reliable data base on ice adhesion to different materials over the full range of icing conditions. The effects of erosion damage on adhesion to blades should be considered.

Ice mechanical properties: The work is all at an early stage, but it is important to obtain an understanding and a reliable data base in order that structural models for deicing may be used. It is recommended that present studies continue.

Erosion impact: Satisfactory test methods are available. Some test standards exist, while others are still being formulated.

Other aspects: Adequate techniques are available for testing deicers and their associated systems in terms of other aspects such as EMC, lightning, chemical compatibility and structural substantiation. The necessity for simultaneous heater cycling and fatigue loading on blades has yet to be established.

### Two-dimensional wind tunnel test

Impingement: Impingement limits can be determined using two-dimensional test techniques, but the complete trajectory determination is not yet possible. Tests have not successfully resolved individual droplets, nor provided the necessary measurement tools to study the apparent anomaly between trajectory predictions and observed catchment limits.

A cooperative effort to develop a data base, possibly by combining monodispersed stream technology with two-dimensional laser velocimetry, should be instituted. This program should focus on providing a general data base for trajectory code correlation, but in particular, for understanding the anomaly which currently limits the usefulness of trajectory codes for deicing system design.

Accretion testing: Accretion testing technology seems to be well in hand, and it has generated some of the most interesting data on ice-accretion shapes and the influence of physical parameters. More data are necessary to resolve questions over the physics of the accretion process and to confirm the heat-transfer models assumed.

Focus research on dynamic ice buildup process.

Anti-icing/deicing: Full-scale anti-icing and deicing tests can be used to simulate in-flight characteristics. Smaller-scale models can be used to define trends, but further research must be conducted to validate the use of subscale models in wind tunnels prior to use as a certification tool. Runback water tends to be a greater problem for subscale models.

If it is desired to develop a capability to investigate thermal deicing systems in model scale, two-dimensional tests to understand the size effect on runback phenomena will be required.

Performance: In spite of the limited amount of data which can be used to substantiate the performance data acquired from artificial and simulated ice tests, it is believed that the information can be used as input to formulate analytical prediction methods for rotor performance with iced airfoils. These test data will be the foundation that will provide the basis for future research and are likely to lead to more cost-effective approaches to rotorcraft certification.

Although the effect of advance ratio is not established, limited tests to date have shown that the shapes on a fixed blade element and on a model rotor are similar and the general trends observed are the same. The rotation movement has only a small influence on the ice-accretion shape.

Efforts should focus on the examination of existing two-dimensional and rotorcraft icing data to first determine which data provides the most accurate correlation information, and then to use that information to upgrade prediction methods.

### Three-dimensional wind-tunnel tests--model rotors.

Useful, though limited, tests to date suggest that there is a significant role for model-rotor testing to investigate important aspects of the rotor icing problem and particularly to provide controlled and documented data for analytical code validation. Although the role of model testing in the development and certification process is less clear, model tests can certainly be used to understand more thoroughly the limitations of other simulation techniques, as discussed in Secs. 4.6 and 6.5.

It is recommended that an internationally supported program be conducted to accumulate coordinated data on model-scale and full-scale flight tests in icing conditions to address the questions raised under "Validation Status" in Sec. 4.5.

As a first step, an ad hoc group should be convened to define the most efficient means of accomplishing this recommendation and those of Secs. 6.5 and 4.6 in a single coordinated program.

### Flight test.

The conclusions and the recommendations on the various aspects of flight test reviewed are as follows.

HISS: The HISS has been an excellent flight test facility for generating an artificial icing environment for test vehicles. It has provided rapid accumulation of test data throughout the U.S. Army moderate icing envelope when natural icing conditions were not available. After 10 years of use, the HISS has proven effective in significantly reducing calendar test time, providing the highest margin of safety and evaluating icing envelope extremes difficult to obtain under natural icing conditions. However, the system requires further development to make it more representative of the natural icing environment. Studies, including flight testing, are continuing in order to understand the effects of differences between the artificial and natural conditions.

Ottawa Spray Rig: The OSR has been useful as a "first look" technique, for instance, for the initial proving of new deicing systems (such as the pneumatic boots for rotor blades). However, efforts to take advantage of it to assist in setting up electrothermal deicing system cycles have produced mixed results. The United Kingdom and France have found it misleading, whereas the U.S. and German development teams feel that they have obtained useful results. Thus, its potential to assist in the certification process is not clear at this time. To establish the ultimate usefulness of a low-speed spray rig, it is essential that the source of the problems encountered be understood. In particular, it must be established whether icing shapes and extent observed in the Ottawa Spray Rig are sufficiently similar to those encountered in forward flight so as to provide the shape information required to use replicated ice to investigate forward flight effects.

Replicated ice: The use of replicated ice is a useful technique for fixed surfaces which can provide valuable evidence for certification and in some cases may be the only method for gaining the necessary justification. To date there has been little application to rotor blades. The future role of the use of replicated ice on rotors in the certification process has yet to be established.

Natural icing: Flight testing in natural icing conditions is, for the moment, the only method covering most of the certification demonstrations, and provides the ultimate means for validation and correlation of many of the analysis and simulation methods. But it has to be extensive, often intensive, and it is therefore expensive. This position will continue until significant improvements are made in simulated icing test methods or in other techniques for justification.

Potential improvements in natural icing test methods include the following:

- Better forecasting of icing conditions and good airborne information

- Lighter and more reliable instrumentation

- Use of production rather than prototype aircraft, if available, so that the test team can be smaller and more flexible

- Use of increased fuel capacity for enhanced range and endurance

- Further improvements to ground analysis

- Although only in its early stages of development, there appears to be considerable potential in the use of video cameras for the observation of ice on rotor blades

Furthermore, full advantage should be taken of all natural icing tests including those for certification to accumulate the data base required for correlation and validation of analytical and simulation techniques. This may have implications on the instrumentation requirements and also the way in which the trials are conducted.

8.4 INSTRUMENTATION

Icing Instrument Comparisons

Liquid water content sensors, when operated over their proper range, are probably accurate to ±20%. This accuracy currently has to be accepted for qualification and certification flight testing. It is probably not acceptable for obtaining comparisons between natural icing test results and icing simulation facilities (i.e., icing tunnels and spray tankers), and for computer code validation, improvements are necessary.

Droplet sizes obtained from the FSSP (Knollenberg) average about 2 to 10 μm higher than that obtained from the sooted slides and rotating multicylinders. In an icing tunnel test at NASA, a variation of several microns in drop size caused a wide variation in ice shapes on a UH-1H airfoil section and a corresponding wide variation in drag increment. Thus, an uncertainty of several microns in drop size would make it very difficult to obtain comparisons between test results in natural icing and in icing simulation facilities, or to validate computer codes. But for qualification and certification flight testing, the uncertainties might be less important so long as the aircraft is tested over a sufficiently wide range of natural icing conditions, provided the LWC is known.

Operating Experience With Icing Cloud Instruments

It is very important that the operating problems of the commonly used cloud instruments be understood and documented. This report documents only a few of the idiosyncracies of these instruments, and should serve only as a precaution to the potential user that proper use of these instruments is both an art and a science.

Some important issues that should be addressed in future research include (1) the development of international calibration facilities and standards for these instruments; (2) the development of a capability to produce mixed conditions in icing wind tunnels to evaluate the response of the various instruments to mixtures of snow and supercooled water droplets; and (3) a systematic study of the sensitivity of the various instruments to airspeed, outside air temperature, liquid water content levels, droplet sizes and distributions, length of exposure to icing conditions, etc.

Finally, the effects of instrument location on cloud concentration, particle separation, and shadowing should be accounted for when interpreting the instrumentation results. An empirical approach, or three-dimensional droplet trajectory codes should be used to assess the effects of instrument location.

Video Tape Documentation Techniques

The U.S. Army has made great strides in the application of high-speed video camera techniques to document ice accretion and ice shedding characteristics on rotors and fixed components. This method has the potential for substantially improving documentation of ice shapes and characteristics on rotors and fixed components, and it should be continued.

Photogrammetry

A nonintrusive means of measuring ice accretion shapes on a rotor in flight would offer a major breakthrough in icing flight testing and a U.S. approach, utilizing photogrammetric analysis of stereo photographs, appears to offer promise.

Advanced Icing Severity Level Indicating Systems (AISLIS)

The AISLIS concept is attractive for helicopters since it will give the quickest possible warning of danger due to icing problems and will also indicate the cause of the difficulty. This should give the flight crew sufficient information to remedy the problem or to take evasive measures. The objectives of this program justify a continuation of the effort when funds become available.

Torque Increment Systems

The ability of the U.K. torque increment systems to register real torque increments in icing has been demonstrated. Further work is needed to improve accuracy in maneuvers and in turbulence, in particular to eliminate false warnings in clear air. The application of the systems for possible enhancement of clearances or optimization of HRB control should be studied.

RAE/Plessey Thermal LWC Probe

The RAE/Plessey thermal probe has proved more responsive than accretion systems in natural icing conditions. Dead time during deicing and loss of response at temperatures close to 0°C are eliminated. Accuracy is high providing the input air data are of good quality. Development is recommended of (1) a less fragile probe, and (2) a complete self-contained system including cockpit display.

8.5 FLIGHT CLEARANCES AND REQUIREMENTS

8.5.1 Flight Clearances

The proposed standard requirements and procedures for compliance for both full and limited clearances should be used to obtain more experience of flight in icing conditions. It is strongly recommended that such experience be documented and made available to NATO countries.

It is necessary to identify any difficulties encountered, during operational experience in icing, in order to assess the level of safety of existing clearances for future improvements.

Meetings of icing specialists in working sessions should be held every 2 years to review experience gained on procedures for compliance, in order to achieve more rapid improvements. It is recommended that AGARD invite the French delegation to organize the first such meeting. Civil Certifying Authorities should be encouraged to participate.

An international study should be conducted to define criteria for judging the validity of each natural icing sortie.

8.5.2 Integration of Analysis, Simulation and Flight-Test Techniques

While sufficient data do not yet exist to prove clearly the extent to which analysis, model, and full-scale artificial and simulated ice testing could expedite the clearance procedure, available evidence suggests that with a more complete technical base, a far more reliable, thorough, and less expensive clearance procedure could be evolved. However, to do this, certain key areas of research must be undertaken to confirm that certain key assumptions implicit in the approach suggested in the report are valid, and to provide a data base for correlation of discrete elements of the analysis. These assumptions are as follows:

1. There is no significant difference between the shapes and extents found at the low speeds achievable in ground-based spray rigs and the speeds of interest for the flight envelope to be cleared which would invalidate dry-air, forward-flight testing of shapes obtained using hover rigs. This assumption is fundamental to the approach suggested and is not yet being addressed by any research program.

2. Rotor deice cycles and coverage allow essentially the same shape and extent of ice buildup at both low and high speeds. This assumption could be relatively easily checked by rotor camera documentation of in-flight shedding at low and high speeds.

3. Replicated ice shapes derived from ice shapes observed in icing ground rig tests, can adequately replicate the aerodynamic effect of natural ice. This assumption is already under thorough examination using two-dimensional testing techniques by NASA.

8.5.3 Certification/Qualification Flight Test and Operational Experience

The HISS artificial icing cloud should be improved to more accurately duplicate the natural icing environment and increase its capability in LWC, duration, and cloud size.

Test equipment and instrumentation should be improved to more accurately document certification icing test results.

A method of documentation of operational experience should be established to obtain data to substantiate the adequacy of certification procedures. Standardized data gathering is required to allow use by member nations.

Encouragement should be given to continued development of analytical codes and ground-based tests and their correlation with general icing data banks, in particular, icing flight-test data.

An internationally supported program should be conducted to assess, by model tests in the S-1 tunnel and in other facilities (if necessary), the effect of advance ratio (speed) on rotor ice accretion and shapes.

Current techniques for preflight preparation in icing conditions contain significant shortcomings and remain a high-work-load task. Improved techniques are necessary. Development of icephobic coatings may alleviate some of the problems, but the economic use of such techniques, with savings in both time and manpower, have yet to be demonstrated.


8.6 METHODS OF PROTECTION

With the exception of the pneumatic deicer, almost no new R&D work has been done on advanced ice-protection concepts recommended for rotors. It appears that electrothermal deicing of rotors has become the de facto standard for the rotorcraft industry. Pneumatic deicers may prove to be a viable alternative to electrothermal deicers, but the rotorcraft industry will have to take the initiative for its implementation and for acquiring operational experience with it.

Fundamental R&D should continue on alternative ice-protection systems to determine if they offer advantages over the electrothermal system, and to form the design data base needed when an electrothermal system cannot meet the vehicle--or mission--specific requirements.

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**14. Abstract**

Helicopter icing remains a significant operational consideration for military helicopters operating throughout Europe and Northern parts of North America. Following the findings of AGARD Advisory Report No.166 "Rotorcraft Icing — Status and Prospects (August 1981), further collaboration was considered beneficial to address the following objectives:

(i)   to proceed with the recommendations of the original group (WG09) on rotorcraft icing

(ii)  to examine rotorcraft icing analysis and modelling

(iii) to consider new methods of ice protection

(iv)  to compare operational experience with ice protected rotorcraft with the design and qualification criteria presently established.

This report contains the findings of an international Working Group including a comparison of icing atmosphere models and forecasting techniques; and an assessment of predictive methods and simulation, flight clearance strategies and requirements. It closes by considering various new methods of icing protection for rotorcraft.

This report was prepared by a Working Group sponsored by the Flight Mechanics Panel of AGARD.

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