DOT/FAA/AR-98/76

Office of Aviation Research
Washington, D.C. 20591

Mixed-Phase Icing Conditions: A Review

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December 1998

Final Report

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U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AR-98/76		

4. Title and Subtitle	5. Report Date
MIXED-PHASE ICING CONDITIONS: A REVIEW	December 1998
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Dr. James T. Riley	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Federal Aviation Administration Airport and Aircraft Safety Research and Development Division Atlantic City International Airport, NJ 08405	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, DC 20591	Final Report
	14. Sponsoring Agency Code AIR-100

15. Supplementary Notes

16. Abstract

This report reviews publicly available evidence bearing upon possible safety hazards due to flight in mixed-phase conditions.

Recent investigations with modern instrumentation suggest that these conditions are more frequent and widespread than had been realized. However, information characterizing these conditions which is suitable for addressing questions of aviation safety is very limited.

Facility simulation of mixed-phase conditions is difficult and well-controlled simulations have been done in very few facilities in the world. It is not known how well the various methods that have been used actually simulate the natural environment, nor with what degree of fidelity it needs to be simulated for the investigation of some safety questions.

The limited data available from research flights does not indicate that there is any difference in performance effects caused by structural icing resulting from flight in mixed-phase cloud rather than in purely liquid supercooled cloud. Furthermore, one flight study suggests that the presence of ice particles in a cloud containing liquid water can reduce structural icing rates that would be observed with the liquid water only, perhaps because of erosion of ice accretion by the ice particles. There are data from two wind tunnel studies which also lend some support to this hypothesis. However, both the flight and tunnel data are for a restricted range of conditions, and do not appear sufficient for generalization.

Major technical reports going back to the 1960s state that exposure to mixed-phase or glaciated conditions (ice particles only in a region of a cloud) can cause anomalies in the performance of engines possessing particular engine design or engine inlet design features such as engine inlet pronounced bends or flow reversal points.

Technical reports published in the 1950s and 1960s state that the capacity of thermal systems may sometimes be exceeded in mixed-phase conditions, but more recent information on this issue in the open literature is lacking.

17. Key Words	18. Distribution Statement
Aircraft icing, Ice particles, Mixed-phase clouds, Glaciated clouds, Liquid water content (LWC)	This document is available to the public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	45	

Form DOT F1700.7 (8-72) Reproduction of completed page authorized

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EXECUTIVE SUMMARY

Task 13C of the Federal Aviation Administration (FAA) Inflight Aircraft Icing Plan, April 1997, addressed mixed-phase conditions (liquid water droplets and ice particles coexisting in a region of a cloud). This report reviews publicly available evidence bearing upon possible safety hazards due to flight in mixed-phase conditions.

It is now well documented that mixed-phase conditions in the atmosphere are common. In fact, recent investigations with modern instrumentation suggest that these conditions are more frequent and widespread than had been realized. However, information characterizing these conditions which is suitable for addressing questions of aviation safety is very limited. This is partly related to difficulties of measurement. Until the late 1970s, measurement was mainly done by use of very labor intensive methods using droplet impact devices. Since then, there has been increasing use of electro-optical two-dimensional probes; these offer substantial advantages but are still of limited resolution and accuracy and provide output which requires substantial processing in order to separate and extract quantitative ice particle and liquid droplet data. New instrumentation introduced in recent years is very promising, but evaluation is not yet complete.

Facility simulation of mixed-phase conditions is difficult, and well-controlled simulations have been done in very few facilities in the world. It is not known how well the various methods that have been used actually simulate the natural environment, nor with what degree of fidelity it needs to be simulated for the investigation of some safety questions.

The limited data available from research flights do not indicate that there is any difference in performance effects caused by structural icing resulting from flight in mixed-phase clouds rather than in purely liquid supercooled clouds. Furthermore, one flight study suggests that the presence of ice particles in a cloud containing liquid water can reduce structural icing rates that would be observed with the liquid water only, perhaps because of erosion of ice accretion by the ice particles. There are data from two wind tunnel studies which also lend some support to this hypothesis. However, both the flight and tunnel data are for a restricted range of conditions and do not appear sufficient for generalization.

Major technical reports going back to the 1960s state that exposure to mixed-phase or glaciated conditions (ice particles only in a region of a cloud) can cause anomalies in the performance of engines possessing particular engine design or engine inlet design features such as engine inlet pronounced bends or flow reversal points. In recent years there have been reports indicating that a particular aircraft engine utilizing an unusual dual-stage, high-solidity first stage low-pressure compressor stator design has experienced power loss instabilities in mixed-phase or glaciated conditions encountered in the anvils of thunderstorms. To address this most recent design concern, draft Advisory Circular 20.XX, titled, “Turbojet, Turboprop, and Turbofan Engine Induction System Icing,” states “Ice accretion on internal engine vanes due to the presence of mixed-phase ice accretions may effect flow capacity and rematch of the engine cycle and should be considered in the critical point analysis.”[1]

Technical reports published in the 1950s and 1960s state that the capacity of thermal systems may sometimes be exceeded in mixed-phase conditions, but more recent information on this issue in the open literature is lacking.

INTRODUCTION

PURPOSE.

The purpose of this report is to review publicly available evidence bearing upon possible safety hazards due to flight in mixed-phase conditions. Mixed-phase conditions exist when liquid water droplets and ice particles coexist in a region of a cloud.

BACKGROUND.

Federal Aviation Administration (FAA) aircraft icing regulations address icing caused by supercooled droplets in the atmosphere which freeze upon or after impact with aircraft surfaces resulting in ice accretions that may be hazardous to flight. Appendix C to Code of Federal Regulations (CFR), Title 14, Parts 25 and 29 contains envelopes specifying liquid water content, droplet size, and temperature values for clouds containing supercooled droplets. These envelopes are used in the certification of aircraft for flight in icing conditions.[2]

FAA regulations do not contain any explicit reference to mixed-phase icing conditions. The only requirements that explicitly mentions ice particles refer to snow. Specifically, 14 CFR Parts 23.1093, 25.1093, 27.1093, and 29.1093 require that turbine engines "must operate throughout the flight power range of the engine (including idling), without the accumulation of ice ... that would adversely affect engine operation or cause a serious loss of power or thrust in falling and blowing snow within the limitations established for the airplane for such operation."[2] Falling and blowing snow is not a mixed-phase condition unless liquid water is present (which would not be expected with blowing snow).

FAA draft Advisory Circular 20.xx [1], states that "The effect of ingesting snow during ground operations can and should be evaluated."

14 CFR 33.68(b) requires ground operation "in an atmosphere that is at a temperature between 15 and 30 degrees Fahrenheit ... and has a liquid water content not less than .... in the form of drops having a mean effective diameter...." Most engine manufacturers demonstrate this certification requirement in an enclosed test facility while spraying liquid water from nozzles into the inlet of the engine. The phase of the water/ice is set by the water temperature and pressure within the spray rig. It has been suggested that it is possible that this test may sometimes actually demonstrate a mixed-phase condition, just under the freezing point of water, if some of the liquid droplets produced by the nozzles freeze prior to striking the test inlet engine surface.

In April 1997 the Federal Aviation Administration (FAA) issued an Inflight Aircraft Icing Plan.[3] Task 13C of the Plan raises the question of possible safety hazards due to flight in mixed-phase conditions. This study was undertaken in response to that task.

Very little fully documented information appeared in the open literature relevant to this question prior to the late 1970s. Information that did appear concerned mainly the frequency of occurrence of mixed-phase conditions and the maximum total water content (ice plus liquid) that might be encountered in such conditions, but not any experimental or analytical investigations of the hazards that such conditions might represent.

There are three references from the 1960s that can be taken as representative of expert icing opinion at that time. However, it is important to note that none of them provide substantive documentation for the opinions that they express; rather, they are based on the very extensive icing experience, much of it in flight, of the authors and their colleagues.

- FAA Technical Report ADS-4, *Engineering Summary of Airframe Icing Technical Data* [4], which was published in 1964 and draws extensively on the National Advisory Committee for Aeronautics (NACA) icing research of the 1940s and 1950s.

- A presentation given by William Lewis at an Aircraft Ice Protection Symposium sponsored by the FAA in 1969.[5] Lewis was one of the leading NACA icing researchers, authoring or coauthoring of many of the NACA reports on atmospheric icing conditions during the 1940s and 1950s.

- A text by O. K. Trunov.[6] Trunov is generally recognized as the most eminent of the Russian aircraft icing researchers. In 1965 he published this very thorough text, which was translated into English and published in 1967 under the title, *Icing of Aircraft and the Means of Preventing It*.

Beginning in the late 1970s, a few reports began to appear on icing tunnel and flight studies of mixed-phase conditions. The icing tunnel tests placed considerable demands on the ingenuity and determination of the experimenters, since there was no routine way of simulating mixed-phase conditions. This remains largely true today, although progress has been made for simulations focusing on engines when it is considered satisfactory to simulate the ice phase with small ice spheres from nozzles. The flight studies benefited from new electrooptical instrumentation that had become available during the 1970s and could be used to characterize the ice phase more efficiently.

MIXED-PHASE CONDITIONS IN THE ATMOSPHERE

COLD CLOUDS.

Aircraft icing occurs in cold clouds, that is, clouds in which the temperature is below 0°C. (Reference 7 is a primary source for the material in this section.) Liquid droplets found in such clouds are said to be supercooled because their temperature is below 0°C; a cloud consisting entirely of such droplets is referred to in this report as a purely liquid supercooled cloud. At temperatures between –4 and 0°C, purely liquid supercooled clouds are common. However, as temperature decreases, the probability increases that at least some ice particles will be present in the cloud, since active freezing nuclei are more numerous at lower temperatures.[8] A cloud in which both supercooled liquid droplets and ice particles are present is called a mixed-phase cloud. At temperatures below about -20°C, many clouds consist entirely of ice particles; such a cloud is called a glaciated cloud. Laboratory experiments indicate that at temperatures below about -40°C, all clouds are glaciated.

The above discussion does not take account of temperature variation within a cloud, which can be considerable, exceeding 10°C even in stratiform clouds of sufficient depth. Thus clouds may have "cold" (<0°C) and "warm" (>0°C) regions, and if the cold region is of sufficient depth, it may contain purely liquid, mixed-phase, and glaciated regions. In the material that follows, it is to be understood that general statements concerning mixed-phase clouds may also apply to a mixed-phase region of a cloud.

Mixed-phase cloud is not stable due to the difference in saturation pressure of ice and water. (For example, air which is "just" saturated with respect to liquid water at -10°C is supersaturated with respect to ice by 10%; at -20°C the corresponding percentage is 21%.) The result is that ice particles grow at the expense of water droplets. The difference in saturation vapor pressure has the net effect of water molecules escaping from water droplets into the ambient air, and water molecules being captured from the ambient air by ice particles.

There are statements in the literature to the effect that the phase transition process proceeds so rapidly in the atmosphere that mixed-phase conditions are necessarily short-lived. For example, reference 5 states: "Because of the difference in saturation vapor pressure, the presence of ice crystals tends to dry up the liquid drops, thus, liquid cloud droplets cannot exist for more than a few minutes in the presence of an appreciable concentration of ice crystals." However, it is well documented that mixed-phase conditions are frequently observed, which may suggest that the transition from mixed-phase to glaciated conditions is more gradual under some conditions. Reference 9 addresses the so-called "phase relaxation time" which relates to the rate at which transition occurs.

This report focuses on mixed-phase clouds. However, it can be difficult to distinguish glaciated clouds from mixed-phase clouds possessing very low liquid water content, both as to assignment to the proper category (glaciated or mixed-phase) and as to possible effects on aircraft, particularly aircraft engines. Thus some discussion of glaciated clouds will be included in this report. Readers wishing a thorough discussion of the characterization of glaciated clouds are referred to references 10 and 11.

ICE PARTICLE INSTRUMENTATION.

A variety of instruments for detecting, counting, sizing, and imaging ice particles has been employed over the years. In reading the literature concerning this instrumentation and the data obtained with it, it is sometimes useful to be aware that the users fall into two main groups. One consists of cloud physics researchers, who are interested in developing a detailed understanding of many aspects of clouds. The information they develop is valuable for a number of purposes; one is improved forecasts, and another, very significant historically, is weather modification through cloud seeding. The other group consists of aircraft icing researchers and engineers, whose interests focus on characterizing the icing environment and determining the effects of that environment on aircraft and how to protect them; this includes the certification of aircraft for flight in specified icing conditions. There is overlap between the two groups, prominent examples being the Research Applications Program at the National Center for Atmospheric Research, and the cloud physics research group at Canada's Atmospheric Environment Service, both of which have made outstanding contributions to the understanding of both fundamental cloud physics and the aircraft icing environment.

For the purposes of this report, the main types of ice particle information obtained from instruments can be categorized as follows:

1. Detection of the presence of ice particles in cloud.

2. Ice water content (IWC). This is the total mass of ice particles per unit volume of air. Related terms are liquid water content (LWC), which is the total mass of liquid water droplets per unit volume of air and total water content, TWC, which is the sum of the first two. Common units for all three are g/m^3.

3. Ice crystal concentration (ICC). This is the total number of ice particles per unit volume of air. Common units are number/L.

4. Size of ice particles. Usually a maximum length is used, and common units are μm.

5. Shape of ice particles. There is a great variety of shapes, a topic briefly surveyed in the section "Types of Ice Particles in Atmosphere." One reason particle shape is important in cloud dynamics is that it influences particle terminal velocity, which effects particle growth by aggregation.

The main types of instruments which provide information about ice particles can be categorized as follows:

1. Instruments which sample a part of cloud so as to determine the presence of ice crystals.

   Clearly, instruments which provide information in categories 2 through 5 above must indicate the presence or absence of ice particles. However, some instruments, especially those used in the early days of aircraft icing research, indicate the presence of ice particles but provide no further information about them. An example of this is the cloud indicator described in reference 11. This instrument was introduced primarily to provide a means, especially needed in patchy clouds, of determining the time of entering and leaving cloud; however, it also proved useful in determining the presence of ice particles in cloud. It consisted of a heated cylinder with a thermocouple to measure the surface temperature at the stagnation point. Upon entering a cloud, the temperature dropped very rapidly, sometimes by as much as 50°F in a second. Since it was more sensitive to liquid water drops than to snow or other ice particles, it could also be used, in conjunction with visual observations, to determine glaciated or mixed-phase cloud. Based on statements in reference 5, it appears that researchers recorded mixed-phase conditions when the cloud indicator supported the existence of ice particles, and at the same time, visual observation of ice accretion on the aircraft indicated that at least some liquid water was present; if there was no accretion, snow or glaciated cloud was reported. The statistics that were compiled concerning the frequency of occurrence of mixed-phase and glaciated conditions using this approach are discussed in the section "Frequency of Occurrence of Mixed-Phase Conditions."

2. Instruments which sample a part of cloud so as to determine the TWC. If only ice particles are present, or there are reliable means of determining LWC, then IWC can be determined since TWC. = LWC + IWC.

   In the late 1950s, studies were conduced in tropical regions in response to engines malfunctioning on Britania aircraft, in glaciated or mixed-phase cloud, in the equatorial zone.[13, 14, 15] These studies employed a pitot-type ice concentration meter mounted on the forward escape hatch on top of the aircraft. It exposed an open ended tube to the airstream so that free ice and water were collected inside the tube. The tube walls were heated by a thermostatically controlled heater system and the melted ice and water were collected in a measuring system inside the aircraft. This instrument measured TWC rather than IWC, but results from the study have been used to put forward standards for IWC, implying that a basis existed for concluding that no liquid water was present in some of the clouds measured. The proposed standards are discussed in the section "Characterization of Mixed-Phase Conditions."

   The Nevzorov hot-wire probe consists of two different sensors for measurement of TWC and IWC, the difference of which yields IWC. The first version of the probe was developed at the Cloud Physics Laboratory of the Russian Central Aerological Observatory in the 1970s, and the current version, incorporating the sensor sensitive to liquid but not ice particles, was designed in the 1990s. [16] This probe has been used in several field experiments conducted since 1994 by the National Research Council and Atmospheric Environment Service of Canada, and has also been used in recent field studies conducted by NASA Lewis Research Center.

3. Instruments which sample a part of cloud by capturing a collection of particles or their impressions on a specially treated surface. Statistics are computed from the individual particle measurements. A problem with such techniques is that some ice particles, particularly the more delicate ones, fragment when they collide with the surface.

   Cloud physics researchers have used a variety of instruments of this general type. The simplest approach is to expose a slide specially coated with an appropriate substance, such as mineral oil, to the airstream for a short period of time. Analysis of such samples involves subtleties and is tedious.

   Another method [7] is to expose a moving strip of 16-mm movie film, covered with a special plastic solution in ethylene dichloride, to the cloudy air so that ice particles impact on the film and become embedded in the solution. Evaporation of the ethylene dichloride leaves a thin plastic skin; ice evaporates through small holes in this skin but plastic replicas of the ice particles are retained on the film (a similar technique can be used for cloud droplets). By counting the number of ice particles collected on a strip of film which has swept through a measured volume of cloud, the concentrations of ice particles in the cloud can be deduced. Again, analysis is tedious and time-consuming, and has rarely been done for more than just spot samples in carefully selected clouds.

4. Instruments which sample a part of cloud particle by particle.

The widely used electrooptical instruments developed by Particle Measuring Systems, Inc. (PMS) are of this type. They are used for both solid and liquid particles. The one-dimensional (1D) optical array probes (OAP) determine particle diameter by counting the maximum number of photodiodes that are shadowed by the particle as it passes through a laser beam. The two-dimensional (2D) versions of the OAP incorporate additional fast electronics to record multiple, sequential measurements or time slices of the particle as it traverses the beam. This makes possible a 2D reconstruction of each shadow, thus yielding information on particle shape as well as size.[10]

An early flight study [17], conducted by the University of Wyoming, exemplifies the use of output from OAP instruments to differentiate ice particles from water droplets (as well as measure the size of large droplets and particles). For this study, the Wyoming King Air aircraft carried three PMS OAPs to measure hydrometeors larger than 37.5 μm in diameter (see table below, which reproduces table 2 from reference 17). (As the footnotes indicate, some researchers consider the counts in the smaller bins of these instruments to be unreliable and ignore them.)

TABLE 1. PMS PROBES USED ON WYOMING KING AIR [17]

Probe	1D-C	2D-C	2D-P
Size Range[(a,b)]	12.5-187.5 μm	25-800 μm	200-6400 μm
Resolution	12.5 μm	25 μm	200 μm
Sample Volume[(c)]	~ 0.5 L	4.8 L	168 L

(a) Diameter or maximum size.

(b) Smallest 1D-C size used is 37.5 μm = 3*12.5 μm (implying that the first two bins were ignored) and smallest 2D-C size used is 50 μm = 2*25 μm (implying that the first bin was ignored).

(c) Per 100 m of flight.

Since the 2D probes record two-dimensional images, they can be used to distinguish, on the basis of shape, between droplets (approximately spherical) and ice particles (irregular). An algorithm for doing so by means of numerical techniques is discussed in reference 18. However, the resolution of the instruments is such that it is generally not possible to distinguish between ice particles and water droplets if the diameter is less than 200 μm.[19, 20]

In addition, IWC can be estimated from these crystal-by-crystal images. However, besides the problems in distinguishing ice from water, there is the problem of additional assumptions having to be made regarding the crystal density and thickness. Such assumptions entail various degrees of uncertainty in the resulting IWC calculations.

5. High quality imaging instruments.

Recently, instruments have been developed which are capable of providing very high quality, high-resolution images. The digital holographic probe [21] permits the discrimination of ice particles from water droplets down to diameters of 10 μm and even makes possible the identification of ice crystal shapes (called habits) and effects of riming on ice crystals. Such an instrument was included on the Convair 580 research aircraft used in the Canadian Freezing Drizzle Experiment (CFDE) field program conducted near St. Johns, Newfoundland, in March 1995. The cloud particle imager [22] is an upgraded version in which modifications to the optics have substantially increased the percentage of in-focus particles. This instrument has been operated on three different research aircraft during experiments in the Arctic, the Canadian Great Lakes, and Texas.

As of this writing, these fine-scale electronic particle images must be treated in much the same way as their hard copy counterparts from glass slide or film. The discrimination between ice and water must be done manually or by algorithms similar to those used with the PMS 2D probes and are subject to similar uncertainties. However, because of their greater resolution, down to several microns for some instruments, sources of error are minimized.

TYPES OF ICE PARTICLES IN THE ATMOSPHERE.

The nature of ice particles in the atmosphere has been extensively studied through a combination of in situ and laboratory techniques. References 7, 23, 24, and 25 are all good sources of information on this topic, and there are many others. This section relies mainly on reference 7.

Symmetrical ice crystals growing directly from the vapor phase can assume a wide variety of habits, all of which can be broadly classified as platelike or prismlike. The basic habit of a crystal is determined by the temperature at which it grows, with changes occurring near -4, -10, and -22°C. Embellishments of the basic habits are determined by the degree of supersaturation of the air with respect to ice. (For example, the branching dendrite is considered an embellishment of a hexagonal sector plate.) Ice crystals are exposed to continually changing temperatures and supersaturations as they fall through clouds, further increasing the variety and complexity of the shapes they can assume.

In a mixed-phase cloud, ice particles also increase in mass by colliding with supercooled droplets which then freeze onto them, a process called riming. Various characteristics (mass, density, terminal velocity) of rimed ice particles differ from those of ice crystals grown exclusively from the vapor phase.

A third mechanism by which ice particles grow in clouds is by aggregation. Aggregation requires collisions, which are more frequent if terminal fall speeds vary significantly. Such variation is greater amongst prismlike crystals than platelike crystals and is significantly enhanced by riming. Aggregation also requires adhesion following collision. The probability of adhesion is greatest at temperatures above about -5°C, a temperature at which ice surfaces are said to become sticky. Furthermore, intricate crystals, such as dendrites, tend to adhere to one another because they become entwined on collision. A snowflake may consist of an aggregation of hundreds of ice crystals.

The variety of ice particles is further increased by processes (sometimes called ice multiplication mechanisms) in the atmosphere which break up ice particles. For example, some ice crystals are quite fragile and may break up into many pieces when they are subjected to mechanical stress. A more complicated ice multiplication mechanism, called splintering, involves water droplets freezing from the outside in after coming into contact with ice particles, followed by an explosion due to expansion of trapped water, resulting in many ice splinters.

Finally, ice crystal type found at a particular location in a cloud is not simply a function of temperature and supersaturation at that location. It is common for a mixture of crystal types to be found. Ice crystals forming at higher (and usually colder) altitudes in the cloud can fall through that cloud to lower altitudes. Thus, one may observe dendritic crystals in a region where the temperature suggests that columns should only be present. The temperature determines the type of crystal that will grow at a particular location but not what crystals may have formed elsewhere and fallen to that location.

This discussion is meant to give an indication of the immense variety and complexity of ice particles in the atmosphere. It is clear that the characterization of an actual population of ice particles in the atmosphere must necessarily be rather incomplete except in special, relatively static conditions. Furthermore, in mixed-phase conditions the characteristics of the ice particle population need to be described in conjunction with those of the associated liquid water droplet population. Studies have indicated that the size spectrum of the water droplet population can influence significantly the size spectrum of ice particle population.[26]

Just as the description of populations of ice particles and water droplets in the atmosphere is necessarily incomplete, test conditions in simulation facilities can only crudely approximate such conditions. A brief survey of simulation practice for mixed-phase conditions is presented in appendix E.

FREQUENCY OF OCCURRENCE.

There is extensive documentation, going back at least to the late 1940s, that mixed-phase conditions are a common occurrence in the atmosphere, at least in the middle latitudes of the Northern Hemisphere where most of the relevant data have been collected. Some of the data is from aircraft icing studies and much is from studies related to the potential efficacy of cloud seeding schemes.

ADS-4 [4] states: “Flight through clouds of ice crystals, snow or mixtures of ice crystals and liquid water is not uncommon.” In support of this assertion, ADS-4 reproduces Table III from NACA TN 1904.[12] The table shows that during 1 year of inflight icing research in northern North America, 23.6 per cent of the total time in visible moisture was in mixed snow and liquid water, and 32.5 per cent was in snow; more than half of the encounters involved ice crystals or snow to some degree. This study employed the cloud indicator described above, in combination with visual observation, to determine mixed-phase and glaciated conditions. Table III is reproduced in its entirety in appendix B.

In his FAA symposium presentation [5], William Lewis made an interesting statement concerning the results of an analysis of cloud and icing frequencies observed on weather reconnaissance flights. Lewis said: "At a temperature of -5°C, sixty percent of the time in clouds was without icing, indicating that the clouds were composed entirely of ice crystals."

This statement is interesting in two respects. First, it indicates that the NACA researchers apparently assumed that when flight in cloud at subfreezing temperatures did not result in any ice accretion, the reason was that the cloud was glaciated. Second, for the study in question, the proportion of presumed glaciated clouds is remarkably high for a temperature of -5°C.

O. K. Trunov includes in his text [6] a table (compiled by I. G. Pchelko) which includes over a thousand observations in icing conditions and shows that 41% of the observations of icing occurred in purely liquid supercooled cloud, 54% in mixed-phase cloud, and 5% in glaciated cloud. This table is also included in appendix B.

Another study [27] carried out in Russia concluded that mixed-phase clouds occurred frequently at temperatures between –5° C and –30°C

Reference 15 reports on 1091 hours of flight data; most was collected either in summertime cumulus clouds in Montana or wintertime orographic-frontal systems of northern California. The report indicates that approximately 85% of the time that liquid water was encountered at least some ice particles were present.

Reference 28 describes a study concerned with the potential for enhancing snowfall in winter orographic clouds which was conducted over the central Sierra Nevada range from 1978 to 1980 as part of the Sierra Cooperative Pilot Project (SCPP). Since the potential is believed to be greatest in an ice-deficient environment, the researchers computed the ratio of LWC to ICC. Considering those cases where LWC was nonzero, the ratio was undefined (i.e., ICC was zero) only 3% of the time. In other words, for this orographic study, liquid water droplets were accompanied by at least some ice particles 97% of the time.

Reference 7 includes a figure, apparently also motivated by interest in cloud seeding, relating the probability of ice particles being present in a cloud to the temperature at cloud top. The probability steadily increases as the temperature decreases below 0°C. Clouds with tops at temperatures between 0 and -4°C generally consisted entirely of supercooled liquid droplets. At cloud top temperatures of -10°C there was about a 50% probability of ice particles being present, and below about -20°C that probability exceeded 95%.

Reference 29 reports on aircraft icing research conducted during the second phase of the Canadian Atlantic Storms Program (CASP II) based in St. John's, Newfoundland. There were 31 flights totaling 119 hours conducted over Canada's maritime provinces and the North Atlantic, and about 20% of the data contain significant ice particle concentrations. For a portion of the rest of the data, not specified in the paper, there were also some ice particles present.

NASA Lewis Research Center has carried out an extensive atmospheric icing research program (1996-98) in the lower Great Lakes region; the primary goal of which has been to study supercooled large droplet (SLD) icing environments. Although only preliminary data are available, it is clear that mixed-phase conditions have been frequently encountered, whether or not SLD was found.[30]

The Canadian Freezing Drizzle Experiment (CFDE) has carried out research campaigns in both Canada's maritime provinces in the northwest Great Lakes region. In CFDE I, in the maritime provinces, mixed-phase conditions existed approximately 20% of the time that liquid water droplets were present during 12 research flights.[31] In CFDE III, in the Canadian Great Lakes region, mixed-phase conditions have also occurred frequently, although only preliminary data is available.[32] The CFDE studies, like the NASA studies, have found that ice particles sometimes coexist with SLD.

Data from the Winter Icing Storms Project (WISP) were obtained in northeastern Colorado during four winter seasons. Nearly all measurements were in clouds containing supercooled liquid water. Of those clouds, 74% also contained ice crystals. Stratified by the temperatures at which the measurements were taken, these percentages ranged from 75% for temperatures between 0 and -8°C, 68% for temperatures between -8 and -12°C, 79% for temperatures between –12 and -16°C, 57% for temperatures between -16 and -20°C, 80% for temperatures between -20 and -24°C, and 100% for temperatures below -24°C.[33]

These results, from a variety of environments in different geographic regions of North America, could be supplemented by others, especially from cloud seeding studies. They provide ample evidence that mixed-phase conditions occur with appreciable frequency in North America, with estimated percentages ranging from 20% to over 90% depending on region, environment, and temperature.

CHARACTERIZATION.

Apparently no atmospheric data on IWC or ICC were collected by the NACA icing researchers of the 1940s and 1950s. ADS-4[4], which relies so heavily on the NACA reports, includes only table C-1 entitled "Ice Crystal Concentration Standards," noting that it was supplied by the National Research Council of Canada. The text indicates that the standards presented are for use in engine testing. Noteworthy aspects of the table are that it lists values for TWC values rather than IWC and that some of the values are very high, 8 g/m^3 in one case, and 5 g/m^3 in several others. The data are similar to, and likely derived from, that which appears in reference 12, which was mentioned earlier and which described research related to engine problems encountered by the Britania.

Trunov's text [6] includes specific discussion of special investigations in the tropic regions of Africa and the Atlantic conducted by the English Meteorological Service in 1956-1958 and listing references 34 and 35. Trunov states that "the reason for carrying out investigations was due to cases of motors dying on the aircraft Britania during icing in crystalline clouds." He states that these "complications" occurred in "crystal clouds" which were "encountered in the tropic regions of Africa where strong shifts of air masses occur due to the great heating of the earth." Referencing Ballard [34], he states that "the maximum concentration of ice is 6 g/m^3, and the maximum size of the crystals reaches 3 mm." About 90% of the particles are said to have had a maximum dimension of less than 150 μm. The phenomenon of "dry" icing was revealed during a flight through summits of cumulonimbus clouds containing a large quantity of ice crystals. Observations made showed that the altitude in the tropics at which clouds containing a large quantity of crystals were found varied from 6000 to 9000 m. The extent of the crystal clouds sometimes reached several hundred kilometers. Trunov states:

> As a result of these investigations a general table of conditions of icing was proposed, which covers a range of altitudes up to 18 km and includes the content of water both in a liquid state and also in the form of crystals. These conditions, given in table 10, were discussed at one of the international conferences on the problem of icing, but they were not accepted as official calculation conditions. It is obvious that the designing of deicing systems by these conditions at a given level of technology is an impractical problem.

Table 10 is also included as table C-2. It essentially is a conversion of table 1-6 from ADS-4 (table C-1 in this report) to metric units, with very slight adjustment.

The JAA currently includes a table in its guidance material [36] which is also similar in format to table 1-6 in ADS-4 and contains some of the same values; it could fairly be called a truncated version of table 1-6 with a mean particle diameter (1 mm) added. In fact, the JAA table has a footnote referencing [13], which implies that the values are based on the data collected with the pitot-type ice concentration meter for determination of TWC discussed in the previous section. This instrument gave values substantially higher than those recorded from any other instrument.

Jeck [37] has proposed standards for inflight ice/snow conditions (not mixed-phase conditions) based on analyses [11, 37] of 7600 nmi of select ice particle measurements in a variety of cloud types over the U.S. at altitudes up to 30,000 ft above sea level (ASL). These standards are included in table C-4 also presented in appendix C. The IWC values stated are substantially lower than those which appear in the other tables discussed in this section, all of which apparently derive from reference 13.

ICING IN MIXED-PHASE CONDITIONS

AIRCRAFT ICING.

In this report, the following definitions are adopted: Structural icing is icing that occurs on any part of the airframe or on any probes or other protuberances. Engine icing is icing that occurs on the inlet lip or within the engine beyond the inlet lip.

Structural icing and engine icing have long been recognized as problems in clouds containing supercooled liquid droplets since these droplets freeze upon or after impact with aircraft surfaces, resulting in ice accretions that may be hazardous to flight.

GLACIATED CLOUDS. Most researchers have viewed structural icing in glaciated clouds as at a rare (or nonexistent) phenomenon since ice particles are believed to bounce off dry, unheated surfaces. However, for engines of some designs, engine icing problems can occur in glaciated clouds if a sufficient mass of ice particles is ingested under certain conditions.

ADS-4 [4] contains relatively little discussion of icing in glaciated (or mixed-phase) conditions and in fact references only one NACA report for the material that it does include. ADS-4 states: "Dry snow or ice crystals are not usually a problem. The exceptions have been in the case of turbine engine inlets of great length and curvature." It also states: "When encountering ice crystals and snow in dry clouds, it is not necessary to turn on the ice protection system."

In his presentation to the FAA Aircraft Ice Protection Symposium in 1969, William Lewis stated: "If a cloud is composed entirely of ice crystals, icing does not occur on external surfaces, whether heated or not." While most sources agree with this statement for unheated surfaces, there are a number of sources, including ADS-4, which disagree that it is always true for heated surfaces.

O. K. Trunov [6] discusses hazards due to glaciated and mixed-phase conditions at several places in his text, albeit somewhat briefly. On page 42 of the English translation, he states that during flight in glaciated cloud, "icing, as a rule, does not occur" because, "in ordinary conditions ice crystals, colliding with the cold surface of the aircraft, slide from it and pass by the air flow." However, although he states that "dry" icing is a "rare phenomenon," he does present a table (B-2) indicating that for a study encompassing approximately one thousand observations of aircraft icing, about 5% occurred in glaciated conditions.

<u>MIXED-PHASE CLOUDS</u>. Aircraft icing occurs in mixed-phase clouds, since by definition such clouds must contain some supercooled droplets, and these will freeze upon or after impact with aircraft structures. However, what is the influence of the ice particles in a mixed-phase cloud upon structural icing? Do the ice crystals bounce off an unheated surface on which there is liquid water, or do they become embedded in the surface water, contributing to the mass of the accretion when the water freezes. How do they affect the operation of ice protection systems, particularly thermal systems? Finally, does the mixture of ice crystals and liquid water pose special problems of internal engine icing for some designs?

ADS-4 states that in a mixed-phase cloud, ice may accumulate and require use of the ice protection equipment. It cautions that the "capacity of thermal systems may be exceeded," however, making it "necessary to escape the icing condition as rapidly as possible." The document also notes speculation that "reports of excessive icing might be the result of flight in mixed clouds with anti-icing systems overtaxed by the increased heat needed first to melt the ice crystals, then to warm and evaporate the water." Later it states: "Documented evidence of severe airframe icing problems in clouds of ice crystals or mixed clouds is lacking, however. As long as the engine continues to deliver the required thrust, operating in ice crystals is not likely to present severe problems."

Lewis states: "In mixed clouds the effect on external surfaces is not materially different from that of the liquid water alone. As long as the air flow is such that the ice crystals are not held in place but are blown along after impingement, the cooling effect of the ice is almost negligible."

Trunov states that "ice crystals contained in mixed clouds" play a role "in the ice formation on the surface of aircraft." He further states that during experimental flights he personally observed that ice particles "were impregnated into a film of ice formed by supercooled drops on the surface of a certain part of the aircraft."

STRUCTURAL ICING.

FLIGHT STUDIES. There are reports in the open literature on three documented experimental studies that address aircraft icing in mixed-phase conditions in the atmosphere. Mixed-phase icing was not the exclusive focus of any of these studies, but all of them give results on the effect of the ice particles on the icing process or the impact of the ice on the aircraft performance.

The first study is reported in references 17 and 38, which are companion papers which describe icing conditions encountered and resulting performance effects, for the University of Wyoming's Beechcraft Super King Air 200T during research flights during the late 1970s and early 1980s. This aircraft is a low-wing, swept T-tail, pressurized twin-turboprop certified for flight into known icing conditions. Pneumatic deicing boots protect the wing and horizontal stabilizer. The windshield, pitot masts, and fuel vents are anti-iced using electrical heat, and the propeller is deiced using electrical heat. Inlet ice protection is also provided. Most of the data for this study were collected either in summertime cumulus clouds in Montana or wintertime orographic-frontal systems of northern California. The analysis of aircraft performance utilizes a method described in reference 39; the investigators compared the rate of climb capability of the aircraft with ice to the rate of climb capability for the clean aircraft under the same conditions.

The aircraft carried three PMS optical array probes, some of whose characteristics are given in the table in the section "Ice Particle Instrumentation." As explained in that section, the 1D-C probe records only sizes, but the 2D probes also record two-dimensional images. Reference 17 states that in this study the 2D probes were generally used to detect ice particles for sizes larger than 200-250 um.

The authors state that their main conclusion concerning mixed conditions is that ice particle concentration was unrelated to performance degradation for this research program. Since this conclusion at least partially depends on their correlation of icing potential with aircraft performance, this aspect of their work will be briefly reviewed.

"Potential accumulation" is defined in this work as "the mass of supercooled water that would accrete, per unit surface area, if the collection efficiency were unity." This is a simple measure; note that collection efficiencies on some surfaces can be as low as 0.2, and other factors, such as sublimation of ice, are not accounted for. Note also that ice particle content of the cloud is not part of the definition. The concept of potential accumulation was employed in a more recent analysis of icing data from the same aircraft collected during the Winter Icing and Storms Project (WISP), but this study did not address mixed-phase conditions.[40]

The potential accumulation was calculated for 505 individual icing encounters which were taken to begin with the first exposure to supercooled water (>0.025 g/m^3) and end when the ambient temperature exceeded 0°C. The authors found that in typical icing conditions, the potential accumulation was well correlated with the effects of icing on the aircraft when all ice protection systems were used. (This good correlation was considered surprising because other parameters possibly influencing performance, such as droplet size spectrum, temperature and altitude, varied over a wide range in the data set.) Specifically excluded from typical conditions are cases where supercooled droplets of 40-300 μm diameter were present. (These were found to be potentially hazardous even with the full icing protection of the Super King Air in operation, showing an effect on performance far greater that would have been predicted on the basis of the liquid water content or volume-median diameter.)

The authors of reference 17 concluded that because of the wide variability in the ice particle spectra for the cases they examined, the good correlation of performance correlation with potential accumulation argues against a large effect attributable to ice particle accretion.

However, they note that the hydrometeor spectra in this study "seldom contained enough mass in the ice phase to account for significant accretion, even with 100% collection efficiency, except in the graupel sizes where substantial sticking to the impacted surfaces is unlikely." Due to this and other limitations of their data, the authors emphasize the weakness of their evidence for generalization.

In conclusion, they state: "Although we cannot claim that ice particle accretion never occurs (for we have seen aggregates stick to the leading edges), or that erosion is unimportant (for we have also observed apparent cleaning of the leading edges after penetration of graupel showers), the effects on performance which we have observed can be explained without attributing any major influence to ice particle accretion."

A second study, conducted by Bain and Gayet, is discussed in references 41 and 42; this report will rely primarily on the second of these references. The study involved icing experiments with an instrumented DC-7 aircraft carried out in Spain during the Precipitation Enhancement Project (PEP) experiment in 1979.

The instrumentation used included three hydrometeor-sizing probes, an FSSP with a 3- to 45-μm range, and two OAPs—a 1D-C with a 20- to 300-μm range, and a 1D-P with a 300- to 4500-μm range. A Johnson-Williams probe was used to determine liquid water content, which the authors note is not fully responsive to droplets larger than 30 μm in diameter.

No direct measurements of ice particle concentration were made by the DC-7 during PEP. However, estimates of ice particle concentrations were made by "comparison of measurements of the 1D-C and ID-P probes to the microphysical measurements performed by a Queen Air which was instrumented with 2D probes during the PEP experiment." In justification of this approach, they briefly describe research using an impactor device and a 2D-C probe which showed that, "in all the studied clouds, no raindrop with a diameter greater than 200 μm was present in the supercooled part of the clouds which implies that all such particles were ice particles."[41]

The main conclusion of the study is that the mixed conditions encountered (all of which resulted in a dry growth regime) indicate that the ice phase plays an important role in the ice accretion process, reducing the rate of accretion substantially. For a range of temperature from -21 to -8°C, the icing rate appeared to be reduced ~50% by the presence of large ice particles in concentrations above 5 L^{-1}. A possible explanation is that the ice particles eroded the ice deposit formed by the supercooled water.

In characterizing the ice particle conditions included in their study, the authors note that in the temperature range from -8 to -21°C, the main crystal habit is planar. They state that the maximum dimension of the sampled ice particles varied from 500 to 1000 μm. Using a mass-to-dimension correlation table, they conclude that the corresponding mean mass of ice particles in the study was 15 μg.

These measurements also suggest that the effect of the mixed conditions (ice crystals present among supercooled droplets) is to reduce the icing rate by more than 50% possibly because of the erosion caused by the large ice particles impinging on the ice deposit. The ice accretion reduction effect was observed in cumuliform clouds most often at temperatures near -20°C and generally for ice particle concentrations greater than 5 L^{-1}. In this study, only particles with a diameter >200 μm are considered to be active ice particles for the erosion process.
Since the mixed-phase conditions were always encountered during a dry growth regime, the authors infer that the observed ice accretion reduction effect could not have been due to liquid water shedding.

The authors caution that "our conclusions cannot be generalized beyond" the conditions included in the study. It may be possible that, at higher temperatures, some ice particles with low density may stick to the surface when the temperature is such that a wet growth regime occurs. They addressed wet growth regimes in an icing tunnel study discussed below.

The third study was done by Ashenden and Marwitz and is discussed in references 18 and 43. This study relied on data from the University of Wyoming King Air, as did references 17 and 38. The work does not employ potential accumulation, the authors noting that its calculation does not incorporate the mass of the ice crystals. The performance calculations are done in a manner similar to references 17 and 38 but with some differences, including the use of a variable propeller efficiency algorithm and the determination of aircraft roll angle components. In order to investigate the effect of the mixed-phase environment, a 2D-C phase classification algorithm was developed to separate the ice hydrometeors from the liquid ones.

The major finding of this study concerned freezing drizzle aloft, and it is briefly discussed here because observations for mixed-phase conditions are directly related to it. The King Air performance degradation rates were higher in freezing drizzle aloft than in any other icing environment studied. It is noted that in the worst case the reserve performance capability of the King Air was consumed within 5 minutes. Observations by the King Air flight crew suggested that the drizzle drops froze as sharp "feathers" or "glaze nodules" at or just beyond the deicing equipment. The authors hypothesize that the sharp feathers or nodules are the primary ice structures which are detrimental to the standard airflow characteristics, resulting in performance degradation.

An important observation particularly striking in two case studies concerned high rates of recovery upon exiting the freezing drizzle and entering mixed-phase conditions characterized by large ice crystals and low amounts of liquid water. The authors suggest that the ameliorative effect of the mixed conditions is due to the feathers or nodules being eroded, or smoothed, by large ice crystals, as was also suggested in reference 41.

ICING TUNNEL STUDIES. A particularly well-documented experimental study conducted in an icing tunnel is discussed in reference 44. The wind tunnel experiments were done with a fixed (i.e., nonrotating) cylinder, and the results were used to evaluate an analytical model for fixed-cylinder icing with runback.

The authors state: "The results of these efforts answer a few of the concerns about mixed-condition icing. They suggest in fact that supercooled water-ice crystal clouds may not pose a serious hazard." However, they also say that "many further questions are raised concerning the details of the accretion mechanism, and these questions will have to be answered before further progress in modeling will be possible."

Part of the motivation for the study arose from reports of helicopters flying in natural icing conditions sometimes experiencing sudden and extreme rates of torque rise, which were not anticipated on the basis of the icing rig hovering flights.[45] The authors state: "Unfortunately, insufficient instrumentation was mounted on board the aircraft to determine the complete microphysical properties of the clouds in which this phenomenon occurred. As a consequence, speculation as to the cause or explanation of these events was not constrained by a complete set of measurements."

The authors list four speculations as to the cause of rapid torque rise. Only Speculation 4, "that unusual or unexpected environmental conditions were encountered, mixed-phase conditions being one possibility," is relevant to this report. The study sought to test the hypothesis that mixed-phased conditions might help to explain the rapid torque rise by incorporating ice crystals into a mathematical model of the icing process and undertaking icing tunnel experiments to examine the assumptions underlying the model.

The method by which the mixed-phase conditions were simulated is discussed in appendix E. Briefly, finely divided, recently fallen snow was injected into the tunnel by means of a hydraulically driven conveyor belt mechanism contained in an insulated box. "Snow with a density of 60 to 270 kg/m^3 was collected out of doors within a few days of its fall and placed in the dry-ice-cooled conveyor belt channel. It was carefully leveled to a depth of 0.02 m and then fed through an oscillating rake at a rate of 10^{-3} to 10^{-2} m/s, before falling through a vertical tube into the plenum. A flat plate was mounted below the end of this tube in order to arrest the fall of any large aggregates, and to break them up." Photographs of the ice particles indicated that there had been some metamorphosis, they were still characterized by "the large surface area to volume ratio typical of many natural ice crystals."

The ICC of the air in the working section was varied by changing the belt speed. It was measured directly with a specially constructed set of five aluminum sampling tubes, screw mounted at 0.05 m intervals on a bar fitted across the measuring section.

At speeds exceeding about 100 m/s, the ice crystal content in the working section consisted of both snow which had been directly injected into the plenum and recirculating particles which had already traveled around the tunnel circuit one or more times. This recirculation did not occur to any significant extent at lower speeds because the ice crystals are able to settle out in the lower section of the tunnel.

The experimental conditions for the tunnel tests were: ambient atmospheric pressure; static temperatures of -5°C ("warm" icing), -15°C ("cold" icing), and -8°C; liquid water contents of 0.4, 0.8, and 1.2 g/m^3; median volume diameter nominally of 20 μm (actual range: 17 to 25 μm), and velocities of 30.5, 61, 91.5, and 122 m/s. As to ice crystal content, an attempt was made to match the ice crystal content with the liquid water content, since although desirable, it would have been to difficult and time-consuming to test a range of ice crystal contents for each liquid water content. "Even the objective of matching ICC and LWC was not always achieved, with ICC and LWC occasionally differing by as much an a factor of 2 or 3."

During some of the mixed condition experiments, high-speed movies were taken of the ice crystal collisions. The speed was high enough to reveal the details of the collisions and the subsequent motion of the collision fragments, but the framing rate was too slow to stop the motion of the impinging ice crystals which consequently appear as streaks on the film.

Generally, the deposits grown under mixed conditions showed some evidence of having grown cooler and drier than their liquid water counterparts. The ice is more milky or opaque and the surface roughness appears to be diminished.

Notable differences among the liquid and mixed deposits were seen to occur in three cases: (a) 61 m/s, -5°C, and an LWC of 1.2 g/m^3; (b) 122 m/s, -15°C, and an LWC of 0.4 g/m^3; and (c) 110 m/s, -8°C, and an LWC of 0.28 g/m^3.

In case (a) the mixed-condition accretion is superficially less rough than the corresponding liquid water growth, but it incorporates many large air bubbles and cavities giving it a slushy, milky appearance.

In cases (b) and (c), the mixed-condition deposits are quite similar to one another in appearance even though the corresponding liquid water deposits look to be very different.

The outlines of these accretions suggest that the ice particles had a considerable shaping influence. The authors suggest that "this effect may be attributable to the interaction of a mechanical and thermodynamic process associated with the ice crystals. The smooth, aerodynamic streamlining of the lateral surfaces of the accretion suggests a possible erosion process which wears down the feathery rime that might otherwise grow outwards in this region."

The effect of the ice crystals in cases (b) and (c) was to reduce the overall mass growth rate by about 25% and to redistribute the remaining deposit mass in a more streamlined fashion.

Thin sections of some of the accretions cut perpendicular to the cylinder axis were made in a way similar to a procedure that has been used for making thin sections of hailstones. The thin sections were photographed in transmitted light to show the bubble patterns and between crossed Polaroids to reveal their crystal fabric. It was hoped that such structural information would cast light upon the nature of the ice growth processes occurring during accretion. Little difference was seen in the bubble or crystal structure of sections from liquid water as opposed to mixed-phase conditions. A possible interpretation of this result—which is consistent with the high-speed movie observations in that the airborne ice crystals break up on impact, and that only a small fraction remains embedded in the surface, the rest splashing away—…

Time lapse and high-speed movies were made for some of the experiments, and in most of the films, it is possible to observe the impact of many individual crystals and thereby gain an initial insight into the ice crystal accretion process. An important qualitative observation was that many of the impacting ice crystals bounce off the surface whether it is wet or dry, leaving no apparent residue in the accretion.

A small fraction of the particles, chiefly the larger crystals and possibly conglomerates, hit the surface and were observed to break up/splash, leaving an identifiable ice residue in the surface. The ejected material, which the authors state "is probably predominantly ice, though it may contain liquid water," is usually carried away in the airstream. Occasionally an ejected particle was seen to re-impinge upon the surface and often bouncing again.

This observation would help explain why the mass and dimensional growth rates of the mixed accretions are not substantially different from the corresponding rates in pure liquid water clouds.

Because the high-speed movies were focused on the central portion of the accretion, they contain no apparent evidence which might help to resolve the question of whether the streamlining which is sometime observed is the result of rime feather erosion by the ice crystals.

A comparison of predicted and observed profiles for mixed-accretion cases demonstrated that the model assumption that when the growth is wet, all the impinging ice crystals stick, or at least enough of them to make the deposit just dry was seriously wrong. In fact, as the high-speed movies and the experimental profiles indicate, not nearly all of the ice crystals adhere to the surface even when it is wet.

The authors conclude that for the conditions examined, "it seems that mixed-condition icing need not pose as serious a concern as had been suspected since they do not lead to greatly enhanced icing rates. The net effect of the addition of ice crystals to the air stream in some cases may even be a small reduction in the mass growth rate coupled with an apparent streamlining of the profiles perhaps due to erosion."

A second icing-tunnel study of icing in mixed-phase conditions was conducted in a mountain top instrumented wind tunnel operating in natural icing conditions. The facility was at the Observatoire du Puy de Dome, located on the summit of Puy de Dome mountain, more than 4,000 feet above sea level. This study, which is described in reference 46, grew out of the flight study presented in reference 42. As previously noted, the observations of icing in mixed-phase conditions for the in-flight study were in a dry growth regime. This study provided results for a wet growth regime.

Two fixed-cylinder ice accretions were obtained under icing conditions that were similar except that (a) one was obtained with supercooled water only, and (b) the other was grown in mixed conditions with a large ice particle concentration.

The ice of example (a) was characterized by a profile of constant thickness across the whole deposit, a glassy aspect of the ice, and an ice surface with large roughness. The ice profile of example (b) was quite different in that the profile was elliptical, the ice had a white aspect, and the ice surface was smooth.

Furthermore, the mixed-phase conditions again resulted in a reduction in accretion. The authors explain this as follows: Let M denote measured accreted mass on the cylinder and M_c denote calculated accreted mass on the cylinder for the given experimental conditions. For example (a), it was found that M = 9.0 g and M_c = 10.6 g, whereas for example (b), it was found that M = 3.0 g and M_c = 7.6 g. Thus for (a), the values of M and M_c are reasonably close, whereas for (b) they show a difference of about 60%.

The authors explain the observed white aspect of the accretion in mixed-phase conditions by the incorporation of ice crystals into the structure. They do not mention any documentation of this happening, and their explanation contradicts the findings of reference 44.

The authors also ascribe the difference in roughness to the assumed incorporation of ice crystals into the structure. They assert that under purely liquid supercooled conditions, "the ice structure presents extended crystals with a radial orientation in contrast with small granular crystals observed in mixed conditions. This leads to a rough ice surface in the first case and a smoother ice surface in the second."

In a dry growth regime, the authors had postulated that the ice particles had bounced off the ice structure, substantially eroding it in the process if the particles were sufficiently large. However, in the wet growth regime, the particles are believed to be incorporated into the structure, thus giving it its white aspect. How, then, is the reduction in accreted mass which is observed in both dry and wet conditions to be explained for wet conditions? The authors ascribe it to a loss of water "induced by a weak heat transfer coefficient" due to the smoother surface in mixed conditions.

ENGINE ICING.

It has been recognized at least since the 1950s that glaciated or mixed-phase conditions can present a hazard to some engines. ADS-4 notes that these conditions are not usually a problem, but then notes: "The exceptions have been in the case of turbine engine inlets of great length and curvature. Concentrations of ice crystals at bends or flow reversal points can result in intermittent shedding into the engine, resulting in engine flameout. This problem may be aggravated by areas of ducting that may be warm from contact with hot sections of the engine." Note that it is generally believed that these concentrations of ice crystals form at aerodynamic stagnation points where local airflow velocity suddenly drops due to the flow path shape. These engine inlet ice collection points are intended to be addressed by 14 CFR 33.77(c), where ice slab ingestion is considered as a result of delayed inlet anti-ice activation. The intent of this part 33 paragraph is to demonstrate that engines can ingest ice slabs that have accreted on the inlet surfaces.

William Lewis [5], stated that "interior ducting having reverse bends or stagnation areas may be subject to icing in snow or mixed cloud."

O. K. Trunov [6] speaks of the "great danger for certain types of engines" from ice crystals. He contrasts an engine "with an almost rectilinear air intake channel" to one in which "the air flow changes the direction of its motion 180 degrees near the combustion chambers." He indicates that the second is much more susceptible to "a negative influence of ice crystals" because of possible "accumulation of ice crystals on the bent section of the air intake."

Since 1988, there have been several incidents in which a particular aircraft engine design, utilizing an unusual dual-stage high-solidity first stage low-pressure compressor stator, has experienced power loss instabilities when exposed to an apparently heavy concentration of ice particles and, in at least some cases, mixed with liquid water. The available flight data recorder and meteorological evidence from these incidents suggests that they occurred most often in the anvil area of thunderstorms. Several occurred when flight crews were taking the appropriate action to avoid the large threats from flight in or around thunderstorms. In each case it is believed that nonaerodynamic glaze ice formed and accumulated on an unusual engine design feature, specifically the dual-stage high-solidity first stage low-pressure compressor stators. This ice accumulation resulted in significant aerodynamic blockage to the core of the engine.

Reference 15 notes that most of the incidents occurred near a flight altitude of 30,000 ft msl, often when flight crews were maneuvering around the strong radar echoes characteristic of thunderstorms. A common scenario was that "the engines lost power slowly at first, culminating in a rapid (uncommanded) reduction of power to flight idle, commonly called engine rollback." Engine power authority usually "returned after descent through the freezing level."

Reference 15 also notes that "in no cases did the pilot or crew report more than trace or light airframe icing at flight altitude," suggesting that very little liquid water was present, which is typically the case in the anvils of thunderstorms.

Anvils of thunderstorms form when the thunderstorm cloud spreads out at the tropopause, where there is a temperature inversion. In the middle latitudes of North America, this occurs at around 30,000 feet msl. Most transport jet aircraft cruise at 33,000 to 40,000 feet msl (above the weather) and so their engines are not exposed to these conditions. However, it has been speculated that in other parts of the world where the tropopause is higher than in North America, and where air travel is increasing, more transport jet aircraft may encounter these conditions.

EFFECT ON A TOTAL AIR TEMPERATURE (TAT) PROBE.

Reference 15, quoted above concerning engine rollback in the anvils of thunderstorms, also discusses testing of a heated TAT probe following instances of erroneous temperature readings from such probes in these conditions.

The probe was tested in a wind tunnel in both all ice particle and mixed-phase conditions, with ice particles of a mean diameter of about 1 mm and IWC as high as 5 gm^{-3}. The test results indicated that the probe tended to clog with ice particles—both with and without liquid water—and that this behavior was intensified by the small concentrations of liquid water used. "When the ice bridge forms, the probe heaters warm the sensor, which now is not ventilated with ambient air, to near the melting temperature of ice (i.e., 0°C)," and the probe registers an anomalous warm temperature. Thus this problem is attributed to the same cause, i.e., sharp turning of internal flow, as the cause that ADS-4, Lewis, and Trunov give for engine problems in glaciated or mixed-phase conditions.

Further work on the ground testing of a TAT probe is reported in reference 47. This study was performed in a wind tunnel and made use of a specially constructed ice particle launch gun. Investigators varied ice particle size and density in their investigation but did not include any data on the performance of the probe in their publication.

EFFECT ON THERMAL ICE PROTECTIONS SYSTEMS.

There is a difference of opinion in the very meager public literature on the question of whether or not ice particles make an additional demand on the capacity of thermal ice protection systems. If they simply bounce off even if the surface is heated, then they do not. On the other hand, if they do not bounce off, additional heat will be required from the system.

In his address to the FAA symposium in 1969 [5], William Lewis stated: "If a cloud is composed entirely of ice crystals, icing does not occur on external surfaces, whether heated or not." However, he gives no references in support of this assertion, and other authorities indicate that the situation is different for a heated surface.

ADS-4 makes a strong statement concerning this matter (without providing a reference) on page 1-24:

> Flight through clouds of ice crystals calls for careful exercise of good judgment by the aircraft pilot. Normally, the ice protection systems should not be turned on, as the airframe and engine surfaces will remain clean. In a 'mixed' cloud, ice may accumulate and require use of the ice protection equipment. The capacity of thermal systems may be exceeded, however, and it may be necessary to escape the icing condition as rapidly as possible.

It also notes speculation that "reports of excessive icing might be the result of flight in mixed clouds with anti-icing systems overtaxed by the increased heat needed first to melt the ice crystals, then to warm and evaporate the water." However, it states that "documented evidence of severe airframe icing problems in clouds of ice crystals or mixed clouds is lacking."

A paragraph on page 5-9 notes the need for a pilot making an accurate judgment as to whether he is in glaciated or mixed-phase conditions in deciding whether or not to turn on his ice protection system and warns of possible serious consequences of making the wrong decision (although, again, no reference is provided):

> When encountering ice crystals and snow in dry clouds, it is not necessary to turn on the ice protection system. However, when ice crystals mixed with liquid water are encountered, it is possible for the capacity of the ice protection system to be exceeded. With the ice protection system in operation at these conditions, the runback may be severe (for thermal systems) and evasive action may be necessary.

In his text, Trunov [6] states that "in the majority of the observations the crystals are not retained on the cold surface of the aircraft. However, if its temperature is higher than 0°C (due to the work of the deicing system, kinetic heating, or other causes), then the crystals touching the surface settle on it, partially or completely melt, and can freeze again."

Trunov also provides a mathematical analysis of heat requirements, and, comparing two equations he derives, "the heat requirement protection from 'crystal' icing is greater than in the case of the liquid drop with the same content per unit volume of air, liquid water, and crystals, other things being equal."

There have been reports that if sufficient heat is not supplied, a sort of snow/ice cap or covering can form on top of a thermal heated leading edge in glaciated or mixed-phase conditions with high TWC. The cap is melted from underneath but is continually replenished from the ice particles in the air stream and therefore can persist as long as the aircraft continues in such conditions.

CONCLUSIONS

1. Mixed-phase conditions in the atmosphere are common. The available data suggest that a conservative estimate is that an aircraft may be in mixed-phase conditions as much as 20% of the time that it is operating in icing conditions, and that substantially higher figures may be appropriate in some geographic areas. This may suggest that neither aircraft nor engines are particularly susceptible to mixed-phase conditions on the basis that the actual number of identifiable related service difficulties has been minimal over several hundred million flight hours accumulated over the last 40 years.

2. The available data indicate that mixed-phase conditions occur with a substantially higher frequency than do supercooled large droplets (SLD) in cloud.

3. Mixed-phase conditions in the atmosphere are extremely variable, and characterization data which are suitable for addressing questions of aviation safety are very limited. (There is more, although still meager, characterization data available for glaciated conditions.)

4. Measurement of mixed-phase conditions requires either labor intensive methods (slides, etc.) or sophisticated probes. Traditionally, electrooptical two-dimensional probes have been used, but these have limited resolution and accuracy. New probes designs are becoming available, but in-flight testing of them has been limited.

5. Facility simulation of mixed-phase conditions is difficult and not done routinely in North America. It is not known how well any of the various methods that have been used actually simulate the natural environment. The uncertainty is compounded by a lack of agreement as to the degree of fidelity necessary for the investigation of various safety questions. For example, while it may be adequate to simulate the ice phase with small ice spheres for investigation of internal engine icing, this is less satisfactory to address questions concerning structural icing.

6. The circumstances described in 3, 4, and 5 present very significant practical problems in using either tunnel simulations or inflight testing to assess possible safety hazards due to mixed-phase conditions.

7. The available data, which is for a single small turbopropeller airplane, do not indicate that there is any difference in performance effects caused by structural icing resulting from flight in mixed-phase conditions rather than in purely liquid supercooled cloud. Exposure to large ice particles following flight in large supercooled droplets in cloud resulted in rapid performance recovery in a few documented cases.

8. The available data indicate that the presence of ice particles in a cloud containing liquid water can sometimes reduce structural icing rates that would be observed with the liquid water only. It has been hypothesized that this effect is due to ice erosion in dry growth regimes and to changes in heat transfer in wet growth regimes. The limited data on reduction of icing rate is for icing tunnel and flight studies at a restricted range of conditions and does not appear sufficient for generalization.

9. Major technical reports going back to the 1960s state that exposure to mixed-phase or glaciated conditions can cause anomalies in engines with pronounced bends or flow reversal points. Documented studies in the open literature elucidating such behavior are lacking.

10. Reports in recent years indicate that one aircraft engine design has experienced power loss instabilities in mixed-phase or glaciated conditions encountered in the anvils of thunderstorms.

11. Major technical reports going back to the 1960s state that the capacity of thermal systems may sometimes be exceeded by mixed-phase conditions. More recent information on this issue in the open literature is lacking.

12. Guidance to pilots as to the operations of thermal ice protection systems should emphasize the differences between appropriate action in mixed-phase as opposed to glaciated conditions as well as how to distinguish between these conditions.

REFERENCES

1. "Turbojet, Turboprop, and Turbofan Engine Induction System Icing." Draft Advisory Circular, 20.xx.

2. Code of Federal Regulations, Title 14, Part 23 and Part 25, Washington, D.C., January 1, 1997.

3. "FAA Inflight Aircraft Icing Plan," Washington, D.C., April 1997.

4. Bowden, D. T., Gensemer, A. E., and Skeen, C. A., "Engineering Summary of Airframe Icing Technical Data," Technical Report ADS-4, FAA, Washington, D.C., 1964.

5. Lewis, W., "Review of Icing Criteria in Aircraft Ice Protection," in Report of Symposium on Aircraft Ice Protection, April 28-30, 1969, Washington, D.C., 1969.

6. Trunov, O. K., "Icing of Aircraft and the Means of Preventing It," FTD-MT-65-490, August 1967.

7. Wallace, J. M. and Hobbs, P. V., Atmospheric Science: An Introductory Survey, Academic Press, New York, 1977.

8. Goody, R., Principles of Atmospheric Physics and Chemistry, Oxford University Press, New York, 1995.

9. Mazen, I. P., "Effect of Phase Transition on Formation of Temperature and Humidity Stratification in Clouds," Proceedings of the International Conference on Cloud Physics, August, 1968, Toronto, Ontario, Canada, pp. 132-17.

10. Jeck, R. K., "Snow and Ice Particle Sizes and Mass Concentrations at Flight Altitudes Up to 9 km (30,000 Ft)," DOT/FAA/AR-97/66.

11. Jeck, R. K., "A New Database of Snow and Ice Particle Measurements at Altitudes up to 30,000 Ft (9 km)," AIAA-90-0195, paper presented at the 28th Aerospace Sciences Meeting, Reno, NV, January 1990.

12. Lewis, W. and Hoecker, Jr., W. H., "Observations of Icing Conditions Encountered in Flight During 1948," NACA TN 1904, June 1949.

13. McNaughtan, I. I., "The Analysis of Measurements of Free Ice and Ice/Water Concentrations in the Atmosphere of the Equatorial Zone," TN 283, Mechanical Engineering, Royal Aircraft Establishment, 1959.

14. Bigg, F. J., Day D. J., and McNaughtan I. I., "The Measurement of Ice Crystal Clouds," Aircraft Ice Protection Conference, England, 1959.

15. Lawson, R. P., Angus, L. J., and Heymsfield, A. J., "Cloud Particle Measurements in Thunderstorm Anvils and Possible Weather Threat to Aviation," AIAA-96-0866 paper presented at the 34th Aerospace Sciences Meeting, Reno, NV, January 1996.

16. Korolev, A. K., Strapp, J. W., Isaac, G. A., and Nevzorov, A. N., "The Nevzorov Airborne Hot-Wire LWC-TWC Probe: Principle of Operation and Performance Characteristics, " to be published in Journal of Atmospheric and Oceanic Technology, December 1998.

17. Sand, W. R., Cooper, W. A., Politovich, M. K., and Veal, D. L., "Icing Conditions Encountered by a Research Aircraft," J. Climate and Applied Meteorology, Vol. 23, No. 10, October 1984, pp. 1427-1440.

18. Ashenden, R., "Turboprop Aircraft Performance Response To Various Environmental Conditions," doctoral dissertation submitted to the Dept. of Atmospheric Science at the University of Wyoming, December 1997.

19. Lawson, R. P. and Cormack, R. H., "Theoretical Design and Preliminary Tests of Two New Particle Spectrometers for Cloud Microphysics Research," Atmospheric Research 35 (1995) pp. 315-348.

20. Korolev, A. V., Strapp, J. W., and Isaac, G. A., "On the Accuracy of PMS Optical Array Probes," in Proceedings of FAA International Conference on Aircraft Inflight Icing, Vol. II, August 1996, pp. 105-114.

21. Lawson, R. P., Korolev, A. V., Huang, T., Angus, L. J., Weaver, K. A., Strapp, J. W., Isaac, G. A., and Cober, S. G., "Improved Airborne Measurements of the Drop Size Distribution in Freezing Drizzle," paper in Proceedings of the 12th International Conference on Clouds and Precipitation 19-23 August 1996, Zurich, Switzerland.

22. Lawson, R. P. and Jensen, T. L., "Improved Microphysical Observations in Mixed Phase Clouds," paper in Proceedings of the American Meteorological Society Conference on Cloud Physics, 17-21 August 1998, Everett, Washington.

23. Pruppacher, N. R. and Klett, J. D., Microphysics of Clouds and Precipitation, N. D. Reidel Publishing Co., Dordrecht, The Netherlands, 1980.

24. Heymsfield, A. J., "Cloud Physics," in Encyclopedia of Physical Science and Technology, Vol. 2, Academic Press, New York, 1987.

25. Houghton, H. G., Physical Meteorology, The MIT Press, Cambridge, MA, 1985.

26. Mossop, S. C., "The Origin and Concentration of Ice Particles in Clouds," Bulletin of the American Meterological Society, Vol. 66, No. 3, March 1985, pp. 264-273.

27. Mazin, I. P., Nevzorov, A. N., Shugaev, V. F., and Korolev, A. V., “Phase Structure of Stratiform Clouds,” 11th International Conference on Clouds and Precipitation, Vol. 1, 1992, pp. 332-335.

28. Heggli, M. F., Vardiman, L., Stewart, R. E., and Huggins, A., “Supercooled Liquid Water and Ice Crystal Distributions Within Sierra Nevada Winter Storms,” J. Climate and Applied Meteorology, Vol. 22, November 1983, pp. 1875-1886.

29. Cober, S. G., Isaac, G. A., and Strapp, J. W., “Aircraft Icing Measurements in East Coast Winter Storms,” J. Appl. Meteor., January 1995, Vol. 34, pp. 88-100.

30. Miller, D., private communication, NASA Lewis Research Center, Cleveland, OH, July 1998.

31. Cober, S. G., Isaac, G. A., Strapp, J. W., and Marcotte, D., "Analysis of Aircraft Icing Environments Associated with Supercooled Drizzle,” Proceedings of FAA International Conference on Aircraft Inflight Icing, Vol. II, August 1996, pp. 1-12.

32. Isaac, G., private communication, Atmospheric Environment Service, Downsview, Ontario, June 1998.

33. Politovich, M., private communication, National Center for Atmospheric Research, Boulder, CO, August 1998.

34. Ballard, O. R. and Quan, B., “Ice Crystals—A New Icing Hazard,” Canadian Aeronautical Journal, Vol. 4, No. 1, January 1958.

35. Payne, C. E. G. and Pitts, G. F., “Proteus Icing Experience,” Aircraft Ice Protection Conference, England, June 1959.

36. Joint Aviation Requirements, JAR-25: Large Aeroplanes, ACJ 25.1419, “Ice Protection (Interpretative Material and Acceptable Means of Compliance),” Joint Aviation Authorities, The Netherlands, May 1994.

37. Jeck, R. K., unpublished note, Federal Aviation Administration William J. Hughes Technical Center, NJ 1994.

38. Cooper, W. A., Sand, W. R., Politovich, M. K., and Veal, D. L., “Effects of Icing on Performance of a Research Airplane,” J. Aircraft, Vol. 21, No. 9, September 1984, pp. 708-715.

39. Lenschow, D. H., “Estimating Updraft Velocity From an Airplane Response,” Monthly Weather Review, Vol. 104, May 1976, pp. 618-627.

40. Politovich, M. K., “Response of a Research Aircraft to Icing and Evaluation of Severity Indices,” J. Aircraft, Vol. 33, No. 2, March-April 1996, pp. 291-297.

41. Gayet, J. F., “L.A.M.P.’s Contribution to the New Characterization of the Aircraft Icing Environment,” INSU No. 85-16, October 1986.

42. Bain, M. and Gayet, J. F., “Aircraft Measurements of Icing in Supercooled and Water Droplet/Ice Crystal Clouds,” J. Appl. Meteor., Vol. 21, No. 5, May 1982, pp. 631-641.

43. Ashenden, R. and Marwitz, J., “Turboprop Aircraft Performance Response to Various Environmental Conditions,” AIAA-97-0305, paper presented at the 35th Aerospace Sciences Meeting, Reno, NV, January 1997.

44. Lozowski, E. P., Stallabrass, J. R., and Hearty, P. F., “The Icing of an Unheated Non-Rotating Cylinder in Liquid Water Droplet-Ice Crystal Clouds,” National Research Council of Canada Report, LTR-LT-96, February 1979.

45. Lake, H. B. and Bradley, J., “The Problem of Certifying Helicopters for Flight in Icing Conditions,” Aeronautical Journal, October 1976, pp. 419-433.

46 Gayet, J. F., Bain, M., and Soulage, R. G., “Role of Ice Crystals on Ice Accretion Process,” paper presented at Second International Workshop on Atmospheric Icing of Structures, Trondheim, Norway, June 1984.

47. Sutton, M. and Hammond, D., “The Development of Facilities for the Simulation of Ice Crystal Conditions,” in Proceedings of the International Icing Symposium, sponsored by the American Helicopter Society, Montreal, Quebec, Canada, September 1995, pp. 247-266.

48. Anonymous, Aircraft Icing Avoidance and Protection, National Transportation Safety Board, Bureau of Technology, NTSB-SR-81-1, September 9, 1981.

49. Rasmussen, R. M., Knight, C., and Hills, A., “Status Report on the Development of a Method to Test Holdover Fluids in a Cold Room Using Artificially Generated Snow,” NCAR and FAA, in press.

51. Marek, C. J. and Bartlett, C. S., “Stability Relationship for Water Droplet Crystallization with the NASA Lewis Icing Spray Nozzle,” NASA TM 100220, AIAA-88-0209, paper presented at the 26th Aerospace Sciences Meeting, Reno, NV, January 1988.

51. Schulz, R. J., “Final Report for Research and Modeling of Water Particles in Adverse Weather Simulation Facilities,” Air Force contract number F40600-94-D-0001, Arnold Engineering and Development Center, April 1997.

52. Tibbals, T., personal communication, Air Force Arnold Engineering Development Center, Tullahoma, TN, February 1998.

53. “Icing Wind Tunnel—Artington (A Facility Available for Hire),” Aerospace Composite Technologies Limited.

APPENDIX A—SUMMARY OF DISCUSSION OF MIXED-PHASE CONDITIONS IN NTSB SAFETY RECOMMENDATIONS A-81-116 AND A-96-54, NTSB SPECIAL STUDY NTSB-SR-81-1, AND NTSB/FAA OFFICIAL CORRESPONDENCE CONCERNING THE RECOMMENDATIONS

The NTSB raised the issue of the possible inclusion of mixed-phase conditions in the FAA's icing certification requirements in Safety Recommendation A-81-116, dated September 24, 1981, which states:

> Review the icing criteria published in 14 CFR 25 in light of both recent research into aircraft ice accretion under varying conditions of liquid water content, drop size distribution, and temperature and recent developments in both the design and use of aircraft and expand the certification envelope to include freezing rain and mixed water droplet/ice crystal conditions, as necessary.

This recommendation, along with three others, followed special study NTSB-SR-81-1, entitled "Aircraft Icing Avoidance and Protection" published on September 9, 1981.[48] The discussion of icing in mixed-phase conditions in the study is limited to two passages. The first occurs near the end of the section entitled "Icing Parameters":

> Water also is found in the atmosphere in ice crystals which include snow and ice pellets (sleet). *Frozen particles do not normally adhere to aircraft surfaces and are not considered a hazard. They may become hazardous when mixed with water drops, but there is insufficient data available to document this. {Italics added.}*

The second passage occurs in the last paragraph of the section entitled "Icing Forecasts":

> The measurement and forecasting of the meteorological parameters associated with icing would be only the first of two parts of an improved icing forecasting system. The second and equally important part would be the evaluation of aircraft performance throughout a reasonable range of the meteorological parameters. This is being done currently to the extent necessary to meet the specifications of 14 CFR 25 for those aircraft certificated to fly into known icing conditions, but considerably more data would be required to specify performance under specific icing conditions. *The range of weather parameters would have to be expanded to include mixed ice crystals and water droplets and the large drop sizes encountered in freezing rain. {Italics added.}*

Thus the report provides no evidence of a hazard specifically related to mixed-phase conditions, stating only that such conditions may be hazardous, but that there was insufficient data available to make a judgment.

From 1981 to 1989, A-81-119 was discussed in nine official letters between the FAA and the NTSB. These letters contain some discussion of the safety hazard due to flight in freezing rain (and, in some cases, freezing drizzle), but there is no discussion of a safety hazard due to mixed-phase conditions.

On October 31, 1994, an Avions de Transport Regional Model 72-212 (ATR 72) crashed near Roselawn, Indiana, after holding in icing conditions. NTSB investigators concluded that drizzle-sized supercooled droplets contributed to the accident; they did not find that mixed-phase icing conditions were a contributing factor. On August 15, 1996, the NTSB issued Safety Recommendation A-96-54 in connection with its investigation of this accident. The recommendation includes mixed-phase conditions, essentially in the same way as A-81-116. It states:

> A-96-54. Revise the icing criteria published in Code of Federal Regulations (CFR), Title 14, Parts 23 and 25, in light of both recent research into aircraft ice accretion under varying conditions of liquid water content, drop size distribution, and temperature, and recent developments in both the design and use of aircraft. Also, expand the appendix C icing certification envelope to include freezing drizzle/freezing rain and mixed water/ice crystal conditions, as necessary.

This time mixed-phase conditions are joined with freezing drizzle as well as freezing rain. Two official letters between the FAA and the NTSB have addressed A-96-54; these letters also contain no discussion of a safety hazard due to mixed-phase conditions.

APPENDIX B—TABLES OF OCCURRENCE OF GLACIATED, MIXED-PHASE, AND PURELY LIQUID SUPERCOOLED CLOUDS

(Table III from NACA TN 1904 [12])

TABLE B-1. FREQUENCY OF ENCOUNTER OF VARIOUS TYPES OF METEOROLOGICAL CONDITIONS DURING THE 1948 OPERATION

Condition	Number of Minimum Condition Prevailed	Percent of Total Flight Time	Percent of Total Time in Continuous or Intermittent Visible Moisture
Clear air	6523	61.1	-
Liquid cloud			
Continuous	209	2.0	5.0
Intermittent			
Clear air predominant	504	4.7	12.1
About one-half clear	368	3.5	8.9
Cloud predominant	325	3.0	7.8
Subtotal, liquid	**1406**	**13.2**	**33.8**
Mixed snow and liquid cloud			
Liquid predominant			
Continuous	180	1.7	4.3
Intermittent	384	3.6	9.2
Snow predominant			
Continuous	310	2.9	7.5
Intermittent	108	1.0	2.6
Subtotal, mixed	**982**	**9.2**	**23.6**
Snow			
Continuous	1122	10.5	27.0
Intermittent	228	2.1	5.5
Subtotal, snow	**1350**	**12.6**	**32.5**
Rain	335	3.1	8.1
Rain and snow	30	0.3	0.7
Freezing rain	13	0.1	0.3
Freezing rain and liquid cloud	41	0.4	1.0
Totals	**10,680**	**100.0**	**100.0**

TABLE B-2. OCCURRENCE OF DIFFERENT PHASES OF CLOUDS (TABLE 2 [6])

		Occurrence of Phases of Clouds in %				Occurrence of Phases of Clouds in %		
Form of Clouds	Number of Obs During Icing	Liquid-Drop	Crystal	Mixed	Number of Obs During Icing	Liquid-Drop	Crystal	Mixed
St, Sc, Ac*	720	74	2	21	138	68	10	22
Ns-Sc - frontal	148	70	-	30	40	40	12	48
Ns - As - frontal	246	12	8	80	254	2	20	78
As - all cases	182	30	12	58	130	2	48	50
Cb - all cases	160	18	3	79	70	-	41	59
		Average Occurrence in %				Average Occurrence in %		
		41	5	54		22	26	52

*of uniform air masses

St - stratus
Sc - stratocumulus
Ac - altocumulus
Ns - nimbostratus
Sc - stratocumulus
As - altostratus
Cb - cumulonimbus

APPENDIX C—TABLES OF SUGGESTED TESTING STANDARDS FOR GLACIATED AND MIXED-PHASE CONDITIONS

TABLE C-1. ICE CRYSTAL CONCENTRATION STANDARDS (TABLE 1-6 FROM ADS-4 [4]) (Supplied by the National Research Council of Canada.)

Ambient Temperature °C	Altitude 1,000 Ft.	Maximum Total Concentration (ice crystals plus LWC) gm/m^3	Maximum Concentration in Liquid Form gm/m^3	Extent Mi.
0 to -20	10 to 30	8	1	0.5
		5	1	3
		2	1	50
		1	0.5	Indef.
-20 to -40	15 to 40	5	0	3
		2	0	10
		1	0	50
		0.5	0	Indef.
-40 to -60	20 to 45	2	0	3
		1	0	10
		0.25	0	Indef.
-60 to -80	30 to 60	1	0	3
		0.5	0	10
		0.1	0	Indef.

Thirty minutes exposure is considered for the “indefinite” extent.

NOTES (Ref 1-29)

1. In the present state of knowledge, it is not possible to say how much of the “total free water contents” tabulated exist in the form of water and how much as ice crystals, because supercooled water has been shown to exist at temperatures down to -40°C. Furthermore the percentage of ice crystals and water may vary considerably in any one cloud.

2. From present information it appears that the worst condition for engine and intake icing in mixed water/ice crystals occurs when there is a small quantity of water present.

3. The following assumptions may reasonably be made for design purposes:

   a. Below -20°C all the water present may be assumed to be in the form of ice crystals.

   b. Of the total free water shown in the 0 to -20°C range, not more than 1 gm/m^3 should be taken as water and the remainder as ice crystals, except where the total water content is shown as 1 gm/m^3, when half should be considered as water and half ice crystals.

   c. When the extent of the condition is shown as “indefinite,” it is acceptable to show that the airplane functions satisfactorily during 30 minutes continuous exposure to the conditions.

TABLE C-2. GENERAL CONDITIONS OF LIQUID-DROP AND CRYSTAL ICING (TABLE 10 [6])

Temperature of the External Air (°C)	Range of Altitudes (m)	General Content of the Water[1] (g/m^3)	Extent of Zones of Icing (km)
From 0 to -20	3000 - 9000	8.0	0.8
From 0 to -20	3000 - 9000	5.0	4.8
From 0 to -20	3000 - 9000	2.0	80
From 0 to -20	3000 - 9000	1.0	> 160
From -20 to -40	4,500 - 12,200	5.0	4.8
From -20 to -40	4,500 - 12,200	2.0	16
From -20 to -40	4,500 - 12,200	1.0	80
From -20 to -40	4,500 - 12,200	0.5	> 160
From -40 to -60	6,000 to 13,700	2.0	4.8
From -40 to -60	6,000 to 13,700	1.0	16
From -40 to -60	6,000 to 13,700	0.25	> 160
From -60 to -80	9000 to 18,200	1.0	4.8
From -60 to -80	9000 to 18,200	0.5	16
From -60 to -80	9000 to 18,200	0.1	> 160

[1]Making up the general content of water is water in the form of drops and crystals but not in the form of vapor.

TABLE C-3. PROVISIONAL DETAILS OF CONDITIONS LIKELY TO BE ENCOUNTERED IN SERVICE (TABLE 3 [36])

Air Temperature (°C)	Altitude Range		Maximum Crystal Content (g/m^3)	Horizontal Extent		Mean Particle Diameter (mm)
	(ft)	(m)		(km)	(n miles)	
0	10, 000	3,000	5.0	5	3	
to	to	to	2.0	100	50	1.0
-20	30,000	9,000	1.0	500	300	
-20	15,000	4,500	5.0	5	3	
to	to	to	2.0	20	10	1.0
-40	40,000	12,000	1.0	100	50	
			0.5	500	300	

NOTES:

1. In the temperature range 0 to -10°C the ice crystals are likely to be mixed with water droplets (with a maximum diameter of 2 mm) up to a content of 1 g/m^3 or half the total content whichever is the lesser, the total content remaining numerically the same.

2. The source of information is RAE Tech Note Mech. Eng. 283, date May 1959.

TABLE C-4. PROPOSED ICE/SNOW TEST SPECIFICATIONS FOR INFLIGHT CONDITIONS [37]

(a) Anvil Clouds (above 25,000 Ft ASL):

	Range of Variables	Representative Values
Altitude	25,000 - 50,000 Ft ASL	25,000 - 35,000 Ft ASL
OAT	-25°C to -50°C	-25°C to -35°C
IWC	up to 1.2 g/m^3	0.6 g/m^3
Maximum Diameter	1 - 10 mm	1 - 10 mm
Horizontal Extent	?	5 - 20 nmi

(b) Cirrus Clouds and Deep Winter Storms (above 20,000 Ft ASL):

	Range of Variables	Representative Values
Altitude	20,000 - 50,000 Ft ASL	20,000 - 35,000 Ft ASL
OAT	-20°C to -50°C	-25°C to -50°C
IWC	0 to 0.2 g/m^3	0.05 g/m^3
Maximum Diameter	0 - 3 mm	1 mm
Horizontal Extent	5 - 100 nmi	20 nmi (cirrus)
Horizontal Extent	100 - 500 nmi	100 nmi (deep winter storms)

(c) Other Snow/Ice Clouds (below 20,000 Ft ASL):

	Range of Variables	Representative Values
OAT	0°C to -30°C	-5°C to -25°C
For OAT from 0°C to -20°C		
IWC - for horiz ext. < 30 nmi	0 to 3 g/m^3	0.6 g/m^3
IWC - for horiz ext. > 30 nmi	0 to 1 g/m^3	0.4 g/m^3
Max Dia.	0 - 10 mm	1- 8 mm
For OAT from -20°C to -30°C		
IWC - for all horiz ext.	0 - 1 g/m^3	0.2 g/m^3
Max Dia.	1 - 5 mm	1 - 4 mm

APPENDIX D—COMMENT ON "THE PROBLEM OF CERTIFYING HELICOPTERS FOR FLIGHT IN ICING CONDITIONS" BY LAKE AND BRADLEY

In October 1976, an article by H. B. Lake and J. Bradley appeared in the Aeronautical Journal entitled "The Problem of Certifying Helicopters for Flight in Icing Conditions."[45] Statements have appeared in the literature ascribing to this paper the assertion that high icing rates were observed in mixed conditions. However, the paper does not include any such statements, and in fact there is no paper in the open literature known to the author which supports this position.

The article by Bradley and Lake was originally presented at the "Icing on Helicopters" Symposium held the preceding year; it described icing trials of a Wessex Mk. 5 helicopter carried out in the United Kingdom over a period of several years. One important finding was that "the effects of icing on the unprotected helicopter rotor can vary enormously. In some conditions there is only a small power increase required, even during prolonged encounters, while on other occasions very large power increases can be required within one or two minutes of encountering icing."

Two references used in this report state that Lake and Bradley ascribed this behavior to mixed-phase conditions. Specifically, reference 17 states that "Ice accumulation due to encounters with ice particles have been discussed by Lake and Bradley (1976), who indicated that under mixed cloud conditions ice particles could contribute to the accumulation of ice" and reference 39 refers to "the conclusions of Lake and Bradley (1976) who attributed the high icing rates they observed to the high concentrations of the ice particles in a mixed cloud."

However, as noted above, the paper does not ascribed the behavior to mixed-phase conditions or to any other cause. The authors report that "for a variety of reasons we have been unsuccessful in our attempts to quantify the icing environment in which we have done our work." Thus they are not able to give even a tentative explanation of this rather perplexing behavior.

Reference 44 states that these findings occasioned speculation "not constrained by a complete set of measurements." Prominent among the possible causes proposed was mixed-phase icing. Perhaps this speculation took place at the symposium at which the paper was originally presented, and perhaps one of the authors took part. This could have led to the statements in references 17 and 42. In any case, there is no discussion of this in the paper itself.

APPENDIX E—SIMULATION OF ATMOSPHERIC MIXED-PHASE CONDITIONS

The simulation of mixed-phase conditions involves two technical problems: first, production of ice particles and second, entrainment of the ice particles along with supercooled droplets in the air flow. These will be discussed in turn, although for some approaches this division is artificial, as the solution of the first is directly linked to the solution of the second.

1. Production of Ice Particles

1.1 *Growth of Ice Particles in a Separate Cold Chamber Under Conditions Which Simulate Those Under Which They Are Produced in the Atmosphere*. Reference 44 mentions an apparently successful attempt to produce small ice crystals for wind tunnel experiments by nucleating droplets with liquid nitrogen and growing them in a supersaturated cold chamber. This approach is limited by the residence time required to obtain sufficiently large particles. Although there have been limited efforts of this kind, apparently a way has not been found to produce sufficient numbers of ice particles using this approach.

1.2 *Collection of Recently Fallen Snow*. This was done for the experiments described in reference 44, which explains that snow was collected out of doors within a few days of its fall and placed in the dry ice-cooled conveyor belt channel in an insulated box. "It was carefully leveled to a depth of 0.02 m and then fed through an oscillating rake at a rate of 10^{-3} to 10^{-2} m/s before falling through a vertical tube into the plenum. A flat plate was mounted below the end of this tube in order to arrest the fall of any large aggregates and to break them up."

1.3 *Production of Bulk Ice Followed by Break-Up/Crushing and Sieving to Obtain Ice Particles of Desired Shape and Density.* Reference 47 describes a project where this approach was taken. This will be described in some detail to emphasize the problems involved.

High-density ice particles were produced by freezing tubs of demineralized water, breaking the ice into progressively smaller pieces, and repeatedly sieving them to obtain the required particle sizes.

Lower-density ice particles were manufactured using a set of water spray nozzles mounted in a low-speed air outlet duct and two screens in the tunnel settling chamber in the wake of the nozzles. It was found that the density of the ice on the screens was correlated with air velocity. Ice was allowed to form on the screens for periods of about 10 minutes, after which the screens were vigorously shaken, and the ice fragments collected. A block of wood with a curved face was used to force the particles through the sieves. The process was repeated three times and particles of specific sizes collected and stored in various buckets. This approach permitted the manufacture of relatively large amounts of particles and their storage so that a series of tests could be conducted in rapid succession. In some cases, particularly with the finer particles, the particles were resieved immediately prior to the test to avoid caking.

The authors note that large amounts of ice formed in many areas of the test facility during ice manufacture using the spray nozzles and some of this was retrieved and used in the tests.

The authors state: "Considerable efforts were required to produce the vast quantities of ice required. Indeed, the amount of ice consumed ... was the limiting factor in the rate of testing. The difficulties of spending day after day crushing blocks of ice into ever smaller pieces in a room at -20°C has to be experienced to be fully appreciated."

1.4 *Shaving of Bulk Ice With a Sharp Instrument Such as a Knife or a Drill*. Reference 49 notes that the fall speed and snow density of ice shavings produced mechanically with a sharp cutting edge are quite similar to the actual densities and fall velocity of natural snowflakes (snow crystals aggregated together).

1.5 *Use of Water Spray Nozzles to Produce Ice Particles*. References 50 and 51 describe the use of water spray nozzles, of the air-blast atomizing type, to provide tunnel conditions ranging from all liquid water to mixed-phase conditions to totally frozen-out ice crystal clouds. This is accomplished by adjustment of the temperature and pressure of both the air and water. The exact process by which the ice crystals in the spray are produced is not fully understood, but tunnel conditions can be correlated to the temperature and pressure of the air and water.

Reference 52 notes that mixed-phase conditions were simulated in the AEDC icing tunnel by using two sets of spray nozzles. One produced liquid water droplets which traveled down the tunnel to became supercooled droplets and the other froze the water particles into ice crystals as they left the nozzle. The ice and liquid water contents were deduced from the tunnel flow and the corresponding amount of water sprayed from each set of nozzles.

2. Entrainment of the Ice Particles in the Air Flow

2.1 *Injection of Ice Particles Into Plenum Using a Hydraulically Driven Conveyor Belt Mechanism Contained in an Insulated Box.* This method was used in the research described in reference 44 (see 1.2 above) using recently fallen snow, but could presumably be used with ice particles produced in other ways.

The ice crystal content in the working section was varied by changing the belt speed. The ice crystal content in the working section was measured directly using a set of five aluminum sampling tubes. The crystals were injected into the tunnel with essentially no horizontal component of velocity; their velocity was assumed to be in equilibrium with the tunnel air stream in the working section.

2.2 *Use of Specially Designed Ice Gun*. In the project described in reference 48, it was decided that in order to accelerate the ice particles to the tunnel airspeed, a compressed air system running at subzero temperatures would be used. A special gun was developed capable of injecting ice particles into a test section. The gun and associated air supply system were capable of producing ice particle concentrations of up 5 gm/m^3 for periods up to 10 minutes at a particle velocity of approximately 170 m/sec (560 ft/sec). The gun design included two cylinders for the ice particles mounted above the air supply/ice mixing section. A piston in each cylinder moved the ice particles at a controlled rate, allowing them to fall down transparent plastic pipes into the mixing section of the gun where they are accelerated to the tunnel velocity along a long bar by high-pressure air.

The research described in reference 47 concentrated mainly on ice crystal clouds, but did include investigation of mixed-phase conditions. Difficulties were encountered in simulating mixed-phase conditions at the higher gun air flows.

2.3 *Use of Spray Nozzles.* If spray nozzles are used to produce the ice particles (see 1.5 above), then the ice crystals are entrained in the spray in the same manner as the liquid water drops.

3. Current Simulation Capability: Limitations and Uncertainties with Respect to Investigation of Safety Issues

The methods described have been used effectively to investigate various specific safety and research questions. For example, the spray nozzle method (see 2.3 above) has been used to investigate questions concerning nozzle icing and the ice particle production method described in 1.3 above has been used with an ice gun (see 2.2 above) to investigate the effect of ice crystals and mixed conditions on a temperature probe. However, these methods require special efforts in most facilities; an on-demand capability to simulate mixed-phase conditions currently exists only in the Artington Icing Wind Tunnel of Aerospace Composite Technologies in England. The tunnel description states that ice crystals are "mechanically produced up to 2.7 kg min^{-1} at a nominal average size of 1 mm." Further details are not provided.[53]

All the methods described have certain significant limitations or associated uncertainties. The spray nozzle method (see 2.3 above) can only be used to investigate questions for which it is acceptable to simulate the ice particles by relatively small spherical particles. Furthermore, direct counting or measurement of the ice crystals in the plenum would apparently require new instrumentation, perhaps using the polarization properties of ice. This problem arises because the main method for distinguishing ice particles from liquid water droplets, used in atmospheric studies, is based on recognizing the irregular shapes of the ice particles, but in this case the ice particles would presumably be quite regular and approximately spherical.

An important limitation of the other methods appears to be the difficulty involved in the production of sufficient quantities of ice crystals if extensive testing is required.

Issues which are carefully addressed in the simulation of purely supercooled clouds, such as flow quality in the tunnel and uniformity of the cloud, would appear to raise difficulties with all the methods described.

All the methods described above use an icing tunnel, and all share a significant limitation with respect to engine testing, namely the inability to simulate the discontinuity between icing particle temperature and local air temperature within the engine. Since the tunnel air is used to supercool the liquid water droplets and to maintain the ice crystals frozen, its static temperature must be subfreezing. For an engine in flight, the local air temperature at a component downstream of a rotating stage can be quite warm while the icing particles reaching that component are still cold due to the slow thermal response of the particles. As a result, the heat balance on the component surface is different for the tunnel test hardware and the actual flight hardware. Attempts to introduce hot air just upstream of the test article have been found to disturb and melt the icing particles.[52]

One important uncertainty with the methods described concerns how well they simulate the natural environment. This is compounded by the circumstance that the degree of fidelity of the simulation necessary for the investigation of some safety questions is itself uncertain.

The conditions in the working section would appear to be substantially more uncertain than those for simulation of a purely supercooled cloud because of difficulties in measuring and counting the ice particles and, in some cases, in determining their velocities.