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Aircraft Icing

A workshop held at
Lewis Research Center
Cleveland, Ohio
July 19-21, 1978

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A workshop sponsored by
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WELCOMING REMARKS

Dr. Bernard Lubarsky
Deputy Director
NASA Lewis Research Center

Good morning! It is my pleasure to welcome the Icing Workshop to the Lewis Research Center. I'm impressed with the renewed interest in icing as represented by the size of this group, and by the attendance of many guests from other countries. If this meeting had been organized a few years ago, I believe we could have all sat around a card table.

Lewis was very active in icing research through the 1940's and early 50's. In this time period, de-icing techniques suitable for large commercial transports were developed in our Icing Research Tunnel which contributed to the all weather operation of current transports. This research effort was terminated in the late 1950's and subsequently the only remaining activity was to provide operational support of the tunnel at the request of other government agencies and their contractors. Within the past few years, this low level of effort has expanded to the point where it is difficult to satisfy all the requests for testing in the Icing Research Tunnel. This renewed interest is driven by both new requirements and new opportunities offered by improved technology developed in recent years. These new requirements encompass the need to obtain an all weather capability for helicopters and general aviation aircraft, and the desire to achieve more efficient equipment for commercial transports.

The interests in achieving all weather operation of helicopters are to meet both a military requirement to operate over Europe during the winter and a commercial requirement to service oil rigs in the North Sea and off Alaskan shores. This capability would almost certainly find additional commercial uses once it is demonstrated. The helicopter lacks the large power and heat sources that are used on a commercial transport to de-ice the aircraft. Therefore, improved techniques are required that are lower power, lighter weight, and lower cost.

The advances achieved in avionics make all weather general aviation a real possibility for the future. Since its payload capability (like that of the helicopter) is relatively small, present methods of ice protection impose serious penalities on its capabilities. Improved ice protection techniques with characteristics similar to those required for helicopters are clearly needed.

Although the icing program of the 1940's addressed principally the needs of CTOL aircraft in that time period, the revolutionary changes in CTOL aircraft for the 1970's and 80's have created new design variables and operational conditions that were never considered in the earlier work.

New technology which has evolved in the past decade can provide new tools in achieving solutions to these icing problems. For example, new de-icing techniques that have been proposed in recent years include microwave and electromagnetic impulse methods that are potentially lighter and lower in power than current methods. Results from the continuing evolution of ice-phobic materials also need to be assessed periodically for aircraft applications. New instrumentation such as lasers provide the means to define the testing conditions and icing environment more accurately. Also, new methods in computational fluid dynamic analysis can provide better predictions of ice collection rates and ice shapes.

I'm pleased to see the renewed interest in icing and wish you a successful workshop. I look forward to reviewing your recommendations.

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APPENDIXES

INTRODUCTION

John H. Enders
NASA Headquarters

BACKGROUND

The recent renewal of interest in flight icing may be surprising to many, but it probably should have been expected. Our experience with safety and operating problems research has been that problems are "solved" for a time, and then, as aircraft designs and operating practices change, these problems re-emerge and call for renewed effort, often in terms of a finer-scale solution than was offered earlier. Icing hazards to aircraft were thoroughly researched nearly 2½ decades ago. Reports were written on icing meteorology, forecasting, ice accretion, and on ways to prevent ice formation or remove ice from surfaces critical to flight. That effort summarized pretty well what was known and understood at the midpoint of this century.

Within a decade of completing that effort, the air carrier fleet moved into the jet age. The operations were characterized by rapid climbs with plenty of power to altitudes above most weather, including icing. Low terminal traffic densities of that day allowed a similar swift descent to landing with little dwell time at icing levels. General aviation and some military traffic continued to contend with icing problems, but they had the improved icing knowledge of the research program to allow modest improvements in operations. Icing, from an applied aviation research standpoint, disappeared from our consciousness, except for the occasional icing-related accident.

Within the past few years, several things have happened to bring about renewed interest in icing. New aerodynamic designs have emerged which raise questions of icing vulnerability for which the existing data are inadequate. Expanded operational regimes for both civil and military rotorcraft as well as for general aviation aircraft have increased the exposures of these two classes of aircraft to icing threats at a point in flight vehicle development and use where expectations of operational dispatch reliability and dependability are high.

WORKSHOP OBJECTIVES

A steady increase in the number of questions on icing vulnerability coupled with an intensified icing test schedule prompted NASA and FAA, with the planning assistance of DOD, to sponsor this Aircraft Icing Specialists Workshop. The objectives of the Workshop were as follows:

(1) To assess the current understanding of fixed wing and rotorcraft operational icing environments and problems

(2) To evaluate facilities requirements for R&D and certification purposes

(3) To examine means of improving icing forecasts

(4) To identify shortcomings in aeronautical icing knowledge which can be alleviated by new research and instrumentation development

To achieve these objectives, a representative cross section of knowledgeable icing specialists in the aviation community were invited to participate in this Workshop. The 113 experts who attended came from various countries throughout the free world and included icing researchers; meteorologists and forecasters; sensor/instrument specialists; general aviation, transport, and rotorcraft airframe and engine manufacturers; and civil and military operators and pilots. In this way, the broadest possible view of the icing problem was obtained, and wherever possible, concensus views of desirable and necessary future action with regard to operating in icing conditions were obtained.

Since the intent of this Workshop was to share information from a wide range of specialist groups, most of whom normally have little or no regular contact with one another, the Organization Committee decided on an interactive format for the meeting. This format provided opportunities for some structured state-of-art overviews of certain icing topics along with group and one-on-one discussions during the three-day meeting. An exchange of ideas, thoughts, and information resulted that could never have been attained from conferences or symposia.

WORKSHOP PROCEDURES

Each participant was assigned to one of six committees. Each committee was assigned a specific area of interest in order to provide a broad, structured spectrum within which the many icing subtopics could be addressed. Each committee chairman organized and guided his committee in its interactions. The Organization Committee formulated a set of guidelines for each committee consisting of a list of objectives and representative questions tailored to each committee's particular interest. The questions were formulated to facilitate the interactive discussions across the specialist group interest lines. The guidelines furnished to the committees are presented on pages 67 to 72.

This Workshop began with welcoming and introductory remarks. The overview papers that followed addressed the recent progress in several areas of aircraft icing and icing meteorology. Following these presentations, each committee met to discuss its objectives and to establish a collective reference point for the interactive sessions that followed during the next day and a half. The meeting schedule (p. ix) shows how the committees interacted so that every participant had opportunities to give and receive views on all topics. On the final morning the committees again met individually to assemble their committee reports. A final plenary session provided time to present the committee reports to the assembly and for general discussion. The keynote presentations and the committee reports are followed in this publication by appendixes that contain an additional report pertinent to the theme of this Workshop, the Workshop agenda, a list of the committees with their members and chairmen, and a list of the Workshop participants.

During the Workshop the attendees toured the Lewis Icing Research Tunnel (IRT) and the Lewis Altitude Wind Tunnel, which has been proposed for modification into a Large Subsonic Propulsion and Icing Test Facility.

COMMITTEE MEETING SCHEDULE

Committee	Chairman
MET - Meteorological Research	Dr. Helmut Weickmann
FOR - Icing Forecasting	Mr. Arthur Hilsenrod
DEV - Systems Development	Mr. Richard L. Kurkowski
CO - Civil Operations	Lt. Col. Thomas West
MO - Military Operations	Lt. Col. George W. Sibert
FAC - Icing Research and Facilities	Mr. Milton A. Beheim

Session	Room					
	Administration Building					10×10 SWT, room 106 or 100
	Auditorium	Foyer (133)	225	14	215	
	Committee					
Panel organization Wed., 1:00 - 2:30 pm	MET	FOR	DEV	CO	MO	FAC
First session Wed., 3:00 - 4:30 pm	CO/FOR	---	MO/DEV	--	FAC/MET	---
Second session Thurs., 8:15 - 9:45 am	CO/DEV	---	FAC/FOR	--	MO/MET	---
Third session Thurs., 10:00 - 11:30 am	CO/FAC	---	MO/FOR	--	DEV/MET	---
Fourth session Thurs., 1:00 - 2:30 pm	CO/MET	---	MO/FAC	--	DEV/FOR	---
Fifth session Thurs., 3:00 - 4:30 pm	MO/CO	---	FOR/MET	--	DEV/FAC	---
Panel report preparation Fri., 8:00 - 9:30 am	MET	FOR	DEV	CO	MO	FAC

EXECUTIVE SUMMARY OF AIRCRAFT ICING SPECIALISTS WORKSHOP

Milton A. Beheim
NASA Lewis Research Center

HISTORICAL PERSPECTIVE

An important chapter in the historical evolution of aircraft is that related to icing research. From 1940 to 1955 the particularly significant efforts made in industry and at government laboratories (particularly NACA) were directed toward defining the natural icing environment, determining its effects on representative aircraft components, and designing techniques for ice protection concepts. The results established a basis for certification criteria and meteorological reporting procedures that proved to be generally acceptable to achieve all-weather capability for the large transport aircraft of that time. When this effort ended in the late 1950's, the principal emphasis in the design of transport aircraft had shifted to jet power. Because of higher installed power and high cruise altitudes, these jet aircraft were exposed less to ice. In fact, they were even more ice-tolerant than propeller transports. The major manufacturers of these aircraft continued to develop increasingly sophisticated analysis and testing techniques for icing protection that were tailored to the specific aircraft being certified. Although the certification criteria were generally recognized to be conservative, the penalties to aircraft performance and cost were not excessive since large quantities of heated, high-pressure air were readily available from their powerplants for ice protection systems on the engines and airframe. For many components of such aircraft it even became possible to eliminate the ice protection systems entirely simply because their physical size was so large that ice accretion was minor in extent and the resulting aerodynamic influence was acceptably low.

This trend in the design of new large transport aircraft continues to the present day. However, in a period of escalating development costs for new aircraft, there is growing interest in a renewed and coordinated icing research effort to achieve an updating or modernization of each aspect of the technological issues that are involved. This includes the data base, analysis methods, test techniques, and test facilities.

In recent years it has become necessary to extend the icing technology to entirely new classes of aircraft: rotorcraft and general aviation. The emerging "small transport" aircraft, the proposed FAR Part 24 airplane, may operate more frequently in icing environments than the large jet transport. The advances achieved in avionics now provide the opportunity to operate in severe weather with these smaller aircraft as well as with the large transports. However, the icing protection requirements for these small aircraft are so uniquely different from those for large transports that an extrapolation of the current base of icing technology is clearly inadequate. The components of these aircraft are smaller so proportionately heavier accretions of ice are more likely to occur. Consequently, their aerodynamic performance will deteriorate more drastically. Penalties for the weight of icing protection systems are also more severe since the payload fraction of these aircraft is already relatively low. In addition, their engines differ in cycle characteristics so large quantities of high pressure heated air are not readily available for ice protection. Consequently, the technological issues requiring modernization not only include those listed earlier for transport aircraft but they also extend to unconventional ice protection concepts.

Furthermore, to avoid undue penalties in design and operation, the certification criteria and weather reporting procedures for large transport aircraft need to be reexamined for their applicability to small aircraft.

OVERVIEW OF ICING EFFECTS ON AIRCRAFT DESIGN

An important step in the design of aircraft for operation in icing conditions is to establish the nature of the most severe icing encounter that may be expected. Although the detailed character of the natural icing environment is complex, the principal parameters are air temperature, liquid water content, and mean drop size. Extreme values for combinations of these parameters are the basis for certification criteria, and they were derived from statistical analyses of rather limited flight data. A typical example is shown in figure 1.

The accretion of ice on an object in an air stream depends on the quantity of water that strikes its surface. When the drops are small compared with the size of the body they tend to follow the flow streamlines around the body and few drops strike its surface. Conversely, when the drops are relatively large they tend to follow straight lines and so impact on the frontal body area. Consequently, larger, blunter bodies collect relatively less ice than smaller, sharper bodies. This effect is illustrated in figure 2. The accretion of ice further depends on surface heat-transfer balances involving phase changes and local heat-transfer rates. Analytical models of these conditions are used extensively throughout the development process for the aircraft and its ice protection system.

The resulting shape of the ice cap depends on the influence of the local flow field in distributing the liquid water over the surface before it freezes. Hence, the rate of freezing is important and so is the distorted shape of the surface that results from the prior accumulation of the growing ice cap. At low temperatures where freezing is rapid, a type of ice called rime forms a streamline shape. For warmer conditions, the water film flows more extensively before freezing and a type of ice called glaze freezes in a horn shape. Representative formations are shown in figure 3. Aerodynamic effects of the ice cap are evaluated by means of artificial ice in an icing wind tunnel, by simulated ice in conventional wind tunnel or flight test programs, or by flying in natural icing conditions.

The principal effects of ice accretion on an aircraft are to decrease pilot visibility, increase weight, reduce aerodynamic performance (such as lower stall limits or lift to drag ratio), or cause structural damage to critical components such as that damage resulting from the ingestion of ice into turbine engines.

The consequences of the latter are so severe that the propulsion system merits top priority for icing protection. Although the degradation of the aerodynamic performance of airframe components varies considerably depending on the component in question, the consequences are potentially of such great importance to aircraft safety that a careful evaluation of icing effects is required in the design and development process. Assessments of these effects determine the extent of icing protection that is selected for a specific aircraft. Two different means for icing protection are common: an anti-icing system is in continuous operation to prevent ice accretion, and a deicing system is operated intermittenly to shed ice after it has developed to a predetermined limit. Deicing has an advantage in reducing the total energy required and thermal systems can be employed. Common means of thermal protection employ heated air ducts or electric resistance heaters located in the component being protected. An alternate approach is a mechanical system using a pneumatic boot which is inflated periodically to break loose the ice cap. Each method offers unique advantages and disadvantages. The disadvantages, which become more obvious in applications to small aircraft or rotorcraft, are evident in terms of high initial and maintenance costs, excessive weight and power requirements, and marginal effectiveness and reliability. To verify that a particular aircraft design is suitable for operation in icing conditions, a flight test program is normally required in the natural icing environment. However, because of the difficulties encountered in locating severe natural icing conditions with a test aircraft, artificial icing tests using tanker aircraft and ground test facilities (icing wind tunnels and engine test cells) play an important role. Certification is then accomplished by a composite analysis and extrapolation of data from all sources. The artificial icing tests verify the limits of specific systems, and the natural icing tests ensure that nothing has been overlooked.

ICING RESEARCH NEEDS

The principal areas where further research is required are summarized in table I. The top portion indicates those technical subjects which are of broad and general interest regardless of the type of aircraft being considered. The bottom portion identifies specific applications of this generalized technology that pertain to aircraft components that are unique to a particular aircraft concept.

GENERALIZED TECHNOLOGY

Meteorology

Table I indicates the four major needs in meteorology that have general applicability in all aircraft icing situations.

Cloud physics. - A fundamental aspect of meteorological research that underlies success in all aspects of the icing problem is a sufficient knowledge of cloud physics. Not only does it influence the techniques for measuring and forecasting the icing environment, but it can also influence the appropriate mode of flight operations. The most significant effort in recent years that relates to cloud physics was directed toward weather modification objectives. Since these weather conditions are closely related to those causing icing conditions, it appears appropriate to reexamine the results of that effort for its applicability to icing research. In particular, it could provide better insight into the finer scale structure of icing clouds. Although this structure may be of lesser importance for high-speed transport aircraft, it can be very significant for low-speed aircraft such as rotorcraft.

Icing environment. - Another aspect of meteorological research is the definition of the natural icing environment that is encountered during flight. The parameters of interest are the extreme values of liquid water content and the mean drop size for various values of outside air temperature. Appropriate combinations of these parameters are established for two different cloud formations: stratiform and cumulus. The values currently being used were developed from a statistical analysis of several hundred flight observations that were made of natural icing conditions in the late 1940's and early 1950's. Although these extreme conditions were used as an interim definition of the environment pending further vertification at a later date, it was never done. Consequently, several questions exist today regarding the validity of these definitions of the icing environment for application to future aircraft. In particular, the following limitations exist:

(1) The older measurements have been extrapolated to an accuracy that exceeds the statistical accuracy of the data.

(2) The accuracy of the older measurement techniques are questioned in light of recent work using modern instrumentation.

(3) The range of altitudes for the old data (from 4000 to 20,000 feet) is too restricted for new types of aircraft.

(4) Extrapolations of these data to low altitudes are now known to be physically unrealistic.

(5) The horizontal extent of the icing cloud has not been adequately defined.

(6) The ground cloud parameters have not been determined.

(7) The fine grain structure of the icing cloud and hence the time dependent characteristics resulting from flight through it have not been defined.

(8) The parameters for defining the mixed conditions of ice particles and supercooled water have not been established.

These limitations are generally viewed as having created an overly conservative view of the icing environment. Although this conservatism may be tolerable for large transport aircraft, the penalties for small aircraft and rotorcraft can be excessive; consequently, a renewed research effort is justified.

Forecasting. - A third requirement is improved weather reporting and forecasting procedures and techniques. The present system of reporting relies entirely on qualitative terms (such as light or severe) that do not recognize the varying susceptibility of different aircraft designs to identical icing environments. For example, light icing for a large transport could be severe for a small airplane. The only reasonable alternative to this problem is to introduce quantitative terms so that an aircraft operator can make operational decisions that are the most appropriate for his own particular aircraft. Although a knowledge of all three icing parameters (water content, air temperature, and drop size) are very much desired, it is evident that drop size is the hardest to measure with present instrumentation and weather observation techniques. However, a knowledge of the other parameters which are more easily measured would greatly enhance the operational capabilities of smaller aircraft.

Remote observation. - The need for techniques for the remote observation of weather conditions in terms that can be interpreted to infer icing conditions is clearly evident. One type of observation that is needed is a large scale view of weather patterns so that the location and extent of icing conditions can be identified and reported. One such approach is to use an airborne automated icing observation system. A second type of observation is a more localized measurement that can be made from individual aircraft so that a "look ahead" capability can be used to select the best flight profile when an icing condition must be entered. It is not yet evident which observation techniques are most suitable for these requirements, but radar or microwave concepts offer some potential.

Aircraft

The next portion of table I relates to generalized technology, and it indicates four important research areas in the design, development, and operation of aircraft.

Ice accretion. - The first area deals with the nature of ice accretion on a variety of geometric shapes. Earlier work in the 1940's identified the general character of these ice formations and their sensitivity to icing parameters. Effective means of analyzing water impingement and heat-transfer effects were evolved in the 1950's so that predictive methods became useful in cases where two-dimensional flow effects were dominant. However, most modern aircraft flow fields exhibit important three-dimensional characteristics. In addition, predictive methods for the ice cap geometry and its influence on the flow field are not well developed because of flow separation effects. In recent years, advances in computational fluid mechanics have been achieved which potentially could provide major improvements in treating these effects. Further development of these analytical tools would be very useful, particularly when a decision must be made early in the design phase whether or not the accretion of ice on an aircraft component has such severe aerodynamic effects that an icing protection system is required.

A second aspect of ice accretion that requires further investigation is the scaling of the accretion process and its aerodynamic influence so that subscale model tests are developed into a more powerful tool than at present. Ground test facilities such as wind tunnels play a very important role in the design and development of aircraft. At the present time, however, those tunnels with the unique capabilities for icing tests are relatively small. The largest such tunnel in North America is the NASA Icing Research Tunnel at the Lewis Research Center with a 6×9 foot test section. Although some full-scale components can be tested, it is obvious that scaling techniques are required to support the design and development of new aircraft. This is particularly true for aircraft with large components that also have a high sensitivity to ice accretion such as the rotor of a helicopter.

A third aspect of ice accretion which requires additional effort is the bond strength characteristics between the ice cap and the aircraft structure. The bond strength characteristics influence the shedding properties of the ice cap as a consequence of aerodynamic forces, centrifugal forces, or vibratory forces. These properties vary depending on the type of ice, the structural material and surface treatment, and the structural temperature. Although initial efforts have been made particularly with respect to the use of icephobic surface coatings, the scope of the work should be expanded as new materials (such as composites) come into wider use and as new applications (e.g., helicopter rotors) become necessary.

A fourth subject relating to ice accretion is the simulation of the ice cap with model ice constructed of fiberglass, plastic, or other conventional materials. Recent work in industry indicates initial success in specific applications so that simulated ice was used on conventional wind tunnel models of aircraft or on flight test aircraft to evaluate the aircraft aerodynamic sensitivity to ice accretion and to assess the need for ice protection systems. If these techniques could be generalized and vertified with additional research, it would provide a powerful tool for developing new aircraft. Large-scale conventional wind tunnels could then be used to assess icing effects, and the flexibility and efficiency of flight test programs could be extended.

A fifth characteristic of ice accretion that justifies some further exploration is the influence of mixed conditions (ice particles with supercooled water drops). The importance of this phenomena may vary depending on the particular aircraft component in question and the design of the ice protection system. In some cases the ice particles may be an abrasive and, as a result, slow the growth of the ice cap; in other cases the ice particle could be captured and increase the heat-transfer load on the ice protection system. Sufficient controversy exists that some additional effort appears necessary to clarify the nature of the problem.

A final aspect of ice accretion that has received only limited effort to date is that resulting from frost accumulation during idle periods of the aircraft on the ground. In severe cases the aircraft surfaces may require cleanup prior to flight. Since the nature of ice accreted this way is significantly different than that accreted in flight, an assessment of frost buildup and the resulting aerodynamic degradation are important issues to be resolved.

Anti/deicing methods. - The next research item indicated on the table for aircraft technology is the anti- or deicing methods. One of the principal methods used in the past is a thermal system: heated air or electric resistance heaters. They work very well provided that either large quantities of heated air are available or that large quantities of electric power can be provided. An additional problem with the electric systems can be the excessive maintenance costs. Although methods of analysis and design for this type of system have been developed within the industry, further improvements could be achieved as indicated earlier by applying advanced methods of computational fluid mechanics. A new question requiring further research is the applicability of thermal protection to composite material structures. Since the heat conductivity of composite materials is very low compared to metals, an obvious problem that needs to be resolved is the runback and refreezing of the water downstream of the heated portion.

Another method of ice protection is the use of pneumatic boots. Although they have been used in a wide variety of circumstances, advances in materials and fabrication technology have extended their potential application to new circumstances (such as rotors) for which design and operation criteria are inadequate.

A third method that has been studied to a limited extent is the use of icephobic material on the aircraft surface. Ideally, these materials weaken the bond strength sufficiently so that ice accretion is not significant. Although such materials have been successfully developed for static conditions, they have not performed well in a high-speed air stream. Some new coatings have recently shown improved characteristics, but they tend to be easily eroded (such as by rain). The general concept is so attractive in terms of simplicity that a continuing search for appropriate materials appears justified.

A new concept that has not yet received much effort in the United States is the electroimpulse method. Electromagnetic coils are used to deflect an airframe surface to break the ice cap loose. Russia has reported success in using the method and further study is appropriate.

Another concept that is undergoing preliminary studies in the United States is the use of microwave energy. A surface wave guide is used to channel the energy to the surfaces requiring icing protection. If ice begins to accrete on the wave guide material, energy is absorbed into the water contained in the ice cap and causes it to shed more easily. One of the problems requiring further study for some applications (such as rotors) is the appropriate selection of wave guide materials with sufficient erosion resistance. The advantage relative to a conventional electrothermal system is that less energy is required and mechanical simplifications can be achieved to enhance reliability. The next phase of research effort appears to be appropriately accomplished in an icing wind tunnel.

Facilities. - The third element of aircraft technology indicated in the table is that related to test facilities for icing research, aircraft development, and certification purposes. Both ground test and flight test facilities are used, and each has a distinct and important function. To date, ground test facilities have been of four types: the engine test cells, the icing wind tunnels, the static environmental chambers, and the outdoor spray systems in cold weather regions. In the United States the engine test cells (such as those at AEDC) have kept pace with modern developments but the icing wind tunnels (such as that at NASA Lewis) have not. In addition, the spray range is relatively limited, altitude test capabilities are not adequate, and the small test sections are very restrictive. Innovative concepts are being examined to expand the usefulness of the static chambers (such as that at Eglin).

A variety of tanker aircraft are being used in the United States for generating artificial icing conditions for flight testing. In general, further refinements are required here also: the spray characteristics and distributions are too limited, the turbulence level may be relatively high, the test time is relatively short, and flight instrumentation is relatively meager. The Air Force, in particular, is developing improved flight equipment.

The area that stands out as being the most deficient is the development of the large icing wind tunnel. Historically the wind tunnel has proven to be the most flexible and efficient means of developing aircraft systems. The need to extend this capability for icing protection and certification of future aircraft is clearly evident.

Instrumentation. - The fourth research area listed in the table is so funamental that it probably is the most important - instrumentation. It is essential to measure the icing environment in flight and in ground test facilities before any of the results can be interpreted accurately. In the 1940's and 1950's relatively clumsy and slow measurement techniques were used with questionable accuracy. Advances in instrumentation have been so dramatic since that time that it now appears possible to achieve highly accurate measurements of icing parameters with real time data displays. Laser concepts employing holographic, interferometric, or collimated beam techniques offer this promise (with additional development effort of highly sophisticated equipment and at relatively high costs). Hence, they will probably find their most useful role in ground test facilities - at least initially.

A second class of instruments that are needed are operational instruments (as opposed to research instruments) that can be used as standard aircraft instrumentation. As indicated in an earlier section, quantitative measurements of local flight conditions will become increasingly important. The instruments described earlier might eventually prove useful in this role also if they can be developed to be sufficiently simple, rugged, and at reasonable cost. Another modern concept for detection and measurement of ice accretion is the microwave concept, and it also justifies further research and development.

APPLICATIONS

Propulsion

Protecting the propulsion system from icing effects is top priority for all types of aircraft.

Inlets. - Not only is the loss of power of major concern for flight safety, but engine components (particularly in turbine engines) are more susceptible to structural damage from ice ingestion. Consequently, to avoid the ice fragments associated with deicing, the inlet has generally employed anti-icing systems designed to not only protect the cowl leading edge but also to prevent runback and freezing within the subsonic diffuser. Most of the effort to date has been directed to relatively simple axisymmetric subsonic concepts, but there is growing interest in nonaxisymmetric designs for VTOL and rotorcraft applications and to both axisymmetric and two-dimensional supersonic designs of high-speed aircraft for which an icing data base does not exist. Furthermore, since a large turbine engine can ingest fairly large ice chunks without structural damage, it is even possible to eliminate some of the traditional ice protection equipment. Consequently, the inlet research effort should not only consider the design of an ice protection system, but it must also be broadened to explore the ice accretion characteristics of unprotected inlets.

Carburetors. - A special class of inlet systems is the carburetion of piston engined aircraft. The view is frequently expressed that carburetor icing is suspected as a cause for several incidents with general aviation aircraft. Although icing protection is provided in the design, there is concern that icing conditions are unsuspected by the pilot until it is too late. Consequently, the emphasis in future research may be to examine new concepts of ice protection that place less demands on the pilot for monitoring and control functions.

Fans and compressors. - Fans and compressors are also indicated on the chart as an additional research area in propulsion. Although engine bleed air is normally used for anti-icing purposes, generalized techniques for predicting the ice accretion characteristics of these components are not readily available. This capability is of particular importance in deciding the extent of icing protection that will be required in new large engines since total protection in the historical sense is no longer required.

Propellers. - In a related manner, icing protection for advanced propeller concepts will also require further research. As a part of the aircraft energy conservation program presently underway in the United States, turboprop research has been renewed to assess its applicability to high-speed transport propulsion. The geometries of interest differ markedly from traditional design, and the icing protection concepts may therefore differ from earlier designs.

Fixed Wing Airframes

Airfoils. - A significant data base has evolved over the years for two-dimensional conventional airfoils. Much more limited data are available, however, for the effects of sweep and for the new airfoil geometries (such as the supercritical designs) that have evolved over the past decade. As indicated in the table, a renewed effort on icing effects on airfoils is needed - not so much to refine ice protection systems as was done in the early 1950's but to determine the performance sensitivity to ice accretion effects so that airfoil selections can be made to avoid using a protection system whenever possible. Particularly for general aviation applications it may even be possible to evolve new airfoil geometries that minimize the possibilities of ice accretion and its deleterious effects on performance.

High-lift devices. - Another research area listed in the table is high-lift devices for airfoils. Not only is the data base nonexistent for new airfoils, it is also very meager for conventional geometries.

Junctures. - A particularly difficult problem in airframe ice accretion is the effect of junctures such as between the fuselage and the wing. It is especially important for rear engined aircraft because of the potential for the ingestion of ice chunks into those engines. Very little data has been developed that relates to this type of ice formation and its shedding characteristics. Recent advances in computational fluid mechanics may prove particularly useful in treating the three-dimensional character of this flow field.

Rotorcraft

The final aircraft application listed in table I is rotorcraft, which includes helicopters, tilt rotors, and tilt-wing turboprops. It is probably one of the most challenging problems from an icing protection viewpoint. Not only is the rotorcraft performance very sensitive to ice accretion effects, but the flow fields are very complex and the conventional icing protection systems can be complicated to install and difficult to maintain. As indicated in an earlier section, unusual geometries for the inlet and propulsion system installation may be required. In addition, for the helicopter, as an example, the inlet is subjected to flow fields that enter from nearly every direction depending on the flight conditions.

Rotors. - As indicated by the table, the main and tail rotors for a helicopter are other major components that may require icing protection. The main rotor is a large, flexible, rotating structure with complex time-dependent flow fields and complex structural attachments. Although electrothermal deicing systems are being developed for near-term applications, the penalties to aircraft design justify a continued search for improved concepts.

Shadow zones. - The airframe flow is also very complex and varies drastically depending on flight conditions. As indicated in the table, shadow zones and enrichment zones are created wherein the icing conditions are completely different from the free-stream conditions. Consequently, ice accretion on localized components can be unusually severe, and it is even difficult to locate icing instrumention in a suitable manner so that useful information is derived.

Stores. - Another characteristic of helicopter operations is to hang irregularly shaped external stores on the outside of the airframe. Not only do they have their own special ice accretion problems, but they may even require their own ice protection systems. Hence, improved methods of three-dimensional analysis and testing are needed.

CERTIFICATION AND DESIGN CRITERIA

The need for modernizing the certification criteria is the subject of much discussion. Existing criteria for transport aircraft have served a very useful purpose, and therefore changes are understandably made with great reluctance. However, there are many instances where they are simply not applicable to all aircraft. Therefore, to avoid the imposition of unrealistic constraints on the growth of aviation, a thorough review is essential to evolve the appropriate requirements for each type of aircraft. Execution of the research program outlined in the previous section would assist in accomplishing this task while maintaining the good safety records of civil aircraft.

For some aircraft types (such as general aviation and rotorcraft) it may be possible to achieve partial certification for operation in icing conditions less severe than those described by figure 1. The icing constraints may be tailored for a specific aircraft in order to minimize the penalties in aircraft performance and cost. However, success in this approach would require the quantitative reporting, forecasting, and onboard measurement techniques described in the research section. It would also require additional pilot education and skills.

Because of the specialized applications of military aircraft, different design criteria may be appropriate for them, but a similar task is equally important because of the changing nature of the types of aircraft and their missions. Key missions wherein icing operations are encountered with rotorcraft include antitank, search and rescue, and antisubmarine warfare; with more conventional aircraft, the close ground support mission may be required in icing conditions.

NASA ROLE

It was a privilege for the Lewis Research Center to host the Aircraft Icing Specialists Workshop. We in NASA were impressed by the widespread interest and concern for this problem in this country and in allied countries as evidenced by the large attendance from organizations located in the United States, Canada, England, France, West Germany, Sweden, Norway, and the Netherlands. The Workshop reinforced our growing awareness of the need for a renewed icing research effort within NASA's Aeronautical Research Program. Participants in the Workshop delineated current and future icing protection needs for virtually every type of aircraft: civil and military rotorcraft, general aviation, subsonic and supersonic CTOL, close support Air Force aircraft, Air Force and Army cruise missiles and RPV's, and Navy VTOL aircraft.

It was clearly expressed that a high regard still exists among industry and the regulatory agencies for the old NACA icing research effort. However, the lack of any serious efforts to advance the state of the art since 1957 has resulted in serious deficiencies in design tools and regulatory criteria for current and future aircraft which obviously have configurations and requirements that differ significantly from those of the 1950's. Workshop participants sharply underscored an essential NASA role to accomplish the following objectives: update the applied technology to the current state of the art; develop and validate advanced analysis methods, test techniques, and icing protection concepts; develop improved and larger testing facilities; assist in the difficult processes of standardization and regulatory functions; provide a focus to the presently disjointed efforts within U.S. organizations and foreign countries; and finally assist in disseminating the research results through normal NASA distribution channels and conferences.

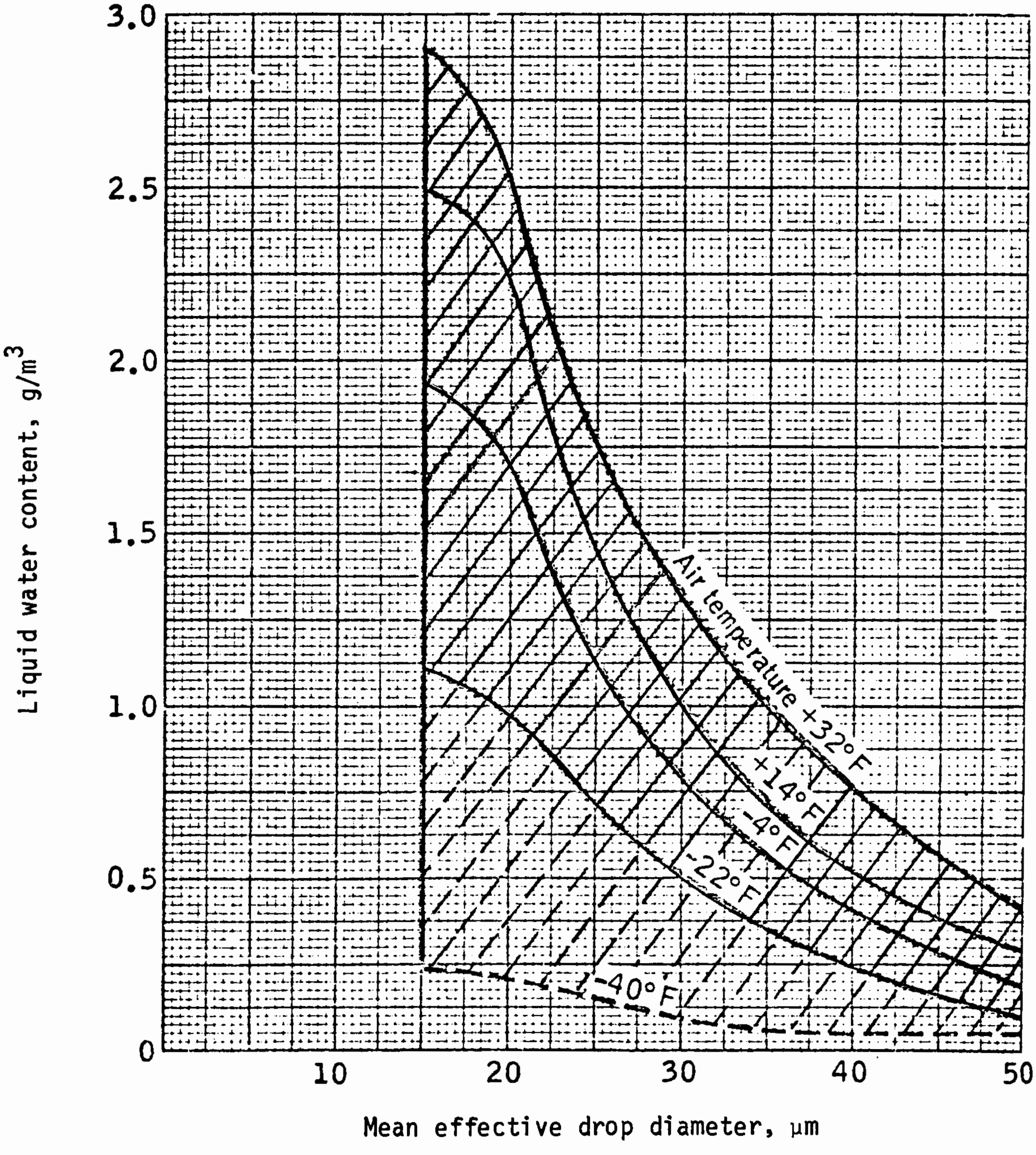
In view of the obvious need, NASA Headquarters has approved the reestablishment of an Icing Research Section at the Lewis Research Center. This Section will support the work already underway in the Icing Research Tunnel and will begin planning a long range program. The new program is anticipated to be a broad and diversified effort similar to that achieved in the earlier NACA research activity. It will be implemented through a joint in-house and contracted effort. In order to insure starting in the right direction and with the proper concurrence of the community of users, the first order of business will be a series of study contracts with industry to define the program for a larger effort in subsequent years.

In addition to the modernization program that has been initiated at Lewis for the existing Icing Research Tunnel, feasibility studies have been initiated for the design of a much larger icing tunnel with higher speed and variable altitude capabilities. The proposed concept will use an extensive amount of existing equipment at the Center, but the eventual outcome will be highly dependent on budgetary constraints.

The Workshop participants stressed the mutual value of continuing liaisons with those who attended the Workshop. Suggestions were also made for the continuing active participation and interest of the many other government agencies who had organized and supported the Workshop. NASA has a supporting role to play, but in many cases the eventual resolution of these problems lies within the jurisdiction of these other organizations.

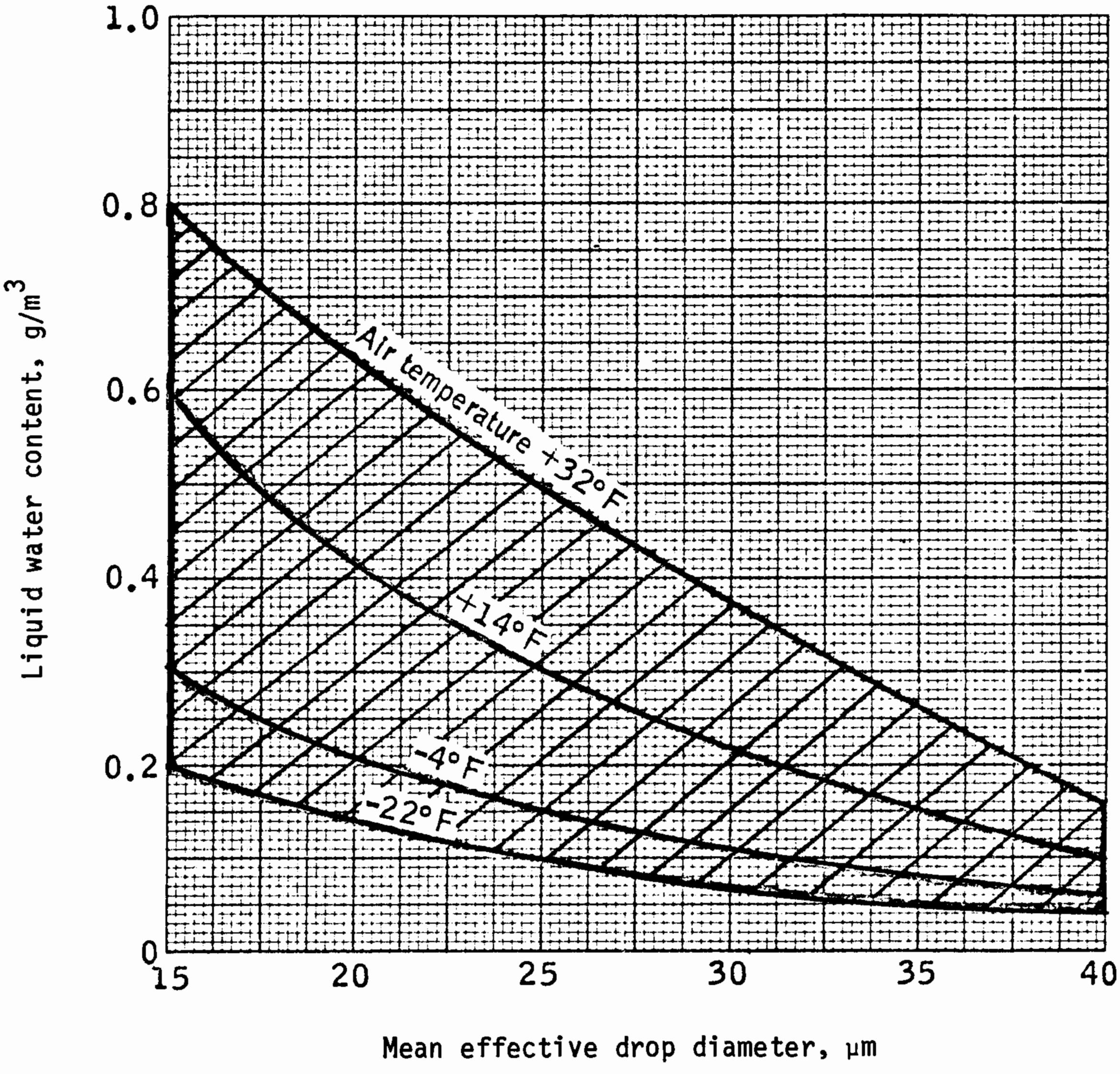
TABLE I. - ICING RESEARCH NEEDS

Generalized technology		
Meteorology	Aircraft	
Cloud physics Icing environment Forecasting Remote observation	Ice accretion Anti/deicing methods Facilities Instrumentation	
Applications		
Propulsion	Fixed wing airframe	Rotorcraft
Inlets Carburetors Fans and compressors Propellers	Airfoils High lift devices Junctures	Rotors Shadow zones Stores



(a) Intermittent maximum atmospheric icing conditions - cumuliform clouds.

Figure 1. - Liquid water content as function of mean effective drop diameter.



(b) Continuous maximum atmospheric icing conditions - stratiform clouds.

Figure 1. - Concluded.

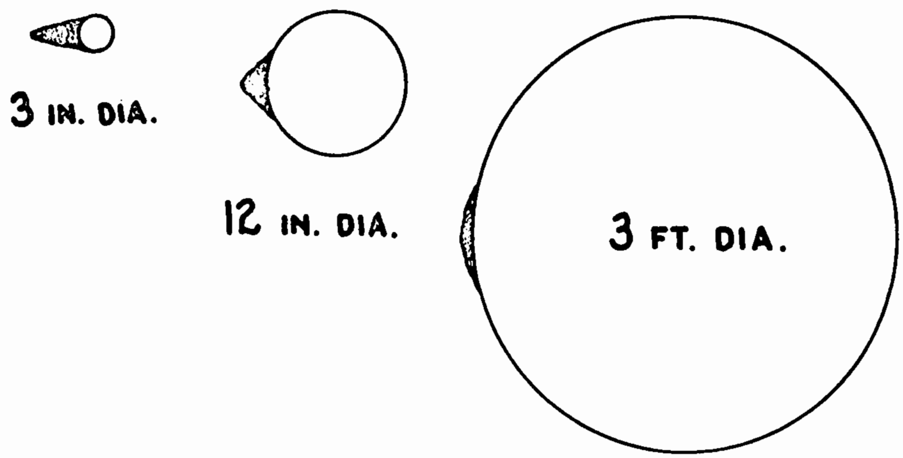
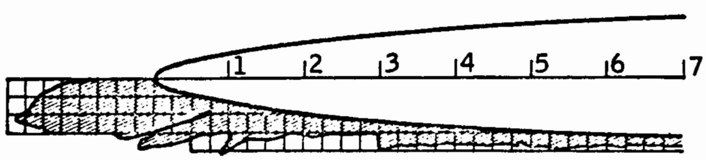
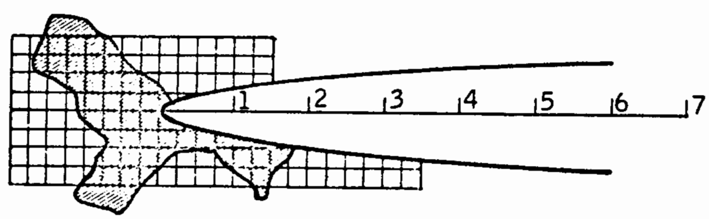


Figure 2. - Effect of size of object on ice accretion.



(a) Rime ice.



(b) Glaze ice.

Figure 3. - Typical ice deposits on a 65A004 airfoil at 2^{o} angle of attack.

ICING OF AIRCRAFT; SOME REMARKS WITH AN HISTORICAL SLANT FROM A CLOUD PHYSICIST

Robert M. Cunningham
Air Force Geophysics Laboratory

In this short presentation I will comment on three areas of interest; Cloud Physics, Nowcasting, and Instrumentation. I wish to compare what was done 30 years ago to what might be done now in light of developments in related areas of cloud physics, weather modification and instrumentation.

Some 30 years ago, during and for a short time after WW II, I was heavily involved at MIT in icing research, icing instrumentation and icing test flying. The work was done under an AF contract and in association with the Army Air Force's contract with NW Airlines in the Minneapolis area. This was the effort that resulted in the development of the hot wing deicing system.

Thirty years ago there was a fairly complete basic knowledge of the physical processes involved in aircraft icing. Of course the presence and importance of supercooled cloud or rain was well recognized. The problem of the collection efficiency of various shaped objects had been extensively explored resulting in the appreciation for the need for knowledge of the drop size spectrum. Complex thermal equations that described the temperature distribution on an ice surface and wing surface have been developed and checked. The difference between particle collision with a surface and accretion resulting in "icing" was recognized. Loss of water by "run back" (complicated when a hot wing was involved) was investigated in the special icing tunnel at MIT and shortly by several other groups including I believe by the large group that formed here at the Lewis Lab. An important theoretical study of the effects of collision, accretion and runback was conducted by the late Frank Ludlum who later applied his ideas to hail stone growth

Progress has been made lately in the area of collision efficiency calculations. Some of the earliest uses for the computer, or rather its immediate forefather, dealt with determining the trajectories of spherical liquid particles around various geometrically defined objects. Modern computers can make short work of the efforts made in this area 30 years ago. Recently we have sponsored work which permits the introduction of odd shaped surfaces into an airstream and in particular allows the description of the trajectory around these surfaces of odd shaped particles, i.e., ice crystals; snowflakes; etc. This effort was carried out in order to determine the proper place and distance from the aircraft skin for installation of ice particle sensors. But I can see application of this recent work to a common but complex icing situation, where both supercooled cloud and ice particles are involved. A few words about icing forecasting or rather nowcasting as some label short range forecasting. Again a fair bit of activity on this aspect of icing along with related statistical or climatological studies were accomplished in the 40's and 50's. The use of temperature to aid in forecasting and determining the chance for and type of icing was made early in the history of icing research. The fact that potential hazardous icing clouds were restricted in time and altitude and were extremely uncommon in certain common cloud types was one of the important results of studies by Porter Perkins and Bill Lewis using the extensive icing records produced by NACA instruments placed on commercial aircraft. I believe no equally extensive cloud census has been made since. The sister science of weather modification sorely needs such a study.

With the mention of weather modification let me digress for a minute. One important product of the rigorous field of icing research 30 years ago was the now considerably larger field of weather modification. One realizes, of course, that icing for the most part occurs in the presence of supercooled clouds, and that the most common weather modification technology requires the same supercooled cloud as the basic working material. The three people most closely associated with the beginning of modern weather modification, Irving Langmuir, Vince Schaefer and Bernie Vonnegut all were working during WW II on icing projects, Langmuir and Schaefer at G.E. on particle trajectory theory and instrumentation and Vonnegut at MIT on tunnel and A/C testing and icing detection instrumentation. One can say that it was to a considerable degree their associations with the icing field that fired their interest in cloud processes and resulted in the development of modern weather modification science and technology.

Perhaps now the older field of A/C icing can benefit by adapting some of the sensors and techniques used by the weather modifiers to the needs of nowcasting icing hazards. The sensors and techniques I am speaking of relate to those used by the weather modification community in their search for potential modification conditions. These sensors and techniques include of course the use of radar. The techniques involve inferences from the return patterns presented by the radar scopes. Now recently the detailed (in space and time) cloud analysis obtainable from the synchronous satellites shows particular promise as a new approach for detecting areas of weather modification potential and therefore regions of probable icing. It is also possible that some of the passive microwave sensors beginning to be used on the weather satellites may be sensitive enough to pick out areas of supercooled cloud, (liquid water is detected, not ice).

Last but perhaps not least is the possibility that modification techniques could be helpful in certain rather limited situations to minimize icing potential, as they have helped to increase visibility in certain landing conditions. These conditions might be particularly applicable to operations with helicopters.

The third subject I have chosen to touch on is instrumentation. I will say just a few words on some of the sensors past and present that have been used to measure the basic hydrometeor parameters involved in icing - i.e., water content and particle spectra.

One sensor has survived the test of time remarkably well, this device is the hot wire water content device or more generally known as the J-W[1], after the inventors. It was, I believe, developed here at the Lewis Labs and now has been available commercially for something like 20 odd years. It still is the standard device (at least for the cloud physicist) for measuring cloud water content of liquid particles less than 30 µm in diameter, which is generally the size range of major interest to the icing specialist. The measurement of water content, above this drop size, is still a wide open field for inventors. We have been working on two devices, but they are both in the experimental category. The old standard, the rotating cylinders of 30 years ago still could be used or adapted, but it is a very awkward device.

There is a very rich history associated with development of particle sizing devices and I hope we haven't heard the last from the inventors. To just mention the range of possibilities, let me again involve my personal experience and take you from the ridiculous to the sublime(?) The first device I tried involved extending one's finger out a top hole in the skin of the nose of the venerable B-17 aircraft. If one could keep the finger out in the stream of particles then their size was less than 200 µm in diameter (drizzle) if one could not one was flying in rain.

An improvement in this raw device came with the black glove or snow stick. This device is still used and it is superior to the new optical devices in determining the amount of rimming (or icing) on the snow particles and, of course, it gives a good qualitative measurement of the degree of icing.

The large step in particle size measurement has come in the last decade with the advent of the optical sensors, principally those developed by Knollenberg. I will not delve into a discussion of these as I'm sure there will be plenty later.

I'll finish this presentation with two summary requests and some required reading to the planners of the next era of icing or deicing technology.

(1) Don't forget that the aircraft icing R&D activities of the '40's was a very active one. Before starting off on some new endeavour it should be quite profitable to make a thorough search for the sometimes elusive report on work of some 30 years ago.

(2) Don't forget that the success of weather modification depends in many cases on the occurrence of the same conditions conducive to aircraft icing. Many past, present and future developments in the weather modification field should be checked, watched and perhaps adopted for use in icing nowcasting, icing instrumentation and testing.

(3) A recent short article in The Meteorological Magazine (May 78) by Peter Ryder nicely summarizes some of the meteorological/cloud physics inputs to icing problems.

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[1]Johnson-William Liquid-Water-Content indicator.

SAFETY HAZARD OF AIRCRAFT ICING

James C. McLean, Jr.
National Transportation Safety Board

My talk this morning is based primarily on the statistical records of aircraft accidents compiled by the National Transportation Safety Board. Based upon these statistics I will try to identify how serious a problem icing is to aircraft, the type of aircraft affected, the pilots involved and, wherever possible, try to identify the areas where a reduction in icing accidents might be most readily accomplished.

During the 5-year period 1973 through 1977 there were 525 accidents involving structural or engine icing. This is 2.54 percent of the 20,625 reported aircraft accidents during the period.

Structural icing:

Table 1 shows a breakdown of structural vs. engine icing accidents Note that engine icing accidents outnumber structural icing accicents by a factor of almost 3 to 2.

Considering the severity of the accidents: 52 percent of the structural icing accidents are fatal vs. only 9 percent of the engine icing accidents. This shows the structural icing to be by far the greater hazard to life.

Looking first at structural icing accidents: What type of aircraft has the problem? Table 2 compares single and multi-engine icing accidents. Here single engine accidents account for approximately 63 percent of the accidents and multi-engine approximately 34 percent. Of these icing accidents, 48 percent of single engine icing accidents are fatal compared with 59 percent of multi-engine icing accidents.

This shows me that icing is more of a hazard to single engine aircraft but that if an accident occurs the multi-engine accident is likely to be somewhat more serious.

Having investigated several accidents where inadvertent entry into icing conditions was a factor, I looked at the type of flight plan in each case. The results of this analysis are in table 3. It is rather obvious here that pilot judgement and/or flight planning is definitely a factor. Although there are situations where icing can be encountered under legal VFR conditions, I suspect that the majority of these cases are inadverent entry into instrument meterological conditions.

With multi-engine aircraft the situation is reversed. 86 percent of the icing accidents occurred when the aircraft was on an instrument flight plan and only 14 percent where they were flying or attempting to fly under visual flight rules.

The question that always arises: Is the pilot getting good weather information? I believe he or she is.

Table 4 shows the evaluation of the accuracy of the weather forecasts available to the pilot. In 54 cases of the 214 accidents, it was not known if the pilot received a weather forecast or it was documented that none was given. I have dropped these cases in order to evaluate only those forecasts that can be documented. Of these 160 cases, 92 percent of the pilots received forecasts which were considered substantially correct; in 7 percent the weather was only slightly worse than forecast, leaving only 1 percent in the "busted" forecast category, a very small part of the total.

I drew the following conclusions from the statistical information on structural icing:

- Structural icing is a small but significant percentage of aircraft accidents.
- Icing accidents, when they occur, are quite likely to be serious and have a higher than average probability of being a fatal accident.
- Single engine aircraft account for almost two thirds of the structural icing accidents, and almost half of the structural icing accidents involve single engine aircraft on VFR flights. In my opionion this can only be interpreted as inadequate training or pilot irresponsibility in flying into conditions that either the pilot and/or the aircraft are not equipped to handle.
- The accuracy of weather forecasts does not appear to be a serious problem. Far more serious is the number of pilots flying into icing conditions without having received an adequate weather briefing. Again, this problem appears to be one of pilot training and responsibility.
- After speaking of the many accidents in which pilot judgement must be considered a factor, there are still a large number of accidents wherein the pilot and aircraft were properly certificated for the flight in which the accident occurred. Whether the pilot or the equipment was at fault often remains a mute question. Better anti-icing equipment may have made up for pilot deficiencies and better pilot techniques may have overcome inadequate deicing equipment. Both aspects must be considered in an icing accident prevention program.

Induction icing:

During the 1973 through 1977 period there were 311 accidents which occurred under conditions conducive to induction icing. This represents 1.5 percent of the accident total.

Table 5 shows some of the statistics on induction icing accidents. Again, and by a much larger margin, the majority of the accidents involve single engine aircraft. In the case of single engine aircraft this type of accident is mostly survivable, with only approximately .8 percent being fatal.

In the case of multi-engine aircraft, as shown in table 6, the chances of being involved in an induction icing accident are quite small, but the chance of it being a fatal accident is quite high compared with single engine aircraft.

Table 7 shows a breakdown of induction icing accidents classified as to IFR and VFR flights. By far, the biggest number of accidents involves single engine aircraft on VFR flights. Multi-engine aircraft end up with, considering the small number of cases, nearly an even split.

I didn't investigate the accuracy of the forecasts here because conditions conducive to induction icing are not generally a forecast parameter. Each pilot, must know the characteristics of his or her aircraft and ask the right questions during a weather briefing or, more importantly, observe conditions in flight.

With induction icing, it is well known, and shows in the statistics, that most of the icing problems involve the float bowl carburetor. Other carburetion systems are subject to icing, although not as frequently, and here the belief by pilots that only float bowl carburetors can have icing problems has undoubtedly contributed to several accidents.

Just as I was proparing these comments the Safety Board sent a recommendation to the Federal Aviation Administration recommending that accident prevention specialists, flight instructors and flight examiners inform all owners and pilots of aircraft which use injection-type, pressure carburetors of the aircraft's susceptibility to impact ice as part of their training or biennial review programs.

The Board also recommended that the manufacturers of aircraft with injection-type, pressure carburetors provide owners with information about impact induction icing and how to cope with it.

There are several ways in which the hazard of induction icing could be reduced or alleviated. These are improvements in the design of fuel systems, changes in the composition of fuel, improved instrumentation and pilot training. Work is being conducted in most of these areas and the improvements will be most welcome by pilots.

TABLE 1

TOTAL ACCIDENTS 1973 - 1977	20,625
ACCIDENTS INVOLVING ICING	525
PERCENT OF TOTAL	2.56
ACCIDENTS INVOLVING STRUCTURAL ICING	214
PERCENT OF TOTAL	1.04
ACCIDENTS INVOLVING INDUCTION ICING	311
PERCENT OF TOTAL	1.51
TOTAL FATAL ACCIDENTS	3455
FATAL STRUCTURAL ICING ACCIDENTS	111
PERCENT OF STRUCTURAL	51.8
PERCENT OF ALL FATAL ACCIDENTS	3.21
FATAL INDUCTION ICING ACCIDENTS	27
PERCENT OF INDUCTION ICING ACCIDENTS	8.7
PERCENT OF ALL FATAL ACCIDENTS	0.8

TABLE 2

STRUCTURAL ICING

TOTAL ACCIDENTS 1973 - 1977	214
SINGLE ENGINE ACCIDENTS	134
PERCENT OF SINGLE ENGINE ICING ACCIDENTS	62.6
MULTI ENGINE ACCIDENTS	80
PERCENT OF MULTI ENGINE ICING ACCIDENTS	37.4
SINGLE ENGINE FATAL ICING ACCIDENTS	64
PERCENT OF SINGLE ENGINE ICING ACCIDENTS	47.8
MULTI ENGINE FATAL ICING ACCIDENTS	47
PERCENT OF MULTI ENGINE ICING ACCIDENTS	58.8

TABLE 3

STRUCTURAL ICING

TOTAL SINGLE ENGINE ICING ACCIDENTS	134
SINGLE ENGINE AIRCRAFT ON AN IFR FLIGHT PLAN	36
PERCENTAGE IFR	26.9
SINGLE ENGINE AIRCRAFT ON A VFR FLIGHT PLAN OR NO FLIGHT PLAN FILED	98
PERCENTAGE VFR	73.1
TOTAL MULTI ENGINE ICING ACCIDENTS	80
MULTI ENGINE AIRCRAFT ON AN IFR FLIGHT PLAN	69
PERCENTAGE IFR	86.3
MULTI ENGINE AIRCRAFT ON A VFR FLIGHT PLAN OR NO FLIGHT PLAN FILED	11
PERCENTAGE VFR	13.7

TABLE 4

STRUCTURAL ICING

TOTAL ICING ACCIDENTS WHERE A WEATHER FORECAST WAS DOCUMENTED	160
FORECAST SUBSTANTIALLY CORRECT	147
PERCENTAGE SUBSTANTIALLY CORRECT	91.9
WEATHER SLIGHTLY WORSE THAN FORECAST	11
PERCENTAGE SLIGHTLY WORSE THAN FORECAST	6.9
WEATHER CONSIDERABLY WORSE THAN FORECAST	2
PERCENTAGE CONSIDERABLY WORSE THAN FORECAST	1.2

TABLE 5

INDUCTION ICING

TOTAL ACCIDENTS 1973 - 1977	20,625
ACCIDENTS INVOLVING INDUCTION ICING	311
PERCENT OF TOTAL	1.5
FATAL INDUCTION ICING ACCIDENTS	27
PERCENT OF INDUCTION ICING ACCIDENTS	8.7
PERCENT OF ALL FATAL ACCIDENTS	0.8

TABLE 6

INDUCTION ICING

TOTAL INDUCTION ICING ACCIDENTS 1973 - 1977	311
SINGLE ENGINE ACCIDENTS	298
PERCENT OF TOTAL ACCIDENTS	95.9
SINGLE ENGINE FATAL ACCIDENTS	23
PERCENT OF SINGLE ENGINE ACCIDENTS	7.7
MULTI ENGINE ACCIDENTS	13
PERCENT OF TOTAL ACCIDENTS	4.1
MULTI ENGINE FATAL ACCIDENTS	4
PERCENT OF MULTI ENGINE ACCIDENTS	30.8

TABLE 7

INDUCTION ICING

TOTAL SINGLE ENGINE INDUCTION ICING ACCIDENTS	298
SINGLE ENGINE AIRCRAFT ON AN IFR FLIGHT PLAN	12
PERCENTAGE IFR	4.1
SINGLE ENGINE AIRCRAFT ON A VFR FLIGHT PLAN OR NO FLIGHT PLAN FILED	286
PERCENTAGE VFR	95.9
TOTAL MULTI ENGINE INDUCTION ICING ACCIDENTS	13
MULTI ENGINE AIRCRAFT ON AN IFR FLIGHT PLAN	8
PERCENTAGE IFR	61.5
MULTI ENGINE AIRCRAFT ON A VFR FLIGHT PLAN OR NO FLIGHT PLAN FILED	5
PERCENTAGE VFR	38.5

CIVIL HELICOPTER ICING PROBLEMS

Peter B. Sweeney
RCA Flight Operations

I would like to convey my appreciation to all of the parties concerned with bringing this meeting about. Personally, I am delighted to have been invited, but more than that, the rotary-wing industry is also most appreciative. I have been asked by the Helicopter Association of America to be their spokesman. Additionally, I am here to represent RCA Flight Operations, a user of IFR Fixed Wing and Rotary Wing aircraft as a business aid.

Many of you may not be aware of the fact that the rotary-wing industry has, since its conception, been treated as though it were the illegitimate child of the airplane industry. This meeting must mean that we have finally come of age. . . matured. . . reached that point in life where an investment will certainly bring about a sizable return. We feel this will be to our advantage in the long run. We look forward to your investment.

It is very difficult for me, or anyone else for that matter, to give a broad overview of our operational experience and problems with respect to icing. We have never been allowed to operate in icing conditions! However, some of the helicopters employed by the civil sector of the rotary-wing industry have been allowed to operate into some level of ice outside the U.S.A., as well as some U.S. Military helicopters having worldwide approval.

The accident rate of rotary-wing aircraft caused by rotor ice accumulated during legal IFR operations is outstanding. You would be hard pressed to find a single fatality. I do not make this comment to attempt to lull you into complacency, but to make sure that you are aware that some helicopters do possess the capability of being certified for some degree of ice capability. This fact has already been documented by the operators in the North Sea area.

We should first certify the individual aircraft to its own limit of ice capability. Then, if this limit is too low, we should start installing anti-ice or deice equipment as required to reach the desired level of operation.

The big push in helicopter operations today is in the off-shore arena. However, on-shore will be the operational arena of the majority of the units in years to come. We need schedule reliability. That is why we decided to pay the price for IFR certification. Our rate (RCA) of IFR (IMC) varies from 2 to 38 percent per month. The annual rate of actual ice is very low relative to our annual flight time. Therefore, we would have a very difficult time justifying the high cost of the anti-ice systems designed for rotorcraft today. The maintenance required and payload penalty by itself would be enough to prevent us from installing a current state-of-the-art system. We need an inexpensive, low-maintenance system for rotary wing.

The weather forecasting system is very unreliable. I am delighted to hear you people are changing some of the definitions. NOW CASTING sounds like a better deal to me. Simply reporting the actual weather is a difficult task in itself. Until this is mastered, we should not have to abide by the unreliable forecasts. The instant a forecaster mentions the word ice in his forecast, helicopters are disallowed from the IFR operations arena. With this proven, documented fact in mind, it would be difficult to justify lugging around all this antiquated equipment for the relatively low exposure rate anticipated. Those that have a high rate of exposure will simply have to put up with the systems of today.

I do have some very strong reservations about helicopters operating in icing conditions. But they revolve around the areas we know little about. For example, the day we sit on the ramp in pouring rain at 33° F, we either take off into below freezing conditions or the temperature drops rapidly. This could cause ice buildup in system locations we might have overlooked so far. The reason for my concern is that most helicopters were certified VFR only and then we warmed them over and changed the handling qualities to meet IFR standards; now we are asking for ice certification. We must insure that the total vehicle is examined, not just the rotor system or the outside skin surface.

In summary,

(1) We need each aircraft certified to it's own capability - not an absolute industry standard.

(2) We need some sort of relief from the inadequacies of the weather forecasting system as it pertains to ice.

(3) We need to improve the "state-of-the-art" as it pertains to rotary-wing icing systems.

(4) We need an inexpensive, clean, low maintenance anti-ice system.

A REVIEW OF THE ICING SITUATION FROM THE STANDPOINT OF GENERAL AVIATION

Dennis W. Newton
Cessna Aircraft Company

SUMMARY

This paper will provide an overview of the present situation in the field of aircraft icing with respect to certification and operation of non-transport category airplanes. Problems of definition are discussed and inconsistencies are pointed out. Problems in the forecasting and measurement of icing intensities are discussed. The present regulatory environment is examined with respect to its applicability and appropriateness to non-transport airplanes.

ICING DEFINITIONS

It must be stated at the outset of this discussion that the current icing situation is in many respects chaotic. This chaos begins with the various definitions of the intensities of icing conditions, and continues in various parts of the Federal Aviation Regulations which are inconsistent with National Weather Service definitions and, in some cases, with each other. The National Weather Service definitions of icing intensity are shown in the table below:

Table 1. Airframe Icing Reporting Table

Intensity	Ice Accumulation
Trace	Ice becomes perceptible. The rate of accumulation slightly greater than the rate of sublimination. It is not hazardous even though deicing/anti-icing equipment is not utilized, unless encountered for an extended period of time - over one hour.
Light	The rate of accumulation may create a problem if flight is prolonged in this environment (over one hour). Occasional use of deicing/anti-icing equipment removes/prevents accumulation. It does not present a problem if the deicing/anti-icing equipment is used.
Moderate	The rate of accumulation is such that even short encounters become potentially hazardous and use of deicing/anti-icing equipment or diversion is necessary.

Table 1. Airframe Icing Reporting Table (Continued)

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

There are two particular characteristics of these definitions which should be noted. First, they are reporting definitions, and nothing more. They do not involve cloud liquid water content, temperature, or any other physical parameter which causes icing conditions to exist in the atmosphere. Therefore, they are not, and cannot be, usable for forecasting the intensity of icing conditions. Secondly, they relate the intensity of the icing condition only to the ability of the equipment aboard the encountering aircraft to cope with the icing. They are therefore not even satisfactory as reporting definitions. It is easily seen that two aircraft of different types, or even two aircraft of the same basic type but carrying different anti-icing equipment, could fly through an icing cloud in formation and then report two different intensities of icing in perfect accordance with these definitions.

Now let us turn our attention to the icing definitions which are made in the Federal Aviation Regulations. These are shown in figures 1 - 4, which define the atmospheric environment in terms of altitude, temperature and the range of liquid water content and droplet size for Continuous Maximum and Intermittent Maximum icing conditions. They are contained in FAR part 25, but are presently included by reference in FAR part 23 and elsewhere in regulations governing certification and operation of various kinds of aircraft in icing conditions. Further discussion of these envelopes follows a bit later. For the moment, however, it should be noted that these envelopes make no reference to intensities of icing condition. They are in no way correlated with the National Weather Service definitions given above.

REGULATORY CONSIDERATIONS

The operating regulations are the next candidates for scrutiny. First checking FAR 91, General Operating and Flight Rules, one searches in vain for any reference whatever to icing conditions for other than large and turbojet powered multi-engine airplanes. FAR 91.31 prohibits operation of a civil aircraft without compliance with the operating limitations for that aircraft. This has ramifications which will be discussed later. Otherwise, there is no FAR 91 rule whatever with respect to light aircraft. However, looking at subpart D of FAR 91, we find that large and turbojet powered multi-engine airplanes having ice protection equipment certified in accordance with the FAR 25 icing envelopes may fly into known or forecast severe icing conditions (91.209). This, of course, contradicts the National Weather Service definition of severe icing conditions. These conditions are by that definition impenetrable, since by definition the equipment fails to reduce or control the hazard and immediate diversion is necessary. Looking at FAR 135, which governs air taxi operators and commercial operators of small aircraft, we again find (135.85) that aircraft certificated in accordance with the FAR 25 envelopes may be flown into known or forecast severe icing conditions. We also find that aircraft not meeting these provisions, but which have certain specified items of de-icing and anti-icing equipment installed, may be flown into known or forecast moderate icing conditions. In the general case, how the operator is to know with any confidence what intensity of icing conditions are likely to be encountered is beyond this author's comprehension, since the National Weather Service definitions change from airplane to airplane and are not suitable for forecasting purposes in the first place. For the sake of completion, it is interesting to look at FAR 121, which governs Air Carriers and Commercial Operators of Large Aircraft. These operators are generally required (121.157) to use Transport Category airplanes, and we find that the rule (121.341, 121.629) does not even mention intensity of icing conditions. It merely prohibits operation in icing conditions which, in the opinion of the pilot in command or aircraft dispatcher, might adversely affect the safety of the flight.

Situations which arise from the foregoing considerations are essentially as follows:

1. Airplanes with ice protection provisions certificated to the Transport Category standards contained in the FAR 25 envelopes can effectively ignore icing forecasts and reports. This is true regardless of the rule under which the airplane is operated and regardless of whether the basic airplane is certificated in the Transport Category.

2. There are many airplanes, mostly certificated before 1972 or thereabouts, which do not have Transport Category ice protection provisions but which also do not have an operating limitation prohibiting flight into icing conditions. Operation of these airplanes in icing conditions is not addressed in FAR part 91, and operation in light and moderate icing conditions is permitted in FAR part 135, provided that certain specified ice protection equipment is aboard.

3. It has been FAA policy since about 1972 to altogether prohibit operation in known or forecast icing conditions for airplanes not having ice protection provisions meeting the Transport Category requirements. These airplanes cannot be operated in any icing condition whatever, in accordance with any operating rule. No amount of ice protection equipment installed on the airplane in any way alters this prohibition until the ice protection provisions have been certificated to the Transport Category standards.

CERTIFICATION ASPECTS

The author knows of little or no objection on the part of manufacturers to the ice protection certification of pressurized airplanes, however powered and whether or not Transport Category, to the provisions of FAR part 25. There seems to be also little objection to such icing certification for multi-engine turbo-charged airplanes which have considerable altitude, speed, and range capability. This, however, leaves a large number and variety of airplanes with respect to which the manufacturer is now forced into one of two alternatives. The first is acceptance of an outright prohibition against penetration of any known or forecast icing conditions, whatever, even though ice protection equipment may be available, and even though there may be older and very similar aircraft without such a restriction. The second is a costly development and certification program, perhaps requiring systems which adversely affect the limitations of the basic airplane due to their high power or weight requirements and resulting in an airplane certificated to be flown by pilots of perhaps limited experience into any icing condition, regardless of severity. Noting that icing conditions are defined in FAR 25 to exist down to temperatures of -22°F and up to altitudes of 22,000 feet, we see that many aircraft would have to be protected against icing conditions which they are very unlikely or even totally unable ever to encounter.

With regard to certification of aircraft to the Transport Category standards, there is first a need for consistent understanding of the FAR 25 envelopes among the manufacturers and the FAA. It must be realized that they are not, and were never represented to be, a statement of a physical relationship between the variables of liquid water content, droplet size, and temperature. Rather, they are an engineering definition which says that all combinations of liquid water content, droplet size, and temperature within the envelopes have a sufficient probability of occurrence in the atmosphere to warrant consideration in the design of Transport Category ice protection equipment. While conditions which fall within these envelopes can be found in the atmosphere without extraordinary difficulty, to attempt to find any particular point in natural icing conditions is likely to be an expensive exercise in futility. This is especially true as the point being sought approaches the corners of the envelopes. This being the case, there is a need for alternatives to testing in natural icing conditions to prove the capability of ice protection systems. Cessna Aircraft Company has had excellent success in using an airborne tanker to investigate various conditions within the icing envelopes and prove each system at its critical condition. It has then been necessary only to fly the aircraft in natural icing at some random point which may be encountered within the envelopes to verify the performance of the systems as a whole. Development of other such tankers, perhaps under the sponsorship of NASA, is highly recommended. They are very useful in terms of verifying the performance of systems in situations which cannot otherwise be found, and are great savers of time and money. Instrumentation for use in flight testing in icing conditions presently serves the purpose, but is in many cases cumbersome and results in tedious data reduction processes. The recent introduction of laser devices for measurements of liquid water content and droplet size spectra is a welcome advance in this area.

INDUCTION ICING

After all these years, it seems that induction icing problems are still with us in light aircraft. There were over 400 accidents attributed to carburetor icing between 1969 and 1975, and the actual number may be more than double that if engine failures for undetermined causes are considered. Efforts are expected to be underway shortly to better define carburetor icing conditions and to determine if fuel additives might be an effective solution, and this is to be encouraged. Development of a simple and inexpensive detection device would also be an appropriate project. A big part of the problem is that the onset of induction icing in general is insidious and may go unnoticed, particularly if the pilot is inexperienced and busy with other tasks.

CONCLUSIONS

In summary, there is a need for a great deal of work with respect to non-transport category icing operations and certifications. First, there is a need for definitions of the intensity of icing conditions which can be uniformly understood and applied. This author has made suggestions in that regard, (ref. 1), as shown in figure 5. These are envelopes of light, moderate, and severe icing conditions based upon NACA work (ref. 2). They are shown superimposed on the FAR 25 envelopes, and it is easily seen that there is considerable correspondence. However, the NACA envelopes have one characteristic which is totally lacking in the FAR 25 envelopes, namely that there exists a method of forecasting these icing conditions. There is a need for something other than the present all-or-nothing philosophy of icing certification to be applied to light airplanes. The NACA envelopes would provide such a possibility. Similar arguments have been made by other authors against the blanket imposition of Transport Category icing standards on helicopters, and other icing envelopes have been suggested. Such arguments and suggestions are expected to be heard at this workshop. At the very least, there should be the possibility of certificating ice protection provisions within an envelope of temperature and altitude appropriate to the limitations of specific aircraft. There exists a need for quantitative definitions of the intensity of icing conditions in terms of forecastable physical parameters. It was the consensus of the icing committee at the second annual workshop on Meterological Inputs to Aviation Systems at the University of Tennessee Space Institute in March of this year that icing forecasts are frequently inaccurate, resulting in needless groundings of both military and civil aircraft and in inadvertant icing encounters when no icing was forecast. Surely the solution to this problem has to begin with a consistently applied physical definition of what icing conditions are. In the regulatory area, there is a need for better understanding of the FAR 25 envelopes, and there is a need for consistency between the operating rules and the various National Weather Service and regulatory definitions. There is a need for quantitative instrumentation, even if only a passive probe of uniformly agreed upon size, to introduce objectivity into pilot reports of icing encounters. Better yet would be a simple and inexpensive liquid water content meter which could indicate to the pilot the intensity of the icing conditions being encountered. Such an instrument could also be used to display the operating limits of the particular aircraft, like many other aircraft instruments. There is a need for artificial icing test facilities, such as airborne tankers. There is a need for better definition and solutions to the induction icing problem. Finally, there is a need for data to determine what icing envelope or envelopes might be applicable to light aircraft and/or helicopters and for development and testing of methods of forecasting such conditions.

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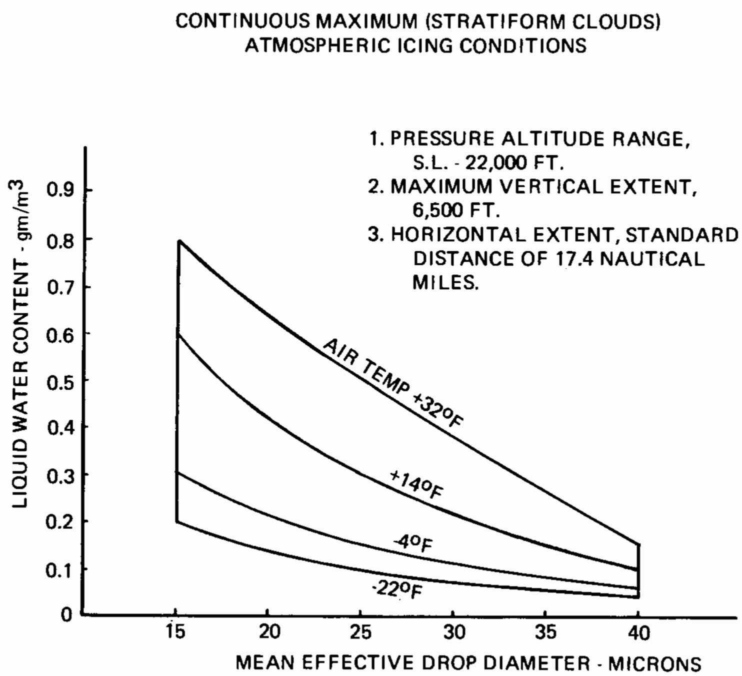

Figure 1.

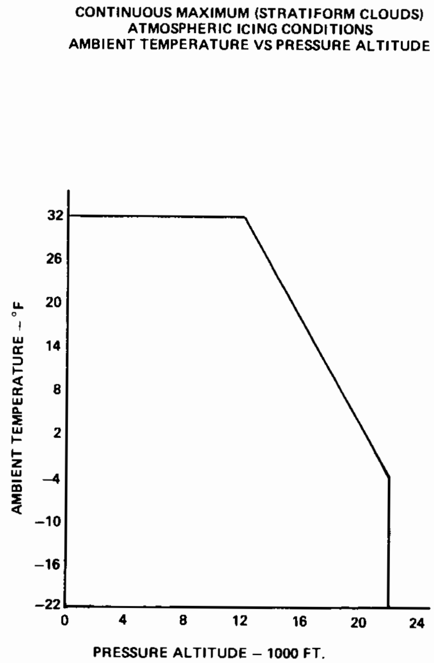

Figure 2.

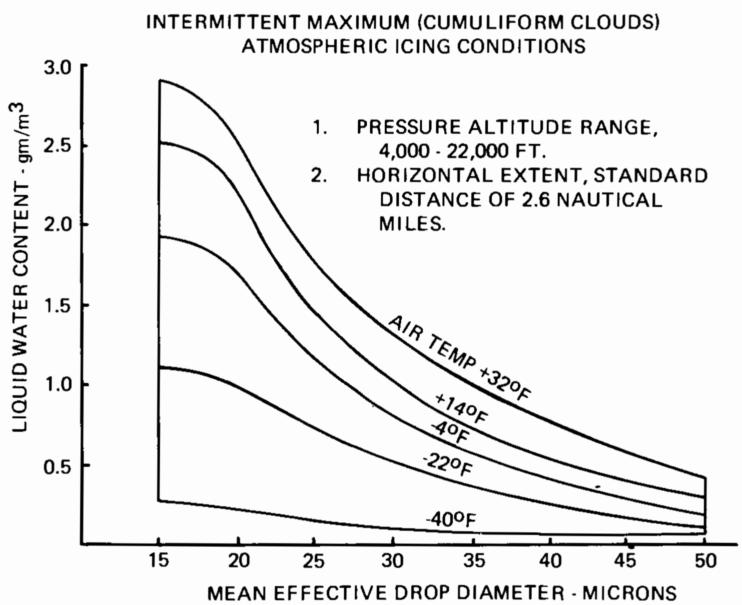

Figure 3.

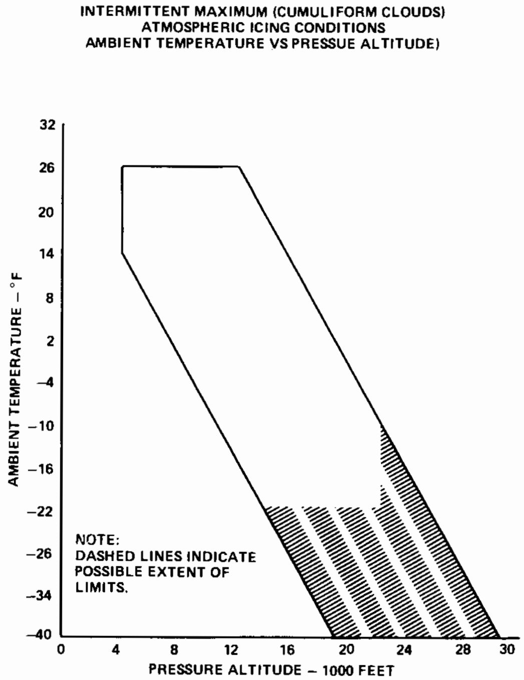

Figure 4.

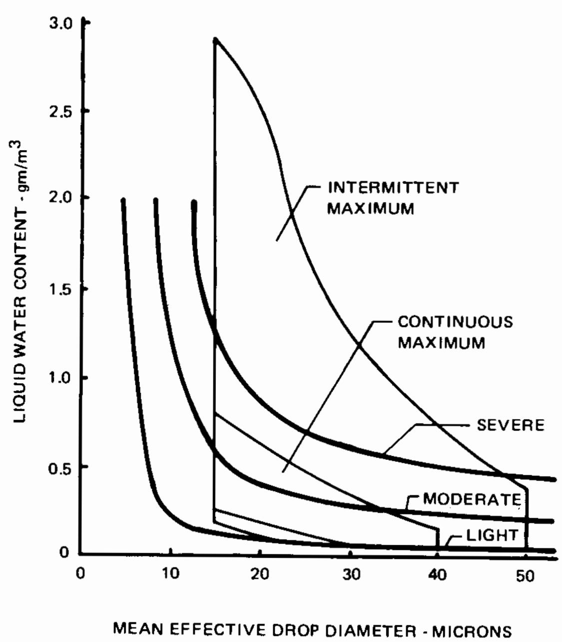

Figure 5.

OVERVIEW OF HELICOPTER ICE PROTECTION SYSTEM DEVELOPMENTS

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SUMMARY

Since 1973, the Applied Technology Laboratory (ATL) of the U.S. Army Research and Technology Laboratories (AVRADCOM) has had an ongoing research and development program intended to develop meteorological criteria for helicopter ice protection systems and to assure that technology would be available to meet future requirements. Helicopter ice protection design criteria have been developed and technology has been assessed. It was concluded that the major technological shortcoming in meeting future helicopter mission requirements was that of helicopter rotor blade ice protection. Airframe components could be adequately protected using existing technology. It was further concluded that the rotor blade could best be protected using the cyclic electrothermal deicing concept.

For R&D purposes a rotor ice protection system was developed for the UH-1 helicopter and subjected to flight testing. During this program, several other shortcomings in technology became apparent. Weight of the ice protection system was found to be objectionable to the operator. The ATL R&D program was expanded to identify and investigate rotor blade ice protection system concepts showing promise of providing lightweight, cost-effective rotor blade ice protection. Microwave, vibratory and ice phobic coating concepts have been assessed and R&D efforts have been planned for their development, but none currently shows promise of fulfilling the need within the next 3 to 4 years. The electrothermal concept remains the only viable concept for immediate application.

Other technological shortcomings have been identified that apply to all low-altitude, slow-flying aircraft, including the helicopter. These include lack of standardized meteorological design criteria; inaccuracy of icing forecasts; ambiguous icing definitions and terminology; lack of icing qualification/certification requirements that are meaningful and affordable; minimal facilities for economical development and certification; and, lack of testing techniques and instrumentation for development and certification purposes.

ATL has developed R&D programs for the future to resolve the basic issues, i.e., to provide a lightweight, cost-effective ice protection system for Army helicopters and a means for helicopters to have mission capability to include flight in icing conditions. This effort includes employment of the icing severity level indication system to supplement the icing forecast. The U.S. Army cannot provide the resources for resolution of other key issues. The cooperation of NASA, NOAA, and the FAA is needed and encouraged in order to resolve

the icing problem for civil as well as military low-altitude, slow-flying aircraft applications.

INTRODUCTION

In December 1977, the Applied Technology Laboratory hosted a coordination meeting between DA, NASA, and FAA to review the status of helicopter icing problems and related research and development programs. During that coordination meeting, the US Army representatives suggested specific areas of work to NASA and FAA representatives. These suggested R&D efforts are listed in Figures 1 and 2. This paper provides the rationale and basis for these suggested R&D efforts, and gives an overview of the ATL helicopter research and development program.

R&D PROGRAM OBJECTIVES

The objectives of the ATL R&D program are to establish accurate design and test criteria for helicopters and to assure that technology will be available to satisfy requirements (see Figure 3). As in any R&D program, where possible, our approach is to attain our objectives in a manner that will allow application of results to current helicopters.

METEOROLOGICAL DESIGN CRITERIA

Before we proceeded with technology developments, we wanted to ensure that any technology-related work was aimed at accurate design criteria. The results of this initial effort are shown in Figures 4, 5, and 6. First, design criteria were established for supercooled clouds. The upper curve (Figure 4.a.) relates the continuous maximum condition and the lower curve (Figure 4.b.) relates the intermittent maximum condition. These criteria are very similar to those in Appendix C of reference 1 (FAR 25) with the exception of the lower temperature limit, which goes to -22°F in FAR 25, and the upper liquid water content limit, which goes to 3 grams per cubic meter for the intermittent maximum condition. The criteria that we have developed for supercooled clouds are not as constraining, and we feel that they should not be as stringent for the Army helicopter as they are for aircraft that normally operate at higher altitudes. These criteria represent the 99th percentile of exceedance probability for altitudes up to 10,000 feet, the normal altitude range of Army helicopters. The right sides of these curves are annotated to relate the subjective terms (trace, light, moderate, and heavy) to liquid water content ranges. It is suggested that the subjective terms be dropped altogether; however, this relationship is based upon our best judgment of what these terms should mean. Design criteria for snowfall and freezing rain, developed under our program, are shown in Figures 5 and 6.

Once confidence was gained that adequate meteorological design criteria for helicopter ice protection systems had been defined, technology assessments were performed. These assessments concluded that technology was basically in hand to satisfy the ice protection requirements of all helicopter components except rotor blades. Therefore, the ATL effort was concentrated in that area. Figure 7 lists the various concepts examined for rotor blade ice protection. Results of analyses of these various concepts concluded that the electrothermal, cyclic deicing concept showed the most promise of satisfactorily meeting the needs. We selected the spanwise shedding concept for development and flight-test purposes.

THE TEST HELICOPTER

Figure 8 shows a two-view drawing of the resulting research helicopter. This icing research helicopter is equipped with ice-protected main and tail rotor blades, using the spanwise shedding concept developed under our program; heated glass windshields; a modified FM whip antenna; two experimental ice detectors that provide signals for control of the rotor ice protection system and for cockpit display of cloud liquid water content; an anti-iced main rotor stabilizer bar; and, a complete flight-test instrumentation system. The instrumentation system includes a hub-mounted camera for photographic coverage of ice accumulations, shedding and runback, and an integrating rate unit (IRU) that integrates liquid water content as a function of time to allow very precise natural icing severity level envelope expansion.

Figure 9 is a photograph of the test helicopter hovering in the Ottawa Spray Rig.

Figure 10 is a photograph of the Sikorsky BLACK HAWK under simulated icing tests behind the US Army Aviation Engineering Flight Activity (USAAEFA) Helicopter Icing Spray System (HISS). This is a CH-47 modified to incorporate a 2500-gallon water tank and a retractable spray boom. Our experimental UH-1H used the HISS for simulated icing tests in the forward flight regime.

FLIGHT-TEST OBJECTIVES

The objectives of our flight-test program are outlined in Figure 11 and include the following: to demonstrate the feasibility of the spanwise shedding concept over the range of design criteria under both simulated and natural icing conditions; to explore the effects of ice accretion and shedding on vibration, loads, performance, stability, and control; to explore the criticality of system control parameters (energy on-time, power density, and the ice detector function); to explore the effects of the engine exhaust with and without the IR suppressor, upon tail rotor heating; to explore the icing characteristics of unprotected components of the helicopter; and, to explore the effects of rotor blade ice protection system failure, incomplete shedding and runback. Further objectives were to establish a correlation between simulated and natural icing test techniques and to ultimately develop an icing research test-bed helicopter.

Figure 12 shows a breakdown of the flight-test hours accumulated to date. A total of 78 hours of productive flight-test time has been obtained including airworthiness testing conducted in 1975, HISS testing conducted at Moses Lake, Washington, in March 1975, Ottawa Spray Rig testing conducted in 1976, and natural icing tests combined with additional Ottawa Spray Rig tests conducted in 1977 and 1978.

Figure 13 shows the various test points that were obtained during the flight-test program. This is a cross plot of the design criteria presented in Figure 4 for supercooled clouds holding droplet size constant at 15 microns. For that droplet size, liquid water content is plotted versus ambient temperature. The natural icing test points obtained to date are included.

Some of the basic results of the studies performed earlier in the program are listed on Figure 14. Because of the estimated weight penalty for existing helicopters, the Army users have been reluctant to state a solid requirement for ice protection on existing helicopters. For example, the estimated weight for equipping the UH-1H with complete ice protection, made in 1974, was 165 pounds. This would mean off-loading one troop from the troop transport mission. Because of this, we began looking for other, lighter weight concepts for rotor blade ice protection. A list of the concepts assessed to date is shown in Figure 15. Each of these concepts shows promise for cost-effective application. A brief description of each of these concepts follows.

ADVANCED ROTOR BLADE ICE PROTECTION CONCEPTS

Microwave Concept

Figure 16 presents a schematic showing how the microwave concept may be applied to rotor blades. Details of the concept are contained in references 2 and 3. Figure 17 compares the microwave concept to the electrothermal concept. From this figure, it is apparent that the microwave concept offers several advantages such as reduced weight, cost, and power. In addition, work performed to date indicates that ice detection is inherent in the concept. Complexity of the system is somewhat reduced and detectability is reduced. Areas of concern remain, however. The effectiveness of the concept has been demonstrated during laboratory tests but actual full-scale demonstrations are necessary to assure that laboratory results are valid. Reliability of oscillators is questionable, maintainability objectives may require a greater level of skill than now exists in Army organizations, and the durability of the leading-edge erosion shield which is also a surface wave guide is expected to be poor. The most significant concern is that the time required to develop the microwave concept for application is estimated to be 7 to 8 years.

The next step planned in the development of this concept includes full-scale icing tunnel tests of the concept applied to a small helicopter tail rotor blade. This step is believed to be necessary to assure that the concept can be physically applied to dynamic components to verify laboratory test results in the dynamic environment.

Vibratory Concept

Figure 18 compares the vibratory concept to the electrothermal concept. Weight, cost, and power requirements are shown to be less, and other advantages are listed. The concept and its features are described in reference 4. Laboratory experiments have demonstrated that the vibratory concept will cause blade ice to shed, but these tests were not conducted in a manner that conclusively proves that ice will shed in a symmetrical manner or under all environmental conditions. The major area of concern is the effect of induced blade modal shapes and resulting structural loads on blade fatigue life. Analyses performed to date indicate that it is possible, with certain blade and shaker designs, to avoid severe fatigue damage. The effect of the induced vibration upon the structural integrity of other airframe and dynamic components also remains an area of concern.

The next step planned in the development of the vibratory concept includes full-scale flight testing to assure that analytical assessments are correct, to allow experimentation with mode shapes, and then to demonstrate deicing effectiveness. The development time is estimated to be 3 to 4 years.

Electro-Impulse (EI) Concept

A schematic of the EI concept is shown in Figure 19. This concept was pioneered in the USSR and some flight testing on fixed-wing aircraft was performed. The US Army has not actively pursued this concept; but based upon available information that is proprietary to the Lockheed-California Company and to Bell Helicopter Textron, the concept is not considered viable for rotor blade ice protection. This concept is compared with the electrothermal concept in Figure 20. Although the power requirements of the EI concept are very small, other features are not as attractive. The major concern is the complexity and weight of the EI concept for rotor blade ice protection. The concept may provide lightweight, cost-effective protection of thin skin leading edges; however, conventional rotor blades, which contain massive leading edges for structural and dynamic purposes, defeat the advantages of the concept.

Pneumatic Concept

During the original assessment of various rotor blade ice protection concepts conducted by the Lockheed-California Company, the pneumatic concept was rejected for several reasons. Details of the assessment are contained in reference 5; however, the primary concern was material technology that would allow construction of pneumatic boots that could withstand the dynamic environment of the helicopter rotor blade. Since then, the B.F. Goodrich Company has further investigated materials and techniques of pneumatic boot manufacture and has conducted limited testing. Details of the B.F. Goodrich effort are proprietary; however, results in general indicate that it may be possible to develop the pneumatic boot concept for rotor blade ice protection.

A schematic diagram of the pneumatic system applied to a UH-1H helicopter is shown in Figure 21. B.F. Goodrich estimates that the system would weigh approximately 30 pounds (43% of the electrothermal system weight) and could easily be applied to existing rotor blades and that cost would be much less than that for the electrothermal concept. Many questions must be answered before this concept can once again be considered viable; however, based upon limited testing conducted to date by B.F. Goodrich, further investigation would be appropriate.

Ice Phobic Coatings

We have managed to take another look at ice phobic coatings, and I would like to summarize this effort. Reference 6 describes an effort conducted jointly by NASA-Lewis Research Center and FAA National Aviation Facility Experimental Center (NAFEC) in which tunnel assessment of over 100 candidate ice phobic coatings was made. None of the coatings was found to be suitable for aircraft applications, although many were found to reduce adhesion force of ice to the test sample. These tests were conducted in the NASA-Lewis icing tunnel. In 1974, ATL decided that since the time frame of the NASA-FAA test program, other substances might be available that could reduce adhesion force sufficiently for application to helicopter rotor blades. We issued an advertisement in "Commerce Business Daily" and received approximately 20 replies. Of the replies received, six substances were selected for laboratory test. Two of the samples had been tested previously during the NASA-FAA program. These test samples were selected because the adhesion force of these substances was found to be low and correlation between our test technique and the NASA-FAA test technique was needed.

The results of testing conducted by the US Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, for ATL are shown in Figure 22. This plots the average shear force required to dislodge the ice from the test sample versus successive or repeated ablation tests. As can be seen, most of the substances produce very erratic results and the adhesion force is fairly high. The curve on the right side of the chart is the baseline, uncoated test sample. Two coatings,showed very low adhesion force repeatedly, as can be seen on the left side of the chart. This was true until the test samples were subjected to simulated rain tests, after which the adhesion force increased to the baseline value. These results indicated that in the supercooled cloud environment, these coatings may have sufficient life to provide rotor blade protection. During the 1977-1978 winter test season, very limited flight-test experiments to obtain data on the life and application techniques were conducted. These flight tests were conducted for ATL by USAAEFA from the Spokane International Airport, Washington, and were completed in mid-February 1978.

Two coatings were tested: a silicone grease manufactured by the GE Silicone Products Division, Waterford, New York, and a silicone oil manufactured by the Dow Chemical Company, Midland, Michigan. Both coatings showed promise, but the life of the Dow substance appeared to be longer. Figure 23 shows the life of the Dow substance under the flight-test conditions. Detailed test procedures and test results are contained in reference 7.

Figure 23 shows that the Dow coating lasted up to 1 hour 17 minutes under the test conditions. For comparison purposes, the Army almost lost a UH-1H during HISS testing in Alaska in 1974. On that occasion, the UH-1H had been in the cloud at liquid water content (LWC) of 0.25 gm/m^3 at -10°C for 22 minutes when most of the ice on one blade shed asymmetrically, causing very severe vibration and extreme difficulty on the part of the crew to recover and land the aircraft. The Dow coating, under the same test conditions, performed as an ice phobic coating. A mild asymmetric shed was observed after 40 minutes at -10°C and 0.5 gm/m^3 and the torque pressure limit of 5 psi (imposed for flight-safety reasons) was reached in 13 minutes at -15°C.

It must be emphasized that these tests were of very limited scope, but the results to date indicate that ice phobics show promise for application to rotor blades and may provide at least a limited capability for flight in icing conditions where the LWC is less than 0.5 gm/m^3 and the ambient temperature is no lower than -10°C. More testing is needed to determine the effects of rain, snow, dust, and other factors on coating performance. A program has been planned for further ice phobic coating development and for fielding kits for operational evaluation. It is strongly emphasized that ice phobic coatings are not expected to provide ice protection over the full range of meteorological design criteria.

CONCLUDING REMARKS

The ATL helicopter ice protection R&D program has established adequate meteorological design criteria for use in the design and certification of helicopter ice protection systems. These criteria should be applicable to other low-altitude, slow-flying (fixed-wing) aircraft. Areas of lagging technology have been identified and R&D efforts have been initiated to reduce the shortcomings. The ATL R&D effort has led to the implementation of a product improvement program to incorporate a partial ice protection system for the UH-1H helicopter. This system will include anti-iced windshields, an icing severity level indication system for cockpit display of cloud liquid water content and outside air temperature, a modified FM whip antenna to preclude antenna damage in the icing environment, and, an alternating current electrical system capable of providing electrical power needs of the partial ice protection system as well as rotor system ice protection if it is included at a later date.

The ATL R&D program has identified the need for improved icing forecasts and simplification of icing terminology and definitions. This subject is addressed in detail in reference 8.

During the R&D program to date, ATL has gained insight into the problems of ice protection system design, test, certification, and operations. Also, an icing research test-bed helicopter has been developed for further research of the icing environment and for icing flight-test evaluation of other subsystem components and instrumentation.

Figure 24 provides a listing of additional icing R&D needs identified to date. Although the meteorological design criteria developed by ATL are considered to be adequate for the Army helicopter, it is considered appropriate for NASA and FAA to verify that these criteria are applicable to civil helicopters and other low-altitude, slow-flying aircraft such as the fixed-wing, general aviation, light aircraft. There is a need for improved icing forecasts, not only for military use, but for civil use as well. To facilitate use of the improved icing forecasts, they must be provided in terms that relate the cloud parameters, i.e., LWC and outside air temperature (OAT). To supplement icing forecasts, the US Army is using icing severity level indication systems. Such systems, which consist of a cockpit display of cloud LWC and OAT, are being incorporated in the UH-1, AAH, and BLACK HAWK designs. There also appears to be a need for additional meteorological data, especially at altitudes below 1500 feet, to confirm design criteria and to improve forecasting accuracy.

Icing qualification/certification requirements for low-altitude/slow-flying aircraft, including the helicopter, are currently based upon the requirements of FAR 25 (ref 1). Based upon the design criteria established by ATL, the FAR 25 requirements seem excessive for the low-altitude/slow-flying aircraft. R&D is needed to confirm that the ATL-developed design criteria apply to low-altitude, slow-flying aircraft and to revise the icing qualification/certification requirements for these aircraft.

ATL has determined that reliance upon natural icing conditions for certification purposes is too costly and time consuming. This applies to military as well as civilian helicopters and low-altitude, slow-flying aircraft. The only solution to this problem is to develop icing simulation facilities for certification as well as R&D purposes. More and larger icing wind tunnels are needed, and ground-based simulators such as the Ottawa Spray Rig and airborne simulators such as the Army HISS need to be improved to provide better simulation of cloud droplet size, larger clouds, and more test endurance. Improvements are also needed to allow accurate measurement of the icing parameters, including OAT, LWC, droplet size, ice crystal content, and to allow in-flight documentation of ice formations.

There is a pressing need to develop advanced concepts for rotor blade ice protection to provide military and civil operators a cost-effective, lightweight means of protecting the rotor blade. Finally, operational experience is needed, as soon as possible, to assure that the concepts being fielded will be beneficial to the user.

Figure 25 presents, in bar chart form, ATL research and development plans to satisfy Army needs of the future. The darkened bars indicate funded plans, while the open bars indicate unfunded plans. As can be seen from this chart, funding is not currently programmed for development of the advanced rotor blade ice protection concepts. Fiscal Year 1980 (FY80) is totally unfunded. Our emphasis, with the minimal available funding, is upon providing a limited operational capability for the UH-1H under icing conditions and attempting to develop and field ice phobic coatings to extend the operational limitations of the UH-1H and possibly other existing helicopters. We do hope that as a result of the research and development, the ultimate outcome will be the establishment of a design guide for helicopter ice protection systems. This design guide would apply to civil as well as military helicopters.

RECOMMENDATIONS

The aircraft icing problem was laid to rest in the late 1950's. This was due to the introduction of high performance jet aircraft and the extensive research performed by NASA during that era. The recent upsurge of the helicopter and other low-altitude, slow-flying aircraft has renewed the need for additional research. Many areas of research and development have been identified and several changes in forecasting, terminology, certification requirements, methodology, and operational procedures are necessary. It is strongly recommended that all agencies of the US Government having responsibility in this important area must develop a unified plan and secure funding to accomplish the research and development objectives. Other nations within the NATO alliance have similar objectives. The United Kingdom has developed a similar plan and is unilaterally embarking upon the objectives of that plan.

The US Government plan must be coordinated with interested NATO nations and agreements reached on which nations will accomplish various tasks independently or collectively. The US Government must then determine tasks to be accomplished by various agencies independently or collectively. To achieve this goal will require a small ad hoc group, consisting of representatives from DOD, NASA, DOT, and NOAA, to develop, coordinate, and administer the plan.

It is recommended that by this means the aircraft icing problem may once again be laid to rest in a cost-effective and timely manner.

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5. Werner, J. B.: Ice Protection Investigation for Advanced Rotary-Wing Aircraft. USAAMRDL-TR-77-38, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, August 1973.

6. Millar, D. M.: Investigation of Ice Accretion Characteristics of Hydrophobic Materials. FAA-DS-70-11, Federal Aviation Administration, National Aviation Facilities Experimental Center, Atlantic City, New Jersey, May 1970.

7. Tulloch, J. S.; Smith, R. B.; Doten, F. S.; and Bishop, J. A.: Artificial Icing Test Ice Phobic Coatings on UH-1H Helicopter Rotor Blades. USAAEFA Project No. 77-30, U.S. Army Aviation Engineering Flight Activity, Edwards Air Force Base, California, June 1978.

8. Adams, Richard I.: An Assessment of Icing Definitions. Presented at U.S. Army Training and Doctrine Command, Seminar on Helicopter Ice Protection, Fort Rucker, Alabama, Feb. 3, 1977.

SUGGESTED NASA R&D

- IMPROVED ICING TEST FACILITIES
  - ICING TUNNELS
  - GROUND BASED SIMULATION FACILITIES
    - COORDINATE WITH CANADIAN NRC
  - AIRBORNE SIMULATION FACILITIES
    - DEVELOPMENT
    - OPERATION
    - MAINTENANCE
- PARTICIPATION IN ARMY PROGRAMS
  - FLIGHT TESTS
  - INSTRUMENTATION DEVELOPMENT
  - ICE PHOBIC COATING RESEARCH
- GENERAL DATA
  - LOW ALTITUDE DATA
  - MIXED CONDITION PHENOMENA

Figure 1.

SUGGESTED FAA EFFORTS

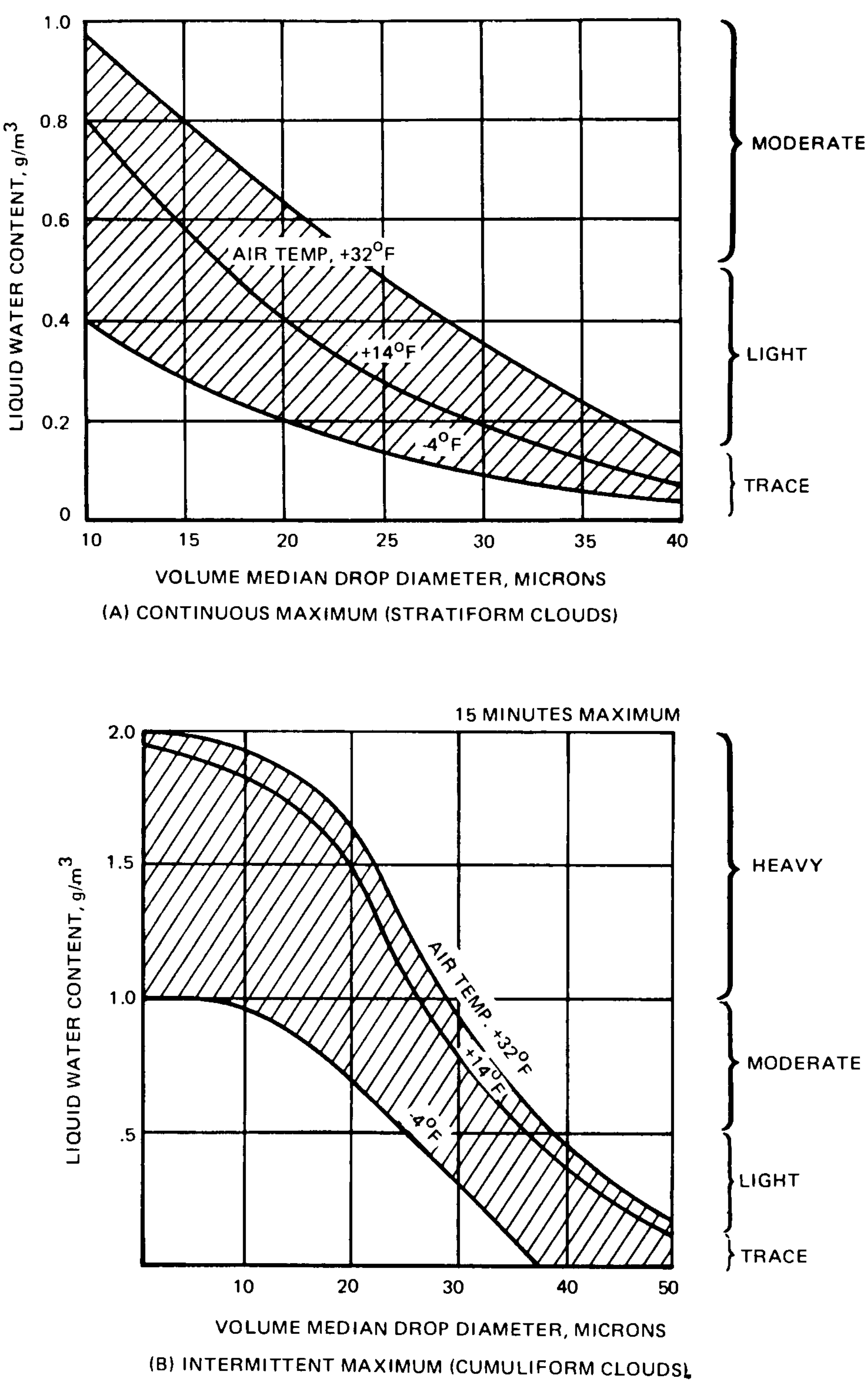
- ADOPT ARMY DESIGN CRITERIA
- COORDINATE/COFUND FACILITIES DEVELOPMENT
- DEFINE CERTIFICATION REQUIREMENTS
- DEFINE ACCEPTABLE CERTIFICATION PROCEDURES
- PARTICIPATE IN ARMY PROGRAMS
    - FLIGHT TEST
- REVISE FAR 25 AND RELATED REQUIREMENTS

Figure 2.

OBJECTIVES

- PRIMARY
    - ACCURATE DESIGN AND TEST CRITERIA FOR EACH FUTURE GENERATION ARMY VTOL AIRCRAFT
    - ASSURE TECHNOLOGY WILL BE AVAILABLE TO SATISFY REQUIREMENTS
- SECONDARY
    - TECHNOLOGY SPIN OFF APPLICABLE TO CURRENT FLEET

Figure 3.



Recommended Atmospheric Icing Criterion.

Figure 4.

FREEZING RAIN SEVERITY LEVELS - 99th PERCENTILE CONDITIONS

(WORLDWIDE)

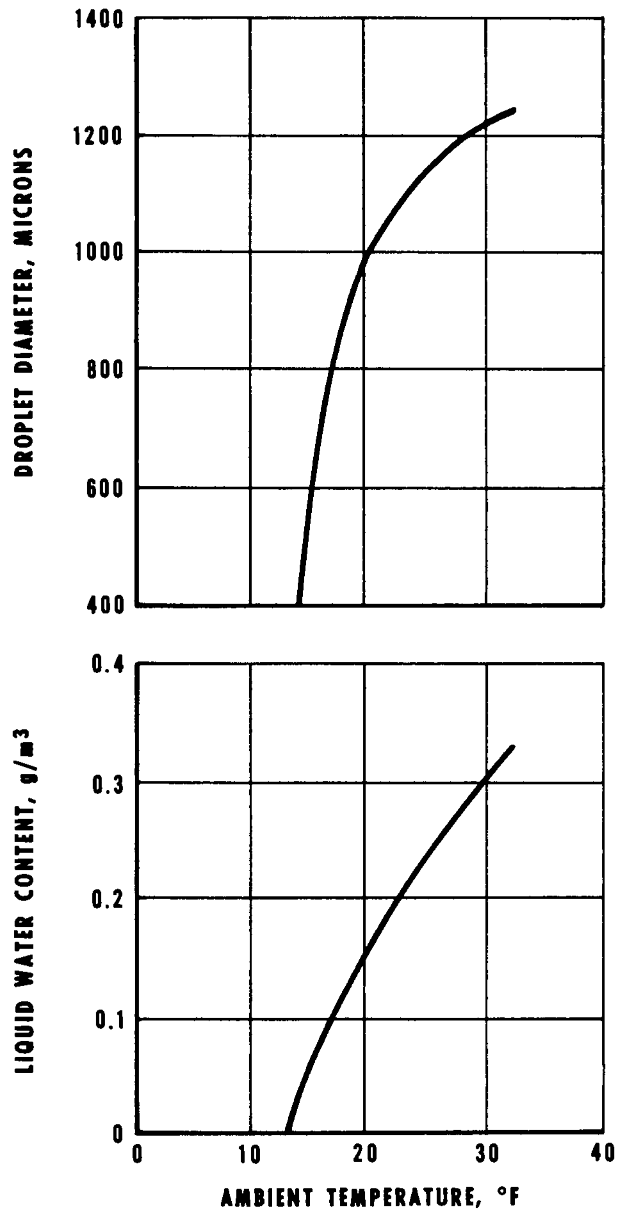


Figure 5.

WORLDWIDE MAXIMUM SNOWFALL LIQUID WATER CRITERIA - 99th PERCENTILE CONDITIONS.

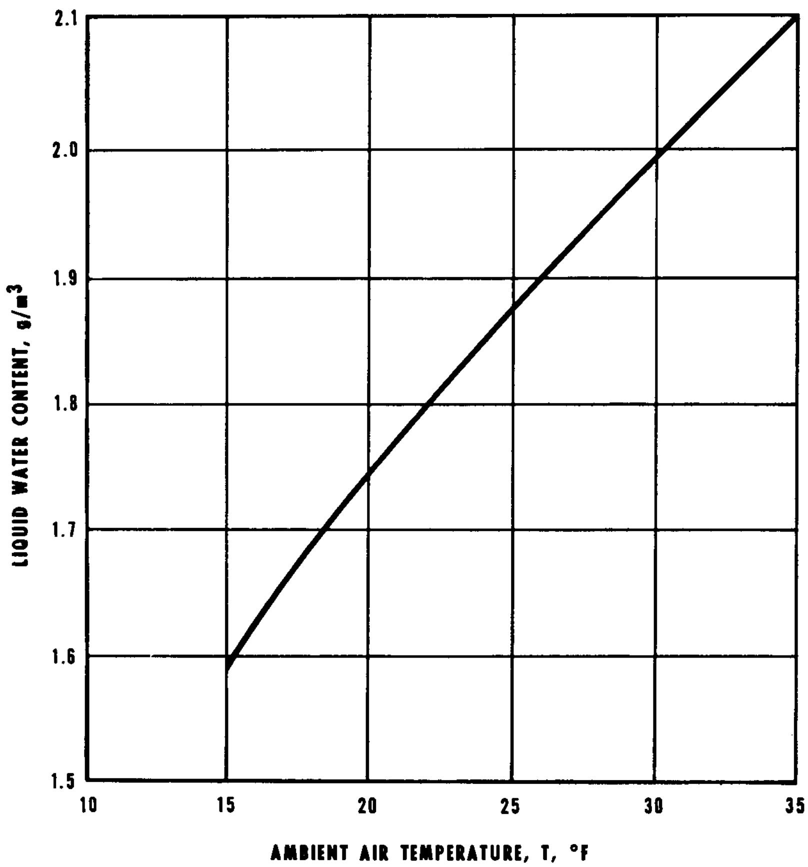


Figure 6.

BLADE ICE PROTECTION CONCEPTS

- **ELECTRO-THERMAL**
- **BLEED AIR**
- **HEATED LIQUID**
- **CHEMICAL FREEZING POINT DEPRESSANT**
- **MECHANICAL PNEUMATIC (BOOTS)**
- **ICE-PHOBIC MATERIALS**
- **ELECTRO IMPULSE**
- **SONIC PULSE**

Figure 7.

GENERAL ARRANGEMENT-UH-1H ICING R&D HELICOPTER

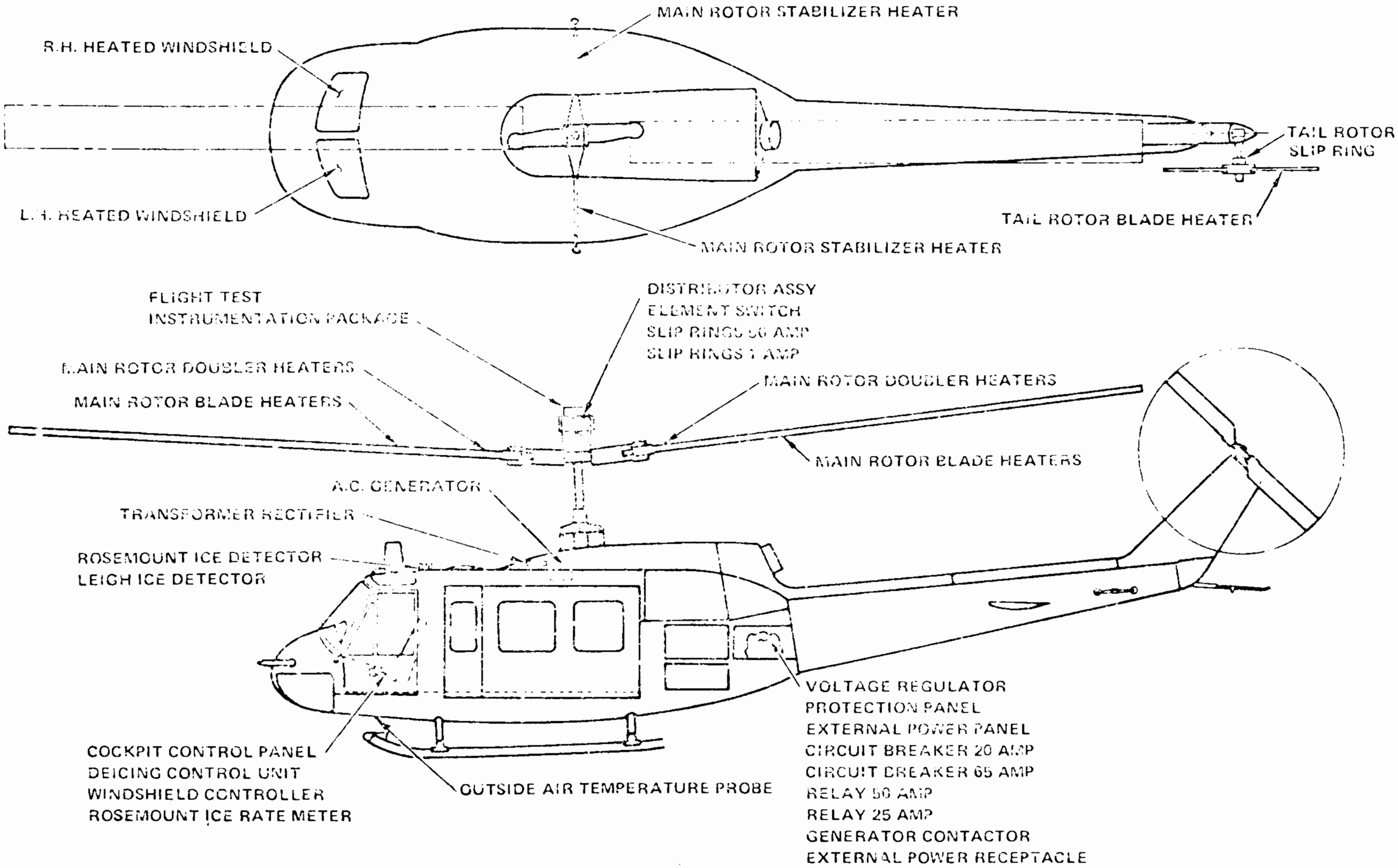


Figure 8.

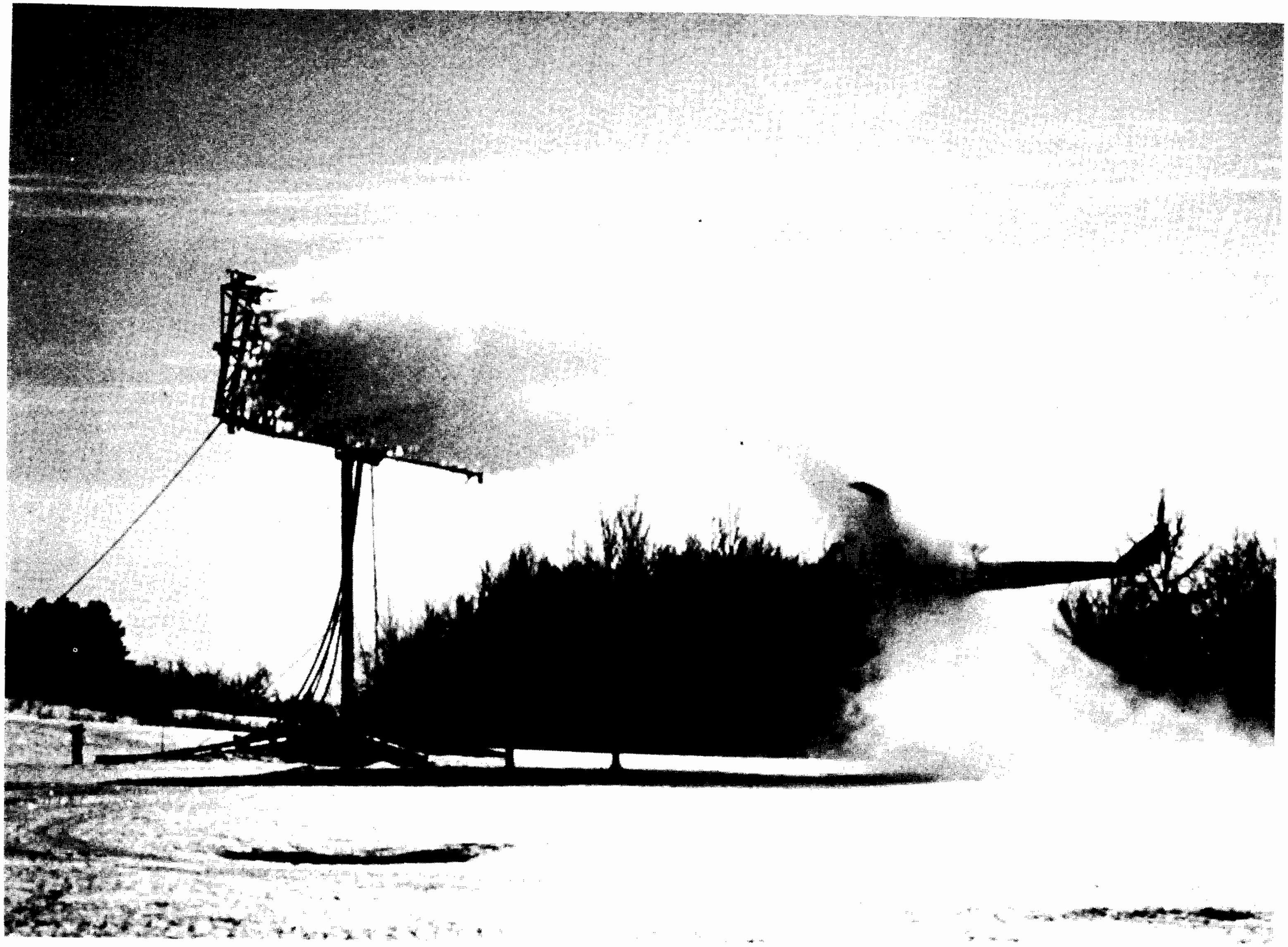


Figure 9.

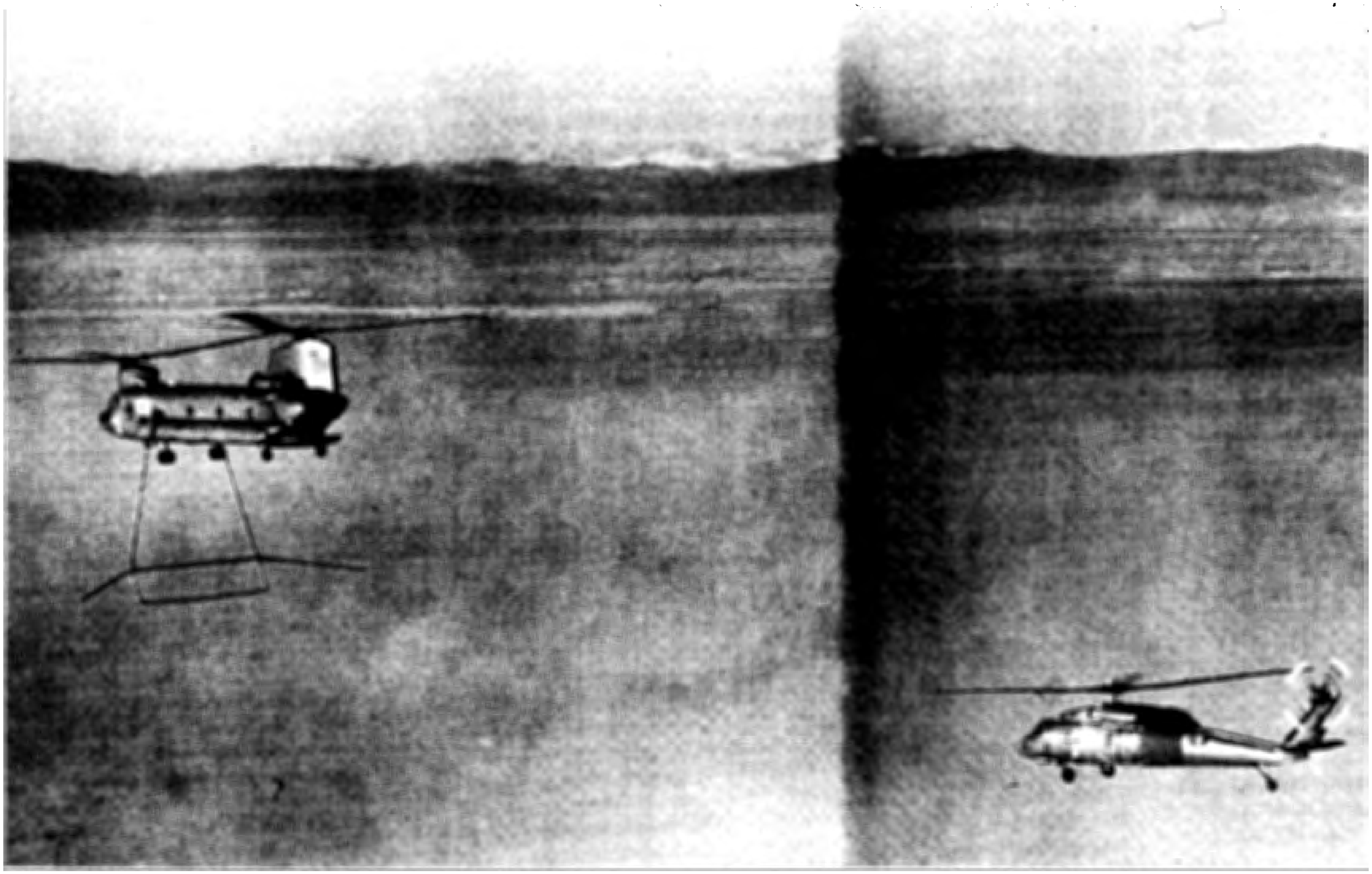


Figure 10.

UH-1H SIMULATED & NATURAL ICING TEST

OBJECTIVES

- **DEMONSTRATE ~ FEASIBILITY OF SPANWISE SHEDDING CONCEPT**
  - OVER RANGE OF DESIGN CRITERIA
  - UNDER SIMULATED & NATURAL ICING CONDITIONS
- **EXPLORE ~**
  - EFFECTS OF ICE ACCRETION & SHEDDING UPON
    - VIBRATION, LOADS
    - PERFORMANCE, STABILITY & CONTROL
  - SYSTEM CONTROL PARAMETER REQUIREMENTS
    - ON-TIME, OFF-TIME
    - POWER DENSITY
    - ICE DETECTOR FUNCTION
  - EFFECTS OF IR SUPPRESSOR
  - ICING CHARACTERISTICS OF UNPROTECTED COMPONENTS
  - EFFECTS OF SYSTEM FAILURE, INCOMPLETE SHED, RUNBACK
- **CORRELATE ~ SIMULATED & NATURAL ICING TEST RESULTS**
- **DEVELOP ~ AN ICING R&D TEST BED HELICOPTER**

Figure 11.

ICE PROTECTED UH-1H
FLIGHT TESTING SUMMARY

EVENT	HOURS	TESTS
GROUND TESTING	9.9	
AIRWORTHINESS FLIGHT TESTING	10.8	
HISS PRODUCTIVE	(15.8)	
HISS IN-CLOUD	2.7	
OTTAWA SPRAY RIG PRODUCTIVE	(39.4)	
OTTAWA SPRAY RIG IN-CLOUD	14.9	
NATURAL ICING PRODUCTIVE	(22.6)	
NATURAL ICING IN-CLOUD	9.3	
TOTAL PRODUCTIVE FLIGHT TIME	(77.8)	
TOTAL HISS TESTS		12
TOTAL OTTAWA SPRAY RIG TESTS		28
TOTAL NATURAL ICING SORTIES		21

Figure 12.

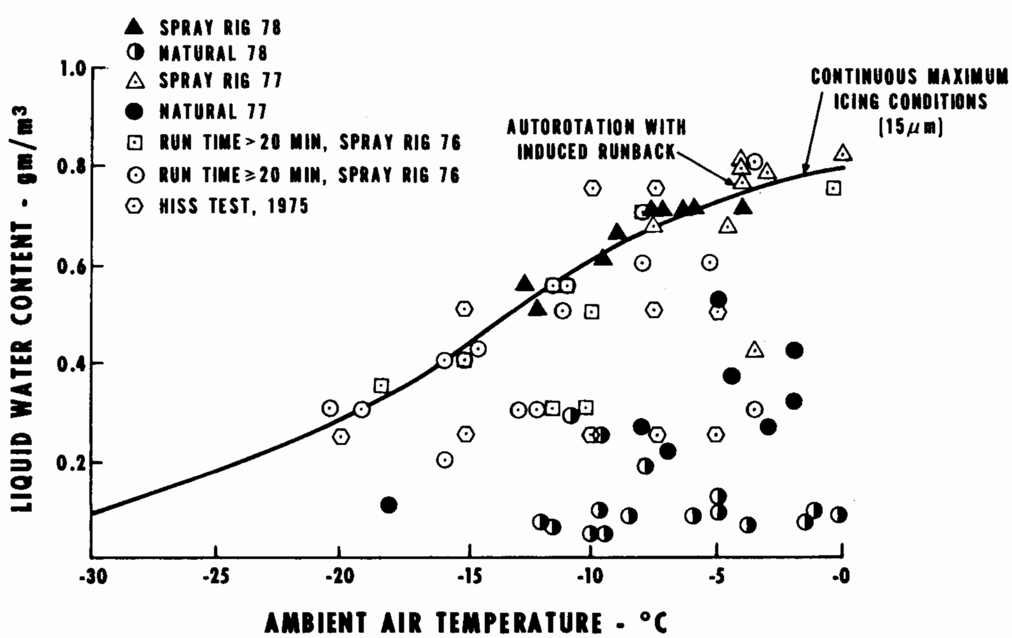


Figure 13.

ESTIMATED PENALTIES FOR HELICOPTER ICE PROTECTION

	EXISTING	FUTURE
• EMPTY WEIGHT	1% TO 6%	<1%
• ENGINE POWER (PEAK)	40-160 SHP	40-160 SHP
• RANGE REDUCTION	13 TO 34%	13 TO 34%
• RELIABILITY	AS HIGH AS BASIC HELICOPTER	
• MAINTAINABILITY	4MMH/1000FH	4MMH/1000FH

Figure 14.

OTHER BLADE ICE PROTECTION CONCEPTS IDENTIFIED NOT EVALUATED BY LOCKHEED

- MICRO WAVE
- VIBRATORY
- FLEXIBLE SUBSTRATE COATING
- RE EVALUATION OF ICE PHOBIC COATINGS

Figure 15.

MICROWAVE DEICER ROTOR BLADE CONCEPT

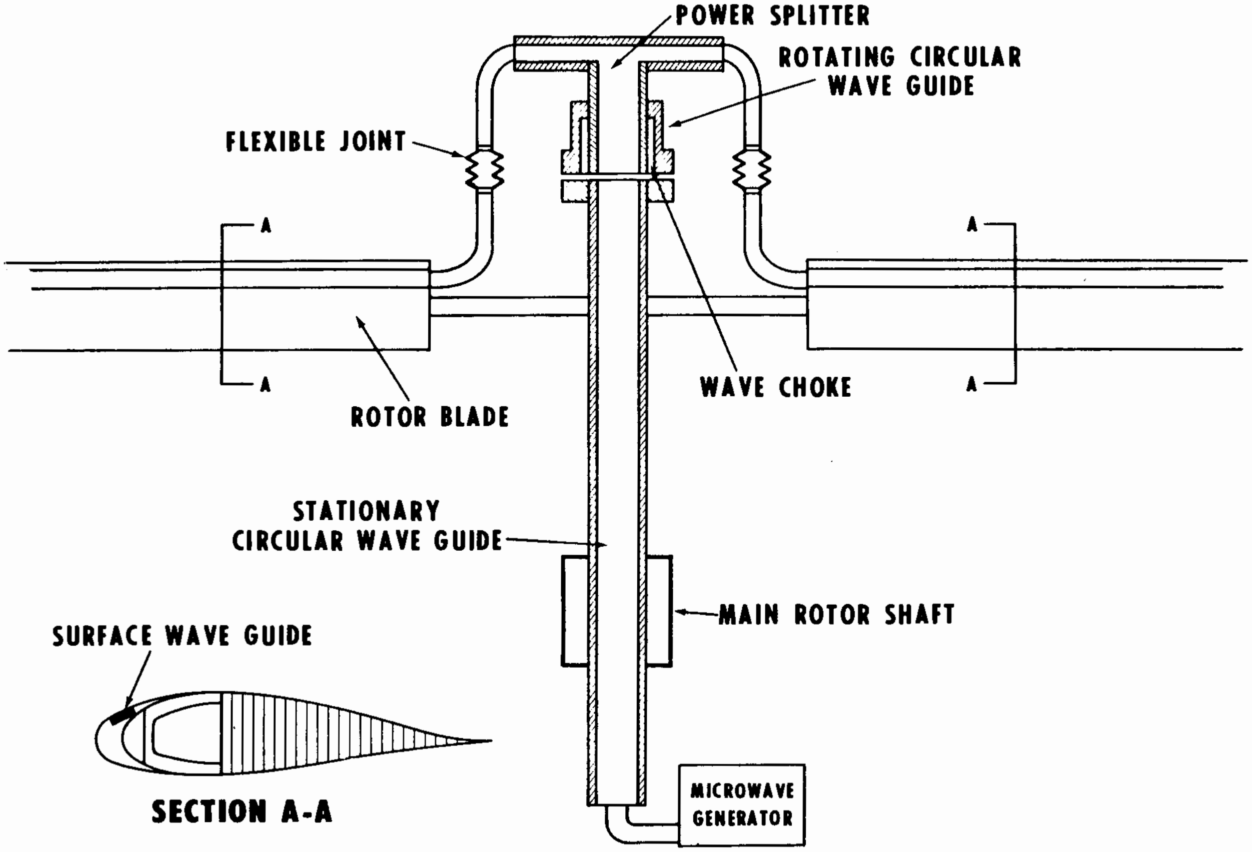


Figure 16.

MICROWAVE BLADE ICE PROTECTION CONCEPT

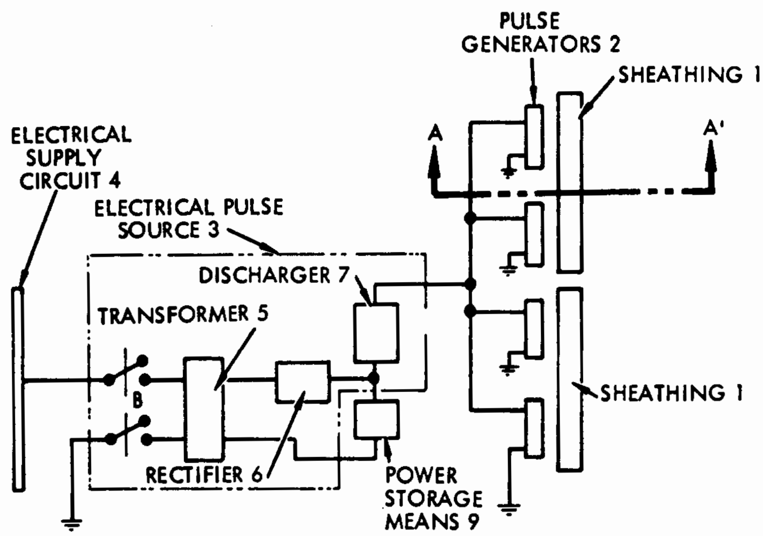
- **ADVANTAGES RELATIVE TO ELECTROTHERMAL**
  - POWER~80% LESS
  - WEIGHT~17 TO 36% LESS
  - ICE DETECTION~INHERENT
  - COMPLEXITY~CONTROL REQUIREMENTS REDUCED
  - COST~27% LESS
  - DETECTABILITY~DIELECTRIC MATERIAL
- **AREAS OF CONCERN/UNKNOWNS**
  - EFFECTIVENESS~LAB DEMO COMPLETE
  - RELIABILITY~OSCILLATORS~VACUUM TUBE
  - ADAPTABILITY~NEEDS PROOF
  - MAINTAINABILITY~GREATER LEVEL OF TRAINING
  - DURABILITY~EXPOSED SURFACE WAVE GUIDES
  - DEVELOPMENT~7 TO 8 YEARS

Figure 17.

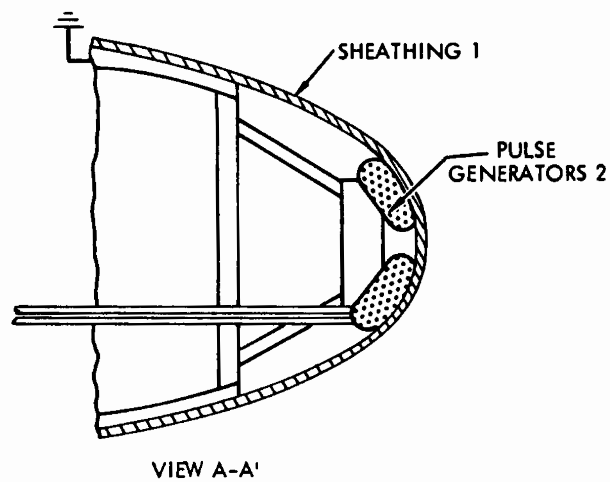
VIBRATORY ROTOR BLADE ICE PROTECTION CONCEPT

- **ADVANTAGES~RELATIVE TO ELECTROTHERMAL**
  - POWER~90% LESS
  - WEIGHT~3 TO 28% LESS
  - COMPLEXITY~VERY SIMPLE
  - ADAPTABILITY~SIMPLE MODS & KITS
  - COST~29% LESS
  - DETECTABILITY~REDUCED METALLIC AREA
  - R&M~POTENTIALLY HIGH
- **AREAS OF CONCERNS/UNKNOWNS**
  - VIBRATION EFFECTS
    - BLADE LIFE/DYNAMIC RESPONSE
    - HUB, TRANSMISSION & DYNAMIC COMPONENT LIFE
    - AIRFRAME, COMPONENTS, CREW
  - COMPLETE & SYMMETRICAL SHEDDING
  - DEVELOPMENT~3 TO 4 YEARS

Figure 18.



Electroimpulse Deicing-Electrical Schematic



Electroimpulse Deicing-Leading-Edge Arrangement

Figure 19.

ELECTRO-IMPULSE ROTOR BLADE DEICING CONCEPT

PENALTIES -- QUALITATIVE COMPARISION TO ELECTROTHERMAL

- POWER -- 1.0 KVA vs 13 KVA
- WEIGHT & COMPLEXITY
  - POTENTIALLY GREATER
- R&M -- POTENTIALLY LOWER
- COST -- POTENTIALLY HIGHER
- DETECTABILITY -- SAME

CONCERNS

- ADAPTABILITY -- THIN SKIN LEADING EDGE -- LOCATION OF COMPONENTS
- FATIGUE LIFE -- HIGH LOCAL STRESSES
- DEVELOPMENT TIME -- 7-8 yrs

Figure 20.

MAIN ROTOR APPLICATION
MECHANICAL-PNEUMATIC DEICER

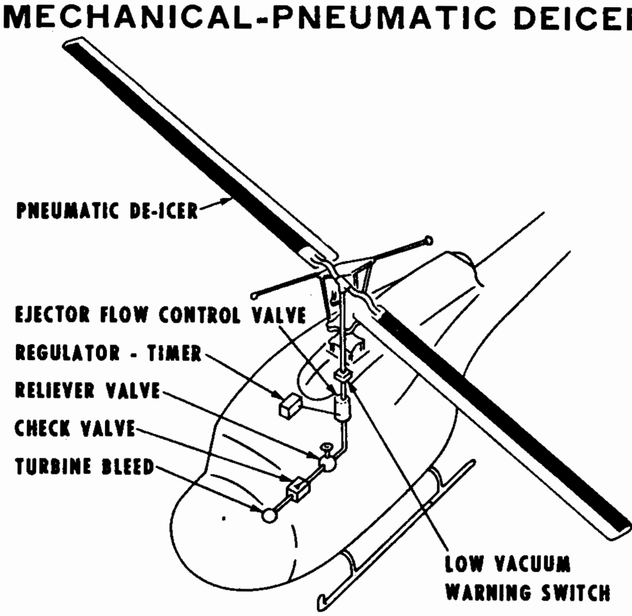


Figure 21.

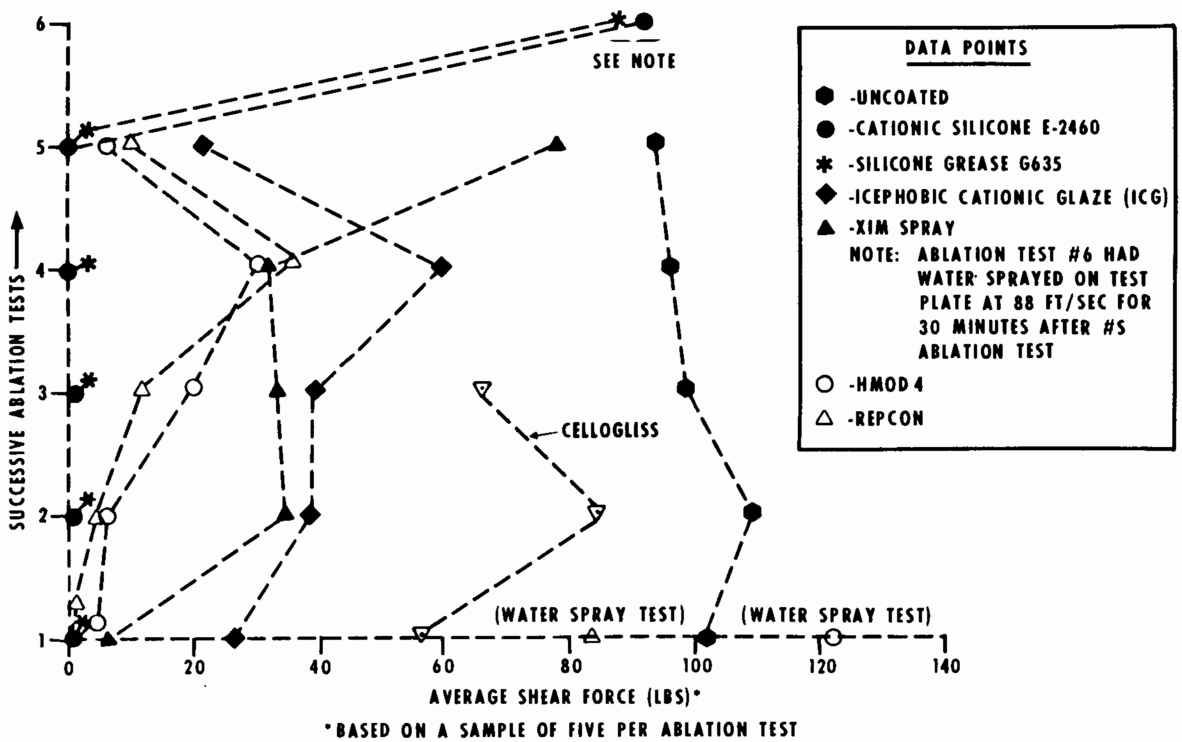


Figure 22.

AVRADCOM

ICE PHOBIC COATING FLIGHT TESTS

- Two Materials Tested (Jan-Feb '78)
- HISS/UH-1H Tests
- DOW E-2460 Most Effective
  - -5°C ; 0.25 g/m³ >79 minutes
  - -5°C ; 0.50 g/m³ >60 minutes
  - -10°C ; 0.25 g/m³ >77 minutes
  - -10°C ; 0.50 g/m³ 40 minutes (mild shed)
  - -15°C ; 0.25 g/m³ 13 minutes (torque limit)
- Effects of Rain, Snow, and Dust, etc. Unknown

Figure 23.

AIRCRAFT ICING R&D NEEDS

- METEOROLOGICAL DESIGN CRITERIA
  - LOW/SLOW FLYING AIRCRAFT
- FORECASTING
  - ACCURACY
  - TERMINOLOGY/DEFINITIONS
  - STATISTICAL DATA
  - COCKPIT DISPLAYS
- QUALIFICATION/CERTIFICATION REQUIREMENTS
  - LOW/SLOW FLYING AIRCRAFT
- FACILITIES DEVELOPMENT AND CERTIFICATION
  - ICING TUNNELS
  - GROUND-BASED SIMULATORS
  - AIRBORNE SIMULATORS
- INSTRUMENTATION
  - OAT, LWC, DROP SIZE, CRYSTAL CONTENT, PHOTO
- DEVELOPMENT OF ADVANCED CONCEPTS
- OPERATIONAL EVALUATIONS

Figure 24.

APPLIED TECHNOLOGY LABORATORY R&D PROGRAM

FUTURE PLANS AND FUNDING LIMITATIONS

Solid Bars = Funded Plans

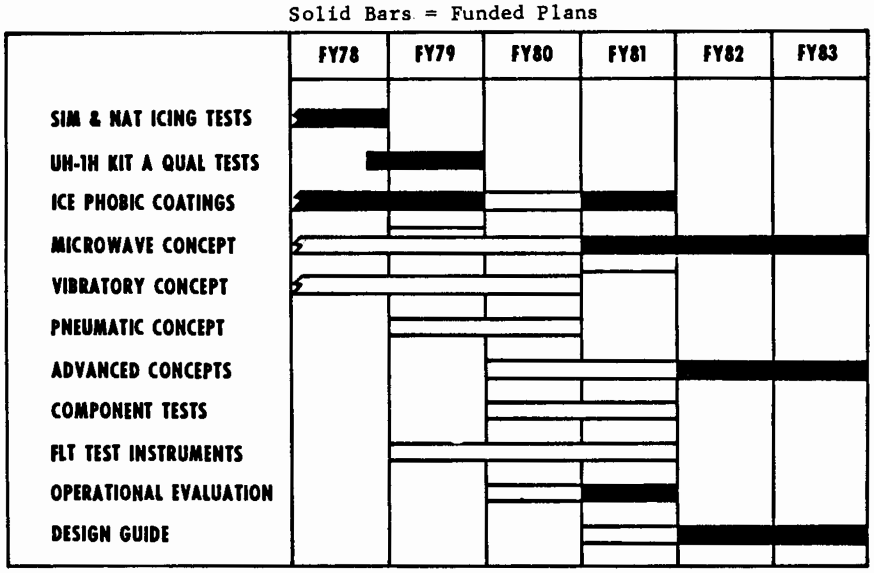


Figure 25.

GUIDELINES - METEOROLOGICAL RESEARCH COMMITTEE

Objective: To define requirements for investigations of the icing environment including:

a. Characterizing icing phenomena in terms of current design, certification, and operational requirements.

b. Describing measurable parameters of interest to forecasters, operators, and for icing simulation.

c. Describing meteorological research instrumentation needs.

Representative questions to be addressed:

1. Assess current understanding of icing meteorology. Is a "finer scale" definition of the icing environment necessary or possible?

2. Is our currently-available meteorology data-gathering capability adequate for all categories of aircraft design and operation (i.e., civil transport, general aviation, civil and military helicopters)?

3. What is our understanding of frost formation on aircraft lifting surfaces? Is it totally predictable?

4. What data-gathering equipment and sensors are currently available for icing meteorology measurements? Is this equipment adequate? practical? If not, what instrumentation R & D is required? Who should do it...government, industry, or both?

5. Can automated observations be devised which are practical and which could easily be transmitted to a forecast office or to flight service stations?

6. Can icing severity levels be better defined? What does severity depend upon?

7. How can the meteorology community work better with the research facilities and simulation community?

GUIDELINES - ICING FORECASTING COMMITTEE

Objective: To define the present capability levels in icing forecasting and information flow to the operator, to explore needs of the operational and design communities, to define additional meteorological research needs, and to identify additional data and instrument requirements for improving forecasting accuracy and reliability.

Representative questions to be addressed:

1. What improvements have accrued to the forecasting of icing in the past decade?
2. Are forecasting services and capabilities commensurate with present design capabilities and operational needs?
3. How accurate (in extent) and reliably can icing region boundaries and icing severity levels be forecast from today's observational network? What improvements could be made if measurement accuracies were improved, observation grid size decreased, and frequency of observations increased? What are the practical limits to such changes?
4. What new sensors, instruments, or analytical techniques should be developed to help the forecaster?
5. Can present satellite observations be practically used?
6. Can frost formation be reliably predicted?
7. What are the problems in predicting snow/rain lines and freezing levels? How reliably can the forecaster discriminate rime and clear icing probabilities?
8. Can research and simulation facilities sensors and instrumentation be of practical use for application to forecaster's observational and analytical needs?

GUIDELINES - SYSTEMS DEVELOPMENT COMMITTEE

Objective: To assess the adequacies of and deficiencies in icing knowledge as it pertains to:

a. Aircraft or helicopter ice-tolerant design,

b. Ice warning and protection systems design,

c. Certification and simulation,

d. Piston and jet engine design

with a view toward improving flight safety, confidence, and operational reliability in icing conditions.

Representative questions to be addressed:

1. What are the major design concerns in providing ice-tolerance?

2. How do the approaches to military and civil designs differ?

3. What shortcomings in meteorological information prevent more effective ice-tolerant vehicle designs or ice warning and protection system designs?

4. What simulation fidelity shortcomings hamper design and certification of vehicle and equipment?

5. Are icing forecast definitions compatible with equipment, engine, and vehicle design specifications?

6. How important is ice accumulation rate as a design factor? Is our knowledge of natural icing phenomena adequate to confidently bracket the range of ice rates likely to be encountered?

7. Is frost an important factor in takeoff and climb performance for large, wide-body (large wing chord) aircraft?

8. What is the outlook for practical icephobic surface treatment in airframe and engine applications?

9. Are ice protection additives or methods for fuels adequate? If not, what are the needs?

GUIDELINES - CIVIL OPERATIONS COMMITTEE

Objective: To define the icing environment of various civil flight operations including:

a. Scheduled Transport (Piston and Jet Engine)

b. Small Fixed Wing, Business and Personal (Piston and Jet Engine).

c. Helicopter Operations (Piston and Jet Engine)

with a view toward identifying achievable improvements in civil icing operational safety and dispatch reliability.

Representative questions to be addressed:

1. What types of operations require risking flight into icing conditions?
2. What is the impact of flight icing or overnight ramp frost accumulation on these operations (e.g., loss of revenue, customers, cancellations, delays, or diversions, etc.)?
3. What phase of operations seem most affected by ice (e.g., flight planning, flight, maintenance)? What design features or components appear to be most sensitive to ice (e.g., engine systems, airframe, sensors, rotors, etc.)?
4. Describe the range of adverse effects of ice (e.g., performance, handling qualities, ice buildup rates, etc.).
5. What are the problems with icing forecasts (e.g., geographical accuracy, icing intensity and extent, freezing levels, type of ice forecast vs that actually encountered, etc.)?
6. What should the minimum protection requirements be for various operations? For what types of ice or frost?
7. What are the relative merits of anti-icing, de-icing, ice detection and warning systems?
8. Is fuel icing a problem?
9. Is meteorological icing information available on a timely basis?

GUIDELINES - MILITARY OPERATIONS COMMITTEE

Objective: To define the icing environment of various military flight operations including:

a. Fixed and Rotary Wing (Piston and Jet Engine)

b. Low Level Flight

c. Search and Rescue

with a view towards identifying achievable improvements in ice-tolerant operations.

Representative questions to be addressed:

1. What is the impact on accident rates of missions requiring flight into icing conditions? Of what nature are the accident causes?

2. Are icing forecast definitions "fine" enough to depend upon for dispatch purposes (e.g., light, moderate, or heavy)?

3. What types of icing protection are acceptable or desirable for military missions? What are the drawbacks of present systems?

4. What types of icing present the most serious operational penalties? What components are most vulnerable (e.g., airframe, rotor, propeller, antenna, weapons, stores, etc.)?

5. What design features seem to present the most icing problems?

6. Describe the adverse effects of icing on performance, handling qualities, etc.

7. Is there prompt enough transmission of meteorological (forecast) information from the met office to the pilot? If not, why not?

8. Is fuel icing a problem?

GUIDELINES - ICING RESEARCH AND FACILITIES COMMITTEE

Objective: To define requirements for facilities, research techniques, and instrumentation including:

a. Dynamic and static ground test facilities

b. Airborne icing simulation facilities

c. Techniques for testing and obtaining credible data for design, certification, and operations purposes,

with a view towards establishing a basis of knowledge and understanding of the icing/equipment interface from which rational ice-tolerant design and operations may proceed.

Representative questions to be addressed:

1. With existing facilities, what do you consider to be the most significant type of icing work needed to support near term requirements for these categories of aircraft:
   a. Helicopters
   b. General Aviation
   c. Commercial Transport
   d. Military (Other than Helicopters)?

2. What are the major limitations of current icing test facilities (both ground and flight) in light of what will be your R & D needs for the next 10-15 years for the above categories of aircraft?

3. What capabilities would be required for new and better icing research facilities (size, expanded operational envelopes, etc.)?

4. What improved instrumentation and data acquisition and processing requirements will be needed?

5. Would the acquisition of new or improved test facilities require private investment or government funding?

6. Are mixed conditions (ice and super-cooled water) of sufficient importance that ground test facilities should be extended to duplicate this environment?

7. Is additional work needed for the verification of artificial ice shapes as compared to those occurring in natural icing conditions? Is additional work needed to assess the effect of scale on frost-limited performance (e.g., large wide-body jet large chord wings)?

8. How frequently must artificial icing test facilities be recalibrated to provide adequate user confidence?

9. Is the drop size limitation of existing ice test facilities a serious constraint or must the spray system range be extended?

10. What do you regard as an adequate calibration of an icing test facility?

11. What novel test techniques would be possible with non-intrusive measurement methods (e.g., laser-Doppler velocimeter, etc.)?

SUMMARY REPORT -

METEOROLOGICAL RESEARCH COMMITTEE

Helmut K. Weickmann
NOAA, ERL, Atmospheric Physics and Chemistry Laboratory

INTRODUCTION

It appears that most research on aircraft icing was accomplished during the 1940's and 1950's. As a consequence of this work, de-icing equipment was designed and installed preferentially in high performance passenger aircraft. With this, the icing problem appeared to be solved. Private aircraft, however, are usually not equipped with de-icing equipment and the increase of their number has increased the number of icing incidents. Also, helicopters are being flown in all weather conditions, but their vulnerability to icing has so far effectively prevented them to become all-weather-flying machines.

It so appears that a new look at the problem of aircraft icing is urgently needed. It was the consensus of the group that a "finer scale" definition of the icing environment is definitely necessary since the presently used icing climatology is designed for long-range high performance aircraft, while most private aircraft, certain military types and helicopters require information which is more detailed in time and space.

We have identified essentially five areas which require attention:

1. Icing cloud environment.

2. Icing climatology

3. The role of the Meteorologist

4. Shape, hardness and opacity of natural ice deposits in dependence of the supercooled or solid hydrometeors.

5. Vulnerability of distinct aircraft types, e.g. helicopters, private one-engine type aircraft, special military airplanes, in icing conditions.

DISCUSSION

1. The Icing Cloud Environment

It is very important to have accurate data of the conditions in supercooled clouds, such as numbers and sizes of supercooled cloud drops, of supercooled liquid cloud and precipitation water content and of the existence of snowfall together with supercooled clouds. Some of these cloud data may vary considerably for identical cloud types from location to location; for instance, the drop size will depend on the number of available cloud condensation nuclei (CCN), which in turn depends on whether the cloud is continental or maritime or whether it forms in a polluted or non-polluted atmosphere. Since the role of the cloud droplet size on the icing characteristics is not quite clear, additional laboratory research is warranted. This must be accomplished before a much needed refined icing climatology can be obtained.

In the appendix, we show unpublished measurements of cloud elements--droplet radii, visibility, liquid water content, droplet concentration per cc--for cumulus humilis, cumulus and cumulonimbus in New Jersey (Plate I, droplet spectrum 1-8; Plate II, droplet spectrum 9-12), for cumulus congestus and cumulonimbus over Florida and the Gulf of Mexico (Plate II, droplet spectrum 13-16; Plate III, droplet spectrum 17-24; Plate IV, droplet spectrum 25-32; Plate V, droplet spectrum 33-34), and of stratus and stratocumulus over New York State (Plate VI).

Only the latter data were taken under supercooled conditions, the former are all taken at temperatures above freezing. There is, however, no reason to assume that the droplet sizes and concentrations are much different in the supercooled part of the clouds, except at low temperatures, say below -20°C; where ice crystals become more numerous and the droplets begin to evaporate. These spectra show a number of typical and important characteristics: The droplet concentration of continental clouds and over polluted New Jersey are considerably higher than over the maritime air of Florida and the Gulf of Mexico. It is also interesting to note that the droplet concentrations and the liquid cloud water contents measured in New Jersey in cumulonimbus clouds agree with those of the cumulonimbus clouds of Florida in spite of the apparently higher number of CCN's over New Jersey. This indicates that in an icing climatology cumulonimbus clouds do not depend on local peculiarities of the CCN concentration.

Note also that cumulus congestus and cumulonimbus clouds have spectra with a long tail of few large drops. These may be very important during the icing process as they may splash and spread out to be molded into an odd shaped ice deposit.

The stratus cloud (Plate VI) was a typical winter type cloud about 4000 feet thick. Its temperature is shown as crosses on the left side of the hatched area and measurements of liquid water content are shown at the elevation at which they were taken. Unless prolonged flight time is required inside this cloud type, icing is of little concern except for the danger of windshield icing.

It is uncertain whether stratiform clouds can be similarly treated in an icing climatology as cumulonimbus clouds, as we know, for instance, that their radii are smaller along the Eastern Seaboard than along the Pacific coastline. A decision can only be made after laboratory measurements of the icing characteristics of different droplet concentrations but constant liquid content have been made.

2. Icing Climatology

As mentioned above, a "finer scale" icing climatology is necessary to permit the increased demands for icing prediction based upon climatological statistics be met. The presently available icing climatology appears to satisfy the needs of long distance and high performance aircraft, all other types - combat support, helicopters, private aircraft - require climatology of water substance and temperature in the atmosphere which is improved and "finer scale" in time and space. The range of interest of temperature is expected to be +5 to -30°C with particular emphasis on the +2 to -10°C regime. It is believed that the probability distribution of the four categories of water substance itemized below and typical hydrometeor distributions to be expected as a function of cloud type, height above base, etc, are required. The four categories are derived by division of water substance into the two phases (solid and liquid) and by size into particles which are moving essentially with air (cloud water) and those falling through it (precipitation). The resolution being sought is thought to be the greater of 0.1 gm^{-3} or 10% of the maximum in any category. Information on the spatial variability of water substance down to a scale of about 1 km is also necessary for some purposes.

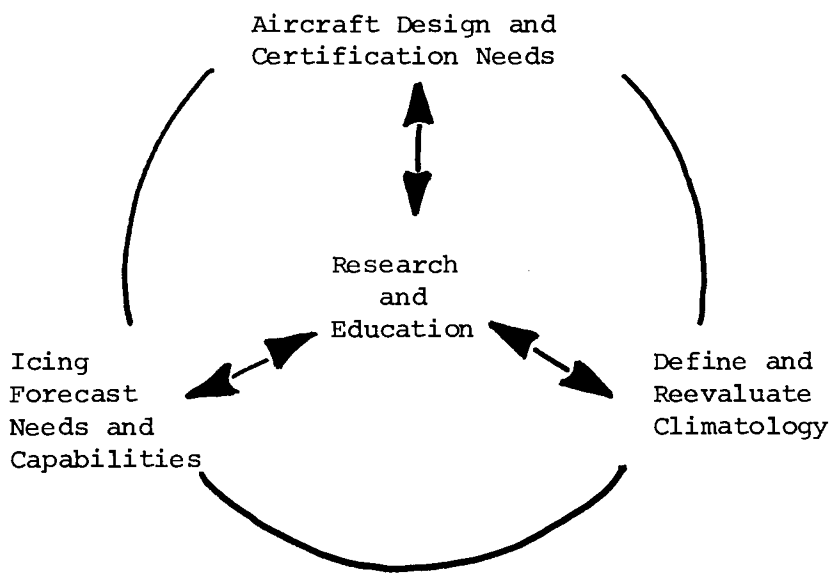
It may reasonably be argued that any attempts to define a climatology of icing parameters more closely must await their full recognition. For example, it may be that drops of diameter greater than say 25 µm play a crucial role in rotor blade icing because of the much reduced collection efficiency experienced by smaller sizes. If this supposition was, in fact, found to be correct, it would certainly have a significant effect on a study aimed at defining the incidence of icing hazards. Nevertheless, although the timing of a study is open to question, there is little doubt that an improved definition of the probability of occurrence of various combinations of atmospheric variables will ultimately be necessary. It has been suggested that if such a study is undertaken more or less in parallel with a properly instrumented study of hazard-creating processes, this will create the most cost-effective solution.

3. The role of the Meteorologist

The meteorologist, with some justification, will argue that the broad envelope of conditions which are likely to create hazards can be (indeed have been) identified. However, the difficulty of discovering the actual physical basis of the creation of icing hazards continually creates pressure for refinement of this envelope. There is little doubt that some refinement is possible, perhaps not through the provision of more detailed statistics, but by applying accepted physical understanding to the problem. Hence, the first role of the atmospheric physicist is likely to be interpretive.

There is a fundamental requirement that progress must be made in understanding the physics of hazard creation. This will not be achieved until instruments are available to observe and quantify the icing process and the co-existing state of the atmosphere. The atmospheric Physicist may reasonably expect to contribute to this required development. Recent improvements in drop sizing instrumentation (Knollenberg, 1976) are likely to assist here.

It is important to recognize here that the climatology of interest is unlikely to be of the commonly measured meteorological variables alone. At first sight the task of defining the climatology of, say liquid water content as a function of temperature, altitude, geographical position and time of year is a horrendous, if not impossible, one. Almost certainly an approach which seeks to separate the problem into climatological and interpretative components will be necessary. Thus, it is suggested that existing synoptic data be used to define the probability of occurrence of, for example, cloud type and amount, cloud base height, and surface temperature over the region of interest and that the relationship between these and icing parameters be established separately.



The role of the Icing Meteorologist

The effective role the meteorologist should assume in the icing community is shown by the graph above. The three descriptions on the loop represent the main deficiencies in the present knowledge of the icing environment for which the meteorologist has responsibility. Research and education, as located in the center of the loop, is a response to these deficiencies. The arrows shown on the figure represent a dynamic interaction within the icing community. The loop itself represents the flow of information that is required for a solution to the problem areas. Some specific examples of the problem areas were identified at the Icing Specialist Workshop as the following.

If forecasting and climatology can only give answers in terms of probabilities of the meteorological icing parameters, then the designer and the certifier must adopt the evaluation of an aircraft ice hazard accordingly.

When the meteorologist needs a better and cheaper measurement system to fulfill a forecasting requirement, the aircraft instrumentation designers must respond by providing adequate data-gathering capability, such as automated observations easily transmitted to a forecast office or to a flight service station.

If forecasting and climatology has access to measurement systems that allow a finer resolution in icing parameters, and thereby better probabilities of certain combined meteorological parameters, then it may become possible for a pilot to use this data to assist in self-forecasting.

If a pilot has a flight manual from the designer and the certifier indicating his icing hazards he may decide to penetrate or avoid the clouds in the area. The meteorologist has a role here of educating the pilots to interpret the meteorological forecasting data.

When the meteorologist finds from the designer or the certifier that in the same environment a helicopter will experience icing and an airplane will not, then he has to redefine the climatology to consider liquid water content (LWC), temperature, droplet size or cloud types rather than classify according to light, moderate, or severe icing.

Another problem area will exist when a meteorologist begins forecasting overnight aircraft frost formation and severity. This means that climatology and forecasting will need to obtain new data for example, on the short and long wave radiation over geographical locations.

The previous six examples demonstrate that if the icing meteorologist maintains his role as shown in the figure, he will provide an important service to the icing community.

4. Shape, hardness and opacity of natural ice deposits in dependence of the supercooled or solid hydrometeors.

The following observations were made in Germany during February, 1941: "A rake consisting of three cylinders had been installed over the cockpit of a Junkers JU-90 four-engine plane.* The diameters of the cylinders were 0.6, 3.0, and 1.2 cm. The base planes of the cylinders could be photographed from inside the plane. From the different thicknesses of the rime depositions on the three cylinders, the average size of the cloud droplets was calculated according to Albrecht's theory of collection efficiency. This theory, naturally, is applicable only as long as the rime deposition is small enough not to disturb the ideal aerodynamic flow around the cylinder.

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* quoted from: Observational Data on the Formation of Precipitation in Cumulonimbus clouds, by H. Weickmann, Chapter V of Thunderstorm Electricity, pages 66-138.

The rime deposition obtained at a temperature of -13°C and an altitude of 1,500 meters, by flying for 50 minutes at an air speed of 270 km/hr through a layer of stratocumulus clouds, is shown in Figure 1, a. The average radius of the cloud droplets was 4.5 μ. Figure 1,b shows a rime deposition obtained at about the same temperature, but in a cloud with a greater average droplet size (5 - 7 μ radius). The cloud layer was an extended altocumulus one, at a height of 3,700 meters. Here the aperture of the cone adjacent to the cylinder wall seems to be greater, probably because of the greater droplet size. We notice two significant properties of the depositions of this temperature range: the opaque appearance and the conical cross-section which points with the flat base toward the direction of flight. The depositions collected from the smallest cylinder are characterized by the most marked broadening. The ice was very hard, and the internal structure showed many layers like polished agate parallel to the base line of the cone.

Depositions which were obtained at higher temperatures looked quite different. Figure 2 a,b shows such an ice deposition which was obtained in the upper part of a stratus layer at temperatures near the freezing point. The average droplet size was characterized by a radius of 8 - 9 μ. The remarkable features of this deposition were: (1) the marked broadening or flattening of the ice on all cylinders, as a result of which the conical shape is almost entirely masked (note this especially in Fig. 2 a); (2) the irregularities which occurred in spite of the fact that this deposition was formed by a continuous accretion process when flying in the same cloud level near the top of the cloud (Fig. 2 b); and (3) the clear ice from which it was mainly formed. During the formation of that deposition, the rate of crystallization obviously was so small that the cloud droplets were allowed to coagulate before they froze, and some of the water was even blown to the rear part of the cylinder, where it froze (note the deposit of ice on the rear surface of the big cylinder in Fig. 2 a,b). Certainly the small rate of crystallization plays an important role in the formation process of this irregular-shaped deposition. While passing cloud parts with a higher water content, small quantities of unfrozen water were blown toward the edges of the deposition and were partly sprayed off and partly frozen as larger droplets. This process results in very unusual flattened forms. It may be important to mention that the cloud contained no precipitation particles of a greater size which could be responsible for the wartlike surface and the irregular shape."

While these deposits accumulate relatively slow, so that evasive action can be taken by the alert pilot, we have reason to believe that a mixture of supercooled cloud and snowfall can lead very quickly to ice accumulation and to a hazardous situation. It is, therefore, the combination of solid and liquid undercooled hydrometeors which requires special and very careful attention.

5. Vulnerability of distinct aircraft types; e.g. of helicopters, private one-engine-type aircraft, special military airplanes.

It appears that little hard data are available from research in icing wind tunnels on the subject of aircraft vulnerability. It is therefore recommended to make optimum use of the NASA icing wind tunnel in Cleveland in order to study the impact of various icing situations "in situ". This is particularly necessary for helicopter icing since ice will deposit differently along the rotor blade and icing may have large impact on the exposed rotor blade steering mechanism with its numerous push rods.

Areas of special attention are icing studies of the windshield and of the air induction into the motor.

Problems of special consideration are the formation of frost in exposed surfaces during a cold night, if the aircraft is located under the clear sky. There one deals with numerous, small individual ice crystals which are frozen to the surface and which would affect the air flow across the wing and stabilizer surfaces. In order to understand and evaluate this phenomenon, close cooperation between the design engineer and the meteorologist (cloud physicist) is necessary.

CONCLUSION

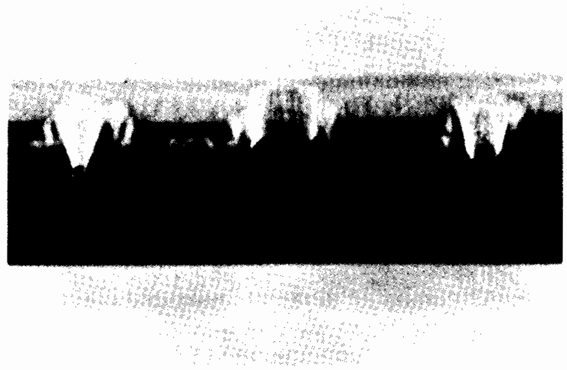
Since the 1940's and 1950's, aviation has increased profoundly, particularly through the number of private aircraft, helicopters and combat support aircraft. Consequently, a new effort for an icing climatology in refined time and space is warranted. Icing characteristics of precipitating and non-precipitating clouds must be determined by measurements of liquid and solid water content, of temperature and cloud droplet spectra. The cloud types to be investigated are (1) stratiform clouds, such as altocumulus, strato-cumulus, stratus as non-precipitating and nimbostratus as precipitating (rain and snow) cloud types or systems. The temperature range is 0 to -30^{o}C; with special interest for the range 0^{o} to -10^{o}C. (2) Convective clouds - this category includes all types of cumulus clouds, precipitating and non-precipitating, from 0^{o}C to the glaciation level (-35^{o}C to -40^{o}C). These investigations must be carried out in continental as well as maritime clouds and in polluted as well as non-polluted regions.

Simultaneously typical ice deposits must be studied as they occur on aircraft in nature. This research must be supplemented by investigations of aircraft vulnerability in the NASA Icing Tunnel. Special attention must be given to windshield and induction icing. With respect to icing instrumentation, it appears that an icing rate meter would be most desirable in addition to a water content meter for both, liquid and solid cloud and precipitation hydrometeors.

ACKNOWLEDGEMENTS

I wish to thank the members of my committee for their help and cooperation, and suggestions, especially Peter Ryder and Mark Dietenberger. Thanks is also due to the organizers of the Icing Specialist Workshop for their well prepared agenda.

a



b

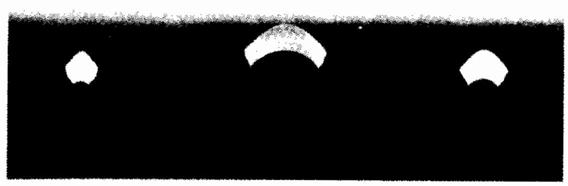


Figure 1 a, b. - Rime ice formed on cylinders during the flight through supercooled clouds. Diameters of cylinders from left to right: 6, 30, and 12 mm. a: mean linear droplet radius 4.5 μ; temperature about -13°C. b: mean linear droplet radius 5 - 7 μ; temperature about -13°C.

a

b

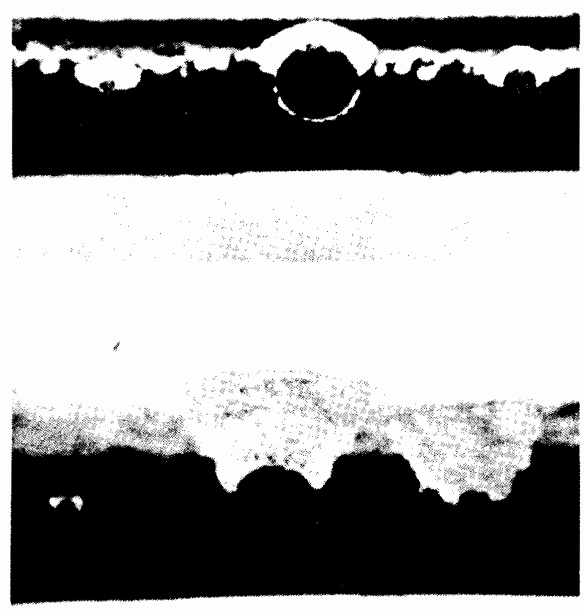


Figure 2. Clear ice formed during the flight through slightly supercooled clouds. Mean linear droplet radius 8 - 9 μ; temperature near freezing point.

APPENDIX

1. Cloud droplet spectra and other cloud elements as measured in all kinds of cumulus cloud and under varying climatic conditions. Plates I thru VI.
2. Replies to Representative Questions Furnished by Conference Chairman
3. Reply to Guidelines for Committee Chairman Reports.

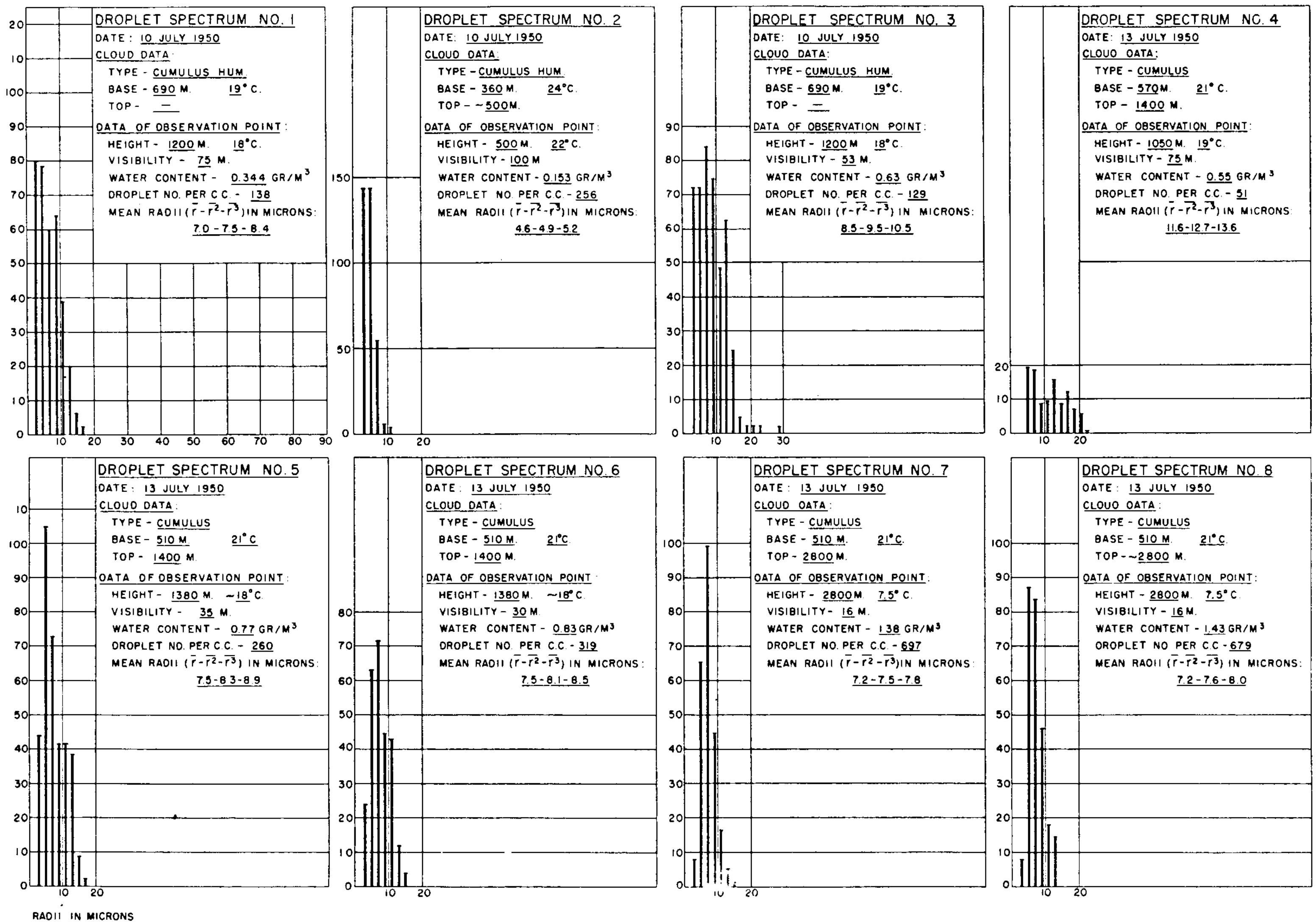

DROPLET SPECTRUM NO. 1
DATE: 10 JULY 1950
CLOUD DATA:
TYPE - CUMULUS HUM.
BASE - 690 M. 19° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 1200 M. 18° C.
VISIBILITY - 75 M.
WATER CONTENT - 0.344 GR/M³
DROPLET NO. PER C.C. - 138
MEAN RADII (r̄ - r̄² - r̄³) IN MICRONS:
7.0 - 7.5 - 8.4
DROPLET SPECTRUM NO. 2
DATE: 10 JULY 1950
CLOUD DATA:
TYPE - CUMULUS HUM.
BASE - 360 M. 24° C.
TOP - ~500 M.
DATA OF OBSERVATION POINT:
HEIGHT - 500 M. 22° C.
VISIBILITY - 100 M
WATER CONTENT - 0.153 GR/M³
DROPLET NO. PER C.C. - 256
MEAN RADII (r̄ - r̄² - r̄³) IN MICRONS:
4.6 - 4.9 - 5.2
DROPLET SPECTRUM NO. 3
DATE: 10 JULY 1950
CLOUD DATA:
TYPE - CUMULUS HUM.
BASE - 690 M. 19° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 1200 M 18° C.
VISIBILITY - 53 M.
WATER CONTENT - 0.63 GR/M³
DROPLET NO. PER C.C. - 129
MEAN RADII (r̄ - r̄² - r̄³) IN MICRONS:
8.5 - 9.5 - 10.5
DROPLET SPECTRUM NO. 4
DATE: 13 JULY 1950
CLOUD DATA:
TYPE - CUMULUS
BASE - 570 M. 21° C.
TOP - 1400 M.
DATA OF OBSERVATION POINT:
HEIGHT - 1050 M. 19° C.
VISIBILITY - 75 M.
WATER CONTENT - 0.55 GR/M³
DROPLET NO. PER C.C. - 51
MEAN RADII (r̄ - r̄² - r̄³) IN MICRONS:
11.6 - 12.7 - 13.6
DROPLET SPECTRUM NO. 5
DATE: 13 JULY 1950
CLOUD DATA:
TYPE - CUMULUS
BASE - 510 M. 21° C
TOP - 1400 M.
DATA OF OBSERVATION POINT:
HEIGHT - 1380 M. ~18° C.
VISIBILITY - 35 M.
WATER CONTENT - 0.77 GR/M³
DROPLET NO. PER C.C. - 260
MEAN RADII (r̄ - r̄² - r̄³) IN MICRONS:
7.5 - 8.3 - 8.9
DROPLET SPECTRUM NO. 6
DATE: 13 JULY 1950
CLOUD DATA:
TYPE - CUMULUS
BASE - 510 M. 21° C.
TOP - 1400 M.
DATA OF OBSERVATION POINT:
HEIGHT - 1380 M. ~18° C.
VISIBILITY - 30 M.
WATER CONTENT - 0.83 GR/M³
DROPLET NO. PER C.C. - 319
MEAN RADII (r̄ - r̄² - r̄³) IN MICRONS:
7.5 - 8.1 - 8.5
DROPLET SPECTRUM NO. 7
DATE: 13 JULY 1950
CLOUD DATA:
TYPE - CUMULUS
BASE - 510 M. 21° C.
TOP - 2800 M.
DATA OF OBSERVATION POINT:
HEIGHT - 2800 M 7.5° C.
VISIBILITY - 16 M.
WATER CONTENT - 1.38 GR/M³
DROPLET NO. PER C.C. - 697
MEAN RADII (r̄ - r̄² - r̄³) IN MICRONS:
7.2 - 7.5 - 7.8
DROPLET SPECTRUM NO. 8
DATE: 13 JULY 1950
CLOUD DATA:
TYPE - CUMULUS
BASE - 510 M. 21° C.
TOP - ~2800 M.
DATA OF OBSERVATION POINT:
HEIGHT - 2800 M. 7.5° C.
VISIBILITY - 16 M.
WATER CONTENT - 1.43 GR/M³
DROPLET NO. PER C.C. - 679
MEAN RADII (r̄ - r̄² - r̄³) IN MICRONS:
7.2 - 7.6 - 8.0
RADII IN MICRONS

Plate I

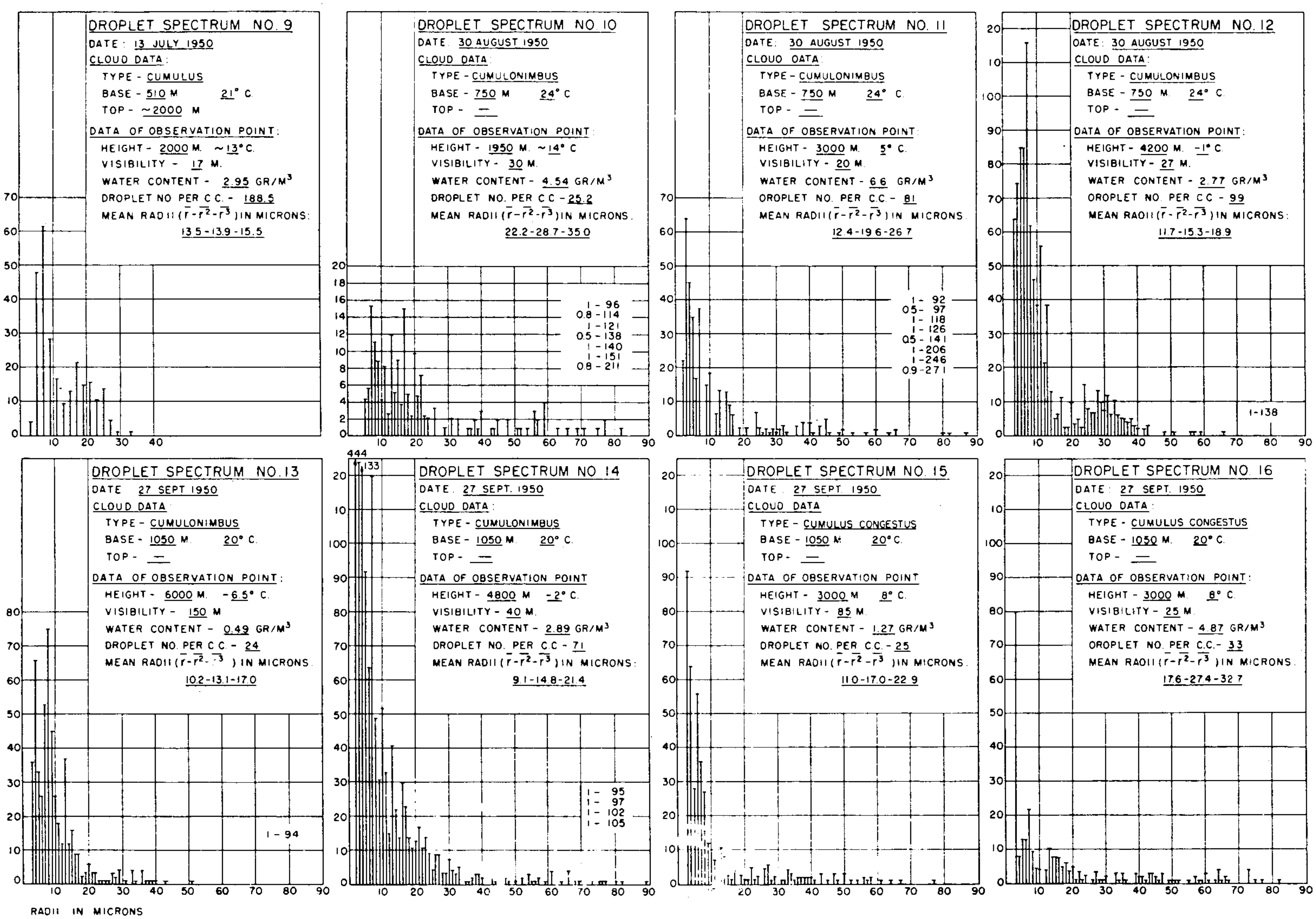

DROPLET SPECTRUM NO. 9
DATE: 13 JULY 1950
CLOUD DATA:
TYPE - CUMULUS
BASE - 510 M 21° C
TOP - ~2000 M
DATA OF OBSERVATION POINT:
HEIGHT - 2000 M. ~13° C.
VISIBILITY - 17 M.
WATER CONTENT - 2.95 GR/M³
DROPLET NO PER C.C. - 188.5
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS:
13.5-13.9-15.5
DROPLET SPECTRUM NO 10
DATE. 30 AUGUST 1950
CLOUD DATA
TYPE - CUMULONIMBUS
BASE - 750 M 24° C
TOP - —
DATA OF OBSERVATION POINT
HEIGHT - 1950 M. ~14° C
VISIBILITY - 30 M.
WATER CONTENT - 4.54 GR/M³
DROPLET NO. PER C.C - 25.2
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS.
22.2-28.7-35.0
1 - 96
0.8 - 114
1 - 121
0.5 - 138
1 - 140
1 - 151
0.8 - 211
DROPLET SPECTRUM NO. 11
DATE: 30 AUGUST 1950
CLOUD DATA
TYPE - CUMULONIMBUS
BASE - 750 M 24° C.
TOP - —
DATA OF OBSERVATION POINT
HEIGHT - 3000 M. 5° C.
VISIBILITY - 20 M
WATER CONTENT - 6.6 GR/M³
DROPLET NO. PER C.C - 81
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS.
12.4-19.6-26.7
1 - 92
0.5 - 97
1 - 118
1 - 126
0.5 - 141
1 - 206
1 - 246
0.9 - 271
DROPLET SPECTRUM NO. 12
DATE: 30 AUGUST 1950
CLOUD DATA:
TYPE - CUMULONIMBUS
BASE - 750 M. 24° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 4200 M. -1° C.
VISIBILITY - 27 M.
WATER CONTENT - 2.77 GR/M³
DROPLET NO. PER C.C - 99
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS:
11.7-15.3-18.9
1-138
DROPLET SPECTRUM NO. 13
DATE 27 SEPT 1950
CLOUD DATA
TYPE - CUMULONIMBUS
BASE - 1050 M. 20° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 6000 M. -6.5° C.
VISIBILITY - 150 M
WATER CONTENT - 0.49 GR/M³
DROPLET NO. PER C.C. - 24
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS.
10.2-13.1-17.0
1 - 94
DROPLET SPECTRUM NO 14
DATE. 27 SEPT. 1950
CLOUD DATA:
TYPE - CUMULONIMBUS
BASE - 1050 M. 20° C.
TOP - —
DATA OF OBSERVATION POINT
HEIGHT - 4800 M -2° C.
VISIBILITY - 40 M.
WATER CONTENT - 2.89 GR/M³
DROPLET NO. PER C.C - 71
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS:
9.1-14.8-21.4
444
133
1 - 95
1 - 97
1 - 102
1 - 105
DROPLET SPECTRUM NO. 15
DATE 27 SEPT. 1950
CLOUD DATA
TYPE - CUMULUS CONGESTUS
BASE - 1050 M 20° C.
TOP - —
DATA OF OBSERVATION POINT
HEIGHT - 3000 M 8° C.
VISIBILITY - 85 M.
WATER CONTENT - 1.27 GR/M³
DROPLET NO. PER C.C. - 25
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS.
11.0-17.0-22.9
DROPLET SPECTRUM NO 16
DATE: 27 SEPT. 1950
CLOUD DATA:
TYPE - CUMULUS CONGESTUS
BASE - 1050 M. 20° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 3000 M. 8° C.
VISIBILITY - 25 M
WATER CONTENT - 4.87 GR/M³
DROPLET NO. PER C.C. - 33
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS.
17.6-27.4-32.7
RADII IN MICRONS

Plate II

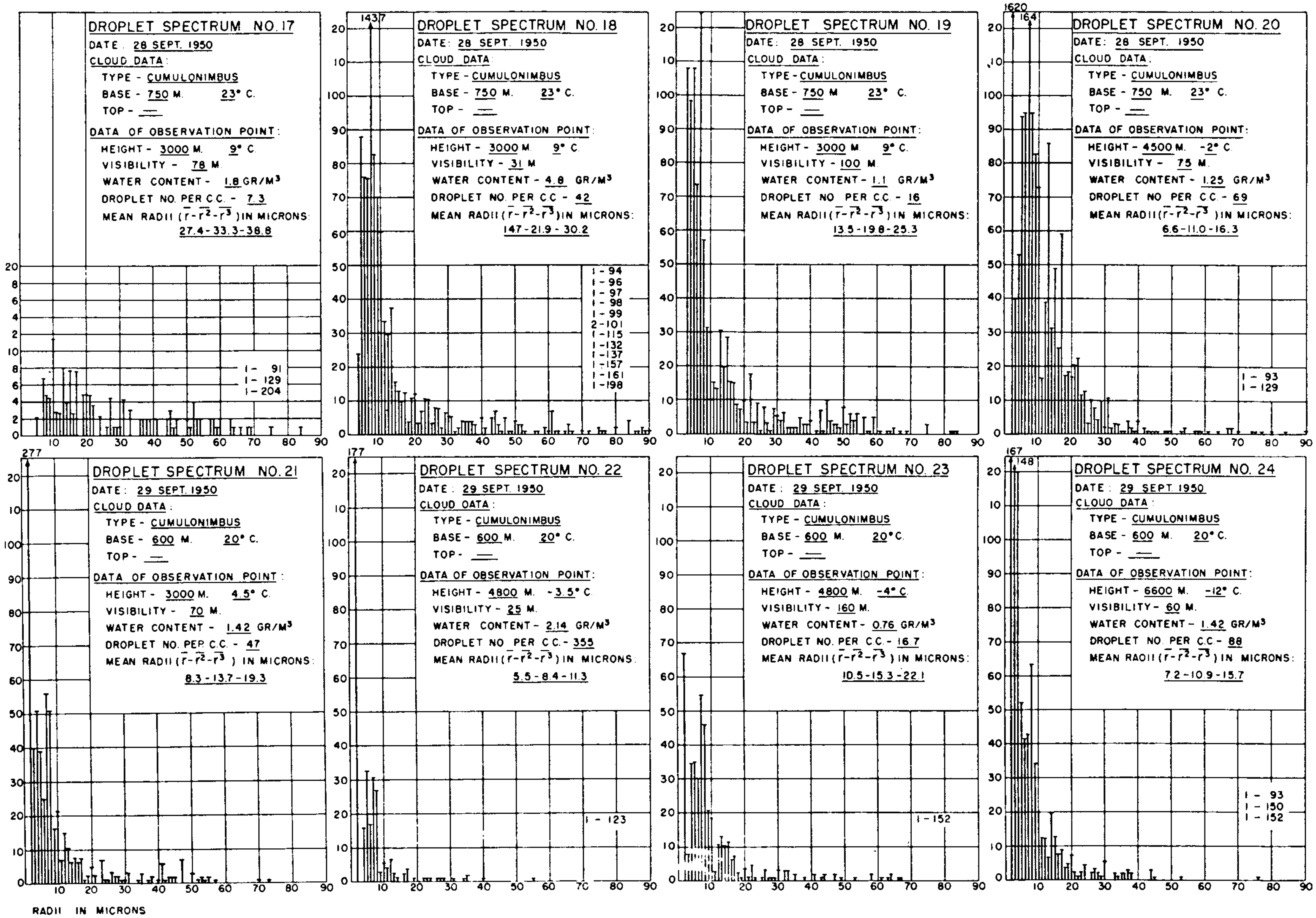

DROPLET SPECTRUM NO. 17
DATE: 28 SEPT. 1950
CLOUD DATA:
TYPE - CUMULONIMBUS
BASE - 750 M. 23° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 3000 M. 9° C
VISIBILITY - 78 M.
WATER CONTENT - 1.8 GR/M³
DROPLET NO. PER C.C. - 7.3
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS:
27.4-33.3-38.8
1 - 91
1 - 129
1 - 204
DROPLET SPECTRUM NO. 18
DATE: 28 SEPT. 1950
CLOUD DATA:
TYPE - CUMULONIMBUS
BASE - 750 M. 23° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 3000 M. 9° C
VISIBILITY - 31 M
WATER CONTENT - 4.8 GR/M³
DROPLET NO. PER C.C. - 42
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS:
14.7-21.9-30.2
143
17
1 - 94
1 - 96
1 - 97
1 - 98
1 - 99
2 - 101
1 - 115
1 - 132
1 - 137
1 - 157
1 - 161
1 - 198
DROPLET SPECTRUM NO. 19
DATE: 28 SEPT. 1950
CLOUD DATA:
TYPE - CUMULONIMBUS
BASE - 750 M 23° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 3000 M 9° C.
VISIBILITY - 100 M.
WATER CONTENT - 1.1 GR/M³
DROPLET NO. PER C.C. - 16
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS:
13.5-19.8-25.3
DROPLET SPECTRUM NO. 20
DATE: 28 SEPT. 1950
CLOUD DATA:
TYPE - CUMULONIMBUS
BASE - 750 M. 23° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 4500 M. -2° C
VISIBILITY - 75 M.
WATER CONTENT - 1.25 GR/M³
DROPLET NO. PER C.C. - 69
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS:
6.6-11.0-16.3
1620
164
1 - 93
1 - 129
DROPLET SPECTRUM NO. 21
DATE: 29 SEPT. 1950
CLOUD DATA:
TYPE - CUMULONIMBUS
BASE - 600 M. 20° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 3000 M. 4.5° C.
VISIBILITY - 70 M.
WATER CONTENT - 1.42 GR/M³
DROPLET NO. PER C.C. - 47
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS:
8.3-13.7-19.3
277
DROPLET SPECTRUM NO. 22
DATE: 29 SEPT. 1950
CLOUD DATA:
TYPE - CUMULONIMBUS
BASE - 600 M. 20° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 4800 M. -3.5° C
VISIBILITY - 25 M.
WATER CONTENT - 2.14 GR/M³
DROPLET NO. PER C.C. - 355
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS.
5.5-8.4-11.3
177
1 - 123
DROPLET SPECTRUM NO. 23
DATE: 29 SEPT. 1950
CLOUD DATA:
TYPE - CUMULONIMBUS
BASE - 600 M. 20° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 4800 M. -4° C
VISIBILITY - 160 M.
WATER CONTENT - 0.76 GR/M³
DROPLET NO. PER C.C. - 16.7
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS:
10.5-15.3-22.1
1 - 152
DROPLET SPECTRUM NO. 24
DATE: 29 SEPT. 1950
CLOUD DATA:
TYPE - CUMULONIMBUS
BASE - 600 M. 20° C.
TOP - —
DATA OF OBSERVATION POINT:
HEIGHT - 6600 M. -12° C.
VISIBILITY - 60 M.
WATER CONTENT - 1.42 GR/M³
DROPLET NO. PER C.C. - 88
MEAN RADII (r̄-r̄²-r̄³) IN MICRONS:
7.2-10.9-15.7
167
148
1 - 93
1 - 150
1 - 152
RADII IN MICRONS

Plate III

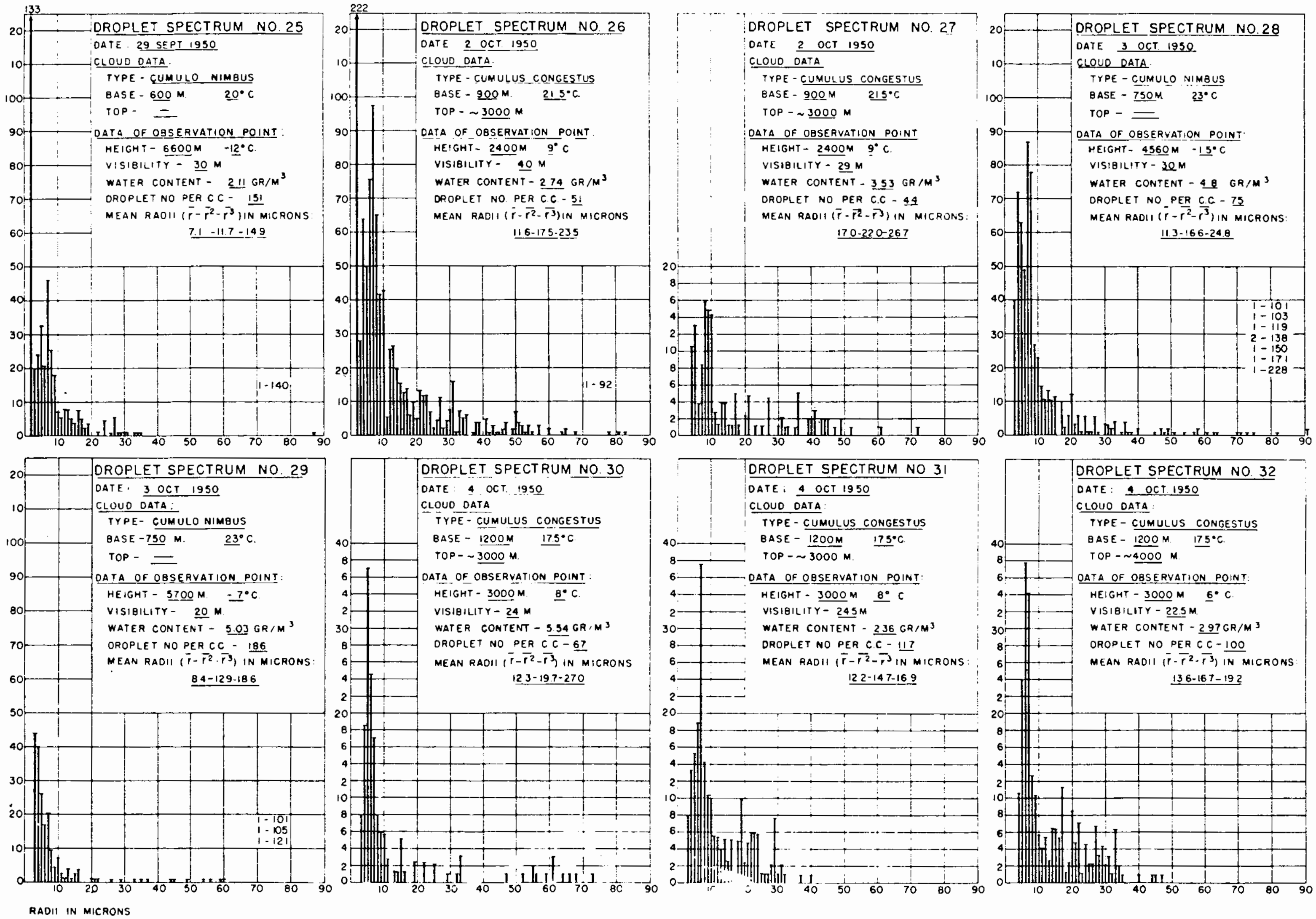
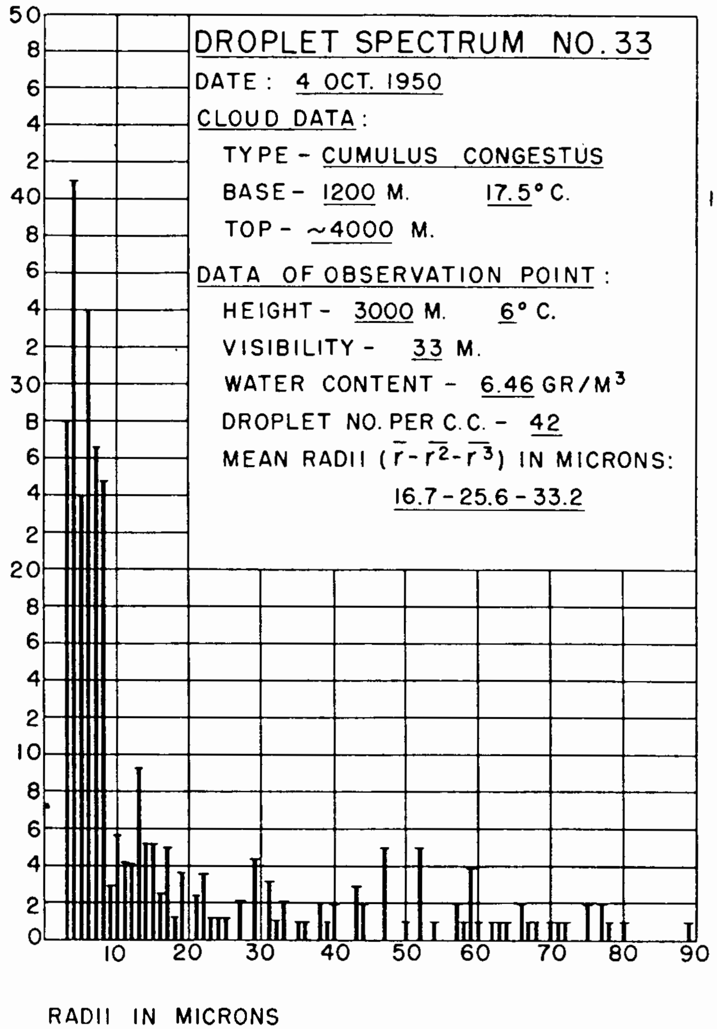

DROPLET SPECTRUM NO. 25
DATE 29 SEPT 1950
CLOUD DATA
TYPE - CUMULO NIMBUS
BASE - 600 M 20° C
TOP - —
DATA OF OBSERVATION POINT
HEIGHT - 6600 M -12° C
VISIBILITY - 30 M
WATER CONTENT - 2.11 GR/M3
DROPLET NO PER C.C - 151
MEAN RADII (r̄ - r̄2 - r̄3) IN MICRONS
7.1 - 11.7 - 14.9
1 - 140
DROPLET SPECTRUM NO. 26
DATE 2 OCT 1950
CLOUD DATA
TYPE - CUMULUS CONGESTUS
BASE - 900 M 21.5° C
TOP - ~3000 M
DATA OF OBSERVATION POINT
HEIGHT - 2400 M 9° C
VISIBILITY - 40 M
WATER CONTENT - 2.74 GR/M3
DROPLET NO PER C.C - 51
MEAN RADII (r̄ - r̄2 - r̄3) IN MICRONS
11.6 - 17.5 - 23.5
1 - 92
DROPLET SPECTRUM NO. 27
DATE 2 OCT 1950
CLOUD DATA
TYPE - CUMULUS CONGESTUS
BASE - 900 M 21.5° C
TOP - ~3000 M
DATA OF OBSERVATION POINT
HEIGHT - 2400 M 9° C
VISIBILITY - 29 M
WATER CONTENT - 3.53 GR/M3
DROPLET NO PER C.C - 44
MEAN RADII (r̄ - r̄2 - r̄3) IN MICRONS
17.0 - 22.0 - 26.7
DROPLET SPECTRUM NO. 28
DATE 3 OCT 1950
CLOUD DATA
TYPE - CUMULO NIMBUS
BASE - 750 M 23° C
TOP - —
DATA OF OBSERVATION POINT
HEIGHT - 4560 M -1.5° C
VISIBILITY - 30 M
WATER CONTENT - 4.8 GR/M3
DROPLET NO PER C.C - 75
MEAN RADII (r̄ - r̄2 - r̄3) IN MICRONS
11.3 - 16.6 - 24.8
1 - 101
1 - 103
1 - 119
2 - 138
1 - 150
1 - 171
1 - 228
DROPLET SPECTRUM NO. 29
DATE 3 OCT 1950
CLOUD DATA
TYPE - CUMULO NIMBUS
BASE - 750 M 23° C
TOP - —
DATA OF OBSERVATION POINT
HEIGHT - 5700 M -7° C
VISIBILITY - 20 M
WATER CONTENT - 5.03 GR/M3
DROPLET NO PER C.C - 186
MEAN RADII (r̄ - r̄2 - r̄3) IN MICRONS
8.4 - 12.9 - 18.6
1 - 101
1 - 105
1 - 121
DROPLET SPECTRUM NO. 30
DATE 4 OCT 1950
CLOUD DATA
TYPE - CUMULUS CONGESTUS
BASE - 1200 M 17.5° C
TOP - ~3000 M
DATA OF OBSERVATION POINT
HEIGHT - 3000 M 8° C
VISIBILITY - 24 M
WATER CONTENT - 5.54 GR/M3
DROPLET NO PER C.C - 67
MEAN RADII (r̄ - r̄2 - r̄3) IN MICRONS
12.3 - 19.7 - 27.0
DROPLET SPECTRUM NO 31
DATE 4 OCT 1950
CLOUD DATA
TYPE - CUMULUS CONGESTUS
BASE - 1200 M 17.5° C
TOP - ~3000 M
DATA OF OBSERVATION POINT
HEIGHT - 3000 M 8° C
VISIBILITY - 24.5 M
WATER CONTENT - 2.36 GR/M3
DROPLET NO PER C.C - 117
MEAN RADII (r̄ - r̄2 - r̄3) IN MICRONS
12.2 - 14.7 - 16.9
DROPLET SPECTRUM NO. 32
DATE 4 OCT 1950
CLOUD DATA
TYPE - CUMULUS CONGESTUS
BASE - 1200 M 17.5° C
TOP - ~4000 M
DATA OF OBSERVATION POINT
HEIGHT - 3000 M 6° C
VISIBILITY - 22.5 M
WATER CONTENT - 2.97 GR/M3
DROPLET NO PER C.C - 100
MEAN RADII (r̄ - r̄2 - r̄3) IN MICRONS
13.6 - 16.7 - 19.2
RADII IN MICRONS

Plate IV


DROPLET SPECTRUM NO. 33
DATE: 4 OCT. 1950
CLOUD DATA:
TYPE - CUMULUS CONGESTUS
BASE - 1200 M. 17.5° C.
TOP - ~4000 M.
DATA OF OBSERVATION POINT:
HEIGHT - 3000 M. 6° C.
VISIBILITY - 33 M.
WATER CONTENT - 6.46 GR/M3
DROPLET NO. PER C.C. - 42
MEAN RADII (r̄ - r̄2 - r̄3) IN MICRONS:
16.7 - 25.6 - 33.2
RADII IN MICRONS

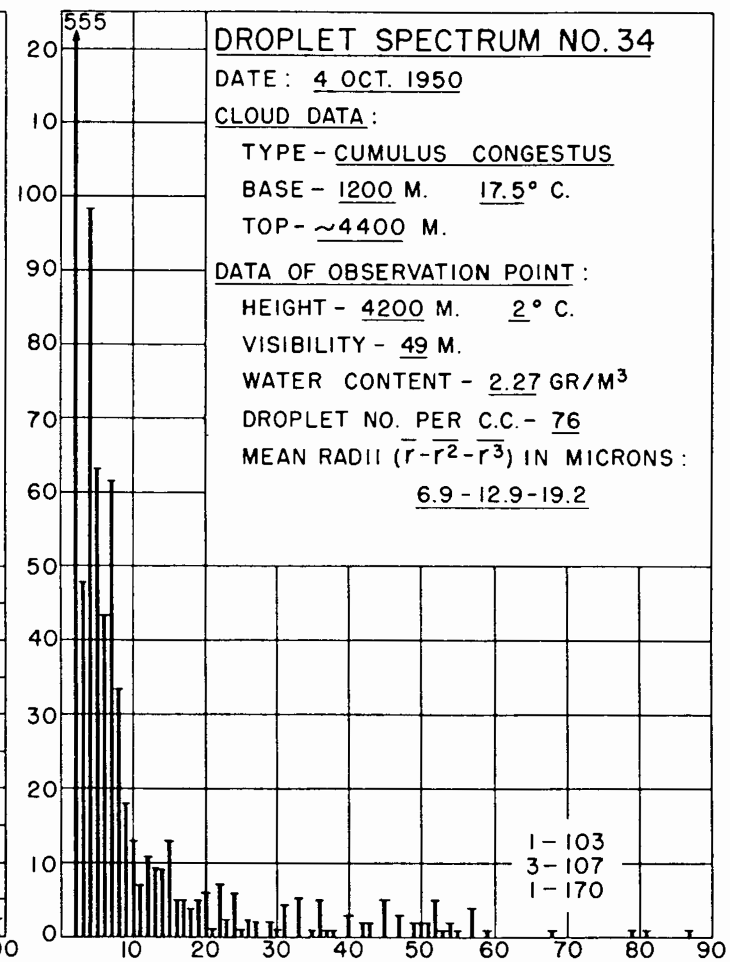
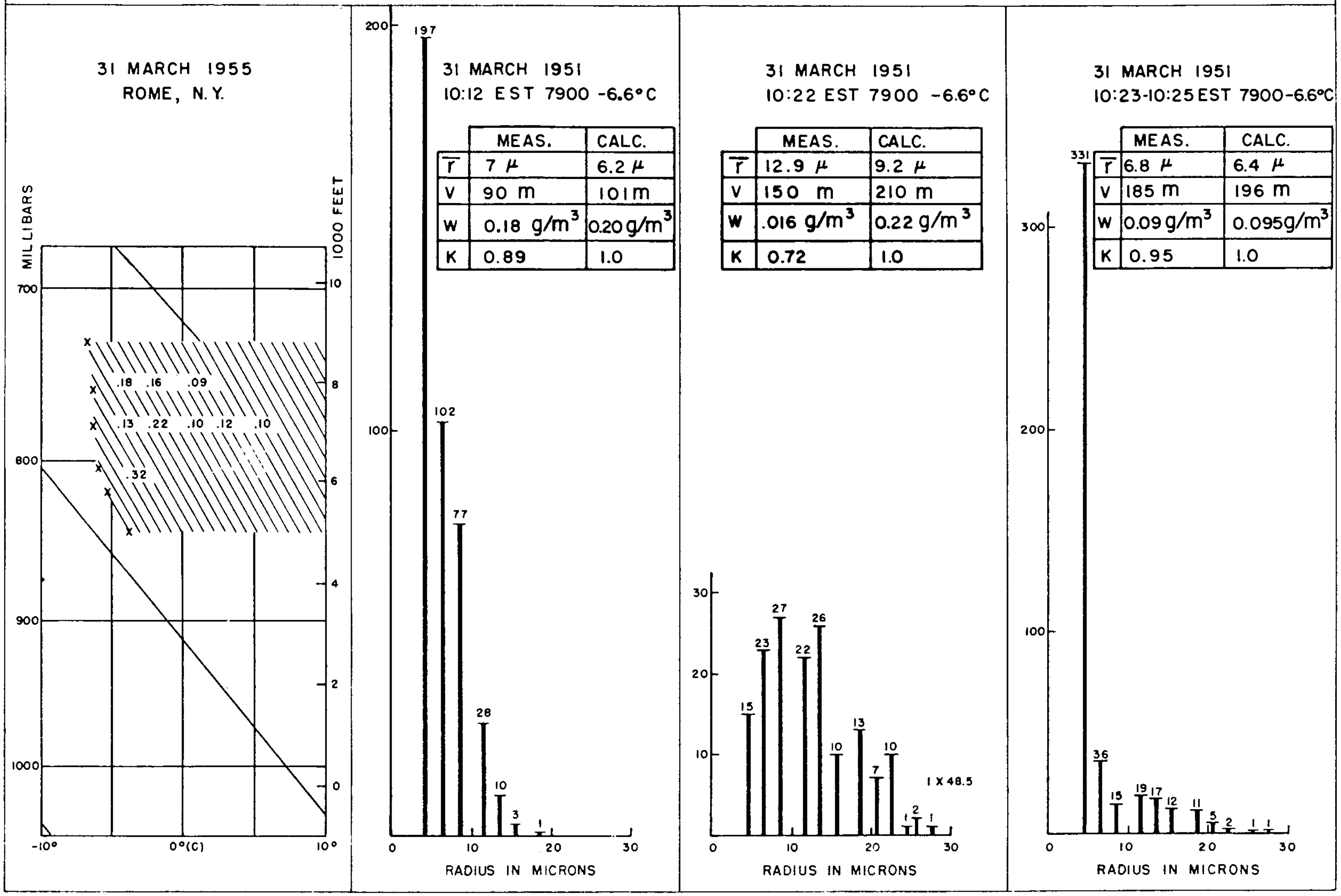

DROPLET SPECTRUM NO. 34
DATE: 4 OCT. 1950
CLOUD DATA:
TYPE - CUMULUS CONGESTUS
BASE - 1200 M. 17.5° C.
TOP - ~4400 M.
DATA OF OBSERVATION POINT:
HEIGHT - 4200 M. 2° C.
VISIBILITY - 49 M.
WATER CONTENT - 2.27 GR/M3
DROPLET NO. PER C.C. - 76
MEAN RADII (r̄ - r̄2 - r̄3) IN MICRONS:
6.9 - 12.9 - 19.2
555
1 - 103
3 - 107
1 - 170

Plate V

STRATUS AND STRATOCUMULUS



31 March 1951, 10:12 EST 7900 -6.6°C

	MEAS.	CALC.
$\overline{r}$	7 μ	6.2 μ
V	90 m	101 m
W	0.18 g/m³	0.20 g/m³
K	0.89	1.0

31 March 1951, 10:22 EST 7900 -6.6°C

	MEAS.	CALC.
$\overline{r}$	12.9 μ	9.2 μ
V	150 m	210 m
W	.016 g/m³	0.22 g/m³
K	0.72	1.0

31 March 1951, 10:23-10:25 EST 7900-6.6°C

	MEAS.	CALC.
$\overline{r}$	6.8 μ	6.4 μ
V	185 m	196 m
W	0.09 g/m³	0.095 g/m³
K	0.95	1.0

Plate VI

REPLIES TO REPRESENTATIVE QUESTIONS FURNISHED BY CONFERENCE CHAIRMAN:

1. Assess current understanding of icing meteorology. Is a "finer scale" definition of the icing environment necessary or possible?

A. As explained above, a "finer scale" definition of the icing environment is necessary for non-high performance aircraft whose ceiling is about 3000 m, for helicopters and certain types of military aircraft.

2. Is our currently-available meteorology data-gathering capability adequate for all categories of aircraft design and operation (i.e., civil transport, general aviation, civil and military helicopters)?

A. It is not adequate for a "finer scale" definition of the icing requirement since this demands measurements in the meso-meteorological range (about 10 to 500 km).

3. What is our understanding of frost formation on aircraft lifting surfaces? Is it totally predictable?

A. Frost formation is the same phenomenon as rime. It may occur under a clear sky, in haze or fog. Its prediction is as difficult as the prediction of dew or rime.

4. What data-gathering equipment and sensors are currently available for icing meteorology measurements? Is this equipment adequate? Practical? If not, what instrumentation R & D is required? Who should do it...government, industry, or both?

A. In order to answer this question, one has to know first what icing parameters need to be known. It appears that the supercooled liquid water content of a cloud is one of the parameters, at the same time, however, one would like to know the amount of solid ice, particularly in form of snowfall. Heavy snowfall through a supercooled cloud in the temperature range of 0 to -10°C can be very dangerous. Also, of course, freezing rain. A vertical pointing 8 m/m cloud radar may be useful but it relays only the conditions over one station. Airborne stations could be valuable as suitably equipped aircraft to measure the supercooled liquid content. There is really no fully developed operational liquid water content meter available, and neither is a reliable icing rate meter developed. Promising for further development may be the nimbiometer, a hot-wire liquid cloud water meter (Merceret and Schricker, JAM, VOL 14, No.3, April 1975), and the Rosemount Ice Detector, Model 871. Here, the sensing element is an axially vibrating tube whose natural frequency changes as ice accumulates on it. At an accumulation corresponding to 0.5 mm (0.020") ice, an output signal is provided to the timer.

5. Can automated observations be devised which are practical and which could easily be transmitted to a forecast office or to flight service stations?

A. This task would require a determined effort by a determined sponsor.

6. Can icing severity levels be better defined? What does severity depend upon?

A. Icing can often be a freak phenomenon due to a convective cloud with high water content embedded in a cyclonic snowfall. For the answer to this question much R & D is necessary which should come from a special Aircraft-Icing-Research Group linked to NASA, the FAA, and NOAA.

7. How can the meteorology community work better with the research facilities and simulation community?

A. By establishing lines of communication between them.

GUIDELINES FOR COMMITTEE CHAIRMEN REPORTS

Your committee report should reflect your committee's viewpoints on the following:

1. From your interactions with the other committees, identify in order of decreasing importance the most pressing needs within the context of your committee's title.

2. State nature of problems (e.g.,operational, R&D, lack of data, procedural, etc.).

3. How soon can problems be reasonably solved? What impact on aviation will be likely if problem is not addressed?

4. What is your assessment of the cost-benefit of these solutions?

5. Is knowledge in hand, or is new effort required to effect solutions?

6. Recommend which organization(s) (Government and/or industry) should be involved in problem solving and identify their respective roles.

REPLY

A general answer to the problems mentioned in the paragraphs 1-6 is as follows:

It appears to be urgently required that special ice research groups be established. The mission of these groups should be to study in the laboratory and in the atmosphere, the icing parameters which prevail in certain cloud types and which most affect various types of the aircraft. These parameters may be different for military aircraft, for helicopters, for private aircraft, etc. Such research groups must closely coordinate, if not cooperate, with the aircraft designer on one side and the meteorological community on the other. They must use the most modern data collection and data analysis systems with which they are able to completely describe the characteristics of an icing cloud as well as the response of the aircraft or helicopter with their various air induction and windshield wiper systems. The complexity of this research calls for a diversified approach such as requires several research centers, for instance, research should be supported at such centers as the NASA-Lewis Research Center, The U.S. Army Cold Regions Research and Engineering Laboratory, the FAA and others. I firmly believe that failure to attack the problem now will severely affect wintertime flying, particularly of the private sector, the military combat support flight requirements, and helicopter all-weather operations.

SUMMARY REPORT - ICING FORECASTING COMMITTEE

Arthur Hilsenrod
Federal Aviation Administration

INTRODUCTION

Aircraft pilots and aircraft dispatchers depend on icing forecasts in flight planning. Inaccurate forecasts result in the loss of time, incompleted missions, and at worst, accidents. A forecast of icing conditions is often sufficient to cancel an individual flight or military flight operation. Most forecasts cover large areas, the condition for which may not apply to a particular flight or given area. Icing forecasts for the 2-3,000 foot altitude range are very often inaccurate. It is necessary to improve icing forecasts to insure safe movement and reduce unnecessary cancellations of flights.

PRESENT FORECAST SYSTEM

Icing forecasts have been provided by the National Weather Service (NWS) and the U.S. Air Weather Service (AWS) for about 15 years without significant changes in the basic techniques used to provide these forecasts (Air Weather Service, 1969).[1]

The basic technique is still to determine the freezing level and associated cloud types that will be at, or above, that level. Improvements have been made, however, in the data inputs to the forecast technique. They include improved forecast models which provide improved temperature and precipitation forecasts.

Satellites can provide information on clouds and cloud cover that could be of use in improving the icing forecasts. There are no indications that an effective model with smaller grid sizes with associated dense observational networks will be available in the near future for the improvement of the icing forecast. Utilization may be made of the increased number of pilot reports that are becoming available. The icing forecast techniques require reexamination to determine means of improving them.

IMPROVED COMMUNICATIONS

In recognition of the value of the most recent weather information to pilot and forecaster, both the NWS and the Federal Aviation Administration (FAA) are undertaking major efforts to develop systems to improve the communications of weather information. The systems will have a significant impact on the speed at which hazardous weather information, e.g., icing conditions, will

[1]Although specific references were not, for the most part, discussed by the panel, they are added for the completeness of this summary.

be transmitted from one aircraft pilot to another, and to the weather forecaster for updating his forecast. The Automation of Field Operations and Services (AFOS) System is being installed by the NWS at Weather Service Forecast Offices (WSFOs), Weather Forecast Offices, and Air Traffic Control Centers. In 3 years, 200 automated weather offices will be linked in an 11,620 mile circuit (see Figure 1) (Weigel, 1978).

AFOS will do away with the present system of teletypewriters and facsimile machines and the enormous quantities of paper they generate and substitute an all-electronic system in which weather information will be displayed on TV screens. A weather map will arrive at the station in about 1/40th the time it takes on paper. Messages will arrive 30 times as fast. A message will go from one station on the main circuit to the station most remote from it in about 25 seconds with error checks at an average of 24 places between them.

The FAA is directing a major effort to integrate data acquisition, data processing, and communications performed in support of aviation into an improved consolidated effective system that will meet both the near-term (1980) and long-term (1990) requirements of all aviation (Aviation Weather System Planning Team, 1978). The new system will have a significant impact on the speed at which hazardous weather information, e.g., icing conditions, will be transmitted (1) from one aircraft pilot to another, and (2) to forecasters for updating the forecast. Figure 2 outlines the systems that will be evaluated to provide fast communications of weather to the pilot.

QUANTITATIVE ICING DATA

Major improvement of icing forecasts will evolve only when we measure, report, and forecast icing conditions in quantitative form. To this end, we need (1) instruments to measure and report icing conditions, and (2) changes in the current definition of icing conditions.

REQUIRED ICING DATA

The atmospheric parameters that are associated with aircraft icing are liquid water content (LWC), drop size distribution (D_o) and outside air temperature (OAT). These are the parameters that are utilized to define the icing standards in the Federal Air Regulations and Military Specifications which aircraft must meet to be certified for flight into icing conditions. As Adams (1978) reported, these design standards are adequate for aircraft that operate above 10,000 feet but are considered excessive for low/slow flying aircraft such as helicopters, many general aviation aircraft, and several military aircraft. The FAA is initiating a review of available icing information from all sources to provide interim icing standards for helicopters.

The availability of icing standards for all aircraft will allow manufacturers to provide quantitative icing limitations for each aircraft for incorporation into the operator's flight manual or handbook of each aircraft. Making at least LWC and OAT information available to the pilot from instrumentation on his aircraft will allow him to assess the vulnerability of his aircraft to the icing conditions he encounters and take courses of action to avoid them as necessary. Further, the collection of LWC and OAT information on a regular basis will permit the development of new techniques for icing prediction.

CHANGE IN ICING DEFINITIONS

Current definitions of icing intensities -- trace, light, moderate, and severe -- were established by the National Coordinating Committee for Aviation Meteorology in February 1964 and adopted by the Subcommittee on Meteorological Services in 1968. It was intended to designate icing intensities in terms of its operational effect upon the reciprocating engine, straight-wing aircraft as a standard. Currently, these intensity terms are interpreted differently for different aircraft. Conditions that cause light rime icing to one aircraft may cause moderate glaze icing to another depending on the design and flight characteristics of the aircraft, e.g., airspeed, aircraft contour or shape, and temperature of the surface upon which ice is accreted, etc. The forecast of icing conditions in quantitative form would be evaluated by the pilot with respect to his particular aircraft.

Quantitative definitions have been advanced relating trace, light, moderate and severe (heavy) icing to liquid water content. Relationships appear in the Air Weather Service Manual (1969) based on the work of Lewis (1947). Newton (1977) also referring to the Lewis (1947) report notes that quantitative definitions relating the rate of collection of ice, at 200 miles per hour on a circular cylinder 3 inches in diameter or a similar system may satisfactorily by utilized for quantitative measurements, and these measurements may be used to verify the forecasts of icing conditions in quantitative form utilizing current forecast techniques. Quantitative relationships have also been advanced by personnel associated with design and operation of helicopters (Werner, 1975 and Kitchens and Adams, 1977).

Drop size distribution (D_o) in these definitions are not currently suggested mainly because the measurement systems for D_o are quite expensive and the addition of D_o was not agreed upon as a critical addition to LWC and OAT for evaluating icing effects on aircraft.

These definitions are useful in clarifying and eventually transitioning to the use of quantitative values only. Within the U.S. it is necessary for each agency to take steps to bring to the attention of the offices of Federal Coordinator for Meteorological Services and Supporting Research the desirability of establishing quantitative standards of icing conditions. Once initial Federal standards are established, international standards can be worked out.

INSTRUMENTATION

For research purposes, a variety of instrumentation, expensive and inexpensive is available to measure LWC, OAT, D_o, ice crystals, and ice accretion rates. If these data were made available on a regular basis, forecast models could be improved and quantitative forecasts issued.

Several ice detectors have been developed and are being used and/or being tested on helicopters (Adams, 1978), small aircraft (Newton, 1977), and transport category aircraft, e.g., L1011. The Environmental Research Laboratories are investigating improved instrumentation. It is desirable that available instrumentation be adapted to provide at least LWC and OAT to the pilot. Eventually, this data could be made part of an aircraft weather observation system that would transmit the information to a forecast office. This information would include, at a minimum, time, height, location, temperature, pressure altitude, or altimeter setting and wind. Such information would be of direct use to the forecaster as well as contribute to the preparation of a much needed route icing climatology.

ICING CONDITIONS IN CLOUDS

There is no existing data base relating types of clouds, sections of clouds, or heights above cloud bases to LWC, OAT, and D_o. Such a data base, in conjunction with the known weather conditions, would assist the forecasters in providing the improved quantitative forecasts.

TIMELINESS OF FORECASTS

Currently, forecasts, including those for icing conditions, are issued 3 times a day. They are updated as new data indicates that changes are warranted. With the advent of AFOS, the NWS will be in a position to provide forecasts every 2 hours for 4-hour periods. Since 95 percent of flights have a duration of 4 hours or less, forecast of 0-4 hours is an important step to meet pilot demands for improved forecasts. More frequent forecasts are part of a plan for improving aviation weather forecasts (Crisci, 1978).

ICING FORECAST MODELS

The AWS has an icing forecast model that can be adopted operationally whenever LWC becomes a regular reporting parameter.

The availability of LWC reports on a regular basis will allow forecasts of the probability of icing conditions utilizing the technique of Model Output Statistics.

The University of Dayton is developing a dynamic model for the forecast of frost, i.e., hoar frost (Dietenberger et. al., 1978). It utilizes conventional data and will be available for operational use in about 2 years.

SUMMARY

Improvement in icing forecasts are required. It can be achieved by obtaining a quantitative data base through development of airborne instruments to measure and transmit at least LWC and OAT. Changes are required in the definition of icing conditions.

RECOMMENDATIONS

Develop, test, and implement airborne automated measuring systems that provide quantitative values of LWC, OAT, and possibly D_0. Initiate efforts within the government to change the qualitative terms of icing conditions -- trace, light, moderate, and severe -- into quantitative values.

Improve the icing forecasts on the basis of a critical review of current forecast techniques and, as quantitative data becomes available, develop improved forecast models utilizing this data.

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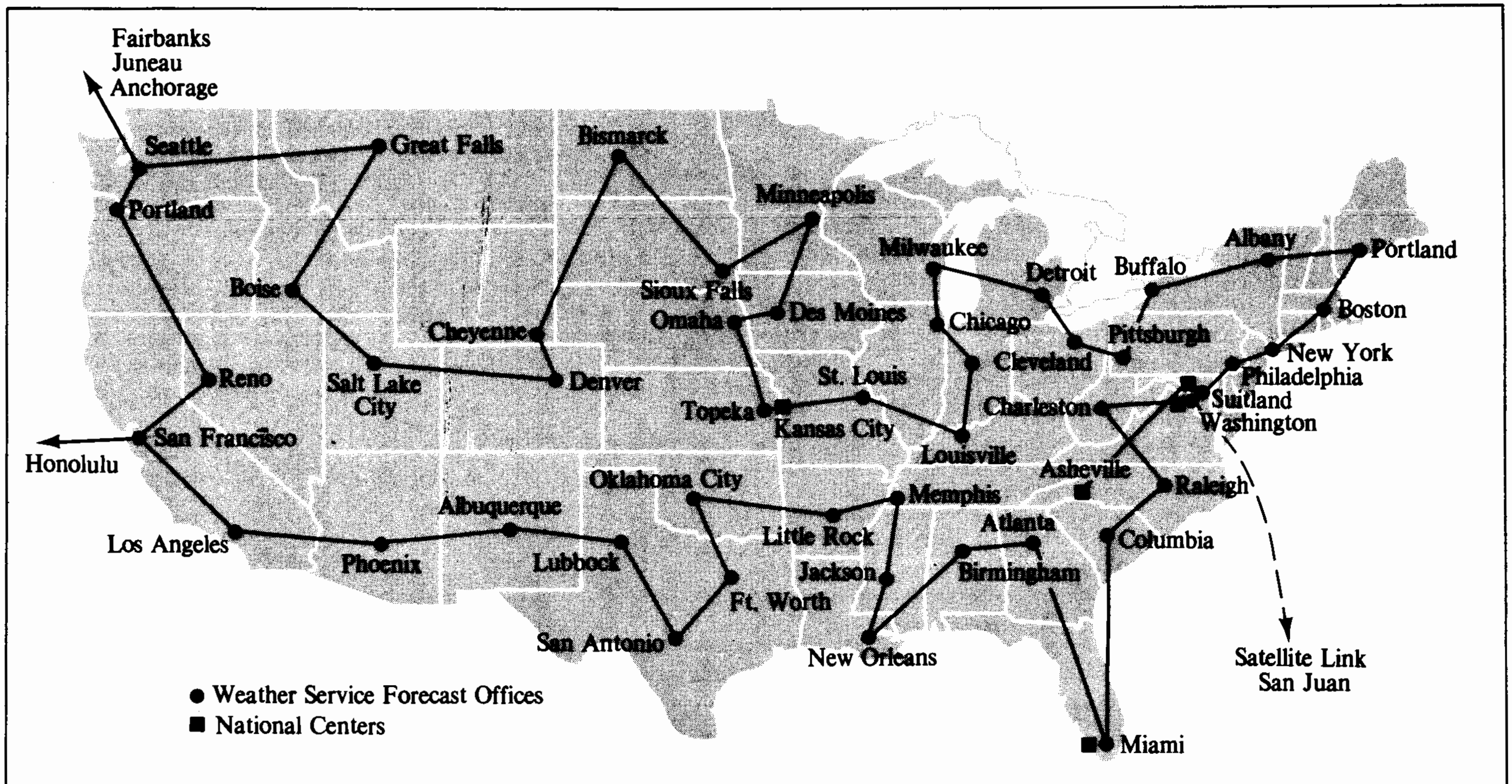
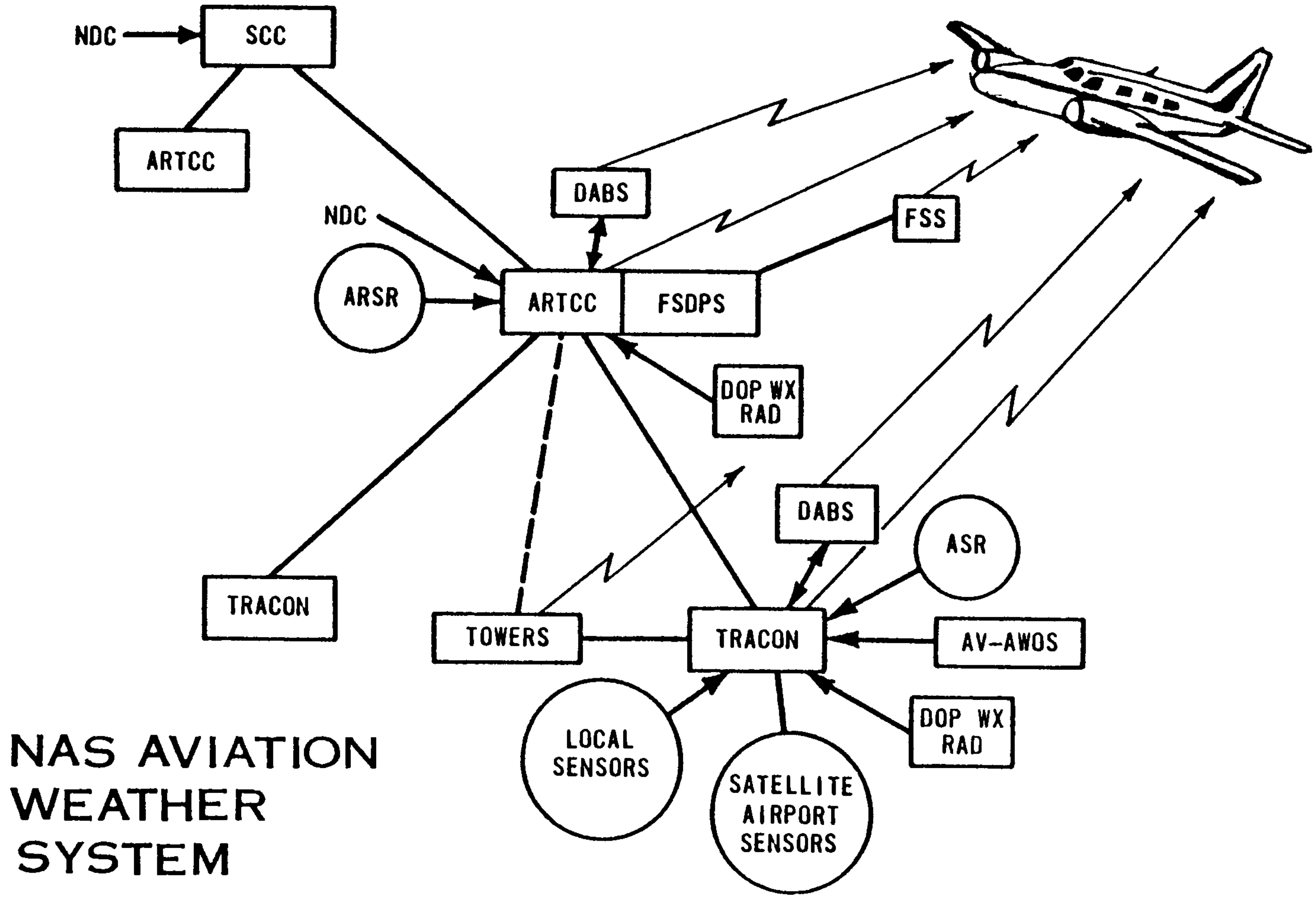


AFOS National Distribution Circuit "Computers talking to computers"

FIGURE 1.



NDC - National Distribution Circuit; ARTCC - Air Route Traffic Control Center; ARSR - Air Route Surveillance Radar; ASR - Airport Surveillance Radar; FSS - Flight Service Station; FSDPS - Flight Service Data Processing System; DOP WX RAD - Doppler Weather Radar; DABS - Discrete Address Beacon System; TRACON - Terminal Radar Control.

FIGURE 2.

SUMMARY REPORT - SYSTEMS DEVELOPMENT COMMITTEE

Richard L. Kurkowski
NASA Ames Research Center

INTRODUCTION

The Systems Development Committee (hereinafter referred to as DEV) met with the five other committees for one and one-half hour sessions in order to try and determine the needs regarding the aircraft icing problem and then to suggest ways to meet these needs. The objective of the DEV Committee was to assess the adequacies of and deficiencies in icing knowledge as they pertain to

(1) Fixed wing or rotary wing ice tolerant design

(2) Ice warning and protection systems design

(3) Certification and simulation

(4) Piston and jet engine design with a view toward improving flight safety, confidence, and operational reliability in icing conditions

There was no question that the main concern of the majority of the workshop attendees was the problem of operating rotorcraft safely in icing conditions. The helicopter has been designed mainly for VFR operations. Now the users (civil and military) are asking for icing operations certification, at least to a "light" ice level. However, no certification regulations exist at present for helicopters operating in icing conditions. The French have certified a helicopter for "all weather operations" using the fixed-wing FAR 25 Appendix C as their criteria. This approach may penalize the efficiency of the system design. The anti-ice and deice systems must be designed for low weight, low power, and low cost, especially for civil applications.

NEEDS

The deficiencies and needs were identified and prioritized by the DEV Committee for various classes of aircraft: rotary wing, fixed-wing low speed, high-performance fixed-wing transport, and high-performance fixed-wing military. In decreasing order of importance the needs are as shown in table I for the various aircraft classes.

As would be expected, there is quite a bit of repetition in the needs for the various classes of aircraft, with slight differences in priorities and emphasis. The overall general needs can be summarized as follows:

(1) A better definition of the icing environment

(2) Improved icing certification criteria

(3) Standardization of certification test procedures

(4) Improved facilities for research tests, development tests, and certification tests -- both ground based and airborne

(5) Improved instrumentation

(6) Improved analytical tools for system design

(7) Central point of aircraft icing expertise

The "bottom line" for all classes is the need for low cost, low weight, low power, and highly reliable ice protection systems.

TECHNICAL APPROACH

For commercial jet transports, the needs have pretty well been met, and accident records show only one fatal crash (due to pitot icing and false crew instrument interpretation and control action). However, continued attention and refinement must be given to the future designs of this class of aircraft. Current icing problems relate mainly to the other classes of aircraft.

The DEV Committee interacting with the other committees attempted to determine the technical approaches which would help meet the needs described in the preceeding section. In general, the systems which can be considered sensitive to icing are the following: engine inlet induction system, propellors, rotors, anti-torque rotors, wings, antennas, flight control system, wind screen, air data system, fuel vents, and environmental systems.

Each system and each aircraft must be carefully considered in the design stage if the aircraft is to be certified for "flight in known icing conditions," and appropriate tests performed to validate the design. Some general design information can carry over from one aircraft to the other. But the broad questions are better definitions of the environment, standardized instrumentation, improved analytical tools and certification requirements, data base for icing design, and improved facilities. Technical approachs to some of the needs in these general areas are now outlined.

General Design Area

<u>Engine inlet - induction system</u>. - Work is needed for jet engine inlets, especially under mixed icing conditions. Ice has been observed to form in the high velocity portions of the inlet downstream of the heated inlet leading edge. New, very high bypass rate engines, especially when operating in extended holding pattern circumstances, result in icing problems, and the designer needs to

consider this. Aft-mounted engines are vulnerable to FOD (foreign object damage) from ice shedding. Large-scale icing tests must be used to answer this question. (One good argument for large-scale icing test wind tunnels.)

Induction icing, especially for general aviation aircraft with float-type carburetors, is a serious problem. Potential solutions to the problem include fuel additives, pressure carburetors, fuel injection, and automatic carburetor heat system. Because of its low cost and high reliability (normally), manufacturers hesitate to do away with the float-type carburetor. Of all the possible remedies just mentioned, the fuel additive may be the cheapest reliable solution if it is added at the refinery. Further work on this approach is required. For example, the sensitivity of engine and fuel system seals to new additives must be carefully tested. (Industry, Government.)

Propellers. - Propeller deicing is the first deice system opted for by general aviation owners. Adequate systems exist, but if new technology could reduce the cost it would help to provide greater numbers of partially protected aircraft. For new design composite propellers, the deice system should be an integral part of the propeller giving a nice smooth propeller surface. Further work in this area is required, both on the deice system and in materials research. (Industry, NASA.)

Advanced propellers such as the Prop-Fan being tested for advanced turboprops is still an unknown as far as icing is concerned. Research and tests are needed. (Industry, NASA.)

Rotor systems. - The sensitivity of rotor blades to icing is now well enough known to provide data for efficient (low weight, low power, low cost) designs of rotor deice or anti-ice systems. Large helicopters with large rotors seem to be more tolerant. A detailed data base should be generated to allow efficient designs to be made. Because of the lack of data, current approaches to the problem have to be too conservative. Systematic research and tests of systems in addition to electrothermal, such as microwave, should be conducted. The test program as proposed by the Army Research and Technology Laboratory at Fort Eustis is a recommended approach. (NASA, DOD, Industry.)

Definition of Environment

Recent data from MBB in Germany was discussed where values of liquid water content (LWC) plotted against liquid water median droplet size and temperature showed LWC values approximately twice as great as the old U.S. data. Resolution of this apparent conflict is required. (Instrumentation differences may account for some of the difference.) Additional data should be gathered as is planned by the United Kingdom. Atmospheric icing data will be obtained at 2500-foot increments from sea level to 10,000 feet and temperatures of $+5^{\circ}$ to -30° C. The lateral and vertical extent of icing will be documented. More programs of this type should be instituted. In addition to dedicated programs, a wealth of data could be gathered by instrumenting some of the domestic and international jet transport fleet. (Meteorological Office (U.K.), Industry, FAA, NASA, DOD.)

Certification

Certification criteria. - As noted earlier, there are no civil ice regulations for rotorcraft. Civil helicopters have been certified in France using fixed wing regulations (FAR 25, App. C) and testing. They feel that this is a conservative approach. The United Kingdom is certifying its helicopters for certain temperature and altitude bands, and this allows a "tailored" or partial icing clearance approach. They validate their systems using ground-based facility testing and verification in natural icing flight tests. The FAA needs to collaborate with France, England, and other countires to try and set a rational set of regulations for helicopter icing certification. The FAA and DOD should also work together, since their icing protection needs are similar.

Standardization. - The parameters used for aircraft design, certification, and operations for icing conditions should be standardized. The suggested parameters are temperature, liquid water content, extent, and droplet size, although droplet size is probably not needed for operations. Certification within different FAA regions should be standardized. This includes design requirements, test procedures, and validation (demonstration) testing.

Analytical Tools and Data Base

The aircraft designer needs an improved data base and computer analysis tools for icing system designs. An agency such as NASA is required to act as a center for knowledge in the aircraft icing area, do basic research and testing, and provide consultation to industry as needed. Techniques such as computer-generated ice shapes and dry air testing of add-on ice shapes show great promise as research tools and should be carried on.

Instrumentation

Ice accretion and buildup. - Pilots of rotary wing aircraft are currently using direct visual indications of ice rate and buildup (e.g., ice formations on wind shield wipers, sponson ice (H-3)). In daytime conditions this is a good indicator of fuselage ice conditions, but it does not tell the pilot anything of the rotor blade ice condition. Onboard instrumentation is required of ice rate, ice buildup, liquid water content, and temperature. Knowledge of rotor ice buildup and rate is required. Improved accuracy of instruments is also required, since the current accuracies are about 25 percent. (NASA, DOD, Industry.)

Induction ice. - Current carburetor ice detectors are not reliable and better systems are needed. Reliable readout of carburetor air temperature would be helpful for present systems. (Industry.)

Facilities

The designer would like to develop and prove system performance in ground-based facilities such as wind tunnels before validating with full-scale flight tests, either simulated (tanker/spray rig) or natural. The development and certification testing in natural icing conditions is at best a frustrating and costly experience. Therefore, techniques for simulating icing conditions will continue to be required and improved. For inflight tanker - spray rigs, improvements are needed in droplet size control, cloud size, and duration. In wind tunnels, a capability for full-scale icing tests is desirable.

The point was made that engine data are next to impossible to scale and therefore full-scale engine tests are defintely required. (NASA, DOD, Industry.)

RELATED TECHNOLOGY ASSESSMENT

An earlier assessment of icing technology by the Society of Automotive Engineers (SAE) was brought to the attention of the committee. The Statement of Work proposed by an SAE panel covers many of the points brought out in the present workshop. A copy of their report (dated May 1978) is included in this report (appendix A). It does not have the emphasis on rotorcraft that the subject workshop had, but it does represent a good nucleus of the work effort which should be carried out.

TABLE I

PRIORITY OF AIRCRAFT ICING PROTECTION TECHNOLOGY NEEDS

NEEDS	CLASS OF AIRCRAFT: LOW SPEED ROTARY-WING	LOW SPEED FIXED-WING	HIGH PERFORMANCE FIXED-WING CIVIL TRANSPORT	HIGH PERFORMANCE FIXED-WING MILITARY
Definition of icing environment particularly at low altitudes including probability data.	1	1	1	1
Civil helicopter icing certification criteria.	2			
Improved civil aircraft certification criteria (FAR Part 23).		2		
International standards for civil icing certification criteria.			2	
Civil helicopter partial (light) icing certification criteria.	3			
Civil fixed-wing partial (light) icing certification criteria.		3		
Icing specification criteria and "tailored" icing specification criteria.				2
Standardization of certification test procedures among FAA Regions, civil and military, U.S. and other countries.	4	4	3	

TABLE I

PRIORITY OF AIRCRAFT ICING PROTECTION TECHNOLOGY NEEDS

CONTINUED

NEEDS	CLASS OF AIRCRAFT: LOW SPEED ROTARY-WING	LOW SPEED FIXED-WING	HIGH PERFOR-MANCE FIXED-WING CIVIL TRANSPORT	HIGH PERFOR-MANCE FIXED-WING MILITARY
Improved large-scale facilities for research, development, and certification testing (including validation of facilities for certification testing) -- wind tunnels, ground-based spray rigs, in-flight spray rigs.	5	5	4	3
Basic design data including ice accumulation shapes, extent, and aerodynamic effects.	6 [a]	7		4
Instrumentation for onboard information on ice acretion rate and total buildup.	7 [b]	6	5	5
A central point of aircraft icing expertise for basic research and consultation (NASA).	8	8	6	6
Low cost, low weight, low power rotor ice protection systems.	9			
Low cost induction icing solution.		9		

FOOTNOTE:

a -- including potential correlation of fuselage and rotor ice accretion

b -- on the airframe and the rotor itself

TABLE I

PRIORITY OF AIRCRAFT ICING PROTECTION TECHNOLOGY NEEDS

CONCLUDED

NEEDS	CLASS OF AIRCRAFT: LOW SPEED ROTARY-WING	LOW SPEED FIXED-WING	HIGH PERFOR-MANCE FIXED-WING CIVIL TRANSPORT	HIGH PERFOR-MANCE FIXED-WING MILITARY
Criteria for effects of lightning, static charge, sand and dust erosion and hail on ice protection equipment.	10			7
Improved analytical tools for predicting ice buildup and shapes using fluid dynamics theory, and methods for predicting large-scale performance under icing conditions based on small-scale, icing test data.	11	10	7	8

SUMMARY REPORT - CIVIL OPERATIONS COMMITTEE

Lt. Col. Thomas C. West
Federal Aviation Administration

SUMMARY

During the deliberations of the Civil Operations Committee, the members attempted to assess the impact of aircraft icing from an operations point of view and identify areas of research which would improve operational viability. It was generally agreed that major deficiencies exist in the area of helicopter ice protection and that, from an economic standpoint, the general aviation population is impeded by not having cost effective ice protection systems capability.

INTRODUCTION

During the initial meetings of the Committee, the membership attempted to define general mission requirements according to priority; identify the major driving factor for each; and finally, consider whether or not a viable alternative existed for mission accomplishment. These mission requirements shown below were addressed to the other committees during joint deliberations as a frame of reference to underline the need for development of the icing technology to serve the general aviation and helicopter population:

MISSION	DRIVING FACTOR	VIABLE ALTERNATIVE
Search and Rescue	Saving Life	None
Mercy Mission	Saving Life	None
Remote Site (Including Offshore)	National Interests Revenue	Delay/Cancel
Scheduled	Revenue	Cancel/Delay/ Other Mode
Unscheduled	Revenue	Delay
Pleasure	Morale	Delay/Cancel

The general conclusion was drawn that forecasting capability in the area of icing left much to be desired and required major effort to rectify. Finally, an attempt was made to list aircraft systems and components which are particularly sensitive to ice accretion as candidates for research. They were as follows: induction systems (particularly carburetors), propellers, wings, antenna, flight controls, wind screen, air data systems, environmental control systems, and fuel vents.

As was true of all committees, the Civil Operations Committee interfaced with the other committees during the 2-day period in an attempt to define technology or other deficiencies in the area of icing as it pertains to civil operations. It was generally concluded that the advent of helicopter instrument flight rules operations was the major driving factor from a technology standpoint which has rekindled the current interest in icing research. This was not to say that problems do not exist in the general aviation area. In fact, considerable discussion related to carburetor icing with the current general aviation engines. It was concluded that, if cost was not a factor, the carburetor icing problem would be resolved. The urgency in the helicopter area stems from its formal entry into the icing meteorological conditions environment in significant numbers and its proposed use in areas where icing will be a major impeding factor. This is currently true in the North Sea operations and will become true with expanded operations off the East Coast of the United States and in Alaska.

The conclusions of the Civil Operations Committee were made in the form of identifying deficiencies and an attempt to define research needs related thereto. These are given below:

Deficiencies:

- Understanding of icing phenomenon on rotor systems far from complete.
- Ability to define and forecast the environment hardly an exact science.
- Regulations and criteria data vague and controversial and nonexistent in rotary wing area.
- System and certification costs are high and prohibitive in some cases.
- Communication across the functional communities from the design engineer to the pilot is garbled, confusing.

Research Needs:

- Better understand sensitivity of rotor systems to ice:
  - Change in aerodynamic characteristics.
  - Autorotation capability.
- Redefine the low altitude icing envelope taking maximum advantage of current data.
- Devise a more comprehensive and responsive forecast data acquisition, processing, and dissemination system:
  - Delete subjective definitions.

    - Add airborne observation.
    - Take forecaster out of the decision making process.
- Review regulations based on current technology:
    - Clarify.
    - Update criteria.
    - Develop regulatory and advisory material to accommodate rotary wing aircraft.
- Reduce systems costs for all aircraft through:
    - Design improvement to include induction systems.
    - Investigation of other ice protection techniques.
    - Development and application of simulation techniques and facilities to conduct icing research and certification.
- Devise a common objective language to be used by all and a system which, by each aircraft, would have its own icing flight envelope:
    - Defined by the designer.
    - Certified by the regulator.
    - Used by the pilot in conjunction with objective forecast to determine his own aircraft's icing capability.
- Investigate the feasibility and applicability of limited icing operations approval with emphasis on air traffic control implications.

Included in the Committee report is a brief dissertation by Mr. Richard L. Newman, a member of the Civil Operations Committee. In his forwarding letter, Mr. Newman characterizes his comments as a "minority report." Quite the contrary to this characterization, I found his submission, for the most part, to be supportive of the Committee report. More importantly, however, I found his points well made and of distinct value to the Committee report. For this contribution, I would like to express thanks to Mr. Newman on behalf of the Committee. The following two pages include Mr. Newman's comments.

The draft report for the Civil Operations Committee of the Icing Specialists' Workshop is misleading in its emphasis on ice protection for rotary-wing aircraft. The problem for small, non-air carrier airplanes is very severe. While much of the research funding today is being spent on rotor ice protection, we should not conclude that only helicopters need ice protection research and development (R&D).

The problems of the small (less than 20,000 pound) airplanes are primarily cost related; however, the state-of-the-art in ice protection for these airplanes is 40 years out of date. Most airplanes in this weight class, including several jets, still use pneumatic deicer boots. If they are to have adequate capability to fly in icing conditions, more effective systems must be developed. Boots are simply not very effective and also require considerable pilot skill to be used properly. To quote Robert Buck, ". . . I've never seen a situation where I couldn't have made it without boots and most of the times I've turned them on have been for amusement." (Weather Flying, p. 188)

The urgency to address both helicopter and small airplane operations from an icing point of view comes from the upsurge of instrument flight rules (IFR) operations. The helicopter is new to the icing meteorological conditions arena. The small airplane, while not new to IFR flying, is being used more and more for corporate, business, and scheduled transportation. We can no longer categorize the small airplane as "some doctor in a Tripacer." The class of airplanes that we are considering is sophisticated, expensive, and, in some cases, turbine powered and pressurized. They need cost effective ice protection systems.

The Committee's recommendations should include:

I. Partial Icing Certification. The operational implications of limited (i. e., less than full Federal Aviation Regulation (FAR) 25) ice protection certification should be evaluated. What will happen if aircraft are approved for flight with less than full icing protection? The study should consider dispatch rules, crew options, airborne instrumentation requirements, forecasting improvements, air traffic control constraints, etc. While this has been talked about mainly in terms of helicopters, it would also apply equally to fixed-wing airplanes in non-scheduled service.

In conjunction with this evaluation, we must seek to answer the question of what levels of icing severity are appropriate for the various types of aircraft in terms of altitude and temperature limits, icing intensity, and geographical limits. The differences between commercial (FAR 121, 127, or 135) and private operations (FAR 91 and 91, Subpart D) should be considered as well.

Any study of limited ice protection certification should examine the record of British Airways' helicopters operating in the North Sea.

II. Ice Protection Development. The question here, put very simply, is "Can inexpensive, effective ice protection systems be developed?" Admittedly, the problems of rotating airfoils are quite different than for non-rotating surfaces. Nevertheless, R&D in both areas must be carried out.

The problems of ice protection for a rotor system (or for a propeller) should be studied in some detail to determine the mechanism of ice formation and accretion, the penalties associated with ice formation, and the best means of protecting the surface.

While the fixed-wing aircraft requires some additional research in terms of ice accretion, the primary effort here should be to determine the aerodynamic penalties, then evaluate the tradeoffs for the various means of ice protection: boots, heated wings (from various sources of heat), icephobic coatings, deicing fluids, etc. Studies of the best geometries to minimize the adherence of ice and to minimize the aerodynamic penalties are required also. As was pointed out, it is not always necessary to protect an airfoil; often, the most cost effective ice protection is to have a design that tolerates ice (such as the B-707 tail). These studies should consider both the incorporation of ice protection in the original design and as an add-on. Perhaps the popularity of pneumatic boots stems from the ease of retrofit.

One subject that should not be passed over lightly is the idea of an expendable anti-icing coating that could be applied just before flight in icing conditions. Even if only a short duration of protection could be achieved, an effective coating might be feasible for both rotary-wing and fixed-wing aircraft.

III. Forecasting. I am sure that all in attendance at the conference would agree that prediction of icing leaves much to be desired. Certainly, forecasting technology must be improved. To achieve this, the first step must be to discard the obsolete icing definitions and replace them with, at first, a crude estimate of the rate of accretion. One question that must be answered is, "Will better pilot reports and airborne instrument packages (for calibrated PIREPS) help provide useful feedback to improve the forecasting state-of-the-art?"

IV. Pilot Education. The question was raised at the conference, "Do pilots have adequate understanding of the physics of ice formation?" During several informal discussions, members of the Committee felt that more meteorology knowledge on the part of applicants for an instrument rating might be in order. It was also suggested that educational materials might be able to help improve pilot knowledge. One must be careful, however, not to seemingly encourage pilots to fly in icing conditions.

V. Engine Induction System Icing. The subject was passed over by the Committee with the consensus that it was a pilot education problem. However, judging by the discussions of induction system icing accidents, this decision by the Committee may have been unwise. Many inlet icing, ice ingestion, or carburetor ice accidents were discussed. I submit that further research is needed, not merely passing off the problem as "pilot error." This problem applies across the board to all aircraft: light airplanes, jet transports, and helicopters.

SUMMARY REPORT - MILITARY OPERATIONS COMMITTEE

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OBJECTIVE

The first task was to define the objective of the Military Operations Committee. The following statement representes the concensus after considering at least 15 individual assessments of the objective: "To define the operational environment of various military aircraft with a view toward identifying ice protection systems (complete or partial) required to insure mission accomplishment." The key portions of the stated objective are operational environment and mission accomplishment.

OPERATIONAL ENVIRONMENT

The committee, recognizing its limitations to define the environment in meterological terms, defined the operational environment geographically as the NATO theater of operations, chiefly central Europe and the North Sea. The definition was next addressed in operational parameters as follows:

Army and Air Force missions: from the surface to 500 feet above ground level for wartime and surface to 10,000 feet AGL in peacetime

Navy missions: from sea level to 10,000 feet AGL for both war and peacetime missions

The Military Operations Committee recognized the need for meteorological data to describe this operational environment in terms useful to researchers and developers working on ice protection systems and to the military operators and decisionmakers called on to operate there in peacetime or fly there in war. This subject was discussed at length with both the Meteorological Research and Icing Forecasting Committees. Other operational environments were considered in light of the military justice term "lesser included offenses." Obviously, the U.S. Army, Navy, Air Force, Marine Corps, and Coast Guard are called on to fly in a wide variety of climatic conditions throughout the continental United States and throughout the world. The U.S. policy highlights the role of NATO first. From an ice-protection viewpoint, central Europe and the North Sea environmental conditions are considered extreme enough that successful operation there in icing conditions should permit winter military operations in a wide geographic area of the world.

MISSIONS

The military missions are wide ranging, in fact, virtually without limit other than one's imagination. The committee chose the following three as key to NATO operations:

Anti-tank
Search and rescue
Anti-submarine warfare (ASW)

Again the technique of "lesser included offenses" was used. For helicopter operations, the chief interest of the committee, the three missions represent both the most important and most difficult for the Army and Marines, Air Force, Coast Guard, and Navy, respectively. The first two missions provide the wartime operational envelope of surface to 500 feet AGL. The third mission provides the Navy operational envelope of sea level to 10,000 feet AGL.

HIGHLIGHTS OF WORKSHOP SESSIONS WITH OTHER COMMITTEES

The Military Operations Committee met with each of the other five committees. The highlights, at least from the military viewpoint, are now presented in the order in which the two-committee workshops occurred.

System Development Committee

The two most important systems to be developed and fielded on miliary helicopters are ice detection and rotor blade ice protection. The systems developers are working in both technological areas and are aware of the military requirements to keep the performance penalties (weight, size, power requirements, etc.) extremely low to insure that ice protection does not degrade the helicopter's role in mission accomplishment. There is a clear role for NASA in developing these technologies as well as a clear role for the military services to cooperate with NASA and one another in the engineering development and fielding of systems which respond to stated military requirements. The U.S. Army developments such as the electrothermally heated blades for the UH-60 BLACK HAWK and AH-64 Advanced Attack Helicopter and the UH-1 partial ice protection kit were discussed. One can neither view these developments, excellent as they are, as the complete answer nor can one ignore the current helicopter fleets of the military services. There is much work to be done in systems development.

Meteorological Research Committee

The key point discussed with this committee is the need for climatology data in the NATO theater. The climatology data must reflect such parameters as liquid water content, air temperature, and droplet size along with the frequency or probability of occurrence. These data are essential to both the systems developers and the military requirements writers. There is no ice protection system which has zero performance penalties associated with it. The military decisionmaker needs the climatology data against which to consider the performance penalties and determine the enhancement of mission accomplishment through ice protection. The Military Operations Committee was gratified to learn of the United Kingdom Meteorological Office study to collect such valuable meteorological data.

The work of two NATO panels under the NATO Army Armaments Group was noted. AC/225(Panel X), Interservice Group on Air Vehicles for Tactical Air Mobility, established a Subgroup on Helicopter Icing. The United Kingdom is hosting the Subgroup Symposium on Helicopter Icing in London on November 6-7, 1978. The second panel involved is AC/225(Panel XII), the Meteorological Panel. Panel XII is working on gathering meteorological data in central Europe to be provided to Panel X.

Icing Forecasting Committee

The Forecasters readily acknowledged that icing forecasts had not improved in the last decade. Within the United States, the Federal Aviation Administration (FAA) is improving the automated systems so they will provide more rapid information to aircrew members.

The need for automated observation instrumentation for icing and other weather factors was agreed on by both committees. A parallel need for onboard instrumentation to provide automatic readouts to replace the highly subjective pilot's report (PIREP) was supported enthusiastically by both forecasters and military operators.

The future of icing forecasts lies in providing quantitative information such as temperature and liquid water content in a probabilistic way so that the operator becomes the decisionmaker rather than the forecaster. Such quantitative/probabilistic forecasts are necessary for pilots, systems designers, and military commanders.

Icing Research and Facilities Committee

The Facilities Committee started this joint session with a summary of its three prior meetings by addressing such topics as the need for improved forecasts, use of partial ice protection systems, certification requirements, new designs for small or low performance aircraft (as compared to high performance transport aircraft), the problems associated with searching for natural ice in systems development and testing, and the needs in research technologies and facilities.

The research needs included such topics as the lack of a clear role for NASA, its corollary need of a focal point in aircraft icing research, updated technology, standardization requirements, correlation of diverse data, redefinition of the atmosphere for meteorologists and systems developers, instrumentation requirements, importance of onboard ice detection, and the need to understand the physics of icing and mixed icing conditions.

The facilities envisioned by both groups included a larger tunnel to permit full-scale testing and assist in the problems of scaling associated with current tunnels. Both groups endorsed the requirement for a transonic tunnel, especially useful for work on the outer portions of rotors.

The existing tanker aircraft with inflight spray rigs were discussed. The problems associated with the often futile search for natural ice in flight testing highlights the requirement for inflight systems which produce artificial ice. Improved inflight systems are needed to support research, systems development, and flight certification.

There was an overwhelming consensus that NASA should take the lead in the United States to provide the required facilities and assume its proper role as focal point in aircraft icing research.

Civil Operations Committee

The Civil Operations Committee led off with a summary of its operational mission requirements: search and rescue, mercy missions, remote site operations (off-shore exploration or geological survey), scheduled and nonscheduled passenger - freight missions, and pleasure flyers. It also concurred with the Military and Forecasters Committees in the need for improvements in icing forecasts.

The two groups discussed the differences and similarities in operation. Consensus was strong in the following areas:

(1) The FAA should make better use of U.S. military data - technology developments in ice protection systems.

(2) The FAA should use military and civil data from other countries to assist in certification actions by FAA.

(3) Better military-civil information exchange is imperative.

(4) Better international information exchange is needed.

SUMMARY

The Military Operations Committee stated its objective as follows: "To define the operational environment of various military aircraft with a view toward identifying ice protection systems (complete or partial) required to insure mission accomplishment." The key portions are <u>operational environment and mission accomplishment</u>.

The operational environment is the NATO theater of operations, chiefly central Europe and the North Sea. The three helicopter missions key to NATO are anti-tank warfare, search and rescue operations, and anti-submarine warfare. From these three missions the following operational parameters were derived: Army and Air Force operations from the surface to 500 feet AGL in wartime and surface to 10,000 feet AGL in peacetime, and Navy operations from sea level to 10,000 feet AGL in both war and peace.

Without summarizing the five meetings with the other committees, it is correct to highlight the one thread common to all sessions -- there is a clear role for NASA in the area of aircraft ice protection technology, especially as such technology is related to helicopters. This focal point role for NASA is evident in the research facilities requirements.

In the NATO arena the Military Operations Committee was pleased to learn of the work being done by the United Kingdom Meteorological Office. The November 6-7, 1978, Helicopter Icing Symposium in London hosted by the United Kingdom under the auspices of AC/225 (Panel X), Interservice Group on Air Vehicles for Tactical Air Mobility and its Subgroup on Helicopter Icing, promises to provide an excellent exchange of information among NATO members in a field critical to insuring combat success.

RECOMMENDATIONS

Intergovernmental cooperation is required to implement most of the following recommendations. This need was articulated well by Richard Adams in his keynote remarks. The problems are great, the funding resources are not, and cooperation is imperative.

1. The two most important systems under development for military helicopters are ice detection and rotor blade ice protection. The U.S. Army is working in both technological areas; however, there is a clear role for NASA.

2. Climatology data for the NATO theater of operations are needed for systems development work and military planning and operations. This area requires international cooperation. Preliminary efforts are underway through the NATO Army Armaments Group, AC/225 (Panel X), and AC/225 (Panel XII). AGARD involvement is under consideration.

3. Automated weather observation instrumentation and onboard instrumentation with automatic pilot and ground forecaster readouts are needed to improve icing forecasting.

4. Icing research and facilities is the area needing greater NASA involvement and direction. In the previous Icing Research and Facilities Committee section specific facility needs were addressed; however, this area is too important for such cavalier treatment. NASA is encouraged to give this area further study and support so that these critical facilities be developed expeditiously.

5. Communcations among the many interested parties must be improved. NASA is to be commended for this NASA Lewis workshop with its government, industry, and foreign participants. NASA's role as the leader in providing needed information exchange must be strengthened.

SUMMARY REPORT - ICING RESEARCH AND FACILITIES COMMITTEE

Milton A. Beheim
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INTRODUCTION

During the 1940's and early 1950's, a fairly active icing research activity in the United States produced many of the tools being used today to provide aircraft ice protection. For example: 1) flight test programs were used to define a "national icing environment" which is the basis for current design criteria and flight worthiness regulations, 2) an icing research wind tunnel was developed at NASA/Lewis (which is still the largest tunnel with icing capabilities in the United States) and is still used extensively for certification purposes, 3) an icing research program was executed which defined the physics of ice formation in sufficient detail that the important parameters were identified and simple analytical procedures were verified, and 4) ice protection concepts were evolved based principally on mechanical devices and on thermal devices employing heated air or electric resistance heaters.

With the advent of turbine transport aircraft, relatively large quantities of heated, high pressure air were readily available and rapid progress was made in achieving satisfactory solutions to the icing problems. The government research role declined rapidly in the late 1950's while the principle aircraft companies developed increasingly sophisticated experimental and analytical methods to achieve certification of the new generation of jet powered transport aircraft. These newer techniques were generally limited in scope however to specific configurations which were of interest for certification. With this class of aircraft, continuing efforts are being made to minimize the amount of icing protection that is required, thereby minimizing initial cost and operating expense. Consequently, more precise definitions of natural icing conditions and improved test facilities are needed to decrease these costs and the costs of certification.

In recent years there has been a growing interest in achieving all-weather capability for entirely different types of aircraft such as rotorcraft, general aviation, and cruise missiles. These aircraft have different types of power plants than the CTOL transports and large quantities of heated air are not readily available. Hence, ice protection can be much more difficult to achieve and alternate methods are sought. Further into the future this interest in icing protection will be broadened to include VTOL and supersonic civil aircraft. Consequently the configurations of practical interest go far beyond those which were ever envisioned during the icing research program of the 1940's and early 50's. For example, new air foil shapes and high lift devices, new inlet and fan configurations, rotor and propeller geometries, and new materials and structural concepts.

In view of this increasing need for improved icing research and facilities, the committee members addressed the principle issues with a great deal of enthusiasm. Chances for success appear particularly good because of the significant advances already achieved in other related fields such as computational methods, instrumentation, and experimental techniques during the past several years. It was noted that the SAE AC-9 Committee had established a panel dealing with aircraft icing research in 1972 and a final report was completed early in 1978. Since those recommendations were of obvious interest to the present committee, copies of the report were distributed and is appended to this summary (Appendix A).

GENERAL OBSERVATIONS

The committee expressed unanimous concern for inconsistencies in rules, regulations, design criteria, and definitions of terms. Some examples are cited in reference 1. In some extreme cases it even results in the requirement to certify icing protection for flight conditions beyond the flight envelope that can be achieved with the aircraft and for atmospheric conditions which cannot physically exist. These inconsistencies can cause excessive costs and development time, and in some cases may even aggravate the hazards of flight. Many problems could be alleviated if partial certification was permitted for less severe icing conditions. However, it may then be necessary to upgrade forecasting techniques to provide quantitative information particularly on liquid water content.

In civil aviation the icing problem is regarded as being particularly severe for small aircraft not only in terms of weight and performance penalties for ice protection systems, but also in terms of its sensitivity to ice accretion during flight. In fact, the observation was made that it is quite possible that the aircraft aerodynamic design may require specific modifications to minimize this sensitivity. In military aviation the U. S. Army has made significant progress in recent years to provide icing protection for rotorcraft but faces serious funding limitations for further research. The Air Force has a growing interest in icing protection for attack aircraft, and both services share a growing interest in cruise missile protection.

All groups expressed great frustration in attempts to search for natural icing conditions to verify the adequacy of specific aircraft ice protection systems. The cost has proved to be so large (up to $50,000 a flight hour) that only limited objectives can be achieved by this means. The flight tests can insure that something was not overlooked, but the system performance must be evaluated elsewhere such as with analysis, icing wind tunnels, and/or icing tanker aircraft.

The participation of several visitors from other countries was an important contribution to the committee's deliberations. Not only did it provide evidence of a widespread interest in the icing problem, but it also provided a basis for future coordination and cooperation. In particular it was evident that: 1) a significant and well planned effort in icing research has already been initiated in the United Kingdom, 2) France is operating an unusually large wind tunnel with icing capabilities, and 3) Sweden is suffuciently concerned with aircraft accidents caused by icing that exploratory studies have been initiated.

RESEARCH RECOMMENDATIONS

NASA's Role

A NASA role exists in the icing problem just as it does in other areas of aeronautical research. It particularly is obvious that portions of the technology being employed is outdated, that some means to achieve standardization must be achieved, and that a focus must be developed to tie together the diverse activities of the industry and other government agencies. An additional effort is required to provide correlations of results from a variety of sources to achieve as much generalization as possible. These functions have been provided by NASA in many other disciplines and icing needs it too. Another traditional NASA function that is needed in icing research is to disseminate information so that it can be shared by all users, thereby minimizing wasted effort to duplicate other researcher's results. This dissemination is needed through reports, bibliographies, and conferences. Although there are additional icing problems which are outside of NASA's jurisdiction such as in certification and forecasting, NASA may be able to provide a third party service to the other participants in facilitating solutions.

Natural Icing Environment

Although a rather extensive flight program occurred in the 1940's and early 1950's to define the natural icing environment, the committee recommends a redefinition of the icing atmosphere for several reasons: a) the old data are presently extrapolated to an accuracy that is not justifiable because the data base is too limited; b) the old data does not cover a wide enough flight corridor and consequently is extrapolated to low and high altitudes in such a manner that physically impossible conditions can exist; c) instrumentation and data analysis methods have advanced sufficiently that there is doubt regarding the accuracy of the old data; d) knowledge of atmospheric physics has advanced to such a point that it now can provide a useful tool in the conduct of a renewed flight program.

Preparations are underway already in the United Kingdom for such a flight program and a careful evaluation of instrumentation concepts is nearing completion. It would be important to maintain liaison with this effort since the icing environment has global variations that need to be considered in atmospheric modeling. In addition it could aid in achieving broader standardization of criteria and experimental techniques.

Physics of Process

Although the fundamental aspects of ice accretion are fairly well known, there are special situations requiring further study. In particular the effects of varying amounts of supercooling are not clear, and the effects of mixed conditions (of ice and supercooled water) are not well defined. It was commented that the significance of these effects may vary depending upon the aircraft component in question; e.g., inlets vs. wings. Neither effect is presently controlled in artificial icing test facilities.

Correlations of Natural vs. Artificial Ice

It is important that confidence be developed in test methods using artificial ice formations. Opinions were divided on this point: one view was that some ice formations occurring with artificial ice are never seen in flight, and the other view was that excellent agreement exists in comparing ice formations provided that the conditions causing ice to form are truly identical. An apparent lack of correlation may result from inaccurate measurements of the atmospheric icing parameters, from the time varying nature of natural icing conditions, or from an inability to accurately record the shape and density parameters of the naturally accreted ice formations. In general, it was agreed that further correlations would be valuable, particularly for the new geometries of emerging interest discussed in the Introduction.

Criteria for Simulated Ice

Important progress has been achieved in recent years in using simulated ice (plastics and fiberglass) to assess the need for icing protection of specific aircraft components (c.f., reference 2). The potential exists that these techniques could be generalized and their use extended to a variety of additional circumstances besides those studied to date. The committee felt that further refinement could provide an important tool for future aircraft design and certification.

Instrumentation

Although significant advances in instrumentation techniques have already occurred, accepted methods of measurement still differ by as much as 25% in determining basic parameters such as liquid water content in ground test facilities. The problem is even more difficult in flight installations because of space and cost constraints. In either case real time readout was regarded as essential because of the strong sensitivity of ice accretion to small changes in artificial icing test variables and because of the time dependency of the natural icing environment. A research and development effort in this area was strongly endorsed by the committee and was generally regarded to be of such fundamental importance that it merited top priority. The United Kingdom has already initiated work of this nature. Several people also expressed the view that newly emerging instrumentation concepts such as those based on laser technology may prove valuable for this application and additional support was desirable.

Computational Methods

One of the most difficult aspects of applying analytical methods to icing calculations is the fluid mechanics part of the problem. The other aspects are the particle trajectories, the heat transfer effects, and the phase changes. The large aircraft companies have already developed sophisticated means of analysis but their availability is not widespread, particularly for the general aviation industry, In view of the recent progress achieved in computational fluid mechanics, even further improvements in analysis could be developed and the committee was enthusiastic that renewed efforts would have a good chance of success in providing more accurate predictive and design methods. Such an effort to improve existing methods and increase their availability was strongly endorsed.

New Deicing Methods

The most common means of ice protection at the present time is by means of heated high pressure air. Although an interest exists in providing additional refinement of this method, principal research interest is directed to electrothermal methods, to icephobic materials, and to microwave and electroimpulse techniques. This shift in emphasis results because the penalties of using hot air are too large for some aircraft types and these other means of ice protection may prove to be more useable with sufficient development effort. The U. S. Army has been particularly progressive in its support of advanced concepts, but the recent decline in financial resources is resulting in a termination of the effort.

FACILITY RECOMMENDATIONS

Existing Ground Test Facilities

In the United States the largest icing wind tunnel is located at NASA/ Lewis. It was put into operation in the early 1940's and the spray system was modified in the early 1950's. Subsequent work has shown that the icing conditions of the tunnel properly represent a portion of the flight environment but do not duplicate the extreme values of drop size and liquid water content which are of interest for certification and research purposes. In addition to extending the spray system capabilities, more modern instrumentation with real time data displays were recommended. Since the tunnel is limited to sea level operation, high altitude conditions must be simulated by using unnatural icing spray conditions. The validity of this technique is not verified, and the limits in spray system capabilities restrict the flight corridor that can be simulated. It was repeatedly observed that the size limitations of the test section (6' x 9') were a serious constraint for certification purposes and for research on rotating components (e.g., props and rotors). There are applications where a higher speed range (above 300 knots) would also be needed.

It was noted that engine icing test facilities in the United States have generally been kept in a more modern state of operation than the icing wind tunnel.

Future Ground Test Facilities

There was general agreement that it is desirable to have a much larger icing wind tunnel with a greater speed range than presently available. A variable altitude capability is desired. Preliminary thoughts regarding the rehabilitation of the Lewis Altitude Wind Tunnel (with 20' and 45' test sections) and a modification of the Ames 40' x 80' Tunnel to meet some of these objectives were described. The committee expressed an interest in both concepts.

Because of the high costs that are inherent in construction of a very large icing wind tunnel, interest was expressed in exploring unconventional concepts to achieve a similar capability. One such approach to achieving a large ground test icing facility was described which is based on using the large environmental facility at Eglund. Fans are required to provide a directed air flow in what is normally a static test facility. Some questions were raised regarding the drive power requirement, but additional study seemed justified.

Again, it was noted that engine icing test facilities are already proceeding to larger sizes. In particular the large new ASTF which will be located at AEDC in Tennessee has this capability.

Flight Test Facilities

Over the years a variety of different tanker type aircraft have been developed to provide a water spray at altitude which then creates an artificial icing environment for the test aircraft. These tanker aircraft include jet and prop powered large aircraft, large helicopters, and small general aviation aircraft. Costs of operating these tanker aircraft vary from $200 to $4000 per flight hour. Some views were expressed that these flight facilities were oversold and actually the spray zone was too limited in size and inadequate in uniformity and in range of drop size and liquid water content. The opposing views were also presented that the test conditions were adequate and offered capabilities in complete system testing that could not be matched in ground facilities. There was general agreement however that the task of each type of facility was complementary to the other and both were needed. Additional effort was regarded as necessary to define the limits of each technique so that future efforts in improving these facilities could be properly directed and their relative merits could be delineated.

One of the problems identified with the present stable of icing tankers in the United States is that their availability is more limited by organizational and jurisdictional boundaries than are the ground test facilities. For example, a well developed and proven tanker aircraft operated by one branch of the military service may not be readily available for use by other government agencies or the civil industry.

SUMMARY

The committee attempted to prioritize the various recommendations. The results were as follows:

Research

1. Develop improved instrumentation/measurement techniques

2. Re-evaluate atmosphere and design criteria

3. Improve and verify simulation/extrapolation/similitude techniques

4. Achieve improved analytical methods

5. Advance methods for accretion modeling - artificial/simulated

6. Develop improved ice protection concepts

Facilities

1. Provide tradeoffs and standardization criteria for ground test and flight

2. Modernize and upgrade current equipment - ground test and flight

3. Increase size of test facilities - explore unconventional concepts

4. Broaden availability of flight equipment

Particularly in the research area, it was noted that there was not a big spread in relative importance of any of the items. The thrust of the entire effort is to achieve the 6th item--ice protection concepts. The other items are listed before it, however, because they are necessary steps to arrive at that ultimate objective.

REFERENCES

1. Newton, D. W.: An Integrated Approach to the Problem of Aircraft Icing. J. of Aircr., vol. 15, no. 6, June 1978, pp. 374-380.

2. Wilder, Raymond W.: Techniques Used to Determine Artificial Ice Shapes and Ice Shedding Characteristics of Unprotected Airfoil Surfaces. Presented at the Federal Aviation Administration Symposium on Aircraft Ice Protection (Washington, D.C.), Apr. 28-30, 1969.

APPENDIX A

Rev. A
May 1978

AIRCRAFT ICING RESEARCH PANEL REPORT TO SAE AC-9 COMMITTEE (AIRCRAFT ENVIRONMENTAL CONTROL SYSTEMS) MAY 1978*

BACKGROUND

At the SAE AC-9 committee meeting #16 in Dallas, (Oct. 18-20, 1972) a decision was made to set up a panel to investigate the state-of-the-art in Ice Accretion Prediction methods and to define to the committee, and the aerospace industry in general, the deficiencies in Technology. It was anticipated that any recommendations as to the need for further research would then be referred to appropriate industry or governmental agencies for sponsorship.

The panel was subsequently constituted under the chairmanship of Mr. V. K. Rajpaul of The Boeing Aerospace Co. Seattle, Wa. Membership of the panel, representing a wide cross-section of aircraft industry, consisted of the following:

Mr. D. P. Howlett	- Hawker Siddely Aviation, England
Mr. G. C. Letton Jr.	- ASD/ENJPC - Air Force Systems Command
Mr. J. B. Werner	- Lockheed California Co., Burbank, Calif.
Mr. J. S. Perlee	- McDonnell-Douglas, Long Beach, Calif.
Mr. R. G. Smith	- Boeing Vertol Co., Philadelphia, Pa.
Mr. F. R. Weiner	- Rockwell International, Los Angeles, Calif.

Mr. J. B. Werner replaced Mr. W. W. Merrill of Lockheed, California who was one of the original members and subsequently resigned due to retirement from Lockheed. Other SAE AC-9 members who periodically participated in the deliberations of the panel include:

Mr. J. R. Anglesio	- Avions Marcel Dassault, France
Mr. Porter Chadick	- Boeing-Wichita
Mr. J. H. Wivell	- British Airways - England

SCOPE

The panel was delegated to define and recommend areas of Icing technology, as related to military, commercial and general aviation, where further research was required. The panel was also required to recommend the most suitable means of implementing this research plan so that the results would not only fulfill the technology needs for future but also make the results known in the public domain. In addition, it was expected that a certain level of uniformity in methods of analysis, test and design evaluation would be evolved from this program for the general use of aerospace industry. The recommendations made in a paper presented to SAE AC-9 committee, ref. 1, were to serve as a baseline from which the panel would proceed in its deliberations.

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PANEL PROCEEDINGS

Several meetings were held by the panel members to discuss the technical and funding sponsorship problems related to icing research. In addition a survey was made of the members to obtain written recommendations and/or a statement of work representing each members view as to the critical gaps in technology and approach to obtaining the solutions. These inputs from the members were thoroughly discussed and the recommendations in the following paragraph of this report represent a summary of opinions expressed in the panel deliberations.

CONCLUSIONS

1. A review of literature on Icing technology reveals that there has hardly been any significant contribution or advancement since the NACA work in the 1950's. Figure 1 illustrates a distribution of significant papers or reports published in the 1940-1970 period.

2. Most of the work in the 1950's was on unswept airfoils using 2-dimensional flow theory. It was concerned with basic water droplet impingement and heat transfer relationships. Ref. 2 is a good summary and design data book based on the research during the 1950's.

3. The aircraft technology of the 1965-1985 period is significantly different in terms of design and operational factors from the technology of 1950's so that extrapolation of published data and techniques can lead to over-design or over-risk situations. For instance, existing methods do not allow accurate prediction of size, shape or location of ice accretions on swept wings, high lift or noise treatment devices, advanced airfoils, variable geometry or 2-dimensional supersonic inlets, or shedding characteristics. Nor is there enough data to predict effects of changed operational procedures such as long hold periods in air traffic patterns, or low level military missions.

4. The gaps in data base and verified analytical methods to predict size, shape, location, and effect of ice accretions on flight surfaces exist equally for all significant categories of aviation - rotary winged vehicles, combat airplanes, commercial V/STOL and CTOL airplanes and general aviation.

5. Improved techniques for analysis, verified by test, will lead to significant benefits in terms of:

   - more accurate drag and stability estimates
   - less landing weight penalties for short/medium range airplanes
   - realistic anti-icing or de-icing system trade-offs
   - greater safety and operational flexibility in adverse weather operation
   - lower airplane development costs
   - improved flight safety

RECOMMENDATIONS

1. The Icing Research Panel recommends that the SAE AC-9 Committee solicit support of the general SAE organization to approach several governmental agencies with a specific program of icing research for their sponsorship, either jointly or singly. The most suitable agencies for sponsoring research in this technology are:

   a) Department of Transportation
      - o Federal Aviation Administration

   b) Department of Defense
      - o Aeronautical Systems Division - AFSC
      - o Air Force Flight Dynamics Laboratory
      - o Air Force Aero Propulsion Laboratory
      - o U. S. Army - (Air Mobility R&D Lab Fort Eustis)
      - o Naval Air Systems Command

   c) NASA
      - o Langley Research Center
      - o Lewis Research Center

2. A research program similar to that outlined in attachment I would be a good basis from which specific work packages could be evolved dealing with needs of the various categories of users of the results of this research. The cost is difficult to predict due to many variables, but can vary between an estimated 1/2 million to 2 million in 1975 dollars depending on sizes of the work packages.

3. Due to the industry wide need for generalized and verified methods and the cost, a government sponsorship of research is preferable to that of a single or group of aerospace companies.

FUTURE WORK FOR THE ICING RESEARCH PANEL

The Icing Research panel should be kept active only up to the point that the SAE recommendations to the government sponsoring agencies have been made and their follow up enquiries satisfied. This should not take more that one year as a good guess.

Submitted by
Vinod K. Rajpaul
Vinod K. Rajpaul, Chairman
Icing Research Panel
SAE AC-9 Committee

May 7, 1975
Rev May 1978

Ref's. 1) "Research in Ice Accretion Prediction Methods," V. K. Rajpaul, paper presented at SAE AC-9 Committee Meeting #16, Dallas, Texas, Oct. 19, 1972.
2) "Engineering Summary of Airframe Icing Technical Data," D. T. Bowden, A. E. Gensemer, and C. A. Skeen, FAA ADS-4, 1964.

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1969	X
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X -- equivalent to one published paper or report.

FIGURE 1 - PROFILE - ICING RESEARCH ACTIVITY IN USA

STATEMENT OF WORK
FOR
SAE RECOMMENDED ICING RESEARCH

INTRODUCTION

Icing environments and icing effects on modern aircraft including the next generation are, to a great extent, unknown due to inadequacies of presently known meteorological data and effects of ice on lift, drag, stability, engine performance, and ingestion. Problem areas can be identified specifically with respect to four modes of operation, as follows:

a. Enroute flight in icing conditions at low altitude associated with aircraft whose primary missions occur at low altitude.

b. Loiter and landing in icing conditions for all aircraft.

c. Ground operation in high dewpoint conditions near icing temperatures for aircraft having high velocity engine inlets.

d. Takeoff operation for aircraft unusually sensitive to icing at takeoff such as V/STOL's.

Due to the critical nature of airfoil aerodynamics during the landing phases of an aircraft's mission, which directly affects landing safety, the nature (shape, size, porosity, etc.) of ice formations is an important consideration. However, data on ice accretion for advanced airfoils (including supercritical) and with large sweep angles are lacking. Engine ice ingestion from ice catch and subsequent shedding from leading edges of air inlets or other forward areas of an aircraft may involve an important safety consideration, considering the possible engine damage potentials and inability to wave-off or go-around if required. Range may be decreased and mission completion capability may be considerably compromised by the presence of unknown quantities of ice on airfoil and engine inlet leading edges.

Very little information currently exists relating meteorological conditions with horizontal extent of icing. No data exist at all for ground or low level (under 2000 ft) icing conditions which are the most critical for airplane safety during landing; sea level or ground cloud liquid-water content is virtually unknown. What kind of icing does high ground humidity cause? What are its icing effects on an aircraft windshield, wing, tail, and engine inlet and duct? Accidents have occurred due to ground fog icing of an engine, unknown to the pilot. The sensitivity of an engine duct to icing caused by air expansion down the duct is peculiar to each airplane; ice distribution down an engine duct has never been adequately identified nor studied.

The need for further work in the area of aircraft icing is the result of the desire by both users and manufacturers to minimize ice protection provisions on new aircraft. This desire stems from the complexity, weight penalty, and maintenance problems associated with ice protection systems. The first step taken towards reducing aircraft ice protection provisions was the elimination of wing and tail surface ice protection. The latest trend now is to also eliminate engine inlet ice protection. The elimination of these ice protection provisions requires proof that ice accretion on these surfaces will not jeopardize performance or flight safety. Presently available data and analytical methods are not considered adequate for accurately and rapidly predicting early in the aircraft design phase the need/non-need for ice protection provisions on all types of flight surfaces and engine inlets or for all types of missions and aircraft. As a result, it is necessary to wait until hardware is available and testing can be conducted to determine the real need for ice protection. This necessitates delaying the decision on ice protection provisions until late in the aircraft development program when system design correction possibilities are limited and any major system changes are expensive.

OBJECTIVE

The objective of further work would be to develop a method, which would be available to and recognized by all of industry and government, for rapidly and accurately determining analytically whether ice protection provisions are required for engine inlets and flight surfaces for all types of aircraft and missions.

WORK EFFORT

To accomplish the objective of this program, the following major areas of work will be required:

1. Conduct a survey of industry, government and literature and compile all available data on ice accretion, ice shedding, icing probabilities, and meteorological icing conditions and accident or incidents due to icing. In addition, all currently used methods by industry for ice accretion prediction, ice shedding prediction, icing probability prediction and.determining effects of icing on aircraft operation should be ascertained. All data obtained during the survey should be reviewed and a determination should be made as to where more data are required. Particular emphasis should be given to the need for more meteorological icing data for low altitudes (sea level to 4,000 ft.) and for altitudes above 22,000 ft.

2. Although some ice accretion data have been developed in icing tunnels at sea levels, methods are required for extrapolation to altitude.

3. Develop spray nozzles to generate realistic drop sizes (20-25μ) for icing and spray tanker aircraft. Develop an accurate and convenient droplet size measuring device suitable for use in flight tests.

4. Investigate ice accretion and resulting ice shapes for (1) swept airfoils with sharp and blunt leading edges, (2) straight and swept airfoils with extremely large leading edge radius, and breakoff from their fillet or blending area and entering engines, (3) sharp leading edges of engine inlets.

   Develop methods to estimate rate of blockage of auxiliary inlets and vents since very little information exists.

5. Investigate ice shedding characteristics of straight and swept engine inlets. Determine by tests the sizes and weights of shed pieces of ice, including ice off a fuselage side. Determine ice trajectories from surfaces ahead of an engine.

6. Establish requirements for upgrading engine ingestion capabilities. Conduct preliminary trade studies of upgraded engine vs inlet anti-icing provisions. Recommend engine companies develop a program on this subject.

7. Correlate existing model scaling parameters against existing test data and generate new test data as required (i.e. several airfoil sizes of the same shape).

8. Develop a complete generalized analytical model for ice accretion and ice shedding as a function of time for all altitudes and temperatures associated with icing, for fixed and rotary winged aircraft. Check validity of the computer program.

9. Develop new icing protection techniques to reduce cost and weight, especially for general aviation purposes.

10. Prepare a manual which defines the procedure and computer programs required for determining the need/non-need for ice protection on engine inlets and flight surfaces for all types of aircraft and missions.

PROGRAM BENEFITS

The analytical procedure developed as a result of this effort would allow one to confidently predict early in an aircraft development program as to whether or not ice protection provisions are required. Such a capability will greatly reduce the risk and cost of flight safety decisions regarding ice accretion on aircraft surfaces especially for general aviation. It will enable reduction or elimination of icing testing. Monetary savings due to eliminating ice protection systems will be maximized by making the decision early in the program. In addition, this procedure will reduce the risk of making a bad decision which would be hard to correct later.

APPENDIX B - WORKSHOP AGENDA

Wednesday, July 19

8:00 - 8:30 am	-	Registration in Administration Building
8:30 - 8:40 am	-	Opening Remarks (John Enders)
8:40 - 8:45 am	-	Welcome, NASA Lewis (Dr. Bernard Lubarsky)
8:45 - 8:55 am	-	General Announcements (David Bowditch)
8:55 - 9:05 am	-	Workshop Procedures (John Enders)
9:05 - 10:20 am	-	Keynote Speakers (Presentation of Theme Topics)

(1) "Icing of Aircraft; Some Remarks With an Historical Slant From a Cloud Physicist" - Dr. Robert M. Cunningham, Air Force Geophysical Laboratory

(2) "The Safety Hazard of Aircraft Icing" - James C. McLean, Jr., National Transportation Safety Board

(3) "Civil Helicopter Icing Problems" - Peter Sweeney, RCA Flight Operations

10:20 - 10:35 am	-	Break
10:35 - 11:30 am	-	Keynote Speakers

(4) "A Review of the Icing Situation From the Standpoint of General Aviation" - Dennis W. Newton, Cessna Aircraft

(5) "Overview of Helicopter Ice Protection System Developments" - Richard I. Adams, U.S. Army Applied Technology Laboratory

11:30 - 1:00 pm	-	Lunch
1:00 - 2:30 pm	-	Panel Organization
2:30 - 3:00 pm	-	Break
3:00 - 4:30 pm	-	1st Session

Thursday, July 20

8:15 - 9:45 am	-	2nd Session
9:45 - 10:00 am	-	Break
10:00 - 11:30 am	-	3rd Session
11:30 - 1:00 pm	-	Lunch
1:00 - 2:30 pm	-	4th Session
2:30 - 3:00 pm	-	Break
3:00 - 4:30 pm	-	5th Session

Friday, July 21

8:00 - 9:30 am	-	Committee Report Preparation
9:30 - 10:00 am	-	Break
10:00 - 11:45 am	-	Committee Report Presentations 1. Meteorological Research 2. Icing Forecasting 3. Systems Development 4. Civil Operations 5. Military Operations 6. Icing Research and Facilities
11:45 - 12:00 Noon	-	Workshop Wrap-Up (John Enders)

APPENDIX C - COMMITTEE MEMBERSHIP

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16. Abstract

This document contains the proceedings of the Aircraft Icing Specialists Workshop held at NASA Lewis Research Center, July 19-21, 1978. The Workshop, sponsored by NASA and FAA with the planning assistance of DOD, brought together many individuals from eight countries to address icing environments and problems; evaluate facility requirements; examine means of improving icing forecasts; and promote new research programs. Included in this group of participants were icing researchers; meteorologists and forecasters; sensor/instrumentation specialists; general aviation, transport, and rotorcraft engine and airframe manufacturers; and civil and military operators.

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