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ROTORCRAFT AVIATION ICING RESEARCH REQUIREMENTS

RESEARCH REVIEW AND RECOMMENDATIONS

By:

A. A. Peterson, L. Dadone and D. Bevan

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Project Manager, William Olsen, Icing Research Section, NASA Lewis Resarch Center, Cleveland, Ohio.

16. Abstract

The status is assessed of rotorcraft icing evaluation techniques and ice protection technology. Recommendations are made for near and long term icing programs that describe the needs of industry. These recommended programs are based on a consensus of the major U.S. helicopter companies (i.e., Bell Helicopter, Boeing Vertol, Hughes Helicopter and Sikorsky Aircraft). As part of this assessment, specific activities currently planned or underway by NASA, FAA and DOD are reviewed to determine relevance to the overall research requirements. New programs, taking advantage of current activities, are recommended to meet the long term needs for rotorcraft icing certification.

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SUMMARY

The current emphasis placed on helicopter icing by the Department of Defense (DOD) and the Federal Aviation Administration (FAA) stems from (1) the increased Instrument Flight Rules (IFR) capabilities of modern helicopters with the associated need for all-weather clearance, (2) the desire to increase the overall utilization of the helicopter with a minimum of weather associated restrictions, and (3) the need to safely operate the helicopter over areas having a wide range of weather conditions, including regions which lack good weather forecasting capabilities.

Much of the ground work permitting many fixed-wing aircraft in both the transport and general aviation categories to achieve all-weather icing clearances has been accomplished through the extensive icing research conducted by NASA during the 1940's and 1950's.

The helicopter has made use of this fixed-wing icing research in many areas, however, the unique characteristic of the helicopter (i.e. rotary wing) coupled with an operating regime that includes hover and low speed, low altitude operations present icing problems not anticipated fully during these early fixed-wing icing investigations.

The purpose of this study (contract NAS3-22384 "Study for Rotorcraft Aviation Icing Research Requirements") is to assess the current status of helicopter icing certification techniques and icing protection technology and to recommend near and long term icing programs responsive to the needs of the helicopter industry. The recommended programs contained in this report are based on a consensus of the major U.S. helicopter companies (i.e. Bell Helicopter, Boeing Vertol, Hughes Helicopter and Sikorsky Aircraft).

The work accomplished under this contract includes:

- Detailed assessment of icing technology and recommendations for icing research
- Assessment of existing icing test facilities, capabilities and recommendations for upgrade and/or new facilities
- Presentation of recommended icing research efforts to NASA and the helicopter industry
- Coordination with and input to Agard Helicopter Icing Working Group (WG09)
- Support of NASA Research efforts, specifically:
    - Prediction of OH-58 tail rotor lift coefficient, mach number and angle of attack variations as a function of thrust and shaft angle for forthcoming tests in NASA Icing Research Tunnel (IRT)
    - Examination of IRT diffuser flow uniformity relative to scaled rotating rotor inflow requirements

- Preliminary examination of rotor scaling parameter relationships and considerations for wind tunnel simulation of rotor icing
- Preliminary examination of a typical composite rotor surface strains caused by the torsion, flap and lag bending loads with and without the presence of ice on the rotor leading edge
- Coordination with Ohio State on the techniques of rotor performance analysis in preparation for the Ohio State study of rotor icing effects

Additionally, a summary of the research recommendations is to be included in an American Helicopter Society paper "Rotorcraft Icing Research Requirements" authored by A. Peterson, L. Dadone and D. Bevan of Boeing Vertol, and Dr. W. Olsen of NASA Lewis, to be presented at the 37th annual forum.

The overall goal is to meet the long term research needs that will permit safe icing flying by rotary wing aircraft and will reduce the icing certification time and cost. This long term effort should include:

(1) The capability of using advanced/new analytical procedures for rotor icing predictions, and for the prediction of overall rotary wing icing flight characteristics.

(2) The capability of conducting fully operational scale model icing tests.

(3) The capability of programming flight simulator models for flight characteristic investigations.

(4) The use of artifical (modeled) ice shapes on the flight vehicle rotor system and other identified critical areas to verify the performance and handling qualities effects.

The paths that must be explored to achieve this overall goal vary in degree of complexity and required effort. Additionally, many short and medium term needs must be satisfied to permit progressive changes in the icing certification process so that tomorrow's flight vehicle can proceed in a more routine program toward certification.

In general, the research centers about:

(1) Development of icing testing techniques based on use of scale models and full scale helicopter hardware (including hubs, semi-span rotors, engine inlets, windshields, etc.) in existing icing tunnels and based on testing complete helicopters in hover and forward flight icing environment (simulated and natural) for verification of:

    - Ice accretion effects on critical surfaces
    - Ice protection systems capabilities

- Aerodynamic and dynamic effects on overall helicopter performance
- Icing environment and ice accretion instrumentation suitable for helicopter certification flight testing

(2) Establish analytical techniques for:

- Development of new ice protection concepts
- Evaluation of preliminary designs for ice protection systems
- Determination of helicopter performance changes and dynamic effects during icing encounters
- Correlation of icing test results from scale model and full scale helicopter hardware icing tunnel testing and from flight testing in simulated and natural icing conditions.

The primary research areas are discussed in more detail in the main body of this report and in Appendix A. A summary of the desired end result in each icing research category is as follows:

(1) Simulated Icing Facilities - to provide:

- Capability for basic and applied research in conjunction with development of applied analytical tools.

- Systems development capability for concept and prototype evaluation.

- Systems verification and certification.

(2) Helicopter Icing Flight Data Survey - to provide:

- Survey of helicopter icing tests.

- Overview of rotor icing and deicing.

- Obtain measured data for use as a basis for test of particle analysis programs.

(3) Rotor Icing Investigation - to provide:

- Analytical means of determining rotor performance translated into helicopter power required changes during icing encounters.

- Analytical means of determining rotor loads during icing and ice shedding.

- Analytical means of evaluating the need for and extent of required rotor ice protection to meet specification/certification requirements.

- Analytical means to meet the requirements of the new Far 29 paragraph 29.1419 "Ice Protection".

(4) Rotor Ice Protection - to provide:

- Evaluation of current rotor ice protection capability to meet icing specification/certification envelopes.
- Means of protection system improvements for upgrading capability and safety while reducing cost/maintenance requirements.
- Development of alternate system concepts.

(5) Engine Inlet Ice Protection - to provide:

- Means of effective analytical design techniques.
- Means of correlating and extrapolating icing test results to the extremes of icing envelope.
- Means of minimizing anti-icing power penalties during ice protection system operation.

(6) Instrumentation - to provide:

- Baseline validity of existing icing cloud measurements.
- Criteria and prototype for new, low cost, standard icing cloud instruments for development, certification and operation.
- Criteria and prototype definition for helicopter icing photographic systems for development and certification testing.

(7) Flight Test - to provide:

- Validation of analytical/test techniques and instrumentation for prediction of icing characteristics.
- Development of procedures leading toward more efficient certification methods.
- Direct impact on certification/flight clearance requirements in terms of mix between analytical prediction methods, artificial (modeled) ice testing, simulated icing tests and natural icing.

(8) Atmospheric Environment - to provide:

- More realistic definition of the helicopter icing environment - Particularly below 3,048 meters (maximum operational altitude for most helicopters).

- Better definition of world-wide icing environment patterns to permit more complete evaluation of certification/flight clearance procedures.

The scope and general recommended research program description are shown in Table 1. Those efforts currently underway or currently planned are summarized in Appendix A and are the result of previous reviews and recommendations that substantially meet the consensus of industry.

These programs meet the long term objective of this study: to define the required program steps to achieve the technology base that will permit routine helicopter all-weather operations. This technology base will provide the tools to allow reliable and effective ice protection and icing clearance to be achieved at a minimum cost/schedule risk impact during development and certification programs undertaken by the manufacturer and operator.

TABLE 1. LONG TERM ROTORCRAFT ICING RESEARCH

CATEGORY	SCOPE	RECOMMENDATIONS
1. Simulated Icing	1.1 Large scale facilities -	o Accomplish update of NRC (Ottawa) spray rig or investigate new hover spray rig
		o Development of large HISS
		o AWT activation to test rotors
	1.2 Small scale facilities	o Design study of required small scale high speed tunnel to supplement and replace the 1'x1' NRC tunnel.
		o Design and fabricate small scale high speed tunnel
		o Develop a model rotor test stand for IRT or AWT use
	1.3 Survey and validation of icing facilities	o Establish calibration standards for ice accretion from standard shapes/airfoils in existing facilities
2. Helicopter Icing Flight Data Survey	2.1 Survey of Existing helicopter icing flight data	o Search and review of existing government helicopter icing test data
3. Rotor Icing Investigation	3.1 Development of droplet trajectory analysis methods	o Extend trajectory codes to helicopter rotor flow environment
		o Definition of Ice Accretion Mechanism in presence of yawed flow, blade flapping and CF.
		o Scale model icing validation from 2-D tests and rotating airfoil tests
	3.2 Definition of ice shapes and accretion patterns	

TABLE 1. RESEARCH DESCRIPTION (CONTINUED)

CATEGORY	SCOPE	RECOMMENDATIONS
	3.3 Degradation in sectional characteristics due to ice accretion	o 2-D Airfoil Transonic Tunnel Program (Steady and Oscillating) with artificial (modeled) ice
		o Definition of unsteady and radial flow effects
		o Definition of standard method for ice accretion effects
	3.4 Preparation of standard source of helicopter airfoil icing data	o Rotor Aerodynamics/Performance Standard Methodology Source
		o Significant changes in new Airfoil Characteristics
	3.5 Evaluation of ice effects on structural blade properties	o Preliminary assessment of current analytical study
		o Standard Rotor Structual Properties Methodology
	3.6 Assessment of overall rotor performance penalties	o Upgrade current performance analysis methods (Ref: 2-G CHAS)
		o Model Rotor Icing (IRT)
		o Wind Tunnel Model Rotor Aerodynamics/Dynamics Icing tests with artificial (modeled) ice shapes

TABLE 1. RESEARCH DESCRIPTION (CONTINUED)

CATEGORY	SCOPE	RECOMMENDATIONS
		o Flight Test Evaluation using data obtained from other agency (Army, FAA, RAF) scheduled Icing Programs
		o Rotor Aerodynamics/Performance Methodology (Test/Theory Correlation)
		o Define Standard Evaluation Procedures
	3.7 Assessment of structural blade load penalties in presence of ice	o Rotor Loads Initial Assessment Using Current Methods
		o Upgrade Prediction Methods for Blade/ Control System Loads
		o Test/Theory Correlation
		o Standard Assessment Procedures
4. Rotor Ice Protection	4.1 Development of advanced heat transfer analysis methods	o Analytical and test correlation using oscillating and rotating airfoil test rig in IRT
		o Thermal analysis standard methods and guidelines for deicing
	4.2 Standard for Assessment of Electrothermal Deicing Systems	o Deicing tests on oscillating and rotating rigs in IRT
		o Control/Response Optimization
		o Correlation with Icing Survey Results
		o Heater element type/ shape/coverage evaluation

TABLE 1. RESEARCH DESCRIPTION (CONTINUED)

CATEGORY	SCOPE	RECOMMENDATIONS
		o Rotor performance/ loads during deice cycle
		o Standard evaluation procedures
	4.3 Ice protection evaluation (alternate concepts	o Investigation of: - Ice phobic - Pneumatic boot - Fluid - Vibratory - Hybrid - Other
5. Engine Inlet Ice Protection	5.1 Ice protection methods	o Analytical techniques development
		o Ice Deflector/ Separator Evaluations
		o Icing tunnel programs (test/theory correlation)
		o Generalized Inlet Configuration Assessment
	5.2 Anti-icing Power penalties	o Power loss determination during system activation
		o Engine Performance Analytical Models to Include Icing Effects
6. Instrumentation	6.1 Verification of current LWC and droplet measuring devices	o Evaluation of in-flight Icing Test data (Hover Rig, HISS, Natural) based on IRT comparison and calibration of icing instruments

TABLE 1. RESEARCH DESCRIPTION (CONTINUED)

CATEGORY	SCOPE	RECOMMENDATIONS
	6.2 Development of new measuring devices	o Criteria development for LWC and droplet measurement o Exploratory tests in icing tunnel of flightworthy prototype hardware to measure performance changes (torque, etc) and ice thickness (i.e. microwave detector)
	6.3 Development of new photographic techniques for in-flight blade ice assessment	o Define Requirements for Photographic Equipment o Exploratory tests in icing tunnel of prototype system o Development of ice modeling techniques (bonded shapes, pneumatic devices, etc.)
7. Flight Test	7.1 Helicopter flight testing with artificial ice shapes	o Whirl tower calibration o Flight test for progressive evaluation of artificial (modelled) ice
	7.2 Validation of monitoring and protection equipment	o Flight test behind HISS o Validation of artificial ice shape use o Definition or standard procedures for evaluating helicopter performance in icing
8. Atmospheric Environment	8.1 Survey of natural icing conditions	o Continue efforts to collect low altitude (less than 3,048 meters) icing data

INTRODUCTION

Overall helicopter and helicopter systems icing studies by airframe manufacturers, helicopter operators and Government agencies have been conducted over the past 20-30 years. These assessments by analysis and test have led to the development of ice protection techniques permitting at least a limited capability for helicopter operation under icing conditions. With the exception of the SA 330 "PUMA", which has received a French authority clearance however, no free world helicopter to date has obtained an unlimited clearance for flight into forecast icing weather. Documention of the current analytical and test techniques and icing criteria status has been accomplished by a study of helicopter icing characteristics, ice protection technology, and test procedures sponsored by the Federal Aviation Administration (FAA) under contract DOT-FA78WA-4258 (Reference 1).

The major conclusions reached during the FAA Helicopter Icing Review were:

(1) Rotor icing and ice protection techniques present a unique set of problems (aerodynamic, dynamic, thermodynamic) that are not easily solvable through fixed-wing ice protection technology. Ice formations on the rotor cause degradation in helicopter performance, the degree of performance change depending upon specific rotor characteristics (airfoil profile, blade loading, mach number distribution, catch efficiency, blade flexibility, rotor/airframe reaction, control loads, etc).

(2) Current analytical tools have the capability to permit preliminary evaluation of the aerodynamic and dynamic effects of rotor ice. Very limited use of these tools has been made to date because a minimal amount of icing test data (icing tunnel, hover, or in-flight) is available or properly documented for test/theory correlation.

(3) Existing icing tunnels do not have the capability to generate exact correlating data because of (a) the inability to rotate full scale rotors and (b) the lack of scaling verification (scaled rotors). Ice accretion/ice shedding data from existing hover and in-flight test facilities is difficult to evaluate because of lack of satisfactory documentation of the icing mechanism and lack of instrumentation to define specifically how the ice is accreting or shedding.

(4) The critical helicopter icing test environment is not clearly defined, particularly for the rotor system. Additionally, the acceptance criteria (by the certifying agencies) based on current test facilities capabilities is not defined.

(5) Electrothermal rotor deicing is the only system to date capable of providing satisfactory rotor ice protection over the full certification envelope (as defined under Federal Aviation Regulations). The optimum utilization of the electrothermal systems has not been explored fully to reduce the current cost, weight and maintenance requirements.

(6) Improvement in existing icing test facilities and creation of new facilities is necessary if major achievements are to be accomplished in the evaluation of helicopter icing and the development of new ice protection methods.

The scope of this effort NASA contract NAS3-22384 is to expand those areas addressed in the FAA study.

To be effective the research efforts must be accomplished in terms usable to the major concerned groups within the helicopter field. Additionally, the development and qualification aspects of helicopter all-weather capabilities must be addressed based on the involved agencies (FAA, DOD, NASA) as well as the manufacturers and operators in establishing the objectives and scope of the helicopter icing efforts.

The goals of the major groups that require helicopter icing research are:

(1) The helicopter manufacturers. The manufacturers are primarily concerned with the determination of the need for specific component/system ice protection, the development of required ice protection systems, the performance tradeoffs due to incorporation of the ice protection systems, and the certification of these systems as a step in obtaining an overall helicopter icing clearance. Within these general guidelines, the manufacturers want to obtain:

- o Uniform and verifiable compliance with requirements and regulations defined for military and civil helicopter icing operations.
- o Safety at minimum cost/weight/complexity.
- o Avoidance of unrealistic ice environment (i.e., design environment beyond the mission needs or capability of the air vehicle).
- o Practical ice detection instrumentation:
  - Accuracy suited to application
  - Minimum Maintainability/Reliability Problems
  - Minimum Weight/Complexity in installation
  - Minimum Cost
- o Practical DeIcing System:
  - Effective operation under clearly defined range of icing conditions
- o Standardized Methods to account for:
  - Ice accretion on critical components
  - Detection during all flight conditions
  - Helicopter performance/loads penalties under icing conditions
  - Ice protection fail/safe criteria

- Flight Simulation/Pilot Training capability under icing conditions.

(2) The helicopter operators. The operators are primarily concerned with level of overall icing clearance and the effects of the clearance and the ice protection systems operation on the helicopter availability and performance capability in terms of the user mission and icing condition probability. The operators general considerations fall into the following categories:

- Cost of ice protection equipment versus cost of time lost due to icing forecast groundings
- Safety of helicopter operation in icing and safety of the installed ice protection equipment
- Reliability and maintainability of the ice protection systems.

(3) The qualifying/certifying agencies. These agencies are primarily concerned with determining compliance with the specified helicopter icing envelope, reviewing and approving the demonstration of ice protection systems and reviewing and approving demonstration of operational and emergency procedures during icing encounters. These agencies require:

- Definition of certification criteria.
- Uniform and verifiable compliance with requirements and regulations.
- Standard methods to account for:
    - Helicopter performance/loads penalties
    - Ice Protection System requirements and performance
    - Fail/safe criteria

ICING RESEARCH DIRECTION

FUNDAMENTAL QUESTIONS

There are a number of fundamental questions that need to be addressed as the icing research efforts described in this document are reviewed. The initial questions deal with the basic reasons for concern of the icing environment. That is: Why should an operator deliberately fly a helicopter into known icing weather? Is icing a major problem to the helicopter fleet?

As more helicopters enter the military and civil markets equipped with IFR capabilities, the potential for icing encounters increases. The manufacturers and operators must, therefore, weigh the cost of ice protection against the cost of not flying due to icing weather forecasts. This issue is also influenced by the weather forecasting capability within an area of operation (i.e., the more unreliable the forecast, the higher the risk of an inadvertant icing encounter during IFR flights).

The second question is difficult to answer exactly because of the localized aspect of icing weather. Some regions of the world report high icing frequencies. For example, the Northern Pacific Regions report (Reference 2) the frequency of supercooled stratus and low cumulus to be 25 to 50% during the winter months. Areas of the Newfoundland Coast report frequencies greater than 25%. The Baltic Sea Regions also report supercooled cloud frequencies greater than 25% in the winter. Generally, in the northern hemisphere, the overall icing probability during the winter appears to be about 5-10%.

Additional questions are raised at this point: What happens to a helicopter when it encounters ice? When and where on the helicopter can ice be expected? How much ice can be expected? What shape will the ice have? What will the ice do? How can the ice be shed or the helicopter protected from ice? Does the definition of all-weather clearance automatically include a requirement for full ice protection equipment? Are ice protection systems safe under all icing conditions? These questions address the specific helicopter characteristics under icing conditions (i.e., will the helicopter continue to fly when accumulating ice?).

The answers are dependent upon a number of factors such as physical size, shape, and location of critical components (engines and rotors, for example), available horsepower reserve, and type and adequacy of the ice protection systems. Generally, with the ambient temperature no more than -5 to -10°C many unprotected rotors will experience tolerable ice accretion as a periodic ice build-up/shedding sequence takes place. As the ambient temperature decreases, the rotor accumulates a more significant amount of ice causing an increase in power required and increased vibration levels. The potential for asymmetrical ice shedding due to ice mass differences between individual blades also increases with the decrease in ambient temperature.

While the need for flight under icing conditions are established by the operator, the problem of defining and certifying a viable helicopter system rests with the helicopter manufacturer and the certifying agencies. It is with this view that the problems of helicopter icing and the research necessary to resolve these problems are addressed.

JUSTIFICATION FOR CONTINUED RESEARCH

In parallel with the questions about the need to fly a helicopter into icing and the need to protect the helicopter once icing has been encountered is the question concerning the need for continued research (i.e. is further icing research justified?) In addressing this question, an examination of "What happens if no further icing research is accomplished?" is necessary.

If no further icing research is accomplished:

(1) (a) The forthcoming icing certification requirements as proposed in the current FAR review will remain unchanged (i.e. the standard icing cloud definition and the compliance procedures). The helicopter will continue to be required to certify within the fixed wing icing envelope even thought the helicopter is primarily operated at the lower altitudes (below 3,048 meters).

(b) As a consequence the time required for an Icing Certification will be extended over several years; attempts will be made to find suitable natural icing conditions meeting the icing envelope at the required high liquid water contents, and at the low ambient temperatures.

(2) There will be little incentive to improve the simulated icing facilities. Additionally, certain facilities may be dismantled (i.e., the NRC hover spray rig and the high speed icing tunnel).

(3) The electrothermal rotor deice system with its inherent problems will be the only active ice protection means available with the potential to meet the full certification icing envelope requirements. No deice system, however, has been certified in the U.S.

(4) Most manufacturers will be discouraged from attempting an icing certification because of the cost of existing ice protection equipment and the cost conducting a certification program.

With a comprehensive icing research program incorporating near, mid and long range efforts, advanced techniques involving complete helicopter modeling and simulation can be achieved resulting in solutions to the current certification problems.

NECESSARY RESEARCH

Near Term Research

This research is necessary to satisfy the near term needs (2-3 years) based on the current certification requirements as they apply to existing helicopters. This research includes improvements in the current simulated icing facilities as necessary to permit duplication of natural icing environment, the development and upgrading of basic analytical tools that are required for both design studies and system qualification, and specific tests necessary for the investigation of ice accretion and ice protection.

This near term research includes the following efforts:

- Simulated Icing Facilities
  - HISS improvement
  - IRT improvement
  - Retention of NRC hover rig
  - Retention of NRC high speed icing tunnel
- Past and Current Helicopter Icing Test Data Review
- Analytical Tool Development - Primarily In:
  - Rotor ice shape prediction
  - Airfoil scaling verification
  - Rotor airfoil sectional performance
  - Heat transfer 1-D and 2-D
  - Electrothermal Deicing Evaluation
- Tests - Primary:
  - 2-D airfoil ice accretion and Rotating airfoil ice accretion/shedding
  - Oscillating airfoil ice accretion/electrothermal deicing
  - Ice-phobic materials (rotating arfoil)
  - Pneumatic boot (full scale rotor)
  - Ice accretion/ice measuring instruments (existing instrument tests)
- Collection and Evaluation of Atmospheric Icing Data

Mid Term Research

This research is necessary to meet the mid term needs (3-6 years) based on projected certification trends (i.e., changes based on current Icing Environment Investigations) as applicable to new helicopter programs. This research includes the planning and development of new icing facilities as necessary to simulate the full certification icing environment, the development of advanced analytical tools and test procedures as required for major advancements in ice protection technology, and the development of concepts to greatly reduce the time and cost of icing certification.

The Mid Term Research includes the following efforts:

- Simulated Icing Facilities
  - Alternate HISS
  - Alternate hover spray rig
  - NASA Altitude Wind Tunnel (AWT) rehabilitation & modification for icing
  - 2-D high speed icing tunnel

- o Analytical Tool Development - Primarily In:
  - Rotor system performance
  - Rotor loads evaluation
  - Basic anti-ice/deice system analysis

- o Tests - Primarily:
  - Model rotor performance with modeled ice (calibrated wind tunnel)
  - Flight test correlation between model and flight results
  - Model and full scale prototypes of promising ice protection concepts
  - Development of new ice measuring test instruments (including photographic means)

Long Range Research

This research is necessary to meet the long range needs into the 1990's for rotary wing aircraft icing certification. This research includes the maximum use of analytical procedures and scale model wind tunnel tests to develop flight simulator model capability and artificial rotor ice test techniques on full scale helicopters to minimize the final icing flight test certification time.

The Long Range Research includes:

- o Further improvement of analytical procedures in rotor predictions, and in overall rotary wing flight characteristics

- o Fully operational scale model icing test capability for example, using company rotors in AWT

- o Flight simulator model development

- o Artificial (modeled) ice shapes on full scale rotors

- o Optimum mix of simulated icing facilities for research, development and certification

SPECIFIC RESEARCH AREAS

The specific areas of research are categorized in order to answer the following basic questions concerning the nature of the research required to define the helicopter characteristics under icing conditions. These questions are then directed to the actions necessary to resolve the questions.

(1) When and where on the rotorcraft can icing be expected?

- o Prediction, detection, measurement and documentation (Table 2)

(2) What shape will the ice have and how much ice will accrete?

- o Identification of ice accretion processes (Table 3)

(3) What will the ice do?

- Assessment of effect of ice accretion (Table 4) and evaluation of spontaneous or uncontrolled ice shedding

(4) How can ice be shed or prevented?

- Protection from ice (Table 5) by controlled shedding or prevention of ice

These actions can be further defined by the specific groups shown in the following tabulations of current and planned activities and recommended activities. The current activities are those efforts presently underway with funds committed; planned activities are those efforts identified and actively being scheduled but without committed funding.

A key research issue is determining the means to protect the rotor from the penalties associated with excessive ice accretion. If a rotor were fully anti-iced, no performance degradation (due to ice) would occur. The power demands from the on-board systems, however, would be excessive. Rotor deicing (with the resultant rotor performance change as ice accrets prior to shedding) appears to be the only practical means of providing ice protection. The degree to which the rotor requires an active mechanism to induce deicing is a function of (1) the individual rotor characteristics and (2) the requirement for a "limited" vs and "unlimited" icing clearance. In other words, over a limited icing envelope, some rotor systems are able to operate safely without active deicing, simply by using their own natural ice shedding capability. Basic ice accretion/ice shedding/rotor performance research is necessary to provide the tools required for prediction of rotor ice effects for the "limited" and "unlimited" icing operation.

TABLE 2. ICE PREDICTION, DETECTION, MEASUREMENT AND DOCUMENTATION

Current and Planned Activities

- Upgrading of HISS and hover spray rig
- Development and application of 2-D/3-D particle trajectory codes to rotors and engine inlets
- Helicopter icing data review
- Comparison of modern and old instrumentation in the IRT
- Microwave ice accretion measurement
- Flight test verification of modern and old instrumentation

Recommended Activities

- Compare data from W/T, spray rig, HISS and natural icing
- New instrumentation development and testing
- Development of new inflight photographic equipment
- Definition of guidelines and standard evaluation methods

TABLE 3. IDENTIFICATION OF THE ICE ACCRETION PROCESSES

Current and Planned Activities

- Upgrading of icing wind tunnel facilities (IRT, AWT)
- Application of 2-D/3-D particle trajectory codes to rotors and engine inlets
- Review of scaling laws, test/theory correlation
- Numerical ice accretion modeling, 2-D/helicopter flow field
- Tail rotor icing tests in IRT
- Static and oscillatory airfoil tests in icing environment (IRT, NRC W/T, proposed new 2-D facility)
- Microwave ice accretion measurement
- Study of impingement/freezing/runback mechanism

Recommended Activities

- Tests on model rotors in IRT and AWT
- Refine numerical ice accretion modeling in the helicopter rotor flow field
- Definition of standard methods to predict and evaluate ice accretion

TABLE 4. ASSESSMENT OF THE EFFECT OF ICE ACCRETION

Current and Planned Activities

- Analytical evaluation of 2-D (sectional) performance degradation with ice
- Analytical determination of rotor performance degradation with ice
- Static airfoil tests to measure 2-D sectional performance degradation

Recommended Activities

- Improvement and validation of airfoil icing codes
- Definition of standard methods to assess the performance penalty due to icing of rotorcraft airfoils
- Static and oscillatory airfoil tests to measure 2-D sectional performance degradation
- Preparation of standard data source on helicopter airfoils with ice
- Definition of effect of ice accumulation on structural blade properties
- Upgrading of rotor performance/blade loads analysis methods to account for ice accretion and asymmetrical ice shedding (as caused by spontaneous or uncontrolled ice shedding)
- Model rotor tests with artificial ice shapes
- Flight tests with artificial ice shapes
- Flight tests behind HISS or in hover spray rig
- Flight tests in natural ice
- Test/theory correlation
- Validation of standard evaluation procedures

TABLE 5. PROTECTION FROM ICE/ICE PREVENTION

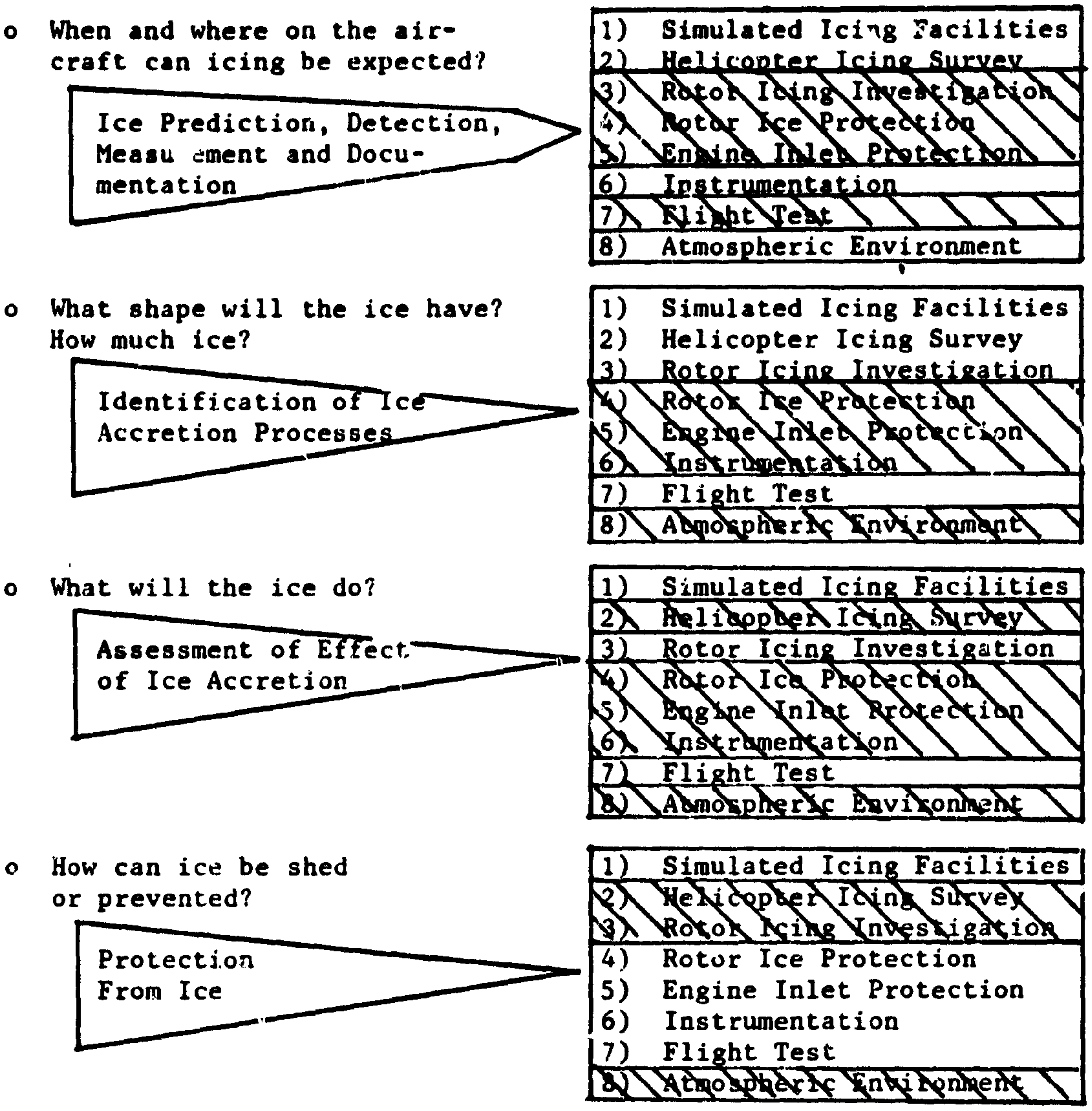
Current and Planned Activities

- Static and oscillatory airfoil anti-icing/deicing wind tunnel tests
- Development of 1-D/2-D heat transfer analysis methods
- Analysis of ice phobic and fluid ice protection systems
- Pneumatic boot tests
- Examine rotor and engine inlet ice protection methods.

Recommended Activities

- Determine feasibility of testing full scale rotor icing/deicing in wind tunnel
- Review and determine feasibility of ice prevention system
- Analysis, design and test of advanced electrothermal de-icing systems
- Rotor performance/blade loads analysis during de-icing cycle
- Prediction of handling qualities during de-icing cycle
- 2-D oscillating airfoil tests equipped for detailed heat transfer measurements
- Further investigation of vibration and microwave de-icing systems
- Develop promising new ice protection concepts
- Flight test verification (HISS, spray rig, natural ice)
- Validation of standard evaluation methods for ice protection systems

TABLE 6. ROTARY WING ICING RESEARCH



Fundamental Questions:	Primary Research Areas:
o When and where on the aircraft can icing be expected? Ice Prediction, Detection, Measurement and Documentation	1) Simulated Icing Facilities 2) Helicopter Icing Survey ▨ 3) Rotor Icing Investigation ▨ 4) Rotor Ice Protection ▨ 5) Engine Inlet Protection 6) Instrumentation ▨ 7) Flight Test 8) Atmospheric Environment
o What shape will the ice have? How much ice? Identification of Ice Accretion Processes	1) Simulated Icing Facilities 2) Helicopter Icing Survey 3) Rotor Icing Investigation ▨ 4) Rotor Ice Protection ▨ 5) Engine Inlet Protection ▨ 6) Instrumentation 7) Flight Test ▨ 8) Atmospheric Environment
o What will the ice do? Assessment of Effect of Ice Accretion	1) Simulated Icing Facilities ▨ 2) Helicopter Icing Survey 3) Rotor Icing Investigation ▨ 4) Rotor Ice Protection ▨ 5) Engine Inlet Protection ▨ 6) Instrumentation 7) Flight Test ▨ 8) Atmospheric Environment
o How can ice be shed or prevented? Protection From Ice	1) Simulated Icing Facilities ▨ 2) Helicopter Icing Survey ▨ 3) Rotor Icing Investigation 4) Rotor Ice Protection 5) Engine Inlet Protection 6) Instrumentation 7) Flight Test ▨ 8) Atmospheric Environment

GENERAL DISCUSSION

SIMULATED ICING FACILITIES

Helicopter and systems icing tests by airframe manufacturers, helicopter users and government agencies have been conducted utilizing a variety of simulated icing test facilities (i.e., icing wind tunnels, environmental cold chamber, rotor whirl towers, hover spray rig, in-flight tankers). Each of these facilities has shortcomings in relating the helicopter ice accretion, shedding, and ice protection system performance to operations in natural icing conditions. Differences in the simulated icing facilities present difficulties in the comparative evaluation of helicopter icing data.

Five types of facility have been and are being used for generation of a simulated icing environment:

- o Icing wind tunnel (NASA Lewis Research Icing Tunnel is one example)
- o Environmental cold chamber (the existing Eglin Air Force Base, Florida climatic hanger is one example)
- o Cold region helicopter or rotor tie-down site (a natural icing site such as has existed on the top of Mount Washington, N.H.)
- o Hover spray rig (i.e. NRC Ottawa spray rig)
- o In-flight spray system (i.e. U.S. Army HISS, USAF C-130)

Present simulated ice sources as reported in NASA TM 81707 (Reference 3) are available through use of existing large scale icing test facilities, i.e., NASA-Lewis Icing Research Tunnel, AEDC (Arnold AFS) Icing Research Cell (and Engine Test Cells), Eglin AFB Climatic Laboratory, Naval Air Propulsion Test Cells (Trenton), U. S. Army Helicopter Icing Spray System (HISS), USAF KC-135 and C-130 in-flight icing spray tankers and the National Research Council of Canada (NRC) hover spray rig. These facilities, currently available for helicopter and helicopter systems evaluation, have particular limitations in size of test window (relative to test configuration size) and in range of icing cloud characteristics (liquid water content and cloud droplet diameter) relative to current icing envelope definitions. Private facilities (industry, universities, etc.) have additional limitations in icing simulation capabilities generally related to size. An overall summary of icing simulation facilities in North America are contained in a table from NASA TM 81707; these tables are reproduced in Appendix B of this report.

Present use of the existing in-flight simulation facilities is principally for military icing investigation and flight clearance programs. Limited commercial investigation efforts are being accomplished using the HISS through inter-agency agreements between the U. S. Army and the FAA. The NRC hover spray rig, which has been used primarily for icing research, systems verification by military agencies and subsystem verification by civilian agencies and by industry is to be phased out of operation by approximately 1985. The NASA-Lewis Icing Tunnel and the Icing Research

Cells at AEDC-Arnold are the only large Government facilities available to industry in the near term for both military and commercial icing certification/qualification of helicopter systems (other than the complete rotor system). No test facility (i.e., icing simulation facility) exists (either government or private) that can provide the complete environment necessary for current helicopter certification because of the existing size and icing cloud parameter limitations, availability, and because of the lack of practical test criteria by the certifying agencies.

Large Scale Facilities

Icing Wind Tunnel. Icing tunnel testing offers the most comprehensive method for determining the performance of non-rotating ice protection system under various ambient conditions. Most icing tunnels have the capability to control Liquid Water Content (LWC), droplet size, and temperature over a specific range. At present the largest of these is the NASA Lewis Icing Research Tunnel (1.83m x 2.74m test section) in Cleveland, Ohio.

One of the major disadvantages of current icing tunnels is the lack of size necessary to test a full scale rotating main rotor. Stationary, and oscillating airfoil sections have been evaluated (without centrifugal force field, blade bending and high mach number effects) in icing tunnels. However direct correlation with rotating airfoils in forward flight has not been achieved. NASA (Lewis) is planning to evaluate a rotating 1.52 meter diameter tail rotor in their Icing Research tunnel to determine if correlation can be obtained with in-flight rotor ice. To date some success by NRC has been achieved in relating low mach number (<.3) icing tunnel airfoil data (stationary) to helicopter rotor icing trial results (at equivalent rotor mach number) in the hover spray rig.

Environmental Cold Chamber. A cold chamber can enclose an entire (tied down) helicopter or rotor system with a controlled environment (ambient temperature, liquid water content). The general problem with a chamber is the recirculation of the icing cloud and snow/ice crystal formations circulating in close proximity to the rotor system due to the chamber floor (unless a high mounting platform is incorporated) and due to sidewall effects.

The largest North American cold chamber, is the Climatic Laboratory at Eglin AFB.

Helicopter Tie-Down Site. The tie-down facility can utilize the natural icing environment as the source. The difficulties are in locating an accessible test site such as the one located at the top of Mount Washington, New Hampshire with a sufficiently long natural icing season. The outdoor site reduces many of the cold chamber problems (recirculation, wall effects) and (if the prevailing wind is sufficient) may provide at least some forward flight simulation.

Hover Spray Rig. The National Research Council of Canada (NRC) Hover Spray Facility (22.86m x 4.57m spray nozzle array suspended about 15 meters above the ground) offers a closely controlled icing environment for development and check-out of ice protection equipment. The hover rig allows rapid access by ground personnel for examination of ice accretion and ice shedding characteristics. Good water droplet size and liquid water content control throughout the FAA Continuous Maximum icing envelope can be maintained during the helicopter hover icing penetration. The major problems are (1) the correlation of the rotor icing with that obtained in flight in natural icing and (2) the limited size of the icing cloud (caused by rotor in-flow) relative to the larger helicopter rotor diameters (i.e., CH-47 with a 18.29-meter diameter, or CH-53 with a 21.95-meter rotor diameter).

The majority of current rotor electrothermal deicing systems in operation today were developed using the NRC facility or are based on data taken in the hover spray rig. Current plans are for continued operation of the facility by NRC personnel until 1985. FAA studies are underway to determine: 1) requirement for continued operation; 2) who will maintain the facility, 3) feasibility of increasing rig size, or 4) need for a new hover facility at a U.S. site.

In-Flight Spray System. A helicopter in-flight tanker is being used by the U.S. Army (termed the Helicopter Icing Spray System (HISS)) to verify operation of various military helicopters under simulated icing conditions. Under a working agreement with the FAA, the HISS is als being used for some civil helicopter icing tests. The HISS consists of a CH-47 helicopter equipped with an 1800 gallon water tank feeding an external 18.29-meter spray boom suspended 4.57 meters below the fuselage. Atomizing nozzles (pressurized water and air) positioned along the boom create the cloud of supercooled water droplets through which the test helicopter flies. The HISS has encountered difficulties in simulating natural icing conditions because of lack of good water droplet size control. During the icing season of January - March 1980 new spray nozzles (Reference 26 describes the spray nozzle development program) capable of producing 20 to 50 micron (median) droplets were incorporated with good success. The major disadvantages of the current HISS are:

- Insufficient icing cloud size for immersion of an entire helicopter (fuselage and rotor).
- Variation of liquid water content within the cloud.
- Downwash wake causing the test helicopter to experience power changes not attributable to rotor ice.

Current HISS improvement efforts involve the installation of a bleed air Auxiliary Power Unit (APU) additional bleed flow (APU plus engine bleed) necessary for larger icing cloud size, and better control of the water droplet size. In addition, studies are underway to define feasible HISS improvements, or an alternate to the present HISS configuration, so that a much larger icing cloud can be achieved with a greater range of liquid water content. AGARD, for example, has recommended a cloud of at least 24 meters across by 9 meters deep with a liquid water content capability up to 3 grams per cubic meter.

Small Scale Facilities

High Speed Icing Tunnel. Rotor airfoil icing investigations require the detailed examination of the ice growth and ice shape with the appropriate mach number and angle-of-attack variations to permit (1) proper correlation with analytical ice growth models, (2) measurement of sectional performance changes due to ice, (3) correlation with ice accretions on oscillating and rotating test rigs, (4) correlation with airfoil performance prediction methods, and (5) to provide comparisons with icing flight tests.

The NRC high speed icing wind tunnel has the capabilities to accomplish the airfoil ice accretion portion of the investigation.

The NRC tunnel has a 1 foot by 1 foot working section within a closed loop circuit with temperature capability to -40°C and liquid water content up to 2.0 grams/cubic meter. The design maximum speed is 0.9 Mach. A recommended 2-D rotor airfoil icing investigation takes advantage of the NRC tunnel capabilities. Unfortunately, the Canadians plan to close this useful facility down. NASA hopes to build a similar facility to replace it.

Rotating Test Rig. The use of an OH-58 tail rotor test rig in the NASA IRT offers an opportunity to determine the feasibility of testing scale model rotors, and/or truncated full scale rotor sections within the 1.83 meter by 2.74 meter test section. The initial tests with the tail rotor will permit the investigation of ice accretions (and sectional ice shapes) over a range of angles of attack and pitch amplitudes within the capability of the teetering arrangement (without cyclic control). A preliminary investigation of the tail rotor aerodynamic characteristics indicates that the rotor shaft should be inclined. This inclination will eliminate the large local angle of attack fluctuations due to rotor wake proximity and to induce a sinusoidal angle of attack variation approximating that of a main rotor.

Survey and Validation of Icing Facilities

Current Surveys of Facilities. A current FAA funded effort will provide a comprehensive examination of available icing test facilities that extends the work reported in NASA TM 81707 (Reference 3); the effort will recommend necessary changes for upgrading existing facilities and new icing test facilities for fixed wing and rotary wing applications.

A number of the existing large scale facilitities and their limitations have been discussed in the introduction to the simulated icing facilities section of this report. One issue that is still unresolved is the direct comparison of the icing clouds generated in each facility to a standard shape/airfoil, as a means of establishing (1) that all facilities produce the same ice shape (at equivalent severity conditions), and (2) a means of correcting the facility results to a standard natural icing condition.

A program is needed to compare icing wind tunnel results with natural icing conditions. Together with results in the NRC hover spray rig, and behind the HISS (and other in-flight icing spray tankers).

Although the HISS comparison most directly affects the helicopter programs, other in-flight tankers (KC-135, C-130, Piper Cheyenne, Cessna 404, Flight Systems T-33) should be included in an overall comparison of icing cloud characteristics for meeting the certification requirements.

HELICOPTER ICING SURVEY

A great deal of the current U.S. helicopter icing experience has been based on testing in the National Research Council of Canada (NRC) Hover Spray Rig (HSR) or behind the U.S. Army Helicopter Icing Spray System (HISS). A test UH-1H (directed by the U.S. Army Applied Technology Laboratory), equipped with electrothermal rotor deicing, electrically-heated windshield and stabilizer bar, and ice detectors has been operated in the simulated icing facilities (HSR and HISS) and in natural icing conditions. The A&AEE (Boscombe Down) has, over the past ten years, been conducting HSR and natural icing trials utilizing primarily the Wessex Helicopter, with and without rotor deice provisions. In addition to testing of electrothermal rotor deicing systems and testing of unheated rotors, effort is being applied by the U.S. Army and the U.K. to the investigation of icephobic coatings for rotor ice protection. Recent icing trials (St. Paul, Minnesota 1979 and 1980) of the CH-47 and UH-60 have taken advantage of available natural icing conditions to expand the experience levels beyond that of the simulated icing facilities.

In general a survey of helicopter icing experience must start with an examination of published and unpublished icing test reports and test summaries from (1) hover spray rig (2) in-flight tankers and (3) natural icing flights. The data should include:

(1) Airfoil (rotor) ice shape & extent as determined by photographs (still and movies) taken from hub, chase plane and ground cameras.

(2) Rotor ice protection systems operation (may include thermal analysis predictions and measured blade temperature).

(3) Correlation of predicted rotor ice penalty using measured helicopter performance (i.e., rotor torque, engine torque, fuel flow)

(4) Engine inlet ice (or ice protection) data and techniques used to provide:

- Anti-icing (electrical, bleed air, etc.)
- Protection from ice particles (i.e., deflectors, screens, separators, etc.)

(5) Windshield and other transparent area ice protection techniques and effectiveness

(6) Ice accretion & ice protection of components (i.e., droop stops, vents, pitot, static ports, etc.)

The following presents a summary (extracted from Reference 1) of recent rotor icing experience and illustrates some of the problems encountered as the rotors accumulate ice based on the conclusions from the reported information:

UH-1H Simulated Icing Tests (HISS) September-October 1973 (Reference 4)

- Asymmetrical rotor ice shedding caused severe vibration.
- Deliberate control inputs to induce rotor ice shedding may cause asymmetrical shedding.
- Rotor ice greater than 1/2 inch severely degrades safe autorotational capability.

AH-1G Simulated Icing Tests (HISS) October-November 1973, March-April 1974 (Reference 5)

- Severe vibrations from asymmetrical rotor ice shedding particularly below -10°C.
- Autorotational rotor speed severely degraded with rotor ice.

CH-47C (Metal Rotors) Simulated Icing Tests (HISS) April 1974 (Reference 6)

- Level flight power increases of 5 to 31% with rotor ice.
- Symmetrical rotor ice shedding with light to heavy icing at -6°C and light icing at -9°C.
- Asymmetrical rotor ice shedding with moderate icing at -9°C.

AH-1J Simulated Icing Tests (NRS Ottawa Hover Spray Rig) January-February 1974 (Reference 7)

- Severe vibrations from asymmetrical rotor ice shedding at temperatures from -4°C to -19°C.

YUH-61A Simulated Icing Tests (HISS) October-November 1976 (Reference 8)

- Conclusions from <u>unheated</u> rotor tests:
  - Level flight power increases of 22 to 28% during 6 to 18 minutes in icing cloud.
  - Some asymmetrical ice shedding occurred causing moderate vibration (-13.5°C and 0.25 GM/M^3 - 18 minutes test run).

  - Autorotational rate increase of 35% and 6% decrease in rotor rpm (full down collective) after 18 minutes in icing cloud.

CH-47C (Fiberglass Rotors) Simulated Icing Tests (HISS) and Natural Icing Tests (Minnesota) February 1979 (Reference 9)

- Conclusions from unheated rotor tests:
  - Fiberglass blades showed minimum evidence of asymmetric shedding down to -12°C in natural icing and to -15°C behind the HISS.
  - No apparent changes in handling qualities with rotor ice.

CH-47D (Fiberglass Rotors) Simulated Icing Tests (HISS) and Natural Icing Tests (Minnesota) February-March 1980 (Reference 10)

- Conclusions from unheated rotor tests:
  - Asymetric shedding occurs at -19° to -20° behind the HISS
  - 10 to 20% increase in power required during natural icing encounters

ROTOR ICING INVESTIGATION

Analysis Methods

Flow Field. Potential flow streamlines can be developed for a variety of contours for two-dimensional, axi-symmetrical and three-dimensional bodies. The potential flow computer programs generally use a numerical solution to calculate stream function derived from equations of continuity and irrotational flow. The program depends upon the accurate representation of the body external boundaries by a series of X, Y and Z coordinates, and by the input of the free stream conditions. The output of the potential flow analysis can be used to determine 1) body streamlines and stagnation region, 2) pressure coefficients along the body and 3) streamline velocities and Mach number. The output data provides the input for particle trajectory analyses, airfoil performance, and heat transfer analyses.

Particle Trajectories. Particle Trajectories over a range of water droplet diameters (or other particles) can be developed for similar bodies as in the flow field analysis. The effects of fuselage interference or rotor wash not normally taken into account in existing programs are required in new program efforts to produce realistic results. Examination of CH-47 ice impingement during the 1979 testing in Minnesota indicates that a downward angle of 20 to 30 degrees should be applied to the trajectories to achieve comparable fuselage impingement results.

The flow field analysis and the particle trajectory analysis are closely related in that the flow field around a body must be first established as an input to the trajectory program. The analytical methodology to establish ice accretion rates uses two digital computer programs; the first establishes the potential flow field about an airfoil or other shape in an airstream and the second establishes foreign body trajectories and impingement locations. The potential flow field is determined by iteratively solving stream function equations, using known boundary values based upon flight speed, ambient conditions, attitudes, etc. The trajectory programs typically use finite difference techniques to calculate trajectories of individual droplets across the flow field until they impinge on a surface or pass out of the area of interest. Multiple trajectory calculations (from specified initial conditions for selected droplet sizes and densities) provide the impingement intensity data.

Definition of Ice Shapes and Accumulation Patterns

There is much evidence (documented in various icing trials reports - see References 4 thru 10) that ice accumulation on rotor blades poses a potential hazard to helicopter operation when operating without an ice protection system beyond the safe self-shedding range of the rotor; however, there is relatively little published data detailing when, where, and how ice accumulates and sheds from helicopter rotor blades in flight. By necessity, most icing/deicing tests on helicopters are operational in scope, since they must verify the adequacy of any deicing equipment installed, and provide guidelines for safe deployment and are not planned for documentation of the nature of rotor ice.

Because of the large centrifugal forces and the vibration characteristics of rotor operation, measurement of rotor ice has been limited to photographic coverage using hub mounted or fuselage mounted cameras on the test helicopter or use of chase plane photography. The "periscope" type hub camera system used on the Wessex (capable of simultaneous photographs of the upper surface - essentially full span - of all blades from one head) has been used as a way of documenting rotor ice build-up and shedding in-flight. Determining the ice shape and thickness, however, is still a problem because of the viewing angle between the camera and the blade. Detailed documentation of rotor ice shapes have only been possible during hover spray rig icing trials for the following reasons:

- o A reduced rotor angle-of-attack change occurs between hover and shut-down, as compared to landings from forward flight icing tests where large angle-of-attack and coning angle changes occur, thus much of the rotor ice can be retained for study after shutdown.
- o There is no temperature change between hover operation and shut-down, while during forward flight the ambient temperatures at altitude may differ greatly from the temperature at ground level.
- o The time from hover cloud exit to shut-down is very short compared to shut-down time after completion of a forward flight test run, thus minimizing effects of sublimation and solar heating of the rotor ice formations.

Most of the available test data about ice accumulation on airfoil shapes and the effects of ice on the airfoil characteristics (lift, drag) comes from fixed wing work. A great deal of the fixed wing performance work has been accomplished by NASA (NACA) in their icing research tunnel (NASA-Lewis) (Reference 14). Additional airfoil icing data is available through efforts such as the Swedish-Soviet Flight Safety Working Group (Reference 15). Fixed wing data is available as an experimental base to develop and validate performance prediction techniques, but as far as helicopter applications are concerned, fixed wing data suffer from the following drawbacks:

- Most available airfoil icing test data (i.e. icing tunnel) is limited to low speed conditions ($M<0.3$), while data of interest in helicopters would have to cover the range from $M = 0.3$ to at least $M = 0.8$.
- Data acquired for fixed wing applications is for ice accretion at fixed incidence, a condition not at all representative of the helicopter flow environment.
- Fixed wing airfoil ice accretions do not account for the centrifugal force field, aerodynamic heating variations (both time variant and along the span) or influence of elastic deflections of the blades on the shape and spanwise extent of the ice.

As has been discussed, while much effort has been expended in attempts to define the rotor ice shapes and accumulation patterns, little data is available that could be used to accurately check the analytical modeling techniques, or to check the rotor icing tunnel results.

The planned testing of 2-D airfoils, along with the oscillating and rotating rig (OH-58 tail rotor) testing should allow a systematic (and detailed) evaluation of the ice accretion process by permitting exact measurements, and contour casts to be made. At each step of the testing, a related computer code should be run to insure that a realistic ice model can be duplicated. At the same time, airfoil scale effects through use of different chord length airfoils can be checked both by test and prediction techniques as part of the process of verifying the scaling parameters.

Assessment of Overall Rotor Performance

Rotor Ice. The effect of rotor ice on rotorcraft performance, handling qualities and flight safety is determined by the combination (or interaction) of the following factors:

- The rotor airfoil geometry (i.e. chord, thickness, external contour, bending, twist)
- The rotor diameter, rpm & number of blades
- The rotor system type (i.e. rigid, teetering, articulated, etc.)
- The environmental conditions in which the rotor is immersed (i.e. icing intensity, ambient temperature)

- Blade spanwise loading (function of rotorcraft gross weight, rotor disc area, solidity and airfoil geometry)
- The use (or non-use) or a rotor deicing system (passive or active)
- The blade thermodynamic properties (i.e. thermal capacity of blade material, surface thermal conductivity
- Blade surface mechanical properties (i.e. ice retension capability (local shear and bending stresses))
- The changes in blade loads and pitching moments

The performance and loads characteristics of a helicopter rotor in forward flight are dominated by the outboard 40% of the advancing and retreating blade. The sectional characteristics having the largest impact on rotor limits are:

- The maximum lift coefficient at Mach numbers from 0.3 to 0.5 (retreating blade)
- The drag divergence and pitching moment characteristics at the advancing blade tip
- The overall sectional pitching moment
- The change in overall profile drag and lift/drag polar

The ice growth along the rotor increases in the spanwise direction (toward the tip) as the ambient temperature decreases and/or as the liquid water content increases. The ice shape, however, is not easily defined because of the leading edge surface temperature distribution (resultant of ambient temperature, water impingement rate, freezing rate, and aerodynamic heating), the aerodynamic and the centrifugal forces which are interacting as the rotor passes through the icing cloud. The non-uniformity of these parameters combined with the blade varying angle of attack in forward flight makes analysis difficult.

In general, rotor ice may cause (depending upon the ice shape and (spanwise and chordwise) extent which exists as a result of the factors noted above):

- Increased power required due to increased blade profile drag
- Increased control loads due to blade stall and/or high pitching moments
- Adverse vibration due to asymmetrical ice shedding
- Decrease autorotational capability due to increased blade profile drag along the inboard portions of the rotor

Assessment of Structural Blade Load Penalties

The analytical assessment of the impact of ice accumulation on rotor performance and loads could be carried out by following the procedure outlined below. The procedure could initially utilize available methods however further theoretical development, and experimental evidence is necessary. Preliminary results illustrating the use of airfoil design methods to predict the effect of ice accumulation are discussed.

The assessment of the impact of ice accumulation and ice shedding on rotor blades includes the following steps:

- Definition of ice shapes and accumulation features on rotor blades over a given range of flight and weather conditions. This is a key item in the process of developing analytical assessment techniques.

- Evaluation of the impact of ice accumulation on the sectional aerodynamic and dynamic characteristics of rotor blades. Much experimental work is necessary on 2-D airfoil sections and scaled rotors to provide a data base to check out the analyses.

- Determination of overall rotor aerodynamic performance penalties and assessment of blade and control load penalties due to:

  - Uniform and steady ice buildup
  - Uneven buildup and/or natural shedding
  - Assymetric ice shedding

- Review of problems related to the use of protection/prevention systems including:

  - Comparison of anti-icing and deicing systems
  - Method of achieving anti-icing or deicing (i.e., electrothermal, ice-phobic, etc.)
  - Capability of protection/prevention system (ambient temperature, liquid water content, time).

  - Examination of unprotected rotor shedding capability.

- Assessment of the impact of residual ice accumulation in presence of active de-icing:

  - Runback ice
  - Impingement aft of protected area
  - Exceedence of deice capability
  - System failure (partial or complete)

Currently the most difficult task appears to be the accurate determination of ice shapes occurring over rotor blades in flight. If ice accumulation during tests can be monitored with some degree of accuracy, experimental and theoretical procedures can be then directed to quantify the aerodynamic and dynamic consequences of rotor blade icing, and a rigorous approach to de-icing systems and flight safety could be then defined.

ROTOR ICE PROTECTION

Ice Protection (i.e., the prevention of ice build-up (anti-icing) or the shedding of accumulated ice (deicing)) can be provided by a number of techniques. Anti-icing is generally used on a helicopter in one of several thermal modes (engine bleed air, hot oil or electrical) as appropriate for windshields, engines and engine inlets, pitot probes, and other ice-sensitive equipment. These anti-icing methods have been adapted from similar techniques developed for fixed-wing aircraft.

Rotor Ice Protection, however, has evolved along a path that differs from the fixed-wing approach because of the unique aerodynamic and dynamic environment experienced by the rotor. Early approaches to Rotor Ice Protection involved the use of hot air (ducted along the rotor leading edge), fluids (expelled along the leading edge) or low ice-adhesion material (ice-phobic) such as Teflon. The only approach that proved satisfactory over the range of rotor icing conditions defined by military and civil specifications has been the electrothermal deicing system.

In electrothermal systems, electrical heater elements made up of strands of high resistance wire, etched or cut metal foil, or sprayed-on metallic deposits are placed along the rotor leading edge in either spanwise or chordwise elements. Electrical power is applied to the elements in a programmed sequence after an amount of ice (generally in the 3 to 10 mm range) has accreted on the rotor. As these leading edge segments heat up, ice is shed (the rotor is deiced) progressively around the chord, or from tip to root. The choice of spanwise or chordwise heater elements is generally made by each helicopter company based upon experiece and developed manufacturing techniques.

Advanced Heat Transfer Analysis

Proper use of heat transfer conduction codes depends upon a accurate definition of the material dimensions, the material properties (specific heat, density, thermal conductivity), external surface conditions (local heat transfer coefficients), heat source, and internal heat sinks.

Additionally, for a deicing analysis, the interface conditions between the blade surface and the ice (or water) require proper modeling to allow an accurate determination of the "trigger" conditions at the moment of ice shedding.

In the electrothermal rotor deice sequence, each heating element (power on sequence) heats the blade external surface adjacent to it. As the surface temperature rises, the local bond (a subject needing further investigation) between the surface and the ice weakens, until finally the ice is shed. At this point the design of the heater configuration becomes critical to the ice shedding mechanism .

In the case of a spanwise heater (heaters installed along the blade span) the ice cap tends to bridge across the heated area and shedding occurs only after sufficient chordwise heat flow has occurred along the blade external surface so that the ice cap becomes too weak to sustain the combination of aerodynamic, centrifugal, and bending forces.

In the case of the chordwise heater (heater installed around the leading edge surface in the chord direction) shedding occurs as the entire ice cap bond segment weakens and permits ice fracture (principally due to the centrifugal forces acting on the segment) along the chordwise boundary with the adjacent (inboard) segment.

The importance of transient heat transfer codes lies in the potential to exactly model and predict these shedding sequences so that much more detailed studies can be accomplished on the trades between chordwise and spanwise deicing heater arrangements and the determination of optimum heater dimensions and power density distribution.

Review of Electrothermal Deicing Systems

Electrothermal systems are incorporated in many helicopter anti-icing and deicing systems because of the adaptability of electrical heater elements into composite material structures (i.e engine inlets, rotors, empennage leading edges). The ability to control heat application and density readily lends the electrothermal deicing concept to the helicopter rotor system.

Current rotor blades such as those used on the CH-46E, and YCH-47D for example are of composite material construction with embedded heater elements. The heat transfer characteristics of the composite construction generally allow a more efficient utilization of electrical power as is noted in Reference 16. The key point in the comparison of deicing efficiency (i.e. heat transfer efficiency) is the thickness ratio (or thermal conductivity ratio) between the inner (heater-to-spar) and outer (heater-to-surface) insulation layers. In the case of the composite blade, the insulation thickness ratio is extremely large, while with metal spar blades the specific design and fabrication of the heater system over the spar determines how efficiently the heat reaches the leading edge surface. It is noted in Reference 16 that insulation thickness ratios of between 3 and 5 are recommended when the deicing system contains a metal substrate.

Several factors require examination in the deicing design configuration. The heater types (wire, etched or cut foil, or sprayed metallic deposit) require analytical and test evaluation to determine if significant heat transfer rate differences occur between heater types. Heater failure modes need to be investigated to determine (a) type(s) of failures most likely, (b) percent of heater effectiveness lost due to heater element partial failure, and (c) best means of minimizing total heater element failure.

The overall rotor deice effectiveness loss due to partial or complete heater element failure requires investigation. Element failures generally fall into the following groups:

(a) Failures due to voids in the surrounding material (lack of proper heat transfer away from the element).

(b) Failures due to element strain (blade strain).

(c) Failures due to improper electrical insulation between heater elements and any adjacent conductive structure.

(d) Failures due to static discharge or lighting strike.

(e) Failures due to penetration of moisture into the element.

(f) Failure at the connectors or lead wire joints.

A concern, particularly in composite rotor construction is the possibility of voids occurring in the material layers near the heater element location. If the void occurs at the element, there is danger of element burn-out with a potential arc occurring across the burned region in addition to the final complete loss of heat from that element. If the void occurs between the element and the external leading edge surface, local high heating of the internal blade material (potentially causing damage) and low heating of the leading edge (affecting the deice capability) will occur.

Tests that measure interface temperatures on a stationary or oscillating airfoil rig (using full scale blade sections) appear warranted as a means of investigating these various problems/concerns.

Alternate Concepts

Ice Phobic. Ice shedding coatings/ice phobic investigations are continuing for helicopter rotor application. The British have investigated the use of a low-adhesion surface film with a flexible sponge rubber substrate applied to a rigid structural base (Reference 17). Peeling or shedding should result because of the concentrated stresses applied to a small area of the ice/surface interface at any one time.

Laboratory testing looked encouraging however wind tunnel and flight tests showed that ice would not peel entirely and some would remain at the blade stagnation region.

As a follow-on to the original flexible substrate deicing investigations, the British have continued with studies of hybrid systems utilizing a narrow spanwise heating strip combined with either an ice phobic paste or a flexible substrate aft of the heater strap as discussed in Reference 18. The effectiveness of a flexible substrate combined with a leading edge heater remains to be determined.

Continuing ice phobic coating investigations are being conducted by the U.S. Army (ATL) using a UH-1H as the primary test vehicle. Initial results of the tests have shown somewhat erratic measured shear force shedding characteristics during repeated cycles, particularly after erosion due to rain.

Limited flight testing of two materials on the UH-1H rotor during January-February 1978 showed encouraging results. Additional tests were conducted during 1979-1980 icing season as reported in Reference 19.

Pneumatic Boot. Pneumatic Boot systems have been extensively developed and improved for fixed-wing aircraft whereby boot inflation operation develop little or no effect upon the airfoil lift. Materials are constantly being improved to overcome the erosion effects due to foreign particle and water impingement. Erosion testing by B.F. Goodrich has indicated some material compositions that may be capable of withstanding the impact and rapid erosion problems experienced by helicopter rotor leading edge materials. Limited non-rotating testing of a pneumatic boot installation has been accomplished by NASA and B.F. Goodrich in the Lewis Research Center icing tunnel to quantify ice shedding capability and aerodynamic effects. Major concerns are (1) the ability of the boot material to withstand the rotor environment, and (2) the impact of boot inflation or rotor aerodynamics. A full scale (UH-1H) rotor with a pneumatic boot installation is tentatively planned for evaluation by NASA Ames and the U.S. Army during 1981.

Chemical. Freezing point depressants (e.g. glycol, alcohol, etc.) as noted in References 20 and 21, can be used in a thin film over the protected surface, thus lowering the freezing point of water and preventing the formation of ice. Although relatively simple in concept, this method presents some drawbacks when applied to rotor airfoil anti-icing or deicing, such as difficulty in obtaining an even flow distribution in the presence of a variable external pressure field; it is an expendable system which requires resupply, a major disadvantage during remote field operations; the fluid distribution holes are sensitive to erosion and clogging, particularly in a dusty environment.

A chemical system was designed and tested on a CH-47 rotor to determine system feasibility (Reference 22). The major problem encountered during whirl tower testing was the non-uniform span distribution of the fluid due to changes in the external aerodynamic flow field coupled with various internal flow channel misalignment problems. The program was discontinued in the early 1960s. Other companies (Bell Helicopter, Lockheed) have investigated chemical systems for helicopter rotors have found similar problems with the fluid external distribution.

Vibratory. Rotor induced vibration at critical ice fracture frequencies offers a potential deicing capability as demonstrated in preliminary testing (see Reference 23). Much additional work is required to provide a system that is not detrimental to rotor and airframe structural components.

Other. The Electric Impulse deicing system developed in the USSR mechanically creates a ripple in the blade which sheds the accreted ice by deforming the skin structure under the ice. The initial deformation is accomplished in a very short period of time at discrete points in the blade. Deicing of the surface between these discrete points depends on the deformation wave being propagated along the surface from the point of initial impulse.

Patented adaptations of this system are being promoted by the USSR which features a pressure pulse in a non-conductive, non-flammable hydraulic liquid generated by an electrical spark discharge, causing the periodic pulsation of a relatively large surface area structure subject to ice buildups.

For this type of system to be successful, it must be applied to structures where the ripple caused by the local deformations can be propagated a reasonable distance without appreciable attenuation.

The Microwave rotor deicing concept has proceeded through analysis and laboratory testing as reported in References 24 and 25, but has not undergone full scale demonstration. The principle of the microwave system is to transmit the microwave energy through a rotor leading edge wave guide. Ice on the leading edge surface extracts a portion of the energy from the passing wave sufficient to cause local shedding. To date, many serious questions about the potential performance of this concept have been raised.

ENGINE INLET ICE PROTECTION

Engine Protection Requirements

Turbine engine operational factors to be considered while operating in icing conditions include:

- Ability of the airframe inlet system to prevent ice accretion, minimize airflow distortion.
- Ability of the engine to maintain ice-free surfaces of the front frame, inlet struts, inlet guide vanes, etc.
- Ability of the engine to withstand ice ingestion, or prevent ice ingestion (i.e. integral foreign particle separator).
- Ability of the engine to tolerate compressor face distortion that may be caused by ice accretion on the inlet system.
- Ability of the engine to supply compressor interstage and/or discharge bleed air in sufficient quantity for engine front frame, strut, guide vane, etc., anti-icing, and to airframe inlet components.
- Ability of the engine to supply maximum required shaft horsepower and to respond quickly during rapid power demands while experiencing compressor bleed extraction and inlet distortion.

The turbine engine must undergo icing and ice ingestion testing to determine the level of damage tolerance and anti-icing capability available from the basic (uninstalled) engine. The results of this testing will be used to establish the degree of inlet ice protection required. FAR Part 33, Subpart E states that turbine engines must ingest, without sustained power loss or required engine shutdown, inlet cowl and engine face ice resulting from a 30 second delay in anti-icing activation, hail (one 1 inch (2.54 cm) diameter for inlets up to and including 100 in^2 (645.2cm^2); above 100 in^2 (645.2cm^2), one 1 inch (2.54 cm) and one 2 inch (5.08 cm) for each 150 in^2 (967.8cm^2) of inlet area), and water (4% of engine airflow by weight). Exception to this ingestion demonstration is stated in the FAR if the engine incoprorates a protective device that can stop (and withstand the impact) of foreign objects, and such device will not obstruct the induction airflow.

Engine ice (and snow) protection may be accomplished mechanically by an inertial separator (such as used in the Pratt and Whitney Aircraft of Canada Turboprop PT6 installation), where the inlet airstream is turned sharply causing water and snow particles to continue straight (undeflected) past the compressor face. In most helicopter engine installations, however, mechanical ice protection can be provided only as part of the airframe installation, and not as an integral part of the basic engine.

The most common form of engine ice protection is thermal anti-icing with the heat supplied by compressor bleed or hot engine oil. The heated areas are generally the engine front frame (including struts) and the inlet guide vanes. If the engine incorporates an integral foreign particle separator (such as in the General Electric T700) anti-icing heat is supplied to the surfaces exposed to the primary airflow.

Engines that incorporate hot oil anti-icing also utilize the heated surfaces as part of the oil cooling system. The disadvantage is that heat is being dissipated from these surfaces even on hot days (unless the oil can be by-passed) with a resulting loss of engine power due to increased air temperature at the compressor inlet.

Engine compressor bleed air, while convenient does entail a loss of engine power (or increase in fuel flow to maintain constant power) when the bleed system is activated. Bleed extraction penalties can range from 2 to 4% power loss at the upper range of icing temperatures (the power loss decreases with decreasing ambient temperature), or 1 1/2 to 2% fuel flow increase at constant power demand. The effect of bleed extraction depends upon the bleed pressure ratio which is a function of the engine compressor pressure ratio and the bleed port stage location.

Engine Inlet Ice Protection Methods

The engine inlet is defined as that portion of the engine induction system supplied by the airframer. The inlet ice protection system must provide a means to:

- Prevent or minimize ice build-ups that may adversely affect the engine.

- Minimize airflow pressure loss and flow distortion under icing conditions.

- Safely withstand the impact of ice from external sources (airframe, rotors, natural (i.e. Hail)) and prevent the ice (or at least those ice pieces large enough to cause engine damage) from reaching the engine compressor.

- Minimize power penalty from the engine.

Engine inlet configurations can be divided into the following groups:

Forward Facing (Pitot or Dynamic) Inlets. This inlet group has high pressure recovery but exposes the engine to external ice (and other foreign objects). This inlet type works well if the engine incorporates an integral separator. The inlet surfaces generally lend themselves to anti-icing by compressor bleed or electrical heating elements.

Forward Facing Internal Inertial Separator Inlets. This inlet group provides engine protection from foreign objects by the use of particle deflection or particle "swirl" (similar to Vortex principal). The inlet surfaces require anti-ice heat which can be supplied by compressor bleed or electrical resistance elements. Because of the varying surface contours fiberglass construction is generally chosen over metal and thus electrical heating can be incorporated.

Forward Facing External Inertial Separator Inlets. This inlet group uses a similar approach as the internal inertial separator inlets for engine protection (i.e. deflection of the particles). The "mushroom" type inlet is an example. The exposed surfaces of the external inertial inlet (in particular the forward facing surfaces) require heat primarily in the anti-icing mode (although deicing may be practical if it can be demonstrated that the shed ice will not enter the compressor airstream, or that the ice pieces are tolerable by the compressor). As with the other noted inlets, heat can be supplied to the inlet surfaces by compressor bleed or electrical resistance elements.

Side Scoop Inlets. These inlets are of a forward facing type, but are installed on the side of the engine compartment rather than in front. The side location offers some protection from ice and other foreign particles and therefore additional engine protection may not be required (demonstration tests are required to determine the extent of engine protection needed). The side scoop inlets may be used as part of an inlet duct system or as the inlet to a plenum chamber.

Side Facing Inlets and Shields. These inlets have generally been derived from forward facing inlet configurations where the need for foreign object protection (in particular, where ice shedding from forward locations) has been demonstrated. The shield (or deflector) in most cases is no more than a section of sheet metal located forward of a simple bellmouth inlet fairing. Generally, no anti-ice heat is used on the shield; the ice is allowed to build-up and break-off on the forward side of the shield. Potential icing problems may occur, however, in low speed flight or hover if supercooled water droplets impinge on the aft side of the shield. Aerodynamic contours may be incorporated into the shield design to improve both the external and internal airflow paths and to reduce the edges and corners upon which ice can acrete. The next step is a side facing inlet system where the simple bellmouth and shield are replaced by a complete contoured inlet duct.

Anti-icing can be incorporated into the side facing inlet duct surfaces as necessary to eliminate accretions from impinging supercooled water droplets.

Enclosed (Vortex Tube) Inlets. This inlet type features a full compartment or enclosure forward of the engine compressor inlet in which a number of sideward facing Vortex (swirl) tubes are installed. The internal swirl vanes of each tube centrifuge the entering particles to the outer tube wall where secondary air (usually supplied by an auxillary blower) draws the particles away from the primary (engine compressor) airflow. The principal reason for this type of inlet installation is to protect the engine during sand and dust operation. Protection from engine icing is also a feature of this installation because of the water droplet inertial effects caused by the sideward facing Vortex tubes (i.e. ice tends to form on the outer tube edges without fully blocking the tube entrance). Emergency air provisions (and ram air during forward flight) can be incorporated into the design by use of forward facing movable plugs or doors. Anti-icing is not generally used with this inlet configuration. However, provisions for maintaining an ice-free emergency air door or plug can be designed into the system.

Plenum Chamber Inlets. Plenum chamber designs can be used in submerged engine installations, in combination with side facing or side scoop inlets. The plenum chamber generally reduces or eliminates the need for anti-icing. Ingestion of snow, however, may present a problem, particularly if the snow contacts a warm surface (unless enough heat is supplied to completely melt the snow).

Screened Inlets. Screened inlets (side or forward facing) can be used to protect the engine compressor from ice accretion (supercooled water drops) and ice impingement (from rotors or fuselage). Unless it can be demonstrated that the screen will not fully ice, provisions for by-pass engine air must be incorporated. A heater (anti-iced or deiced) screen could be installed, however, the energy requirements have generally shown that this is not a viable choice.

INSTRUMENTATION

Icing measurements on a helicopter presents a more complex problem than on a fixed-wing aircraft because of (1) the extreme variations between the rotor velocities (therefore rotor ice accretion rates) and the fuselage velocities during forward flight, and (2) the large flow field directional changes between hover and forward flight.

Results of current helicopter icing tests have indicated a need for both icing severity (in terms of liquid water content) and total ice accumulation (or rate of build-up on a critical component) to give the pilot a reference for icing encounters in specific helicopter types.

In the rotor blade deicing system where the ice detector signal is required to be proportional to the ice accretion rate on the rotor blades, placing the ice detector on the rotor blade would be highly desirable from a detection and accretion rate standpoint. Due to the accretion characteristics at various temperatures and icing intensities, the detector should be located approximately midspan. This presents many design problems with regard to the blade structure, the deicing blanket design, the blade balance, the aerodynamic drag, the vibration, and high "g" environment. For these reasons, all ice detectors to date have been fuselage-mounted and the proportionality is achieved by a time delay between the ice detector and the signal that initiates deice cycles.

Icing instrumentation can be defined in several categories as follows:

Liquid Water Content and Ice Accretion Indicators

These instruments are used for test measurements and for cockpit signal and/or ice protection activation.

Direct Liquid Water Content Measurement. This includes those instruments that physically measure the water content by capture of a water mass sample or by calculating the water content by droplet size sampling. An example is the Laser Spectrometers currently in use on test helicopters and fixed wing aircraft. The spectrometers, using either light scattering or shadow image techniques to record water drop images, can compute the liquid water content based on total water mass of the droplets.

Icing Rate Measurement. This includes those instruments that measure the rate of accretion of a specific thickness or mass of ice. These instruments can generally convert the icing rate signal to liquid water content if the proper airspeed corrections are achieved. Several currently or previously available detectors fall into this category:

- The Rosemount Ice Detector uses a change in axial vibration of the sensing element (initially at 40 KHz) to trigger an icing signal. Ice accumulating on the probe decreases the resonant frequency which is sensed and input to the icing rate meter as an analog voltage representing ice thickness. Both aspirated and non-aspirated detectors have been tested on helicopters.

- The Leigh Ice Detector uses a sensing head with an ejector to draw in ambient air allowing ice to build up on the sensor probe (inside the head). The ice on the probe intercepts an infrared light beam, thus indicating an icing rate which is processed through an analog-to-digital converter into a liquid water content/severity meter output.

- An ice detector developed by United Controls based on the attenuation by ice accretion on an airfoil section of a Beta particle beam passing along the airfoil leading edge between a Strontium 90 source and a Geiger-Muller tube. The Beta particle attentuation triggered output circuitry at a controller which passed a signal to an airframe system (signal light, deice controller, etc.) and also deiced the airfoil in preparation for a new sequence.

Moisture Rate (Inferential) Measurement. This includes those instruments that detect the presence of moisture and infer the moisture rate (and hence liquid water content) by electrical resistance or electrical power change. Examples of these are as follows:

- The Normalair Garrett Detector utilizes an inferential technique to compare the temperature change between a wet and dry sensor. The power differential required to maintain the same temperature on both sensors is related to the intercepted liquid water content. The electrical signal is processed into an output meter displaying liquid water content.

- The Johnson-Williams instrument is primarily intended as a research unit for measuring liquid water content. Change of resistance of an electrically heated wire due to the cooling effect of impinging liquid drops is processed into a signal proportional to liquid water content.

Total Ice Accretion Measurement. This includes a variation of the icing rate instruments in which the total amount of ice accreted on a critical component is inferred by the accumulated icing rate signal. A similar approach can be used to record the amount of ice up to a specific reference level at which time a deicing system can be activated.

Icing Indicators. These passive indicators are used to note the presence of ice on, for example, a small probe or airfoil. If periodic notations of the ice thickness are made, the average liquid water content can be calculated. Examples are:

- A single probe ice accretion device (such as the Normalair Garrett Limited Indicator) or a two-bladed indicator (i.e., the "Harvey Smith") with a second blade set at a reference angle to the accreting blade. The total ice thickness can be determined by these devices, and the rate of ice growth calculated.

- A thin rod or airfoil which may have manual deicing capability, designed to give the pilot a visual indication of ice build-up. A variation of this can be created by use of photoelectric light beam along the leading edge of an airfoil shaped rod. Ice, interrrupting the light beam, is sensed by a photodetector which can then signal a controller triggering the heater circuit and activating a specific signal to the pilot.

Water Droplet Size Measurement

The use of these instruments is usually confided to test programs.

Direct Droplet Size Measurement. This includes those instruments that physically capture the droplets and those that photographically or electronically measure the droplets such as the Laser Spectrometers, the oil or gelatin coated slide, and the use of holographic photography.

Indirect Droplet Size Measurement. This includes the drop size and drop distribution inferred by rate of capture on rotating or stationary cylinders and stationary spheres.

Test Validation Instruments

Ice Physical Record. This includes those instruments (such as photographic) that record the ice accretion rate, shape, location and duration.

Ice Effects Measurement. This includes the instruments for measuring the performance, dynamic, and load changes due to ice.

Development Of New Icing Environment Measuring Devices

As noted in the review of current and prior ice (LWC, rate) measuring and droplet size measuring devices two significant areas are lacking:

(1) A means of detecting the presence and rate of ice on the rotor.

(2) An inexpensive and reliable means of obtaining droplet size measurements.

One approach to the rotor ice detection question appears to be by use of a microwave system (currently funded for development testing by NASA NAS3-22765). If the problems of location on the rotor, erosion protection, and deicing of the sensor can be solved, this approach appears promising.

Droplet size measurement devices other than the stationary cylinder, sphere, or rotating cylinder that do not require large electronic support systems, or special camera/microscope equipment have not surfaced to date.

Development Of New Techniques For Inflight Ice Accretion Measurement

Several photographic techniques have been tried to obtain rotor ice shape and ice extent. Because of the centrifugal forces and blade balance problems involved in mounting a camera on the rotor, photographic coverage of inflight rotor ice accretion and shedding has been limited to photographs (still or movies) taken from hub mounted or fuselage mounted cameras on the test helicopter, or photographs taken from Chase aircraft. A variation of the hub mounted camera is the "periscope" type system used on the Wessex Helicopter. The Wessex "periscope" uses a hub mounted prism which transmits a top blade surface view to a hub mounted camera. The prism permits simultaneous photographing of each rotor blade at selected intervals so that various shedding characteristics can be examined.

The basic problem with the current photographic techniques is that ice shapes (profile shape) and ice thickness are extremely difficult to estimate because of the oblique viewing angle between the camera and blade. There is a need therefore to develop techniques that enhance the photographic ice image (i.e. computer simulation, ultrasonic, microwave, etc.) to create a realistic ice profile at selected rotor stations.

FLIGHT TEST

Helicopter Flight Testing with Artificial Ice Shapes

A major problem in simulated and natural icing flight tests is the determination of power required and control loads increases due to rotor ice accretions representative of the extremes of the specification icing envelope.

While rotor ice protection functions can be checked out and qualified during in-flight icing tests, the effects due to (1) runback (excess deice heater on time), (2) incomplete shedding (short heater-on time), (3) heater failure (single or multi-element), (4) excess ice before deice activated, are not easily determined.

The use of artificial ice shapes (modeled ice shapes) can significantly shorten the time required to determine the magnitude of these icing effects by permitting specific ice shapes to be placed on the rotor at specific locations to duplicate the worst-case situation.

Prior testing in icing tunnels to verify the technique and to examine the rotor start-up and shut-down procedures is required to provide the proper shape/location criteria and to determine the control capability necessary. Analytical prediction of the aerodynamic and dynamic effects of the ice can be used to determine the shapes based on the specification icing envelope extremes required to determine performance changes.

The final check-out of the artificial ice shapes can be accomplished on a rotor whirl tower where close monitor of rotor performance and loads can be observed, and changes to the ice shape and location can be readily made. Prior to a flight program, the rotor instrumentation can be calibrated on the whirl tower.

Validation Of Ice Monitoring And Protection Equipment

Validation of ice protection systems normal operating and emergency procedures may be done during flight test operations using simulated icing conditions. To reduce the total flight time required for system validation these steps are recommended:

(1) Dry air flight check-out of specific instrumentation that permits measurement of blade surface conditions (surface temperature), blade loads (root torsion, control loads) and deice cycle time (for thermal systems).

(2) Flight tests behind in-flight icing tanker to check-out and calibrate the ice measuring instrumentation, and to measure the ice shapes and locations on the rotor (verification of the artificial ice shapes).

ATMOSPHERIC ENVIRONMENT

The basis for the current meteorological criteria defining the icing environment used by the FAA and the military is the analysis of surveys accomplished by NACA (now called NASA) during the 1940's and 1950's using fixed-wing aircraft.

A primary intent of these NACA icing surveys was to introduce a design criteria for thermal ice-prevention (anti-ice) systems by providing a rate, duration, and frequency of occurrence of various icing conditions.

A majority of the research flights on which the NACA design criteria data is based were conducted around the Great Lakes and West Coast Regions of the United States. Much of this data was taken above 3,962 meters with a limited amount taken as low as 1,219 meters. Much additional icing data was taken after the original meteorological factors tabulated in NACA TN 1855 were published. This additional data however, has not been reflected in the meteorological factors which form the reference base for the FAR Part 25 Appendix C Icing Envelope.

A current NASA effort is to review and analyze the measured in-flight icing data that was not incorporated into NACA TN 1855. Additionally, Canadian and USSR icing data is being added to the sample so that a more complete look at icing survey results below 3,048 meters is obtained. The results of this work, combined with the Naval Research Laboratory (NRL) cloud survey, and the FAA/University of Wyoming low altitude icing survey should go far in establishing the basis for a realistic helicopter icing envelope.

CONCLUSIONS

United States Helicopter Icing Research as progressed very slowly over the past 20 to 30 years. NASA's new initiatives coupled with active FAA and DOD programs are moving to resolve many of the open issues addressed in this report because of the increased desire by helicopter operators for all-weather capability; similarly, the need exists within the helicopter industry for techniques/procedures to permit helicopter icing certification in minimum time/expense/risk.

Currently available tools are inadequate for the detailed study of ice accretion and ice shedding. The definition of these icing characteristics is essential for the determination of rotor performance changes during icing encounters.

The rotor stands out as the key area requiring a major effort. Verification of rotor capability during "unprotected" operations in icing will have a great bearing on the usefulness and safety of a "limited" icing envelope clearance. Additionally, the degree to which the rotor requires an active deice mechanism to achieve "unlimited" icing capability needs to be determined. Thus, the need exists to develop the proper analytical tools, and to upgrade the test capability so that approaches to understanding rotor ice effects and predicting rotor capability can be accomplished.

The success in developing a reasonable cost icing certification procedure depends largely upon the maximum availability of upgraded and new simulated icing facilities. Current facilities lack the capability to permit simultaneous testing of all helicopter systems, thus complete duplication of natural icing flights cannot be accomplished, however, the difficult and time consuming problem of locating natural icing (particularly the higher liquid water contents) within the normal helicopter operating altitudes (up to 3,000 to 4,500 meters) makes use of the simulated facilities extremely important. Simulated icing facilities use combined with developed instrumentation and analytical procedures will allow extrapolation of icing tunnel and in-flight icing test data (simulated and natural) to the limits of the required certification icing envelope.

In order to accomplish the basic research, analytical tool development, and icing facilities improvement the following must be accomplished:

(1) Upgrading of the existing major icing test facilities must continue as rapidly as funds permit.

(2) Airfoil ice accretion tests in a 2-D high speed icing tunnel must be undertaken as soon as possible so that:

   (a) Existing 2-D facilities capabilities can be used,

   (b) Validity of ongoing analytical predictions can be checked,

   (c) Correlation with rotating airfoil tests can be made, and

(d) Decision on necessity for NASA high speed 2-D icing tunnel can be made.

(3) Validation of airfoil codes must proceed to the point that both aerodynamic and dynamic effects due to ice accretion and ice shedding (protected and non-protected rotors) can be predicted.

(4) Ice protection concepts (rotor and engine inlet) must be explored. In particular, an alternate to the electrothermal rotor deice system is of prime importance.

(5) Instrumentation concepts for measuring the in-flight icing environment, and for measuring rotor ice are required.

Comparison summaries of the recommended icing research by the FAA, General Aviation and Agard, independently derived, is presented in Tables 7, 8 and 9. These tables illustrate the commonality of direction with the programs described in this report. Because of limited available funding, this recommended research will require close coordination to take maximum advantage of each program and to avoid duplication of effort.

RECOMMENDATIONS

The research programs are divided into eight categories as follows:

(1) SIMULATED ICING FACILITIES

- Large Scale Facilities - Helicopter and Major System Test
- Small Scale Facilities
- Survey and Validation of Icing Facilities

(2) HELICOPTER ICING FLIGHT DATA SURVEY

- Helicopter Icing Survey

(3) ROTOR ICING INVESTIGATION

- Development of droplet trajectory analysis methods
- Definition of Ice Shapes and Accumulation Patterns
- Degradation in Sectional Characteristics Due to Ice Accretion
- Preparation of Standard Source of Helicopter Airfoil Icing Data
- Evaluation of Ice Effects on Structural Blade Properties
- Assessment of Overall Rotor Performance Penalties
- Assessment of Structural Blade Loads Penalities in Presence of Ice

(4) ROTOR ICE PROTECTION

- Definition of Advanced Heat Transfer Analysis Methods
- Evaluation of Electrothermal Deicing Systems
- Alternate Concepts Evaluation

(5) ENGINE INLET ICE PROTECTION

- Ice Protection Methods
- Engine Performance Penalities

(6) INSTRUMENTATION

- Verification of Current LWC and Droplet Measuring Devices
- Development of New Icing Environment Measuring Devices
- Development of New Techniques for Inflight Ice Accretion Measurement

(7) FLIGHT TEST

- o Helicopter Flight Testing with Artificial Ice Shapes
- o Validation of Ice Monitoring and Protection Equipment

(8) ATMOSPHERIC ENVIRONMENT

- o Survey of Natural Icing Conditions

These programs are further expanded in Appendix A into:

a) Programs Underway and/or Funds Committed
b) Programs Planned However Funds are Not Yet Committed
c) Programs Recommended - Funding Source to be Determined

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TABLE 7 COMPARISON OF FAA PROGRAM SUMMARY FOR HELICOPTER ICING CERTIFICATION RESEARCH AND NASA RESEARCH EFFORTS UNDERWAY/PLANNED/ RECOMMENDED (PROPOSED)

FAA RESEARCH PLAN AND PROGRAMS	RELATED NASA RESEARCH EFFORT
METEOROLOGICAL ICING CRITERIA	ATMOSPHERIC ENVIRONMENT
o NRL ICING CLOUD FLIGHT SURVEY o U. OF WO. LOW ALTITUDE ICING DATA SURVEY	o STAT. SURVEY OF EXISTING CLOUD DATA - TO SUPPORT DEFINITION OF HELICOPTER ICING ENVELOPE
TEST AND OPERATIONAL METHODOLOGY	FLIGHT TEST
o PARTICIPATION IN HELICOPTER ICING DEVELOPMENT/CERTIFICATION PROGRAMS - TO DEVELOP RATIONALE FOR NEW STANDARDS	o PROPOSED COOPERATIVE PROGRAM WITH PLANNED ICING FLIGHT TEST - TO VERIFY METHODOLOGY AND ICING INSTRUMENTS
ICE PROTECTION	ROTOR ICE PROTECTION
o ROTOR BLADE ICE PROTECTION CONCEPTS EXPLORATION	o PROPOSED ELECTROTHERMAL DEICING EVALUATION o PROPOSED ALTERNATE DEICING SYSTEMS EVALUATION: - ICE PHOBIC, FLUID, PNEUMATIC BOOT, VIBRATORY, MICROWAVE
	INSTRUMENTATION
o ICING SEVERITY SENSOR AND DISPLAYS	o VERIFICATION OF CURRENT LWC AND DROPLET INSTRUMENTS o DEVELOPMENT OF NEW MEASURING DEVICES o DEVELOPMENT OF NEW ICING PHOTOGRAPHIC TECHNIQUES

TABLE 7 (CONTINUED) COMPARISON OF FAA PROGRAM SUMMARY FOR HELICOPTER ICING CERTIFICATION RESEARCH AND NASA RESEARCH EFFORTS UNDERWAY/PLANNED/ RECOMMENDED (PROPOSED)

FAA RESEARCH PLAN AND PROGRAMS	RELATED NASA RESEARCH EFFORT
ICING CERTIFICATION TOOLS	SIMULATED ICING FACILITIES
o ICING TEST FACILITIES	o PLANNED IRT UPDATE
- HISS IMPROVEMENT (FAA/ARMY)	o AWT REHAB
	o ROTOR TEST RIGS
- NATIONAL ICING FACILITIES REQUIREMENTS INVES. (SYS. CONT. INC.)	o 2-D HIGH SPEED TUNNEL INVES.
	OVERALL HELICOPTER ICING EVALUATION AND ROTOR ICING EVALUATION
o ANALYTICAL TOOLS	o 2-D & 3-D DROPLET TRAJECTORY DEVELOPMENT (NASA CONTRACTS)
- DROPLET TRAJECTORY/IMPINGEMENT	
- PREDICTION OF ICE SHAPES	o ICE ACCRETION MODELING (NASA GRANTS)
- EFFECTS OF ICE SHAPES ON AERODYNAMIC/DYNAMIC BEHAVIOR	o ROTOR/PROP PERFORMANCE (NASA GRANT)
- EFFECTS OF PERFORMANCE, STABILITY, CONTROL	o PROPOSED ROTOR PERFORMANCE INVESTIGATION EFFORTS
	o QUASI-STEADY FLOW SCALING (NASA/USAF)
	o FIXED & ROTATING AIRFOIL SCALING (GRANT)
SNOW SIMULATION	o SNOW FLAKE TRAJECTORY STUDIES
ICING CERTIFICATION STANDARDS AND PROCEDURES	o RECOMMENDATIONS BASED ON FACILITIES, CAPABILITIES, ANALYTICAL TOOL DEVELOPMENT, AND FLIGHT TEST EVALUATION
o INTERIM STANDARDS	
o FLIGHT TEST GUIDES	
o ADVISORY MATERIAL	

TABLE 8 COMPARISON OF GENERAL AVIATION RECOMMENDED ICING RESEARCH AND RELATED RECOMMENDED HELICOPTER ICING RESEARCH

GENERAL AVIATION RECOMMENDED RESEARCH	RELATED HELICOPTER RESEARCH - FUNDED/PLANNED/PROPOSED/RECOMMENDED
SIMULATED ICING FACILITES	SIMULATED ICING FACILITIES EFFORTS
o ICING TANKER FACILITY	o LARGE SCALE
o PRODUCTION OF MIXED ICING CONDITIONS IN WIND TUNNEL	o SMALL SCALE
o METHODS FOR ICE SIMULATION (FOR DRY AIR TESTS)	
OVERALL ICING EVALUATION	OVERALL ICING EVALUATION
o 3-D COMPUTER CODED FOR ICE ACCRETION	o DROPLET TRAJECTORY 2-D, 3-D
o COMPUTERIZED ICING DATA FILE	o ICING SURVEY
o TRAINING FILMS FOR GENERAL AVIATION PILOTS	
ICING EVALUATION	ROTOR ICING EVALUATION
o SCALE MODEL ICE TESTING	o ICE SHAPE AND AIRFOIL SCALING
o ICE ACCRETION ANALYSIS TECH.	o ROTOR AIRFOIL SECTIONAL (2-D) PERFORMANCE EVAL.
o COMPUTER CODE DEVELOPMENT AND VERIFICATION FOR AIRFOILS	o AIRFOIL SECTIONAL DATA PREP.
o ICING RESEARCH TUNNEL TESTING OF AIRFOILS (AERODYNAMIC PERFORMANCE)	o EVALUATION OF LOCAL BLADE EFFECTS o OVERALL ROTOR PERFORMANCE EFFORTS
o COMPUTER CODES FOR ICE SHEDDING CHARACTERISTICS	o ROTOR LOADS EVAL.
o UNSYMMETRICAL SHEDDING FROM WINGS AND HORIZ. STAB.	
o WIND-TAIL INTERACTION IN ICING	
o HORIZONTAL TAIL STALL WITH ICING	
o FLIGHT CONTROL SURFACE FLUTTER	

TABLE 8 (CONTINUED) COMPARISON OF GENERAL AVIATION RECOMMENDED ICING RESEARCH AND RELATED RECOMMENDED HELICOPTER ICING RESEARCH

GENERAL AVIATION RECOMMENDED RESEARCH	RELATED HELICOPTER RESEARCH - FUNDED/PLANNED/PROPOSED/RECOMMENDED
ICE PROTECTION-WINGS/TAIL	ROTOR ICE PROTECTION
o ANTI-ICING CONSIDERATIONS OF COMPOSITES	o HEAT TRANSFER ANALYSIS METHODS
o ICE PROTECTION TRADEOFF STUDIES	o ELECTROTHERMAL DEICING EVALUATION
o BALANCE HORN DESIGN FOR WING/TAIL ICING	o ALTERNATE SYSTEMS EVALUATION
o ICE-PHOBIC COATINGS OR FLUIDS	
o ANTI-FREEZE FLUID SYSTEMS	
o PNEUMATIC BOOT FUNDAMENTALS	
o NEW ICE PROTECTION SYSTEM STUDY	
ICE PROTECTION - OTHER	ENGINE INLET ICE PROTECTION
o TURBOPROP ENGINE INLETS	o ICE PROTECTION METHODS
o CARBURATOR ICING RESEARCH	o ENGINE PERFORMANCE PENALTIES
o ENGINE HEAT FOR ICE PROTECTION	
o RATE OF BLOCKAGE OF AUXILIARY AIR INLETS & VENTS IN ICING	
INSTRUMENTATION	INSTRUMENTATION
o ICING INSTRUMENTATION	o VERIFICATION OF CURRENT LWC & DROPLET INSTRU.
- ATMOSPHERIC PARAMETER MEASUREMENTS	o DEVELOPMENT OF NEW MEASURING
	o DEVELOPMENT OF NEW ICING PHOTOGRAPHIC TECHNIQUES
FLIGHT TEST	FLIGHT TEST
o SIMULATED ICE ON AIRFOILS FOR CERTIFICATION	o COOPERATIVE PROGRAM WITH PLANNED ICING FLIGHT TEST

TABLE 8 (CONTINUED) COMPARISON OF GENERAL AVIATION RECOMMENDED ICING RESEARCH AND RELATED RECOMMENDED HELICOPTER ICING RESEARCH

GENERAL AVIATION RECOMMENDED RESEARCH	RELATED HELICOPTER RESEARCH - FUNDED/PLANNED/PROPOSED/RECOMMENDED
ATMOSPHERIC ENVIRONMENT	ATMOSPHERIC ENVIRONMENT
o INVESTIGATION OF FROST ACCUMULATION DURING GROUND OPERATIONS	o ICING CLOUD DATA

TABLE 9 COMPARISON OF AGARD NATIONAL ICING PROGRAM SUMMARY AND NASA-LEWIS RESEARCH EFFORTS UNDERWAY OR PROPOSED

COUNTRY	RESEARCH PROGRAM	RELATED NASA RESEARCH EFFORT
FRANCE	1. ICING CLOUD SURVEY	1. STAT. SURVEY OF EXISTING CLOUD DATA. (NOTE: ADDITIONAL DATA BEING GATHERED BY NRL AND U. OF WO. UNDER FAA CONTRACTS)
	2. ICE ACCRETION MODEL	2. U. OF DAYTON ICE ACCRETION MODEL
	3. THERMAL ICE PROTECTION MODEL	3. U. OF TOLEDO 1-D & 2-D TRANSFER CODES
	4. ACCRETION MODEL VALIDATION BY TESTS	4. PROPOSED 2-D TESTS, NRC HIGH SPEED ICING TUNNEL
	5. DEICE TESTS - VALIDATION OF THERMAL MODEL	5. PROPOSED OSCILLATING AIRFOIL DEICING TESTS
	6. COLLECTION OF ICING TEST RESULTS	6. PROPOSED HELICOPTER ICING SURVEY
	7. ROTOR (PART & FULL SCALE) ICING TESTS - TUNNEL	7. ROTATING AIRFOIL ICING TESTS IRT - (OH-58 TAIL ROTOR)
GERMANY	1. ICING FLIGHT ANALYSIS	1. PROPOSED HELICOPTER ICING SURVEY
	2. HELICOPTER ICING TESTS	2. PROPOSED HELICOPTER ICING FLIGHT TEST
NETHERLANDS	1. HELICOPTER ICING ENCOUNTER REPORTS	1. ----
UNITED KINGDOM	1. ICING CLOUD SURVEY	1. STAT. SURVEY OF EXISTING DATA
	2. IMPROVED ICING INSTRU.	2a. ICING INSTRU. VALIDATION
		2b. PROPOSED CRITERIA DEVELOPMENT FOR IMPROVED ICING INSTRU.

TABLE 9 (CONTINUED) COMPARISON OF AGARD NATIONAL ICING PROGRAM SUMMARY AND NASA-LEWIS RESEARCH EFFORTS UNDERWAY OR PROPOSED

COUNTRY	RESEARCH PROGRAM	RELATED NASA RESEARCH EFFORT
UNITED KINGDOM (Cont'd)	3. IMPROVED PHOTOGRAPHIC TECHNIQUES TECHNIQUES	3. PROPOSED DEVELOPMENT OF IMPROVED PHOTOGRAPHIC
	4. ASSESSMENT & DEVELOPMENT OF SERVICE AIRCRAFT INSTRU.	4. PROPOSED NEW INSTRU. DEVELOP.
	5. MODEL DEVELOPMENT - IMPINGEMENT, ACCRETION, THERMAL	5. U. OF DAYTON (ICE ACCRETION) OSU (DROPLET TRAJECTORIES) U. OF TOLEDO (1-D & 2-D HEAT TRANS.)
	6. AIRFOIL AERODYNAMICS TESTS (WIND TUNNEL) - MODELED ICE	6. PROPOSED SCALED ROTOR WIND TUNNEL EVALUATION
	7. DEICING TESTS - VALIDATION OF THERMAL MODEL	7. PROPOSED OSCILLATING AIRFOIL DEICING TESTS
	8. ICE-PHOBIC MATERIAL INVESTIGATION	8. CLARKSON COLLEGE ICE-PHOBIC COATING INVESTIGATION

APPENDIX A

ROTORCRAFT ICING RESEARCH SUMMARY OF SPECIFIC ACTIVITIES

The following is a discussion of these programs with specific recommended actions, approaches or considerations as appropriate within each category.

SIMULATED ICING FACILITIES

Large Scale Helicopter and Major System Test. Several actions are underway/planned or recommended to improve the existing facilities capabilities to permit icing research and icing clearance.

(1) Improve the U.S. Army HISS Icing Test capability by increasing the spray cloud size from the present (11 meters across and 1.8 to 2.4 meters deep) and improve the liquid water content/droplet size control. A Phase II improvement effort is underway which provides for increased airflow/air pressure (through use of a bleed air APU) thus allowing spray nozzles to be added to the full spray boom extent (18.3 meters across).

(2) Specifications for an alternate in-flight icing spray tanker and hover test facility are being generated under an FAA contract to System Control Inc. The desired facility will be able to produce an icing cloud large enough for all current and projected helicopters and V/STOL aircraft, with the capability to match the existing and projected icing cloud environment (LWC, D).

(3) Improve the NASA icing research tunnel test capability as follows:

- o Low speed (46-185 kilometers/hour) icing simulation
- o Low range (0.1 GM/M3 to 1.0 GM/M3) of liquid water content and droplet diameter (10 to 50m) within helicopter speed range (46-370 kilometers/hour)
- o Small water droplet (<10m) for scale airfoil icing investigations
- o Snow production (or definition of system requirements for snow generation)
- o Mixed production (ice crystal + liquid water)
- o Investigate use of IRT diffuser section for testing of manufacturers model rotating rotors (up to approximately 3 meters in diameter).
- o Include oscillating airfoil test rig capability

(4) Update the NRC Hover Spray Rig (if the planned phase-out direction can be changed) to increase the icing cloud size (the present spray cloud gives good coverage for rotors up to about 11 meters diameter) and provide increased range of liquid water content up to approximately 2.0 grams/cubic meter.

Small Scale Test. The primary efforts are directed toward the development of two capabilities. The first is a rotating test rig for scaled rotor blade icing tests in the IRT. The funded OH-58 tail rotor icing tests represents the initial step in the development of this capability. The second effort is to develop a capability to test 2-D airfoils under icing conditions at mach numbers representative of the full scale rotor system. To accomplish this second effort the following is recommended:

(1) Conduct 2-D airfoil icing tests in the NRC high speed icing tunnel. NRC is currently planning to remove the icing capability from this tunnel, therefore, this effort is dependent upon reaching a working agreement between NASA and NRC to keep the NRC facility open and permit use for the recommended icing program.

(2) Based on the evaluation of the NRC 2-D airfoil icing tests, prepare specifications for a NASA 2-D high speed icing tunnel, incorporating necessary changes from the NRC design to permit accurate airfoil aerodynamic performance measurements. The new high speed tunnel should have a test section of .3 meter by .9 to 1.8 meters (to be determined) with mach number capabilities up to .6-.7. The tunnel should be suitable for rotor ice shape determination (with test/analytical correlation), performance changes, scale airfoil icing validation, and icing instrumentation development (liquid water content, droplet diameter, cloud temperature).

Survey and Validation of Icing Facilities. Expansion of surveys conducted by NASA and FAA to include review of existing facilities capabilities and standard shape ice accretion measurements to examine (or validate) the test result variations between facilities.

ROTORCRAFT ICING RESEARCH

1 - SIMULATED ICING FACILITIES

1.1 - LARGE SCALE FACILITIES - HELICOPTER AND MAJOR SYSTEM TEST

a) UNDERWAY/FUNDS COMMITTED

1.1.1) ARMY HISS IMPROVEMENT PROGRAM (PHASE II). IMPROVE SPRAY CLOUD SIZE, LWC RANGE AND DROPLET SIZE.

1.1.2) DEFINITION OF SPECIFICATIONS FOR ALTERNATE HISS SYSTEM. CIVIL AND MILITARY REQUIREMENTS.

1.1.3) DEFINITION OF SPECIFICATIONS FOR AN ALTERNATE HOVER SPRAY RIG. CANADIAN/U.S. LOCATION (SYSTEM CONTROL INC., CONTR. DTFA01-80-C-10080, TASK 3).

b) PLANNED/FUNDS NOT COMMITTED

1.1.4) UPDATE NASA/LEWIS ICING RESEARCH TUNNEL (IRT). IMPROVE LWC AND DROPLET SIZE RANGE TO MEET CIVIL/MILITARY HELICOPTER REQUIREMENTS.

1.1.5) REACTIVATE THE VERY LARGE ALTITUDE WIND TUNNEL (AWT) (I.E., AS AN ICING TUNNEL).

1.1.6) CONSTRUCTION OF AN OSCILLATING AIRFOIL TEST RIG FOR THE ICING RESEARCH TUNNEL (IRT).

c) RECOMMENDED

1.1.7) UPDATE OF THE NRC (OTTAWA) SPRAY RIG. IMPROVE THE SPRAY CLOUD SIZE AND THE LWC RANGE. BECAUSE OF THE PLANNED PHASE-OUT OF THE NRC FACILITY IN 1985, AN ALTERNATE HOVER SPRAY RIG MAY BE REQUIRED.

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
1.1.1) HISS (PHASE II)	▽═══					ARMY/FAA	
1.1.2) ALTERNATE HISS	▽═					FAA(STUDY)	
1.1.3) ALT. HOVER SPRAY RIG	▽═					FAA(STUDY)	
1.1.4) UPDATE IRT		═══				NASA	
1.1.5) ACTIVATE AWT		═══	═══	═══	═══	NASA*	
1.1.6) IRT OSC.AIRFOIL RIG		═══				NASA	
1.1.7) UPDATE OTTAWA SPR.RIG		═══	═══	═		FAA(STUDY)	
(NOTE: BY CURRENT PLANS THE NRC (OTTAWA) SPRAY RIG WILL BE PHASED OUT IN 1985)							

*EST.1987 AVAIL.

ROTORCRAFT ICING RESEARCH

1 - SIMULATED ICING FACILITIES

1.2 - SMALL SCALE FACILITIES

a) UNDERWAY/FUNDS COMMITTED

1.2.1) CONSTRUCTION OF A TAIL ROTOR TEST RIG FOR THE ICING RESEARCH WIND TUNNEL (IRT) AT NASA/LEWIS

b) PLANNED/FUNDS NOT COMMITTED

1.2.2) NRC .3M X .3M HIGH SPEED ICING TUNNEL. SHORT TERM RETENTION AND MAINTENANCE (PROPOSED).

c) RECOMMENDED

1.2.3) DEVELOP SPECIFICATIONS FOR A SMALL SCALE, HIGH-SPEED ICING WIND TUNNEL TO SUPPLEMENT AND REPLACE THE .3M X .3M NRC WIND TUNNEL.
1.2.4) DESIGN AND CONSTRUCTION OF A SMALL SCALE, HIGH SPEED SUBSONIC MACH NUMBER ICING WIND TUNNEL.
1.2.5) CONSTRUCTION OF A TEST STAND TO CONDUCT MODEL ROTOR TESTS IN THE ICING RESEARCH TUNNEL (IRT) AND/OR IN THE ALTITUDE WIND TUNNEL (AWT).

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
1.2.1) TAIL ROTOR TEST RIG	▽═					NASA	
1.2.2) NRC .3M X .3M TUNNEL	═	═▶	PLANNED PHASEOUT OF NRC TUNNEL			NASA	
1.2.3) SPECS FOR NEW W/T		═				NASA	
1.2.4) CONSTRUCTION OF NEW W/T			═			NASA	
1.2.5) MODEL ROTOR TEST STAND		═	═	═	═	NASA	

ROTORCRAFT ICING RESEARCH

1 - SIMULATED ICING FACILITIES

1.3 - SURVEY AND VALIDATION OF ICING FACILITIES

a) UNDERWAY/FUNDS COMMITTED

1.3.1) SURVEY OF ICING FACILITIES IN NORTH AMERICA (NASA TM 81707)

1.3.2) SURVEY OF EXISTING FACILITIES (SYSTEMS CONTROL INC., FAA CONTRACT DTFA01-80-C-10080)

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

1.3.3) COMPARE ICE ACCUMULATION PATTERNS OVER STANDARD SHAPES OR AIRFOILS FROM ALL ACTIVE ICING TUNNELS.

1.3.4) COMPARE WIND TUNNEL, OTTAWA SPRAY RIG, HISS, AND NATURAL ICING RESULTS OVER STANDARD SHAPES AND WITH CONSISTENT INSTRUMENTATION.

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
1.3.1) SURVEY-N. AMERICA	▽═					NASA	
1.3.2) FACILITIES SURVEY	▽═					FAA	
1.3.3) ICE FROM ACTIVE W/T's		═					
1.3.4) ICE SHAPE COMPARISON			═				

ROTORCRAFT ICING
RESEARCH ASSESSMENT

1 - SIMULATED ICING FACILITIES

PROGRAM CATEGORIES AND STATUS	LEVEL	FUNDING COMMITMENT OR EXPRESSED INTEREST					FUNDED = F PLANNED = P RECOMMENDED = R	
		AGENCIES			FIX WING	ROT WING	ADVISORY GROUPS	
		NASA	FAA	DOD	GA TRANS		AGARD	OTHER
FUNDED								
1.1.1			F	F		R		
1.1.2			F			R	R	
1.1.3			F			R	R	
1.2.1		F				R		
1.3.1		F	R					
1.3.2			F					
PLANNED								
1.1.4		P				R	R	
1.1.5		P			R	R	R	R(HAA)
1.1.6		P				R		
1.2.2		P				R	R	
RECOMMENDED								
1.1.7			R			R	R	
1.2.3		R				R		
1.2.4		R				R		
1.2.5		R				R		
1.3.3		R	R			R		
1.3.4		R	R			R		

HELICOPTER ICING FLIGHT DATA SURVEY

A helicopter icing survey is necessary to obtain and review the U. S. Government test data from C-130, HISS, NRC hover spray rig and natural icing. The U. S. Army, Navy and Airforce have all conducted helicopter icing tests in these various facilities. Documentation of the test results in many cases is very sketchy and in particular, many of the icing photographs (stills, movies) are not contained or even referenced in published documents.

A systematic review of this data is required relating the photographs to the measured icing environment, and identifying the ice formations on the rotors, engine inlets, rotor hubs, controls, windshields and other critical areas. Measured test output from ice detectors, rotor and engine torque, rotor and fuselage vibration, thermal ice protection systems, temperatures and other parameter should be correlated with the photographic data as much as possible.

Rotor ice accretion, and rotor ice shedding during deice system activation are key items in this survey. This information will form the basis of the initial airfoil ice shape prediction and the prediction of deice effectiveness.

ROTORCRAFT ICING RESEARCH

2 - HELICOPTER FLIGHT DATA SURVEY

2.1 - HELICOPTER ICING SURVEY

a) UNDERWAY/FUNDS COMMITTED

b) PLANNED/FUNDS NOT COMMITTED

2.1.1) HELICOPTER ICING SURVEY. SEARCH AND REVIEW OF EXISTING U.S. GOVERNMENT HELICOPTER ICING TEST DATA FROM HISS, NRC HOVER RIG AND NATURAL ICING. EMPHASIS ON RESULTS OF ROTOR ICING AND PRICING, ENGINE INLET PROTECTION, ROTOR HUB, CONTROLS ICING AND OTHER CRITICAL AREAS. PHOTOGRAPHIC CORRELATION WITH KNOWN TEST CONDITIONS MOST IMPORTANT.

c) RECOMMENDED

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
2.1.1) HELICOPTER ICING SURVEY		═				NASA	

ROTORCRAFT ICING RESEARCH ASSESSMENT

2 - HELICOPTER FLIGHT DATA SURVEY

PROGRAM CATEGORIES AND STATUS	LEVEL	FUNDING COMMITMENT OR EXPRESSED INTEREST					FUNDED = F PLANNED = P RECOMMENDED = R	
		AGENCIES			FIX WING	ROT	ADVISORY GROUPS	
		NASA	FAA	DOD	GA TRANS		AGARD	OTHER
FUNDED								
PLANNED								
2.1.1		P	R			R	R	P (FRANCE) P (GER)
RECOMMENDED								

ROTOR ICING EVALUATION

The rotor icing investigation category is divided into major topics in order to better define the specific activities which make-up the overall subject. Within each topic the analytical, test and final correlation tasks are discussed as follows:

Water Droplet Trajectory Codes. The water droplet particle trajectory codes currently under development (2-D codes for airfoils, 2-D and 3-D codes for lifting and non-lifting bodies) require extension to represent the particle path within the rotor flow environment.

Consideration should be made for the flow field kinematics both into the rotor (for rotor icing studies) and downstream of the rotor (for rotor wash effects on the fuselage, inlets, and aft or tail rotor. Additionally the flow field and rotor mach number, and yawed flow effects must be taken into account to properly represent the particle path.

Use of this extended code will assist in correlating icing test data taken in the hover rig, behind the in-flight tanker and in natural icing.

Definition of Ice Shapes and Accumulation Patterns. The efforts under this topic involve the definition and validation of model scaling laws as they pertain to the rotating airfoil (steady flow, stationary airfoils and bodies are also considered), the development and test of ice accretion airfoil models in 2-D, oscillating and rotating configurations, and the final correlation of the scaling parameters for ice shapes on airfoils.

(1) The scaling parameters require detail study to determine aerodynamic, thermodynamic, water droplet trajectory and ice accretion similarity for comparison of full scale and part scale airfoils (and other helicopter components).

The various parameters involved (tip speed, advance ratio, local heat transfer, liquid water content, droplet diameter, etc.) must be evaluated to determine the significance of permitting off-scaling variations in selected parameters in order to obtain proper matching of the remaining parameters.

For example, a determination is required to show how a shift in blade mach number ratio affects the ice shape, or what relationship between velocity ratio and droplet size ratio must be maintained to maintain equal water catch efficiencies between the model rotor and full scale.

(2) The ice accretion airfoil models will provide the basis for addressing many of the scaling factors, and will also indicate the best method of simulating the actual (full scale) rotor icing characteristics (i.e. 2-D, oscillating, rotating).

(3) The OH-58 tail rotor (teetering rotor) test rig set-up in the IRT offers the opportunity to investigate the ice accretion mechanism over a constantly varing angle-of-attack, mach number, range with changes of shaft angles, thrust levels and advance ratios. Addi-

tionally, ice phobic material investigations and electrothermal deicing studies appear feasible on this test rig. Because the tail rotor has no cyclic control, the variation of blade angle of attack around the azimuth (and associated mach number variation) is generally not as great as with a main rotor. However, by inclining the shaft, a angle of attack variation will be introduced.

(4) The matching of rotor ice shapes between the rotating blade and the oscillating blade and the overall comparison of these shapes with those obtained during the "icing survey" should guide the decision on the best method for experimentally determining valid rotor ice shapes.

(5) An analytical exercise corresponding to these experiments should show the blade angle of attack and speed variation with time for large and small rotors with articulated, teetering, or bearingless main rotors and for a teetering tail rotor with and without cyclic pitch.

The results of this overall effort should establish:

- Analytical validation of averaged ice accumulation shapes from fixed incidence calculations at constant Mach number.
- Analytical extension of ice shape averaging to rotating airfoils tests (variable incidence and Mach number).
- Definition of mechanism of ice accumulation in presence of centrifugal forces based on test and analytical evaluations.
- Empirical determination of surface roughness conditions for a range of ice shapes.
- Analytical evaluation of scale effects.

<u>Degradation in Sectional Characteristics Due to Ice Accretion</u>.

(1) Modification and validation of existing separated flow analysis methods is required to handle specifically the ice accumulation problems (roughness).

(2) Improved methods are required to analytically assess the impact of surface (ice) roughness (i.e., thick boundary layer methods).

(3) Systematic 2-D tests of various ice shapes are required for typical helicopter rotor airfoils. To achieve this:

- A thorough 2-D airfoil wind tunnel test using a transonic tunnel is recommended to document (and permit correlation with analytical programs) the effect of several typical rotor icing shapes (determined experimentally) on the lift, drag and pitching moment characteristics of typical rotor airfoils:

- NACA 0012
- NACA 23012
- Typical thick and thin rooftop sections (e.g., VR-7, -8, SC 1095)
- Typical thick and thin advanced (transonic) airfoil sections

o The effect of icing on the unsteady aerodynamic characteristics (dynamic stall delay) of rotor airfoils needs to be quantified by conducting an oscillating airfoil test ($0.2<M<0.7$) on at least one airfoil with and without a representative ice shape.

(4) It is necessary to revise the unsteady aerodynamic models in selected performance/loads programs and to incorporate dynamic stall data from the oscillatory icing tests.

Preparation of Standard Source of Helicopter Airfoil Icing Data

(1) The existing rotor performance methods will have to be upgraded to allow the evaluation of blade icing effects by utilizing:

o Potential flow/boundary layer interaction methods
o Viscous transonic analysis methods
o Advanced boundary layer analysis
o Separated flow analysis

(2) It will be necessary to compute approximate rotor performance degradation as function of degree and type of icing on selected distributions of rotor airfoils

Evaluation of Ice Effects on Structural Blade Properties

(1) The analytical determination of changes in elastic properties is required (torsional and flapwise stiffness) as a function of ice shape.

(2) The methodology requires definition to account propertly for the extension of ice beyond the leading edge (i.e., mass and C.G. variations).

Assessment of Overall Rotor Performance Penalties.

(1) Upgrading of current rotor performance analysis methods is necessary.

(2) Model/full scale rotor tests are required with realistic artificial (modeled) ice shapes.

- Scaled rotor tests are necessary to examine the influence of ice (modeled) shape and mass on rotor performance (aerodynamic and dynamic) including the effects of asymmetrical icing. The investigation may include the effects of teetering, articulated and bearingless rotor systems as well as rotor airfoil contour and blade stiffness.

- Tests should be planned to measure in-plane and out-of-plane vibrations from asymmetric shedding of ice and from rotor dynamics.

- Analytical review is required of the simulated ice shapes and mass data to define specification for NASA icing rotor test stand, hub configurations, blade configurations balance, instrumentation specifications, data reduction requirements and list of auxiliary facilities requirements.

(3) Flight tests are necessary with complete performance and loads instrumentation, and advanced ice monitoring techniques.

(4) Extensive test/theory correlation is required with updated performance analysis methods.

Assessment of Structural Blade Loads Penalties In The Presence Of Ice

(1) It is necessary to modify the loads (dynamics) analysis programs to allow for the investigation of both steady ice accumulation and uneven shedding.

(2) Test/theory correlation is required with updated blade structural loads analysis methods.

3 - ROTOR ICING INVESTIGATION

3.1 - DEFINITION OF DROPLET TRAJECTORY ANALYSIS METHODS

a) UNDERWAY/FUNDS COMMITTED

3.1.1) GENERAL 2-D PARTICLE TRAJECTORY CODE FOR EXTERNAL FLOWS ABOUT 2-D AIRFOILS, AND INTERNAL FLOWS FOR 2-D INLETS (NAS3-22448)

3.1.2) 3-D PARTICLE TRAJECTORY CODE FOR FLOWS ABOUT NON-LIFTING BODIES (NAS3-22199) - COMPLETED

3.1.3) 3-D PARTICLE TRAJECTORY ABOUT LIFTING BODIES (NAS-22146)

3.1.4) WATER DROPLET TRAJECTORY ABOUT ROTOR BLADES (OSU, NAG3-109)

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

3.1.5) EXTEND TRAJECTORY CODES TO THE HELICOPTER ROTOR ENVIRONMENT BY INTRODUCING ROTOR AND ROTOR FLOW FIELD KINEMATICS, MACH NUMBER EFFECTS AND YAWED FLOW EFFECTS.

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
3.1.1) 2-D PARTICLE TRAJEC	▽					NASA	
3.1.2) 3-D, $C_L=0$ TRAJECT.	▽					NASA	
3.1.3) 3-D, LIFTING TRAJECT	▽					NASA	
3.1.4) ROTOR BLADE TRAJECT	▽					NASA	
3.1.5) ADVANCED ROTOR FLOW FIELD PARTICLE TRAJECTORY		═	═			NASA	

3 - ROTOR ICING INVESTIGATION

3.2 - DEFINITION OF ICE SHAPES AND ACCUMULATION PATTERNS.

a) UNDERWAY/FUNDS COMMITTED

3.2.1) EVALUATION OF SCALING LAWS FOR BODIES IN QUASI-STEADY FLOW (NASA/USAF)
3.2.2) SCALING LAWS FOR FIXED AND "ROTATING" AIRFOILS (U. OF TENN., NAG3-90)
3.2.3) NUMERICAL ICE ACCRETION MODELING FOR RIME ICE, GLARE AND "IN-BETWEEN" (UNIV. OF DAYTON NAG3-65, OSU NAG3-109)
3.2.4) ANALYTICAL MODELING OF RIME ICE BUILDUP ON 2-D AIRFOILS (OHIO STATE UNIV., NAG3-   )

b) PLANNED/FUNDS NOT COMMITTED

3.2.5) STATIC 2-D AIRFOIL TESTS IN THE IRT FOR CORRELATION WITH OSU ANALYSIS.
3.2.6) OSCILLATING AIRFOIL TEST IN THE IRT - ICE SHAPE AND DE-ICING TESTS.
3.2.7) TAIL ROTOR ICING TESTS IN THE IRT - ICE ACCRETION, ICE PHOBICS, ICE SHEDDING.
3.2.8) 2-D AIRFOIL ICING INVESTIGATION IN THE NRC HIGH SPEED ICING WIND TUNNEL.

c) RECOMMENDED

3.2.9) DEFINITION OF THE ICE ACCUMULATION MECHANISM IN PRESENCE OF YAWED FLOW, BLADE FLAPPING AND CENTRIFUGAL FORCES.
3.2.10) CORRELATION OF SCALING DATA FROM 2-D WIND TUNNEL TESTS (STATIC AND OSCILLATORY) AND ROTATING RIG TESTS. CORRELATION WITH THE RESULTS OF SCALING LAW INVESTIGATIONS.

TASK		81	82	83/4	85/7	88/91	AGENCY	COST
3.2.1)	SCALING LAWS/BODIES	▽═					NASA/USAF	
3.2.2)	SCALING LAWS/AIRFOILS	▽═					NASA	
3.2.3)	ICE ACCRETION MODELS	▽═					NASA	
3.2.4)	2-D AIRFOIL RIME ICE	▽═					NASA	
3.2.5)	2-D STATIC TESTS IN IRT	═	═				NASA	
3.2.6)	2-D OSC. TESTS IN IRT		═	═			NASA	
3.2.7)	IRT TAIL ROTOR TESTS	═	═				NASA	
3.2.8)	2-D HIGH SPEED AT NRC		═					
3.2.9)	DEFIN. OF BLADE ICING EFF.				═			
3.2.10)	SCALING CORRELATION		═	═				

ROTORCRAFT ICING RESEARCH

3 - ROTOR ICING INVESTIGATION

3.3 - DEGRADATION IN SECTIONAL CHARACTERISTICS DUE TO ICE ACCRETION

a) UNDERWAY/FUNDS COMMITTED

3.3.1) ANALYTICAL EVALUATION OF ROTOR/PROPELLER PERFORMANCE IN ICING CONDITIONS (OHIO STATE UNIV, NAG 3-109)

3.3.2) ICE ACCRETION SECTIONAL PERFORMANCE PENALTIES ON FIXED WING AIRFOILS. ANALYTICAL METHOD DEVELOPMENT (OSU., NAG 3 -)

b) PLANNED/FUNDS NOT COMMITTED

3.3.3) NASA/LEWIS IN-HOUSE 2-D WIND TUNNEL TESTS TO MEASURE ICE ACCRETION AND DRAG PENALTIES ON MODERN GENERAL AVIATION AIRFOILS (DATA BASE FOR OSU AND DAYTON ANALYTICAL WORK).

3.3.4) IMPROVEMENT AND VALIDATION OF AIRFOIL ICING CODES.

c) RECOMMENDED

3.3.5) 2-D WIND TUNNEL TESTS OF TYPICAL HELICOPTER AIRFOILS WITH MODELED ICE.

3.3.6) UNSTEADY (OSCILLATORY) TESTS OF 2-D AIRFOILS WITH MODELED ICE.

3.3.7) INTERPREDATION OF DATA FROM OSCILLATORY TESTS OF AIRFOILS WITH ICE (TASK F) AND DEFINITION OF EMPIRICAL UNSTEADY AND RADIAL FLOW FORMULATION FOR ROTOR PERFORMANCE AND LOADS CALCULATIONS

3.3.8) DEFINITION OF A STANDARD METHOD TO DEFINE ICE ACCRETION EFFORTS ON 2-D AIRFOILS.

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
3.3.1) ROTOR/PROPELLER ANALYSIS	▽═					NASA	
3.3.2) 2-D AIRFOIL ICE ANALYSIS	▽═					NASA	
3.3.3) GA AIRFOIL ICING TEST		═				NASA	
3.3.4) AIRFOIL ICING CODES	═	═				NASA	
3.3.5) HEL. AIRFOIL ICE(STATIC)			═				
3.3.6) HEL. AIRFOIL ICE(OSC.)				═			
3.3.7) UNST. DATA ANALYSIS					═		
3.3.8) AIRFOIL/ICE STANDARDS				═	═	NASA/FAA	

ROTORCRAFT ICING RESEARCH

3 - ROTOR ICING INVESTIGATION

3.4 - PREPARATION OF STANDARD SOURCE OF HELICOPTER AIRFOIL ICING DATA

a) UNDERWAY/FUNDS COMMITTED

3.4.1) A SET OF ESTIMATED AIRFOIL CHARACTERISTICS IN PRESENCE OF ICE, COVERING THE MACH NUMBER AND ANGLE OF ATTACK RANGES OF INTEREST FOR HELICOPTER ROTOR OPERATION, WILL BE PREPARED AS PART OF THE ONGOING ROTOR AIRFOIL ICING STUDY AT OSU (NAG3-109).

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

3.4.2) DEFINE THE FORM IN WHICH HELICOPTER AIRFOIL ICING DATA SHOULD BE DOCUMENTED, AND PREPARE STANDARDIZED DOCUMENTATION OF ICING EFFECTS ON SELECTED HELICOPTER AIRFOILS.

3.4.3) ICING DATA FOR STATE-OF-THE-ART ROTOR AIRFOILS TO QUANTIFY POTENTIALLY SIGNIFICANT DEGRADATION ON TRANSONIC CHARACTERISTICS

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
3.4.1) PRELIM. AIRFOIL DATA	▽═══					NASA	
3.4.2) STANDARD DATA SOURCE		═══	═══			NASA/FAA	
3.4.3) ICING ON NEW SECTIONS				═══		NASA/FAA	

ROTORCRAFT ICING RESEARCH

3 - ROTOR ICING INVESTIGATION

3.5 - EVALUATION OF ICE EFFECTS ON STRUCTURAL BLADE PROPERTIES

a) UNDERWAY/FUNDS COMMITTED

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

3.5.1) A PRELIMINARY ASSESSMENT MAY BE POSSIBLE AS PART OF THE CURRENT OSU STUDY TO QUANTIFY ICING EFFECTS ON ROTORS AND PROPELLERS (NAG3-109).

3.5.2) DEFINITION OF STANDARD METHODS TO ACCOUNT FOR STRUCTURAL BLADE PROPERTIES IN PRESENCE OF ICE AND DURING ICE SHEDDING (e.g. MASS DISTRIBUTION, c.g., PITCH INERTIA, FLAPPING INERTIA, ETC.)

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
3.5.1) PRELIMINARY CALC.	═	═				NASA	
3.5.2) STANDARD METHODS	═	═				NASA/FAA	

3 - ROTOR ICING INVESTIGATION

3.6 - ASSESSMENT OF OVERALL ROTOR PERFORMANCE PENALTIES

a) UNDERWAY/FUNDS COMMITTED

3.6.1) A PRELIMINARY ASSESSMENT OF ROTOR PERFORMANCE PENALTIES WILL BE CARRIED OUT IN CONJUNCTION WITH THE OHIO STATE UNIVERSITY PROPELLER/ROTOR ICING STUDY (NAG3-109).

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

3.6.2) UPGRADE CURRENT PERFORMANCE ANALYSIS METHODS TO ACCOUNT FOR ICING EFFECTS. TIE IN WITH THE SECOND GENERATION COMPREHENSIVE ROTOR ANALYSIS PROGRAM (2- CHAS)

3.6.3) CONDUCT MODEL ROTOR ICING TESTS IN IRT (6'x9' TEST SECTION)

3.6.4) CONDUCT MODEL ROTOR TESTS WITH ARTIFICAL (MODELED) ICE SHAPES ON THE BLADES. POSSIBLE WIND TUNNELS ARE IRT, AWT, NASA LANGLEY, NASA AMES, BOEING VERTOL.

3.6.5) TIE-IN WITH ONGOING FLIGHT TESTS WITH ADVANCED ICE MONITORING EQUIPMENT

3.6.6) COMPREHENSIVE TEST/THEORY CORRELATION: ANALYSIS, WIND TUNNEL AND FLIGHT TEST

3.6.7) DEFINITION OF GUIDELINES AND STANDARD EVALUATION PROCEDURES

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
3.6.1) PRELIM. PERF. EVAL.	▽═					NASA	
3.6.2) UPGRADE ANALYSIS		═		═	═	NASA	
3.6.3) MODEL ROTOR TESTS (IRT)		═	═		═		
3.6.4) MODEL ROTOR TESTS				═		NASA	
3.6.5) FLIGHT TESTS		– –	– –	– –	– –		
3.6.6) TEST/THEORY CORREL.			═	═		NASA/FAA	
3.6.7) STANDARD PROCEDURES				═	═	NASA/FAA	

ROTORCRAFT ICING RESEARCH

3 - ROTOR ICING INVESTIGATION

3.7 - ASSESSMENT OF STRUCTURAL BLADE LOAD PENALTIES IN PRESENCE OF ICE

a) UNDERWAY/FUNDS COMMITTED

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

3.7.1) INITIAL ASSESSMENT OF BLADE LOADS PREDICTION CAPABILITY USING CURRENT METHODS: 1) SYMMETRICAL ICE BUILDUP, 2) ASYMMETRICAL LOADING, 3) ASYMMETRICAL SHEDDING
3.7.2) UPGRADE BLADE/CONTROL SYSTEM LOADS PREDICTION METHODS
3.7.3) TEST/THEORY CORRELATION: ANALYSIS, WIND TUNNEL TEST, FLIGHT TEST
3.7.4) DEFINITION OF GUIDELINES AND STANDARD EVALUATION PROCEDURES

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
3.7.1) ASSESSMENT		═	═			NASA	
3.7.2) UPGRADE METHODS			═	═		NASA/FAA	
3.7.3) TEST/THEORY CORREL.				═	═		
3.7.4) STANDARD PROCEDURES				═	═	NASA/FAA	

ROTORCRAFT ICING
RESEARCH ASSESSMENT

3 - ROTOR ICING INVESTIGATION

PROGRAM CATEGORIES AND STATUS	LEVEL	FUNDING COMMITMENT OR EXPRESSED INTEREST					FUNDED = F PLANNED = P RECOMMENDED = R	
		AGENCIES			FIX WING	ROT	ADVISORY GROUPS	
		NASA	FAA	DOD	GA TRANS		AGARD	OTHER
FUNDED								
3.1.1		F	R					
3.1.2		F	R		R			
3.1.3		F	P		R	R		
3.1.4		F	R					
PLANNED								
RECOMMENDED								
3.1.5		R				R		

ROTORCRAFT ICING
RESEARCH ASSESSMENT

3 - ROTOR ICING INVESTIGATION

PROGRAM CATEGORIES AND STATUS	LEVEL	FUNDING COMMITMENT OR EXPRESSED INTEREST					FUNDED = F PLANNED = P RECOMMENDED = R	
		AGENCIES			FIX WING	ROT WING	ADVISORY GROUPS	
		NASA	FAA	DOD	GA TRANS		AGARD	OTHER
FUNDED								
3.2.1		F	R		R		R	F (USAF)
3.2.2		F	R		R	R	R	
3.2.3		F	R		R	R	R	P (FR) P (UK)
3.2.4		F	R		R	R	R	
3.3.1		F			R	R		
3.3.2		F			R			
3.4.1		F				R		
3.6.1		F	R		R	R		
PLANNED								
3.2.5		P				R		
3.2.6		P	R		R	R	R	
3.2.7		P	R			R	R	P (FR)
3.2.8		P				R	R	
3.3.3		P			R			
3.3.4		P			R	R	R	
RECOMMENDED								
3.2.9		R				R		
3.2.10		R	R			R		
3.3.5		R				R		
3.3.6		R				R		

ROTORCRAFT ICING
RESEARCH ASSESSMENT

3 - ROTOR ICING INVESTIGATION (CONT'D)

PROGRAM CATEGORIES AND STATUS	LEVEL	FUNDING COMMITMENT OR EXPRESSED INTEREST					FUNDED = F PLANNED = P RECOMMENDED = R	
		AGENCIES			FIX WING	ROT	ADVISORY GROUPS	
		NASA	FAA	DOD	GA TRANS		AGARD	OTHER
RECOMMENDED								
3.3.7		R				R		
3.3.8		R	R		R	R	R	
3.4.2		R			R	R		
3.4.3		R				R		
3.5.1		R			R	R		
3.5.2		R	R			R	R	
3.6.2		R				R		
3.6.3		R				R		P (UK)
3.6.4		R				R		
3.6.5		R	R	R		R	R	
3.6.6		R	R	R	R	R		
3.6.7		R	R	R	R	R		
3.7.1		R	R			R		
3.7.2		R	R			R		
3.7.3		R	R			R		
3.7.4		R	R		R	R		

ROTOR ICE PROTECTION

Definition of Advanced Heat Transfer Analysis Methods. The transient heat transfer analysis techniques can be verified through measurements taken from tests on the oscillating airfoil rig utilizing sections of current electrically heated rotors.

Several approaches can be taken in the examination of the heat flow through the blade material:

(1) Examination of the effect of internal heat sinks on the amount of heat reaching the external surface, such as leading edge balance weights, metal spars, internal lighting conductors can be accomplished.

(2) The effects of the material build-up between the heating element and the external surface such as the bonding material layers, erosion shield(s), material transitions (local material changes) can be examined.

(3) The thermal conductivity through typical sections of composite blade material can be measured (section by section) and used as a standard for blade thermal studies. Currently the stated thermal conductivity of many of these materials is based only upon vendor catalogs or upon comparison with similar material in handbooks.

Evaluation of Electrothermal Deicing Systems

(1) An evaluation of electrothermal deicing test results can be obtained from helicopter icing survey.

(2) Blade material thermal evaluation can be accomplished based on results of thermal analysis and examination of deicing effectiveness as a function of heater element shape, type (wire, foil, sprayed metal) coverage (% of chord and span) and arrangement (chordwise vs spanwise elements).

- Effective use of electrothermal deicing requires investigation of the various heater element (and blade material) arrangements (i.e., chordwise vs. spanwise elements, chordwise extent of heater elements along the upper and lower surface, element firing sequence).

(3) Control response analysis is necessary to determine element-on-time schedules, and ice detector responses.

- The effects of deice system failure need evaluation in terms of:

  (a) complete vs. partial failure probability

  (b) aerodynamic/dynamic results

  (c) overall flight safety probability

(4) Aerodynamic/dynamic evaluation of the rotor prior to and during deice cycle (use of rotor icing evaluation effort) can be accomplished.

Alternate Ice Protection System Evaluation.

(1) Update the current ice phobic tests with new materials (coatings) and evaluate the aerodynamic/dynamic effects during ice build-up and shedding cycles on the OH-58 tail rotor test rig.

(2) Review the results of forthcoming pneumatic boot tests by NASA Ames to determine if further test efforts are warranted.

(3) Evaluate fluid deicing systems on rotating blade rig.

(4) Examine the preliminary results of vibratory and microwave studies to determine if further effort is warranted.

(5) The design criteria for alternate rotor ice protection requires the definition of:

- degree of protection required (i.e., time duration, extent of rotor covered, ambient temperature range, liquid water content range)
- cost/weight of the system
- system complexity (i.e., control system requirements)
- system reliability and failure modes

ROTORCRAFT ICING RESEARCH

4 - ROTOR ICE PROTECTION	4.1 - DEFINITION OF ADVANCED HEAT TRANSFER ANALYSIS METHODS

a) UNDERWAY/FUNDS COMMITTED

4.1.1) 1-D AND 2-D CONDUCTION HEAT TRANSFER CODES. MULTI-LAYERED STRUCTURES WITH ICE (UNIV. OF TOLEDO, O., NAG3-72).

4.1.2) ASSESSMENT OF CONNECTIVE HEAT AND MASS TRANSFER COEFFICIENTS ON THE SURFACE OF ARTIFICAL ICE SHAPES BY NAPHTALENE SUBLIMATION METHODS. (NAG)

4.1.3) EXAMINATION OF THE ASSUMPTIONS MADE IN THE DERIVATION OF THE ENERGY BALANCE EQUATION. STUDY OF THEIMPINGEMENT, RUNNING AND FREEZEING ON SINGLE WATER DROPLETS (NAG)

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

4.1.4) OSCILLATING AIRFOIL THERMAL DE-ICING TESTS, FOR DETAILED MEASUREMENT OF ICING/DE-ICING HEAT TRANSFER EFFORTS ON BLADES WITH STATE-OF-THE-ART COMPOSITE SPAR. RESULTS WILL BE ALSO USEFUL TO CHECK OUT HEAT TRANSFER CODES. THIS KIND OF TEST WILL REQUIRE SPECIAL PURPOSE AIRFOIL MODELS EQUIPPED WITH AN ICE PROTECTION (e.g. ELECTROTHERMAL) AND EXTENSIVELY INSTRUMENTED WITH THERMOCOUPLES.

4.1.5) DEFINITION OF STANDARD HEAT TRANSFER METHODS AND DE-ICING GUIDELINES.

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
4.1.1) 1-D, 2-D ANALYSIS	▽═					NASA	
4.1.2) NAPHTALENE SUBLMATION	▽═					NASA	
4.1.3) SINGLE WATER DROPLETS	▽═					NASA	
4.1.4) OSC. HEAT TRANS. TESTS		═	═	═		NASA	
4.1.5) STANDARD METHODS				═	═	NASA/FAA	

4 - ROTOR ICE PROTECTION

4.2 - EVALUATION OF ELECTROTHERMAL DE-ICING SYSTEMS

a) UNDERWAY/FUNDS COMMITTED

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

4.2.1) ELECTROTHERMAL DEICING TESTS ON THE OSCILLATORY AIRFOIL RIG IN THE ICING RESEARCH WIND TUNNEL (IRT).
4.2.2) CONTROL/RESPONSE OPTIMIZATION OF ELECTROTHERMAL SYSTEMS
4.2.3) EVALUATION OF ICING TEST RESULTS FORM HELICOPTER ICING SURVEY (2.1.e)
4.2.4) EVALUATION OF DE-ICING EFFECTIVENESS AS A FUNCTION OF HEATING ELEMENT SHAPE, COVERAGE AND LOCATION.
4.2.5) ROTOR PERFORMANCE AND BLADE LOADS ASSESSMENT DURING DE-ICING CYCLE
4.2.6) DEFINITION OF A STANDARD EVALUATION PROCEDURE

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
4.2.1) OSC. AIRFOIL TESTS (IRT)			═			NASA	
4.2.2) CONTROL/RESPONSE				═		NASA	
4.2.3) ICING SURVEY EVAL.			═			NASA	
4.2.4) DE-ICING EFFECTIVENESS			═	═		NASA	
4.2.5) PERF/LOADS DURING CYCLE				═		NASA/FAA	
4.2.6) STANDARD EVAL. PROC.					═	NASA/FAA	

ROTORCRAFT ICING RESEARCH

4 - ROTOR ICE PROTECTION

4.3 - ALTERNATE (NON-ELECTROTHERMAL) CONCEPTS EVALUATION

a) UNDERWAY/FUNDS COMMITTED

4.3.1) DEVELOPMENT OF ICE-PHOBIC COATING (CLARKSON COLLEGE, NAG3-145)

4.3.2) DEVELOPMENT OF FLUID ICE-PROTECTION SYSTEMS (U. OF KANSAS NAG3-71).

4.3.3) DEVELOPMENT OF AN EXPERIMENTAL RIG FOR THE NASA IRT TO MEASURE THE INTERFACIAL SHEAR STRESS FOR PROMISING ICE PHOBIC SURFACES

b) PLANNED/FUNDS NOT COMMITTED

4.3.4) ICE PHOBIC TESTS ON THE TAIL ROTOR TEST RIG IN THE IRT

4.3.5) PNEUMATIC BOOT SYSTEM EVALUATION (NASA/AMES)

4.3.6 TEST OF A PNEUMATIC BOOT DE-ICER ON THE OSCILLATORY AIRFOIL RIG ON THE IRT

c) RECOMMENDED

4.3.7 EVALUATE FLUID DEICING SYSTEM ON ROTATING BLADE RIG - ON THE BASIS OF FAVORABLE RESULTS OF THE U. OF KANSAS STUDY (4.3.2).

4.3.8) EVALUATE VIBRATORY AND MICROWAVE DEICING SYSTEMS. PRELIMINARY WORK HAS BEEN COMPLETED, BUT NO FOLLOW-ON EFFORTS HAVE BEEN PLANNED AT THIS TIME.

4.3.9) EVALUATION OF NEW NON-ELECTROTHERMAL DEICING SYSTEMS.

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
4.3.1) ICE PHOBIC STUDY	▽═					NASA	
4.3.2) FLUID ICE PROTECTION	▽═					NASA	
4.3.3) ICE SHEAR STRESS MEAS.	▽═					NASA	
4.3.4) TAIL ROTOR ICE PHOBIC (IRT)		═				NASA	
4.3.5) PNEUMATIC BOOT (AMES)	═	═				NASA/AMES	
4.3.6) PNEUMATIC BOOT (IRT)		═	═			NASA	
4.3.7) FLUID DEICING TEST			═			NASA	
4.3.8) VIBRATORY/MICROWAVE			═ ═	═		NASA	
4.3.9) NEW SYSTEM EVALUATION				═	═	NASA	

ROTORCRAFT ICING RESEARCH ASSESSMENT

4 - ROTOR ICE PROTECTION

PROGRAM CATEGORIES AND STATUS	LEVEL	FUNDING COMMITMENT OR EXPRESSED INTEREST					FUNDED = F PLANNED = P RECOMMENDED = R	
		AGENCIES			FIX WING	ROT WING	ADVISORY GROUPS	
		NASA	FAA	DOD	GA	TRANS	AGARD	OTHER
FUNDED								
4.1.1		F			R	R	R	P (FR,UK)
4.1.2		F						
4.1.3		F						
4.3.1		F	R	R	R	R	R	P (UK)
4.3.2		F	R		R			
4.3.3		F	R	R		R	R	
PLANNED								
4.3.4		P	R	R		R	R	
4.3.5		P	R			R	R	
4.3.6		P	R		R		R	
RECOMMENDED								
4.1.4		R				R		P (UK)
4.1.5		R				R		
4.2.1		R				R	R	
4.2.2		R				R	R	
4.2.3		R				R		
4.2.4		R		R		R		
4.2.5		R		R		R		

ROTORCRAFT ICING
RESEARCH ASSESSMENT

4 - ROTOR ICE PROTECTION (CONT'D)

PROGRAM CATEGORIES AND STATUS	LEVEL	FUNDING COMMITMENT OR EXPRESSED INTEREST					FUNDED = F PLANNED = P RECOMMENDED = R	
		AGENCIES			FIX WING	ROT	ADVISORY GROUPS	
		NASA	FAA	DOD	GA TRANS		AGARD	OTHER
RECOMMENDED								
4.2.6		R	R	R		R		
4.3.7		R	R					
4.3.8		R	R		R			
4.3.9		R				R		

ENGINE INLET ICE PROTECTION

Ice Protection Methods.

(1) Evaluation of anti-icing techniques is required (bleed air, electrothermal, freezing point depressants) for typical helicopter inlet systems.

(2) Evaluation is required of ice deflection/ice blockage and particle separator configurations.

(3) Development is required for analytical techniques to permit generalized inlet configuration design studies and assessment of ice protection techniques.

Engine Performance Penalties

(1) Determination of engine power available is required during activation of an anti-icing system or during ice blockage (i.e., inlet screen, ice deflector).

(2) Analytical determination is necessary to predict induction flow pressure loss during icing, and correlation with measured pressure surveys.

ROTORCRAFT ICING RESEARCH

5 - ENGINE INLET ICE PROTECTION

5.1 - ICE PROTECTION METHODS

a) UNDERWAY/FUNDS COMMITTED

5.1.1) EVALUATION OF POTENTIAL APPLICATION OF FREEZING POINT DEPRESSANTS (U. OF KANSAS, NAG3-71)
5.1.2) IN-HOUSE EFFORT TO STUDY METHODS FOR SEPARATING PARTICLES OUT OF ENGINE INLET FLOWS (INERTIAL SEPARATORS) - NASA/LEWIS

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

5.1.3) DEVELOPMENT OF ANALYTICAL TECHNIQUES TO ASSIST IN INLET CONFIGURATION DESIGN, UTILIZING U. OF TOLEDO HEAT TRANSFER METHODS. (4.1a)
5.1.4) EVALUATION OF ICE DEFLECTION/ICE BLOCKAGE/PARTICLES SEPARATOR CONFIGURATIONS
5.1.5) TEST/THEORY CORRELATION WITH DATA FROM CONTRACTOR RUN IRT INLET TESTS
5.1.6) DEVELOP TECHNIQUES FOR GENERALIZED INLET CONFIGURATION ASSESSMENT

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
5.1.1) FREE RING POINT DEPRESS.	▽═					NASA	
5.1.2) PARTICLE SEPARATORS	▽═					NASA(In-House)	
5.1.3) ANALYTICAL METHODS	═	═				NASA	
5.1.4) ICE PROTECTION CONFIGS.			═	═		NASA	
5.1.5) IRT TEST/THEORY CORR.				═		NASA/FAA	
5.1.6) GENERALIZED METHODS				═	═	NASA/FAA	

ROTORCRAFT ICING RESEARCH

5 - ENGINE INLET ICE PROTECTION

5.2 - ENGINE PERFORMANCE PENALTIES

a) UNDERWAY/FUNDS COMMITTED

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

5.2.1) DETERMINATION OF POWER LOSSES DURING ACTIVATION OF DE-ICING SYSTEM AND DURING BLOCKAGE DUE TO IOE.

5.2.2) DEVELOPMENT OF ENGINE PERFORMANCE ANALYTICAL MODELS INCLUDING ICING, ICE BLOCKAGE, DE-ICING EFFECTS.

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
5.2.1) POWER LOSS ASSESSMENT		═				NASA/FAA	
5.2.2) ANALYTICAL MODELS			═	═		NASA/FAA	

C-2

ROTORCRAFT ICING
RESEARCH ASSESSMENT

5 - ENGINE INLET ICE PROTECTION

PROGRAM CATEGORIES AND STATUS	LEVEL	FUNDING COMMITMENT OR EXPRESSED INTEREST					FUNDED = F PLANNED = P RECOMMENDED = R	
		AGENCIES			FIX WING	ROT WING	ADVISORY GROUPS	
		NASA	FAA	DOD	GA TRANS		AGARD	OTHER
FUNDED								
5.1.1		F			R			
5.1.2		F				R		
PLANNED								
RECOMMENDED								
5.1.3		R			R	R		
5.1.4		R				R		
5.1.5		R			R	R		
5.1.6		R			R	R		
5.2.1		R				R		
5.2.2		R				R		

INSTRUMENTATION

Verification of Current LWC and Droplet Measuring Devices.

(1) It is necessary to continue current instrument comparison in NASA IRT to accomplish:

- Verification of existing liquid water content measuring devices (ice detectors, ice rate indicators).
- Verification of existing water droplet measuring devices (laser spectrometers, oiled slide, gelatin slide, rotating cylinder) in an icing tunnel

(2) Review of current flight test instrumentation is necessary to determine the (i.e. LWC, droplet) results in the hover spray rig, behind the HISS, and in natural icing (primary initial data base is the test UH-1H operated by Eustis).

Development of New Measuring Devices

(1) Continue the effort on microwave ice accretion measurement with prototype application on rotor.

(2) Develop criteria for LWC and droplet size measurement.

- Development of "rotor icing effects" instrumentation (i.e., profile drag changes, asymmetric shedding forces, ice phobic coating effectiveness)
- Development of icing environmental instrumentation for in-flight icing research (natural and simulated icing) with potential for use in helicopter icing certification/clearance programs

(3) Develop prototype configurations for test and evaluation and for potential use as a pilot monitor during flights cleared into icing conditions.

Development of New Icing Photographic Techniques.

New Icing photographic techniques are required to permit detailed studies of rotor icing, engine inlet icing, and overall helicopter icing in order to provide correlating data with the predicted performance of ice protection systems and the prediction of ice accretions. While the primary emphasis is the documentation of rotor ice/ice-shedding (because of the difficult task of obtaining useful data), the engine inlets particularly those inlets with screens/deflectors/ separators/submerged configurations, require attention because of potential run-back and snow accretions.

(1) Determine specific critical areas to be photographed (i.e., rotor LE).

(2) Evaluate existing photographic means.

(3) Develop criteria for optimum system.

(4) Develop prototype for test and evaluation.

6 - INSTRUMENTATION

6.1 - VERIFICATION OF CURRENT LWC AND DROPLET MEASURING DEVICES

a) UNDERWAY/FUNDS COMMITTED

6.1.1) CURRENT TESTS OF MODERN AND OLD INSTRUMENTS IN THE IRT.

b) PLANNED/FUNDS NOT COMMITTED

6.1.2) FLIGHT TEST VERIFICATION OF MODERN AND OLD INSTRUMENTATION (FAA).

c) RECOMMENDED

6.1.3) REVIEW OF FLIGHT TEST RESULTS: HOVER SPRAY RIG, HISS, NATURAL ICING.

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
6.1.1) IRT TESTS	▽═					NASA/USAF	
6.1.2) FLIGHT TEST VERIFICATION	═	═				FAA	
6.1.3) REVIEW OF FLIGHT TEST DATA		═	═	═		NASA/FAA	

6 - INSTRUMENTATION

6.2 - DEVELOPMENT OF NEW MEASURING DEVICES

a) UNDERWAY/FUNDS COMMITTED

6.2.1) MICROWAVE ICE ACCRETION MEASUREMENT. DEVELOPMENT OF INSTRUMENTATION BY IDEAL RESEARCH INC. (NAS3-22765)

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

6.2.2) DEVELOP CRITERIA FOR LWC AND DROPLET SIZE MEASUREMENT.
6.2.3) DEVELOP PROTOTYPE FLIGHTWORTHY INSTRUMENTS FOR TEST AND EVALUATION.

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
6.2.1) MICROWAVE SYSTEM	▽═					NASA	
6.2.2) LWC/DROPLET CRITERIA		═	═			NASA/FAA	
6.2.3) PROTOTYPE DEVELOPMENT				═	═	NASA	

6 - INSTRUMENTATION

6.3 - DEVELOPMENT OF NEW PHOTOGRAPHIC TECHNIQUES FOR INFLIGHT ICE ASSESSMENT

a) UNDERWAY/FUNDS COMMITTED

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

6.3.1) DETERMINE CRITICAL ROTOR BLADE AREAS TO BE PHOTOGRAPHED. EVALUATE EXISTING PHOTOGRAPHIC MEANS AND DEFINE THE SPECIFICATIONS FOR NEW PHOTOGRAPHIC EQUIPMENT.

6.3.2) DEVELOP, TEST AND EVALUATE PROTOTYPE EQUIPMENT.

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
6.3.1) SPECIFICATIONS		═	═			NASA/FAA	
6.3.2) PROTOTYPE DEVELOPMENT			═	═	═	NASA/FAA	

ROTORCRAFT ICING
RESEARCH ASSESSMENT

6 - INSTRUMENTATION

PROGRAM CATEGORIES AND STATUS	LEVEL	FUNDING COMMITMENT OR EXPRESSED INTEREST					FUNDED = F PLANNED = P RECOMMENDED = R	
		AGENCIES			FIX WING	ROT WING	ADVISORY GROUPS	
		NASA	FAA	DOD	GA TRANS		AGARD	OTHER
FUNDED								
6.1.1		F			R	R	R	F (USAF)
6.2.1		F						
PLANNED								
6.1.2			P				R	
RECOMMENDED								
6.1.3		R	R			R		
6.2.2		R	R		R	R	R	P (UK)
6.2.3		R	R		R	R		
6.3.1		R		R		R	R	P (UK)
6.3.2		R		R		R		

FLIGHT TEST

Helicopter Flight Testing With Artificial Ice Shapes. Artificial (modeled) ice shapes based on icing tunnel and aerodynamic tunnel efforts are recommended for the full scale helicopter. Prior to actual helicopter rotor installation of the artificial shapes, a whirl tower test of these shapes is recommended to check the rotor performance and dynamics (loads) and to calibrate the rotor instrumentation (torque, torsion, flapping, bending).

Validation Of Ice Monitoring And Protection Equipment. Simulated icing tests behind the HISS and natural icing tests will be necessary to validate the use of artificial (modeled) ice shapes.

7 - FLIGHT TEST

7.1 - HELICOPTER FLIGHT TESTING WITH ARTIFICIAL ICE SHAPES

a) UNDERWAY/FUNDS COMMITTED

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

7.1.1) WHIRL TOWER CALIBRATION OF ROTOR INSTRUMENTS

7.1.2) FLIGHT TESTS WITH ARTIFICIAL ICE SHAPES OVER VARIOUS REPRESENTATIVE EXTENTS OF ROTOR BLADE TO QUANTIFY PERFORMANCE AND LOADS PENALTIES IN ABSENCE OF ICE PROTECTION. ASSESSMENT OF FLYING QUALITIES PRIOR TO ICE SHEDDING. ASSESSMENT OF MAXIMUM ALLOWABLE ICE BUILDUP TO PROVIDE A BASIS FOR THE DEFINITION OF THE DE-ICING CYCLE.

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
7.1.1) WHIRL TOWER CALIBRATION		═	═				
7.1.2) F/T WITH ARTIFICIAL ICE SHAPES			═	═	═		

ROTORCRAFT ICING RESEARCH

7 - FLIGHT TEST

7.2 - VALIDATION OF ICE MONITORING AND PROTECTION EQUIPMENT

a) UNDERWAY/FUNDS COMMITTED

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

7.2.1) FLIGHT TESTS BEHIND HISS WITH ADVANCED ICE MONITORING AND PROTECTION EQUIPMENT.
7.2.2) FLIGHT TEST VALIDATION OF ARTIFICIAL ICE SHAPES AND HISS RESULTS USING NATURAL ICING CONDITIONS.
7.2.3) DEFINITION OF STANDARD PROCEDURE TO VALIDATE A HELICOPTER DEICING SYSTEM.

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
7.2.1) FLIGHT TESTS - HISS	=	= =	= =	= =	=		
7.2.2) FLIGHT TESTS - NATURAL ICE	=	= =	= =	= =	=		
7.2.3) DEFINE STANDARD PROCED.			═	═	═		

ROTORCRAFT ICING RESEARCH ASSESSMENT

7 - FLIGHT TEST

PROGRAM CATEGORIES AND STATUS	LEVEL	FUNDING COMMITMENT OR EXPRESSED INTEREST					FUNDED = F PLANNED = P RECOMMENDED = R	
		AGENCIES			FIX WING	ROT WING	ADVISORY GROUPS	
		NASA	FAA	DOD	GA TRANS		AGARD	OTHER
FUNDED								
PLANNED								
RECOMMENDED								
7.1.1		R				R		
7.1.2		R				R		
7.2.1		R	R	R		R		
7.2.2		R				R		
7.2.3		R	R	R		R		

ATMOSPHERIC ENVIRONMENT

Survey Of Natural Icing Conditions. Continued efforts are recommended to obtain and analyze the available natural icing data. Of prime importance is that data between ground level and 3,048 meters.

ROTORCRAFT ICING RESEARCH

8 - ATMOSPHERIC ENVIRONMENT

8.1 - SURVEY OF NATURAL ICING CONDITIONS

a) UNDERWAY/FUNDS COMMITTED

8.1.1) COLLECTION OF OLD NACA CANADIAN & USSR ICING CLOUD DATA (PRIMARILY BELOW 10,000 FT)
8.1.2) NRL CLOUD SURVEY UNDER CONTRACT WITH FAA
8.1.3) LOW ALTITUDE ICING SURVEY (U. OF WYOMING, FAA CONTRACT)

b) PLANNED/FUNDS NOT COMMITTED

c) RECOMMENDED

TASK	81	82	83/4	85/7	88/91	AGENCY	COST
8.1.1) SURVEY OF OLD NACA CANADIAN USSR DATA	▽═					NASA	
8.1.2) NLR CLOUD SURVEY	▽═					FAA	
8.1.3) LOW ALTITUDE ICING	▽═					FAA	

ROTORCRAFT ICING
RESEARCH ASSESSMENT

8 - ATMOSPHERIC ENVIRONMENT

PROGRAM CATEGORIES AND STATUS	LEVEL	FUNDING COMMITMENT OR EXPRESSED INTEREST					FUNDED = F PLANNED = P RECOMMENDED = R	
		AGENCIES			FIX WING	ROT WING	ADVISORY GROUPS	
		NASA	FAA	DOD	GA TRANS		AGARD	OTHER
FUNDED								
8.1.1		F			R	R	R	P (UK)
8.1.2			F				R	
8.1.3			F				R	P (FR)
PLANNED								
RECOMMENDED								

APPENDIX B

SUMMARY OF ICING SIMULATION FACILITIES

NASA TM81707 (W. Olsen-Lewis Research Center) compiles a survey of aircraft icing simulation test facilities in North America. These tables from the NASA TM presenting the facilities capabilities are reproduced in this Appendix.

CAPABILITIES OF ICING SIMULATION TEST FACILITIES IN NORTH AMERICA

[Capabilities estimated by technical contact person for each facility.]

A. WIND TUNNELS

Facility 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	Comment
					Test chamber	Uniform icing cloud	Air speed, km/hr	Min. total air temperature, °C	Altitude, m	LWC, g/m³	Vol. med. drop size, µm				
A-1	NASA - Lewis Research Center (Cleveland, OH) (a) IRT	FSC, I MB, R, IA, P[d]	ICE, FR[d]	Wind tunnel	H = 1.8 W = 2.7 L = 6	$h_u = 0.9$ $w_u = 1.8$	10 to 470	-30	0	[e]0.5 to 3.0	[e]11 to 25	Rot. cycle. and various modern instruments (rot. cyl.)	J. Reinmann (216)433-4000	All year	Modernization nearly complete
	(b) AWT - Rehabilitation	FSC, I, MB, R, CPU, G, P	ICE, FR, SI	Wind tunnel	D = 6 D = 14	$d_u = 4.5$	10 to M = 1.0 Up to 95	-30	0 to 15 000	0.2 to 3.	10 to 50+ (nozzles changed)	Various modern instruments	J. Yusko (216)433-4000	All year	Proposed for 1987
A-2	Lockheed (Burbank, CA)	MB, FSC, I	ICE	Wind tunnel	H = 1.2 W = 0.8	$h_u = 0.5$ $w_u = 0.3$	90 to 340	-30	0	0.7 to 4.0	10 to 25	Rot. cyle. (rot. cyl.)	B. Robinson (213)847-6121	All year	------------------------
A-3	Boeing (Seattle, WA)	MB, 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. cycle., oil slide (am. cyl.)	R. Wilder (206)342-4776	All year	------------------------
A-4	NRC (Ottawa, Canada) (a) Large Tunnel	~~FSC, MB, I~~ ~~G~~	~~ICE~~ ~~FR~~	~~Wind tunnel~~	[illegible]	[illegible]	[illegible] ~~30 to 110~~	~~-30~~	~~0~~	------	~~15 to 30 (nozzles changed)~~	~~Rot. cycle., oil slide (rot. cyl.)~~	~~A. Price~~ [illegible]	[illegible]	[illegible]
	(b) High Speed	MB, FSC	ICE	Wind tunnel	H = W = 0.3	$h_u = w_u = 0.25$	90 to M = 0.8	-30	0 to 9 000	0.2 to 2.	15 to 25	Oil slide (rot. cyl.)	A. Price (613)993-2371	All year	To be mothballed
A-5	AEDC Research Cell (Arnold AFB, TN)	FSC, MB	ICE	Free jet d = 0.3	D = 0.9	$d_u = 0.3$	150 to $M_{jet} = 0.7$	-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) (a) Low Speed	MB	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	MB	ICE	Wind tunnel	H = 0.15 W = 0.3 L = 0.8	$h_u = w_c = 0.1$	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
A-7	Frost Tunnel (Univ. of Alberta, Canada)	MB, IA	ICE	Wind tunnel	D = 0.8 (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)432-3180	All year	------------------------
A-8	UCLA Cloud Tunnel	MB, CP	ICE, R	Vertical wind tunnel	H = W = 0.15 L = 0.5	$h_u = w_u = 0.1$	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	Army Natick R&D (Natick, Mass.) Climatic Chamber	G, FSC, H	FR, R, S	Wind tunnel	H = 3 W = 4.5 L = 18	-----------	4 to 65	-30 and lower	0	10 cm rain/hr	Not measured (rain gauge)		M Kellberg (617)653-1000	All year	Mainly physiological tests of humans

B. ENGINE TEST FACILITIES

[Note that most free jets can do wind tunnel types of tests.]

Fa-cility 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	Comment
					Test chamber	Uniform icing cloud	Air speed, km/hr	Min. total air temperature, °C	Altitude, m	LWC, g/m^3	Vol. med. drop size, µm				
B-1	AEDC (Arnold AFB, TN) (a) ETF	EDC	ICE	Direct connect d = 1.8	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	J. Hunt (615)455-2611	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	Planned for 1985
B-2	Detroit Diesel Allison (Indianapolis, IN) (a) Comp. Test Facility	Inlet and compressor stage	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 0 to 3 000	0.2 to 3.5	15 to 40	Rotating cylinders	W. Stiefel (317)243-4006	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	W. Stiefel (317)243-4060	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	-35	0 to 6 700	0.2 to 9.0	15 to 40	Oil slide	J. Barlock (203)565-2001	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 9.0	15 to 40	Oil slide	J. Barlock (203)565-2001	All year	----------------------
	(c) P&W Sea Level Facility	EDC	ICE	Direct connect	Varies with test cells	Spray bars sized to engine	0 to M = 0.5	-20 (ambient)	0	0.2 to 9.0	15 to 40	Oil slide	J. Barlock (203)565-2001	Winter	----------------------
B-5	McKinley Climatic Lab Engine Test Cell (Eglin AFB, FL)	CPU, FSC	ICE, SI FR, R	Fan blown 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. Concluded. ENGINE TEST FACILITIES

[Note that most free jets can do wind tunnel types of tests.]

Facility 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	Comment
					Test chamber	Uniform icing cloud	Air speed, km/hr	Min. total air temperature, °C	Altitude, m	LWC, g/m^3	Vol. med drop size, µm				
B-6	Naval Air Propulsion Facility (Trenton, NJ) (a) Five small engine cells	EDC, CPU, I, FSC, MS	ICE, SI, FR, R	Free jet d = 0.6	H = 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 Mgr. (609)896-5655	All year	--------
	(b) Two large sea level cells	EDC, CPU, 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.)	Resource Mgr. (609)896-5655	All year	--------
	(c) Three large altitude cells	EDC, CPU, I, FSC, 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.)	Resource Mgr. (609)896-5656	All year	--------
B-7	Teledyne Altitude Cells (Toledo, OH) (a) Chamber 1	CPU, EDC	ICE, SI, FR, R	Free jet or direct connect, d = 0.3	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. Trautz (419)470-3230	All year	--------
	(b) Chamber 2	CPU, EDC	ICE, SI, FR, R		H = 2.5 W = 2.5 L = 4	Spray bars sized to engine	0 to M = 0.7+	-30 and lower	0 to 15 000	Up to 3.	15 to 25	Rotating cylinders	R. Trautz (419)470-3230	All year	--------
B-8	Avco Lycoming (Stratford, CT) (a) 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.)	J. Sherman (203)378-8215	All year	--------
	(b) Engine Test Facility	EDC	ICE, FR	d = 0.4	W = 3.7 H = 2.7	Spray bars sized to engine	0 to 200	-30 and lower	0	0.1 to 3.	15 to 40	Oil slide (rot. cyl.)	J. Sherman (203)378-8215	All year	--------
				d = 1.2	Outdoors			-20						Winter	
B-9	NRC, Cell #4 (Ottawa, Canada)	EDC, CPU	ICE, SI	Free jet or direct connect d = 0.75	H = W = 7.5	Spray bars sized to engine	0 to 650	-20 and lower	0	0.2 to 2.	15 to 40	Oil slide (rot. cyl.)	W. Grabe (613)993-2214	Winter	--------
		CPU, P		d = 2.0			0 to 93	Ambient							
B-10	Garret Icing Facilities: (Phoenix, AZ) Cell 1, Cell 2, and Cell 3	CPU, I EDC, FSC, P	ICE, SI	Free jet or direct connect, d = 1.0 to .1	H = 3 W = 4 L = 10	Spray bars sized to engine	M = 0.01 - 0.7	-30 and lower	0 to 15 000	0.1 to 6.0	10 to 50	Rot. cyls. (Rot. cyls.)	J. Pyne (602)267-3853	All year	--------

C. LOW VELOCITY FACILITIES

Facility no.	Facility name (Location)	Type 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	Comment
					Test chamber	Uniform icing cloud	Air speed, km/hr	Min total air temperature, °C	Altitude, m	LWC, g/m^3	Vol. med drop size, μm				
C-1	NRC Helicopter Spray Rig (Ottawa, Canada)	FLT (helicopters in hover)	ICE, FR	Wind blown spray outdoors	$D = \infty$	Spray manifold $h_s = 4.5$ $w_s = 23$	Ambient wind, 20 to 46 (gusty)	-20 (ambient)	0	0.1 to 0.8	30 to 60	Oil slide (rot. cyl.)	T. Ringer (613)993-2430	Winter	To be mothballed in 1986
C-2	G. E. Cross Wind Facility (Peebles, OH)	CPU, P^d, R^d	ICE, FR	Free jet outdoors	$D = \infty$	$d_s = 4.5$	90	-20 (ambient)	0	0.4 to 3.0	15 to 50	Knollenberg spectrometer (rot. cyl.)	R. Keller (513)243-4403	Winter	----------
C-3	McKinley Climatic Lab (Eglin AFB, FL.) (a) Main Chamber	FS, R^d	ICE, SI FR, R	Fan blown spray indoors	$H = 21$ $W = 78$ $L = 78$	Spray manifold $h_s = 3$ $w_s = 9$	0 to (30 to 75^c) (depending on L_B)	-30 and lower	0	0.1 to 3	12 to 40 800 to 1500 (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 spray indoors	$H = 7.5$ $W = 9$ $L = 40$	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 80 800 to 1500 (nozzles changed)	Particle interferometer (rot. cyl.)	R. Tolliver (904)882-3626	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 80 800 to 1500 (nozzles changed)	Particle interferometer (rot. cyl.)	R. Tolliver (904)882-3626	All year	----------
C-4	U.S. Army CRREL Cold Room (Hanover, NH)	FSC, MS R, IA	ICE, SI, FR, R	Fan blown spray indoors	$H = 1.1$ $W = 0.7$ $L = 1.5$	--------	0 to 20	-30 and lower	0	1 to 2.5	10 to 60	Cascade impactor	G. Ashton (603)643-3200	All year	----------
C-5	Mt. Washington Observatory (Gorham, NH)	FS, CP, MS	Natural icing of tied down equipment on top of mountain				0 to 100 (gusty)	-20 and lower	1000	Generally severe natural conditions		Rotating cylinders	J. Howe (603)466-3388	Fall to spring	----------
C-6	U.S. Navy PMTC (Pt. Mugu) Climatic Hangar	FSC, FS, G	R, FR	Fan blown spray indoors	$H = 7.6$ $W = L = 18$	$h_s = w_s = 1.2$	0 to 75	-30 and lower	0	30 cm rain/hr	500 to 4500	Oil slide (rain gauge)	D. Everett (805)982-8011	All year	----------
			S							5 cm snow/hr	50 to 100				
C-7	Acton Environmental Test Corp. (Acton, Mass.)	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	1000 to 6000	Not measured (rain gauge)	R. Gilley (617)263-2933	All year	----------
C-8	NRC (Ottawa, Canada) Cold Chamber #1	G, FS	FR, S^d	Fan blown spray indoors	$H = 4.3$ $W = 4.5$ $L = 15.2$	$d_s = 1.2$ to 2.5	0 to 55	-30 and lower	0	0.3 cm rain/hr	500 to 1000	Screen method (accumulation rate)	T. Ringer (613)993-2430	All year	----------
	NRC (Ottawa, Canada) Cold Chamber #2)	G, FS	FR	Fan blown 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 1000	Screen method (accumulation rate)	T. Ringer (613)993-2430	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	$H = 3.7$ $W = 5.5$ $L = 9$	--------	to 35	-30 and lower	0	------	--------	-------------	A. Hauver (613)592-2830	All year	----------

D. TANKERS FOR FLIGHT TESTS

[In addition, most airframe companies can test aircraft in natural icing.]

Facility no.	Facility name (Location)	Types of icing tests run (a)	Weather simulated (b)	Time in icing at high LWC, min	Size of spray, m		Range of parameters used in icing tests^c					Instruments used for local drop size and (LWC)	Technical person to contact	Test season (Need temp at altitude)	Comment
					At nominal distance L_D	Manifold	Air speed, km/hr IAS	Min. total air temperature, °C	Altitude, m	LWC, g/m^3	Vol. med drop size, µm				
D-1	Air Force (Edwards AFB, CA) (a) KC 135 Tanker	FR.	ICE, N R, FR	60	At $L_D = 60$ $d = 3$	$d_s = 1.2$	300 to 650 (370 nom.)	-20 (ambient)	1200 to 9000	0.05 to 1.5 0.5 to 32.	20 to 36 200 to 800	Knollenberg spectrometer (")	R. Morrison (805)277-3000	All year	Final calibration in 1981
	(b) C 130 Tanker	FR.	ICE, N R, FR	60	At $L_D = 60$ $d = 5$	$d_s = 1.2$	190 to 300 (280 nom.)	-20 (ambient)	1200 to 9000	0.05 to 1.5 0.05 to 32	20 to 35 desired 200 to 800	Knollenberg spectrometer (")	R. Morrison (805)277-3000	All year	Planned for 1981
D-2	Army HISS Helicopter Tanker (Edwards AFB, CA)	FR.	ICE, N	30	At $L_D = 50$ $h = 3$ $w = 12$	$h_s = 1.8$ $w_s = 12$	110 to 140 (120 nom.)	-20 (ambient)	600 to 3500	0.1 to 1.0	25 to 30 desired	Knollenberg spectrometer (Leigh)	C. Frankenberger (805)277-2271	Normally winter	Testing to increase cloud size
D-3	Cessna 404 Tanker (Wichita, KA)	FR.	ICE, R, FR, N	60	At $L_D = 150$ $d = 6$	$d_s = 0.6$ (V-bar)	165 to 330 (280 nom.)	-20 (ambient)	300 to 6000	0.05 to 4.0	20 to 40 (water nozzles)	Gelatin slide (J&W)	D. Hazelwood (316)946-0000	All year	------------------
D-4	Piper Cheyenne Tanker (Lock Haven, PA)	FR.	ICE, FR, R, N	14	At $L_D = 30$ $h = 3$ $w = 5$	$h_s = 1.2$ $w_s = 1.8$	200 to 300 (240 nom.)	-20 (ambient)	300 to 6000	0.1 to 1.7	30 to 50	Gelatin slide (J&W)	J. Bryerton (717)748-6711	Not summer	------------------
D-5	Flight Systems T-33 Tanker (Mojave, CA)	FR.	ICE, R, FR, N	45	At $L_D = 60$ $d = 2.5$	$h_s = 0.3$ $w_s = 0.9$	230 to 420 (370 nom.)	-20 (ambient)	300 to 9000	0.1 to 1.0	17 to 50	Knollenberg spectrometer (")	J. Ligon (805)824-4081	All year	------------------

ABBREVIATIONS, AND FOOTNOTES FOR TABLES

[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; IA = ice adhesion; CP = cloud physics; R = rotating experiments (e.g., helicopter rotor models and propellers); G = ground transport and installations in freezing rain; FS = full-scale aircraft; FLT = flight tests of aircraft; I = inlets with suction; P = complete propeller engines; H = human physiological experiments.

[b] Whether simulated: ICE = icing cloud environment; SI = solid ice particles; FR = freezing rain; R = rain; N = natural icing; S = snow.

[c] Parameter ranges vary with conditions; request operating envelopes from contact person.

[d] Modification to do this has been seriously proposed.

[e] Tests in progress to extend these limits.