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16. Abstract <p>The FAA International Conference on Aircraft Inflight Icing, held on May 6-8, 1996, in Springfield, Virginia, was attended by over 400 participants from the U.S. and nineteen foreign countries. The conference included a review of major aspects of airworthiness when operating in icing conditions. It consisted of an opening plenary session, five working group sessions addressing (1) Icing Environmental Characterization, (2) Ice Protection and Ice Detection, (3) Forecasting and Avoidance, (4) Requirements for and Means of Compliance in Icing Conditions (Including Icing Simulation Methods), (5) Operational Regulations and Training Requirements, and a closing plenary session. One of the primary areas of concern at the conference was icing due to supercooled large droplets (SLD).</p> <p>Volume I of the conference proceedings covers presentations of the speakers at the opening plenary session and the reports of the co-chairs of the working groups at the closing plenary session.</p> <p>Volume II of the conference proceedings is a compendium of technical papers presented in the various working groups.</p>			
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FAA INTERNATIONAL CONFERENCE ON AIRCRAFT INFLIGHT ICING

PLENARY SESSION PROCEEDINGS

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Executive Summary

The FAA International Conference on Aircraft Inflight Icing, held on May 6-8, 1996, in Springfield, Virginia, was attended by over 400 participants from the U.S. and 19 foreign countries. The conference was an integral part of the third phase of the response of the Federal Aviation Administration (FAA) to an accident of a transport category aircraft in October 1994. The goal of this phase is to review current certification requirements, applicable operating regulations, and forecast methodologies associated with aircraft icing under varying environmental conditions. The conference included a review of major aspects of airworthiness when operating in icing conditions to determine if changes or modifications should be made to provide an increased level of safety.

One of the primary areas of concern at the conference was icing due to supercooled large droplets (SLD) (or other icing conditions outside of the FAA icing certification envelope described in Appendix C of Part 25 of the Federal Aviation Regulations).

The conference began with a plenary session on May 6 during which presentations were given by representatives of the FAA, the Joint Airworthiness Authorities, foreign airworthiness authorities, and national organizations concerned with flight safety.

The attendees met in working groups from mid-afternoon on May 6 to noon on May 8. The titles of the working groups were: Icing Environmental Characterization, Ice Protection and Ice Detection, Forecasting and Avoidance, Requirements for and Means of Compliance in Icing Conditions (Including Icing Simulation Methods), and Operational Regulations and Training Requirements.

The working groups began with technical presentations intended to provide a survey of the state of the art and knowledge for the respective groups. The technical presentations were followed by discussions resulting in recommendations for short-term actions in areas such as operations, training, and education and for long-term efforts such as research, development, and rulemaking.

The conference closed with a plenary session on the afternoon of May 8, which was devoted to reports by the working groups and closing remarks by

Anthony Broderick, FAA Associate Administrator for Regulation and Certification.

Volume I of the conference proceedings covers the plenary sessions. Speakers at the opening plenary session submitted written text to accompany their presentations, and these are reproduced in this volume. This is followed by the reports of the co-chairs of the working groups, Administrator Broderick's closing remarks, and a roster of registrants for the conference. The recommendations in the working group reports will be evaluated in the preparation of an FAA inflight icing plan with specific actions and milestones.

Volume II of the conference proceedings is a compendium of technical papers presented in the various working groups. All papers included were either received in response to a "call for papers" or were invited papers of special interest to the conference. In addition, the FAA working group co-chairs had the prerogative of granting time for brief presentations in response to requests made directly to them. In some cases, the FAA co-chairs asked that the papers accompanying these brief presentations be included in Volume II. These papers can be found in the appendix at the end of Volume II.

Welcome to the Conference

**DAVID R. HINSON
ADMINISTRATOR
FEDERAL AVIATION ADMINISTRATION**

Good morning and welcome to everyone. Thank you for being here for this important conference.

We are fortunate to have the world's best experts on hand as we continue to seek ways to further enhance safety for aircraft in icing conditions. Looking at the abstracts of the papers to be presented during this conference, I am impressed by their breadth and scope and the areas to be discussed. The adage that aviation shrinks the globe is certainly true for us. It's a small world for those in civil aviation, and the FAA values its many associations with the participants here today.

Before I begin, I would like to recognize our hosts--the many talented professionals in the Regulation and Certification organization, as well as the Technical Center in Atlantic City, New Jersey. Your contributions in bringing together aviation experts from throughout the world are to be commended.

No problem has a higher priority than safety, and everyone here this morning can claim credit for measurable success. We have all been working together, and this cooperation has made a significant difference.

Flight in icing conditions has been a concern to pilots and aircraft designers almost as long as airplanes have been flying. The heroic cross country mail flights in the 1920's and 1930's were plagued by ice during winter flights. We often proudly speak of the science of aviation and how improvement in technology has made flying safer since the early days of the cross country mail flights. The continued innovative application of technology has, today, made flying the world's safest mode of transportation. While we can take pride in aviation's overall safety record, we must not relax our effort to maintain the highest standards of aviation safety.

Aviation, however, is far from being an industry settling into stolid maturity. It is more dynamic than it has ever been. Since the FAA was created in 1958, air travel in the United States has grown from about 50 million

passengers a year to over 550 million. Worldwide air travel is expected to more than double over the next 20 years, with an average annual growth rate of 5.1 percent. The resulting increase in the number of airplanes will increase exposure to the icing environment.

Our goal of "zero accidents" is an ambitious one. It requires not only a new approach but an entirely new structure--a structure where safety issues such as icing are addressed and solutions sought by all who have a stake in ensuring the safety of our skies. This conference is an effort to tackle the issue of airplane inflight icing directly by bringing together pilots, engineers, weather forecasters, operators, and researchers.

Now is the opportunity to take a fresh look at inflight icing issues and to develop innovative solutions to these issues. Over the years, the international aviation community has worked cooperatively to reduce the hazards of windshear, mid-air collisions, and aircraft aging. I am positive that, together, we can do the same with inflight airplane icing.

As we all know, aviation safety is the one essential precondition for industry vitality. In this spirit, we have pooled the results of research and new technology to meet each new challenge to safety. I don't believe anyone here assumes this conference will solve all the icing issues. Unfortunately, I don't think we will come up with a silver bullet to protect all airplanes. If someone thinks they have, we definitely will be talking to you. But we will learn a lot here; and with that information, we can make things better.

Almost 4 years ago, on May 28 and 29, 1992, we sponsored a conference in Reston, Virginia, on aircraft ground deicing. The results of that conference have made things better. Today, we have approved winter ground deicing programs that have greatly reduced the safety concern of ice build-up during ground operations prior to takeoff.

I don't doubt there will be a cost to whatever actions we take in the future, but we pay for inaction: the potential for loss of life, the loss of public confidence in effective government, and a reduction of the public trust in air safety. This price is unacceptable.

My hope is that throughout this conference we can share our expertise and strive forward to even greater levels of cooperation as we face this important safety issue.

Thank you.

Conference Charge

ANTHONY J. BRODERICK ASSOCIATE ADMINISTRATOR FOR REGULATION AND CERTIFICATION FEDERAL AVIATION ADMINISTRATION

Thank you very much, David; and I thank all of you for being here, especially those of you that have traveled from outside the United States to attend this International Conference on Aircraft Inflight Icing. Your presence is a recognition that aircraft icing is not only a concern within the United States but throughout the world. We value your expertise, recognize the work that some of you have made in specific areas of icing, and hope to learn both from you and with you.

The importance of this meeting cannot be overstated. As the Administrator stated earlier, operation of airplanes in ice conditions has been a safety concern almost as long as airplanes have been flying. Many of us in the aviation community when asked to describe icing conditions can immediately recite the definition in the Aeronautical (formerly Airman's) Information Manual or the airplane flight manual: "Visible moisture and temperatures below 5 degrees Celsius." Asked to describe freezing drizzle or freezing rain, the response depends on who you ask. We hear terms such as Supercooled Drizzle Drops (SCDD) or Supercooled Large Drops (SLD) used as references or hear numbers like 100-500 microns water drop diameter for freezing drizzle and 500-1500 microns for freezing rain. Even if the technical community had agreement that these numbers and terminology were correct, which we don't, they wouldn't mean much to a flight crew trying to make an approach into Chicago's O'Hare Airport on a cold and rainy evening. Just think of it, one (1) micron is one millionth of a meter. To put it into perspective, the typical lead in a mechanical pencil is one half or 0.5 millimeters. That is 500 microns! Try as much as we can, we still can't get pilots' eyesight calibrated to recognize this size range.

What we do agree on is that no civil aircraft is certificated for flight in these conditions.

Nearly eighteen months ago, I announced the establishment of a three-phase program to look at the hazard of SLD. Phase I involved assisting the

National Transportation Safety Board (NTSB) in the investigation of the tragic accident in Roselawn, Indiana, on Halloween night 1994. While the NTSB has not published their report concerning the probable cause of this accident, the FAA has taken positive actions arising from the NTSB safety recommendations issued as a result of their investigation. We have completed all actions resulting from our own review. This phase is complete.

Phase II, which started in March 1995, looked at turbopropeller powered airplanes with unpowered flight controls and mechanical deicing systems currently used in regularly scheduled passenger service. Recently 17 final rule Airworthiness Directives (AD) were issued as a result of the Phase II review. These AD's will be discussed, separately, later in the conference. Phase II is complete. This conference is the start of Phase III.

The purpose of this conference is simple to describe but not easy to accomplish. That purpose is ensuring safe airplane flight operations when icing conditions exist in an area, especially when the conditions commonly referred to as freezing drizzle and freezing rain occur. The FAA believes that ensuring safe operations in these conditions could require certification of airplanes in SCDD or SLD, or keeping the certification standards as they are now but improving the forecasting and avoidance requirements so as to assure that airplanes do not enter these conditions, or requiring a mix of both.

To this end, the conference seeks to bring together, in various working groups, experts in the fields of weather forecasting, aircraft certification, flight operations, ice protection and ice detection systems, and icing research. Technical papers will be presented followed by discussion of the current state-of-the-art and future trends in each of these areas. Each working group will report out recommendations as to short and long term actions they believe are warranted. These recommendations need not be limited to the FAA but can be directed to any organization that can affect improvement in aircraft inflight icing. One example could be a recommendation to the National Weather Service concerning changes to the aviation weather forecasting system.

The FAA will review the recommendations from the working groups and, by late summer, develop an icing program plan outlining those actions we will take to ensure safe operation in icing conditions.

Let me conclude by saying again the FAA is hoping to learn both from you and with you with the goal of improving the safety of inflight airplane operations with respect to icing conditions in general and freezing drizzle and freezing rain in particular. Let me turn the conference back over to Dan Salvano to introduce the speakers for this plenary session.

Review Of Phases I and II

**JOHN P. DOW, SR.
SMALL AIRPLANE DIRECTORATE
AIRCRAFT CERTIFICATION SERVICE
FEDERAL AVIATION ADMINISTRATION**

Ladies and Gentlemen, I'd like to extend my welcome and express my appreciation for your participation, especially to those of you who have traveled a great distance to be here for this conference.

It should be helpful to spend a few minutes reviewing the events and activities that led to this Phase III conference — Phases I and II.

I am John Dow from the Small Airplane Directorate in Kansas City, Missouri.

On January 11, 1995, the Associate Administrator for Regulation and Certification, Tony Broderick, announced a phased plan to address roll upset and related icing issues following the fatal accident of American Eagle Flight 4184, in Roselawn, Indiana, on October 31, 1994.

Phase I comprised those remedial actions involving the accident airplane.

Phase II focused on screening airplanes in-service with design features similar to the accident airplane, operating in regularly scheduled revenue passenger service which are equipped with unpowered controls and pneumatic deicing boots. The screening process evaluated the potential for uncommanded aileron movement and unacceptable control wheel force with a ridge of ice aft of the active part of the deicing boots forward of the ailerons.

Phase III is the long-term program for an in-depth review and subsequent action for a range of different aspects of inflight icing. Those aspects are: protection and detection, means of showing compliance, icing environment characterization, forecasting and avoidance, and operations and crew training. Those topics will be addressed in the five working group sessions.

Preliminary information available after the accident suggested very strongly that the accident occurred in an icing environment that contained a

substantial volume of supercooled water droplets predominantly in the range of 100 to 400 microns in diameter. Droplets in this size are characterized as freezing drizzle. Since ice accreted in these conditions may not be controllable by the ice protection system, it is considered severe.

The FAA had the task of assessing the effects of ice accretion in that environment. Such a task was problematic due to the lack of global characterization data of the freezing drizzle environment and validated test means to simulate that environment or predict the resulting ice shapes. Ultimately, a data source was found providing well instrumented measurements of the cloud physics in limited penetrations of the freezing drizzle environment and the USAF was able to simulate this environment by operating its icing tanker in a non-normal way. In summary, an ATR 72-212 was flown to Edwards Air Force Base in Southern California in early December 1994, for simulated icing tests behind the NKC135. This airplane — a Boeing 707 sized airplane — has an icing array mounted on an aerial refueling boom resembling a large shower head used to dispense water droplets that create a simulated icing cloud in sub-freezing temperatures.

This first-time effort will be addressed by Mr. Gilbert Defer, formerly of ATR who will address that subject in detail.

Tanker testing at the accident airplane configuration resulted in accretion of a substantial ridge beyond the active limit of the wing deicing boot coverage when the flaps were extended to 15 degrees. Subsequent dry air flight tests with artificial ice shape matching the accreted ice nearly replicated the accident profile.

As a result of the subsequent dry air testing, ATR increased the coverage of the upper surface outer wing deicing boots from 5 percent on the ATR-42 and 7 percent on the ATR-72 to 12 1/2 percent on both models. FAA mandated that change on March 27, 1995, to be effective in June 1995. This change prevented growth of a ridge of critical height in the event of an inadvertent encounter in freezing drizzle.

Further as a part of the Phase I program, the FAA conducted a special certification review of the ATR-42 and -72. The findings of that special certification review were that both airplanes were in full compliance with the applicable DGAC and FAA/JAA requirements. In fact, the ATR-72 complied with a special condition which was issued by the DGAC of France. That requirement is viewed by many as more stringent than FAR/JAR 25 and is the basis for the JAA notice of proposed amendment, NPA 25 F219. Eric

Parelon will be presenting a paper discussing that particular NPA this afternoon in the working group for requirements for and means of compliance.

Phase II started in March 1995. At that time, the FAA initiated a review of airplanes for potential hinge moment anomalies. The candidate types included Part 23 and Part 25 airplanes equipped with pneumatic deicing boots, non-powered flight control systems, and employed in regularly scheduled revenue passenger service. The reason for assessing this population first was based upon the potential exposure to icing conditions. Other airplanes will be evaluated in turn. The issue of how all airplanes will be addressed is one of the reasons for this meeting here today.

During a meeting in June 1995, here in the Washington area, the FAA addressed with 23 airplane manufacturers, vendors and other groups, the results of the investigation of the ATR-72 and how best to screen airplane designs for potential hinge moment reversals or control anomalies. Four methods were discussed. The method employed by most manufacturers was a high-speed ground taxi test with a 1-inch high quarter round molding, flat edge forward, just forward of the ailerons. The control wheel forces and other data measured during taxi tests would be extrapolated to the holding condition and evaluated against force criteria.

Following are airplanes that were evaluated during this program: Beech 99, 200, 1900/-C/-D; Jetstream Aircraft Ltd. ATP/HS 748; de Havilland DHC-6, DHC-8-100, -200, -300, DHC-7; Dornier 328; EMBRAER EMB-110, EMB-120; Fairchild SA 226/227; Fokker F-27, 50; Jetstream 3101/3201, 4101; Saab 340; and Shorts SD3-30/-60. One airplane was taken to the next step, the EMBRAER EMB-120, and was actually tested behind the tanker at Edwards AFB. No modifications were required on any of the airplanes that the Federal Aviation Administration (FAA) evaluated during this Phase II program.

Four other airplanes outside the Phase II criteria were voluntarily evaluated by their manufacturers. They were the CASA C-212, Cessna 208, CN-235, and the Saab 2000. The CN-235 and the Saab 2000 evaluations are still in progress and are expected to be resolved successfully in the near future.

As a result of all this questions have arisen about how frequently freezing rain/freezing drizzle conditions are observed in flight and what, if any, problems were associated with those occurrences. These questions were addressed by a survey Regional Airline Association (RAA) and the FAA

established in mid-October 1995 a voluntary reporting system called the Unusual Icing Reporting Program to obtain pilots' observations of severe icing conditions. The program consists of the pilot submitting a report to the airline, the airline forwarding the report to the RAA, and the RAA removing identification and forwarding to the FAA for use by the FAA and any other organizations who would care to get copies of this information. This information was sent to the Air Line Pilots Association (ALPA), the National Center for Atmospheric Research, and other organizations.

From October 1995 until January 1996, thirteen reports were received of unusual icing conditions. These were not incidents; these were simply observations of ice by reporting flight crews. Predictably, since there has been a great deal of information supplied to the ATR pilots in several different documents along with specialized training we received the most number of reports on the ATR-42 airplane. There were no roll or control anomalies reported on ATR's. There were no unusual events reported on the ATR's at all, simply observations of ice.

On the three reports submitted on other airplanes there were comments made about the speed/power and control deflection/force relationships, but no incidents involving the other airplanes either. Pilots of other types successfully used similar cues and procedures as ATR to detect and exit the icing condition. These procedures included disconnecting the autopilot and changing altitude by 2,000 to 4,000 feet. Reports were received on freezing rain, freezing drizzle, and runback ice. Steve Green will present the results of a program ALPA has conducted.

Finally, one of the programs that has taken high priority with the FAA is rulemaking action. The FAA determined that the flight crews of the airplanes we discussed earlier were not provided with information to help them determine when the airplane was in an icing condition outside the envelope or what they should do when they happened to be in that particular icing environment. On January 25, 1996, the FAA issued 17 Notices of Proposed Rulemaking (NPRM's) and subsequently issued the 18th. After reviewing the comments, 18 Final Rule Airworthiness Directives were issued on April 24, 1996. All the time, effort, and comments submitted in response to the NPRM's was certainly appreciated.

The FAA team worked long and hard to review each and every comment and provide a thoughtful answer. I would like to compliment Kathi Ishimaru and Rose Upton of the Transport Airplane Directorate and Scott Wesley of the Small Airplane Directorate for their tremendous effort.

John P. Dow, Sr., Federal Aviation Administration

Basically, this is the prologue, to how we happen to be here today and some of the actions that have led up to this particular meeting.

Thank you for your attention.

Inflight Icing: A Review of Some JAA Activities

**GRAHAM D. WEIGHTMAN
JOINT AVIATION AUTHORITIES
U.K. CIVIL AVIATION AUTHORITY**

Abstract

This paper presents an overview of the JAA's activities on airworthiness flight requirements for Large Transport Aeroplanes with respect to Inflight Icing.

Flight Characteristics in Icing Conditions

JAR/FAR 25.1419 "Ice protection" requires that the aeroplane must be able to safely operate in the continuous maximum and intermittent maximum icing conditions of JAR/FAR 25 Appendix C. Draft JAA Advisory Material (AMJ 25.1419) provides an interpretation of the phrase "to safely operate" as regards flight performance and handling qualities. This Advisory Material is contained in the JAA Notice of Proposed Amendment 25F-219 and has been used for some years for JAA and European national certifications and validations to JAR 25. It is currently subject to harmonisation for adoption for JAR and FAR 25.

Ice Contaminated Tailplane Stall (ICTS)

A pushover manoeuvre to zero g to test for tailplane stall/elevator overbalance was developed by the JAA in the Advisory Material described above and was adopted by the first ICTS workshop in Cleveland in 1991.

Inadvertent Entry into Conditions not covered by Appendix C

The JAA has not been heavily involved in the follow-up to the Roselawn accident because the FAA's investigations have been conducted directly with individual European Authorities and manufacturers. However, the JAA offered comments on the proposed AFM revisions and would wish to co-operate in any future developments.

The JAA has made a proposal for future rule-making regarding inadvertent entry into conditions not covered by Appendix C.

Discussion

Introduction

This paper presents an overview of the JAA's activities on airworthiness flight requirements for Large Transport Aeroplanes with respect to Inflight Icing. As this conference will undoubtedly put much emphasis on flight in Supercooled Large Droplet (SLD) conditions, it would be useful to clarify that work on other aspects of flight in icing conditions continues.

Because of the recent accident history three major icing issues are already being addressed, i.e., tailplane stall, ground de-icing and roll control anomalies. However, there remains a need for a comprehensive review of the airworthiness certification of aircraft for operation in icing conditions. The JAA has developed Notice of Proposed Amendment (NPA) 25F-219 addressing performance and handling qualities for flight in icing conditions and Certification Review Items (CRIs) covering type certification for flight in icing conditions, using this NPA as a basis, have been raised against JAA certifications and validations for some years.

With both the tailplane stall and roll control anomaly issues, attention has been focused on turboprop aeroplanes. This obviously has nothing to do with the type of powerplant but a recognition that turboprops are likely to have the design features relevant to the problems (i.e. non-powered, reversible control surfaces and boot de-icing systems) compounded by greater exposure to icing conditions as a result of short-haul operations at lower altitudes and speeds. However, other classes of aeroplane should also be considered. Turbojets, particularly small ones, may have manual control systems and de-icing boots and so may also be susceptible to tailplane stall and roll control anomalies. Large turbojet aeroplanes generally don't have major problems today with inflight icing but the extent of airframe ice protection is reducing with every new design. For these reasons inflight icing should be treated in a consistent and comprehensive manner across all aeroplane types.

Flight Characteristics in Icing Conditions (NPA 25F-219)

There was concern in the JAA Flight Study Group (FSG) in the mid-80s regarding incidents and accidents to turbopropeller powered aeroplanes in icing conditions, typically tailplane stall or stalling and control problems

following loss of performance. It was also recognised that little material existed addressing satisfactory standards for flight characteristics (performance and handling qualities) for operation in icing conditions. To develop this material, the FSG established an Icing Sub-Group, comprising Flight and Systems specialists from the European Authorities and industry.

The Icing Sub-Group held its first meeting in 1987. Its initial task was to consider tailplane stall/elevator over-balance and a push-over manoeuvre to zero "g" was developed to address this. It was considered that the push-over manoeuvre provided a suitable test to cover the situations in service which might lead to tailplane stall. This is addressed in more detail later in the paper.

A further task was to develop policy on aeroplane performance and handling qualities criteria for flight in icing conditions and this was based on identification of existing practices and a review of the clear air flight test requirements. The intention was to formalise and harmonise the various European practices and this aim was made more urgent by the advent of JAA Joint Certifications.

At this stage the French DGAC prepared Special Conditions for the type certification of turboprop aeroplanes based on the early work of the Sub-Group, Transport Canada Advisory Material and its own experience. With modifications to accommodate wider application, these Special Conditions subsequently formed the basis for the Sub-Group's future discussions.

The Icing Sub-Group discussed the status of the new material, i.e., whether it was appropriate to introduce new regulations or advisory material. Since it also introduced the so-called "sandpaper ice" and guidance on the surface roughness of the ice shapes it was decided to relate this material to JAR 25.1419, where it would clearly complement the existing JAR Advisory Circular Joint (ACJ) 25.1419.

JAR 25.1419, Ice Protection reads:

"If certification for flight in icing conditions is desired, the aeroplane must be able to *safely operate* in the continuous maximum and intermittent maximum icing conditions of Appendix C...."

The Sub-Group considered that the phrase "to safely operate" clearly needed interpretation and NPA 25F-219 therefore proposed the introduction of Advisory Material Joint (AMJ) 25.1419 to do this. The basic premises behind the NPA are:

- i. No credit can be given for the probability of encountering icing conditions - if certification for flight in icing conditions is sought, those conditions are considered a normal operating environment and the probability of encountering icing conditions must be assumed to be 1 for the purpose of certification.
- ii. The same criteria should be applied to turbojet and turboprop aeroplanes since they operate in the same atmosphere and are subject to the same physical laws.
- iii. Notwithstanding (ii), there are clearly differences in the characteristics of aeroplane types, their operating characteristics and the effectiveness of ice protection systems that should be recognised and taken into account in the demonstration of compliance.
- iv. The aircrew's workload is often higher in the icing environment.

A continuing and critical theme throughout the development of the NPA has been the standard of airworthiness that should be required. Some degradation in flight characteristics is to be expected in icing conditions but to what extent? If it is requested for certification, flight in icing conditions must be considered a normal operation. It is possible to argue, then, that there is no justification for any degradation below the minimum standards of the flight requirements of JAR/FAR 25 Subpart B. This leads to the statement that "full compliance with the performance and handling requirements of Subpart B must be shown for flight in icing conditions". In fact, the approach adopted for the NPA was more pragmatic, concentrating on what were considered to be significant issues and allowing engineering judgement in the extent to which compliance with the normal Subpart B flight requirements must also be shown for icing certification.

NPA 25F-219 was first submitted to the JAA consultative process in 1991 and Issue 2 was published for subscribers' comments on 23 April 1993. During its development, the NPA had been used in many certifications and it was formally adopted for certification as JAA Interim Policy INT/POL/25/10, pending formal acceptance for JAR 25. This has now been re-classified as Temporary Guidance Material TGM/25/02 following the introduction by the JAA of this latter category.

In 1994 the NPA was raised as a FAA/JAA harmonisation item and the Flight Test Harmonisation Working Group (FTHWG) has been tasked with reviewing NPA 25F-219 and the comments received during the public consultation on the NPA. The FTHWG has held four meetings to date on this item. The last was in February 1996, at which the group took a different approach to that in the NPA: where the NPA proposes Advisory Material to 25.1419, the FTHWG is discussing a rule change to add a new 25.21(g) to identify specific performance and handling qualities requirements which must be met in full in icing conditions. The remaining flight requirements will then be covered by advisory material.

The FTHWG has recommended the concurrent harmonisation of the systems requirements of JAR/FAR 25.1419 and ACJ 25.1419 and has recognised the need to work closely with the new Ice Protection Harmonisation Working Group.

Development of NPA 25F-219

1987	Icing Sub-Group established by the JAA Flight Study Group
1991	NPA 25F-219 submitted to the JAA for internal consultation
1993	NPA published for subscribers' comments on 23 April
	NPA adopted as Interim Policy INT/POL/25/10 (later re-classified as Temporary Guidance Material TGM/25/02)
1994	Subscribers' comments received
	Harmonisation of the NPA and resolution of subscribers' comments established as an FAA/JAA Harmonisation item
	Harmonisation item submitted to the Flight Test Harmonisation Working Group. First meeting held in Toulouse in October
1995-96	Harmonisation of the NPA in the Flight Test Harmonisation Working Group continues

Ice Contaminated Tailplane Stall (ICTS)

Several accidents and incidents have occurred because the crew encountered a large elevator force reversal following manoeuvring to low load factor or selection of landing flap in approximately 1g flight. The rapid pitch divergence, the high and/or abrupt changes in control forces, the surprise factor and possible disorientation in poor visibility can result in a situation where there is a high probability of this loss of control leading to an accident.

The push-over manoeuvre to zero g contained in NPA 25F-219 was presented by the JAA to the first ICTS Workshop at NASA Lewis, Cleveland in 1991. It was seen as a suitable flight test to cover the above concern because it:

- i. provides a modest margin during a deliberate push-over to low load factor (say 0.3 to 0.4g), a manoeuvre sometimes seen in training, positioning etc., or in a low g situation induced by a gust, and
- ii. accounts for the downwash change due to selection of a larger flap setting because the pitch rate induces an increased negative angle of attack at the tailplane which reflects that due to the downwash change.

The push-over manoeuvre was adopted by the FAA for its Part 23 and Part 25 Memoranda on ICTS. This issue is also currently being addressed by the Flight Test Harmonisation Working Group.

Inadvertent Entry into Conditions not covered by Appendix C

The JAA has not been heavily involved in the follow-up to the Roselawn accident because the FAA's investigations have been conducted directly with individual European Authorities and manufacturers. However, the JAA offered comments on the proposed AFM revisions and would certainly wish to co-operate in any future developments.

The JAA has made a proposal for future rule-making regarding inadvertent entry into conditions not covered by JAR/FAR 25 Appendix C as follows:

- i. Consider the effects of flight in ambient atmospheric conditions consisting of cloud droplets with mean effective diameters greater than those within the limiting icing envelopes of JAR/FAR 25 Appendix C.

- ii. Evaluation of these effects should include:
- Determination of methods for detection of flight in icing conditions not covered by Appendix C, which may include specific visual cues of ice accretion and/or detection devices.
 - Determination that the aeroplane can safely exit icing conditions not covered by Appendix C.

It is envisaged that this proposal will be progressed by the Flight Test and Ice Protection Harmonisation Working Groups.

Conclusion

The JAA considers inflight icing to be a very significant issue and has put considerable effort into furthering the international debate. It is important that any future airworthiness regulation on this subject is fully harmonised between FAA, JAA and Transport Canada.

French Action Plan to Consolidate Air Transport Safety in Icing Conditions

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FRANCE**

Abstract

The main French organizations involved in the air transport have met several times and defined a national action plan to consolidate air transport safety in icing conditions. These organizations include aircraft operators, aircraft and equipment manufacturers, air traffic controllers, meteorologists, scientists, the aviation authority, accident investigators. The action plan has five objectives :

- i. To specify current aircraft certification requirements according to the best knowledge of the real atmosphere,
- ii. To develop airborne systems to detect severe icing conditions,
- iii. To improve current icing forecasting for the flight preparation and to develop an immediate weather forecasting service for severe icing situations,
- iv. To improve pilots' education and training on icing phenomenon and its consequences,
- v. To improve circulation of icing information between meteorologists, air traffic controllers and pilots.

The main challenges are scientific and of an economic nature. Another challenge is the mutual understanding between the different participants in the icing world.

In spite of all efforts devoted to air transport safety, aircraft accidents in icing conditions still occur. Of course, the current average safety level of air transport in icing conditions in the world is very high. And I would like to thank today all those who have contributed to this high level of safety. But,

the number of all weather operations is increasing quickly. If nothing is done, accidents will occur more frequently in the next years. This scenario is not acceptable. The aeronautical community should commit itself to new efforts to improve safety of future air transport in icing conditions. And I know many organizations in the world who have decided to do so.

What I am going to present today is the French action plan to consolidate air transport safety in icing conditions. This will give you a global vision of what we are doing in France on aircraft in-flight icing issues.

This plan was defined after several meetings between the main French organizations involved in the safety chain of aircraft flight in icing conditions. These include¹ aircraft operators, aircraft and equipment manufacturers, air traffic controllers, meteorologists, scientists, the aviation authority, accident investigators.

The action plan is built upon 5 objectives.

i. To specify current aircraft certification requirements according to the best knowledge of the real atmosphere

Recent experience shows that icing can occur outside atmospheric conditions which have been used as a reference by aviation authorities in the world (except those of Eastern Europe) to certify aircraft airworthiness in icing conditions. This icing phenomenon is very rare but we know now that it can create ice forms outside the protected areas of aircraft and it can dangerously damage the flying qualities of aircraft. I will qualify these particular and dangerous icing conditions : "severe icing conditions".

Concerning existing fleet, French aircraft manufacturers have evaluated airworthiness of their turboprop aircraft in severe icing conditions. They have enhanced icing protection measures related to deicing equipment, operational procedures and pilot training. They have presented and discussed their results with all interested aviation authorities in the world. This work has resulted in new safety standards which all turboprops manufacturers in the world should aim at. Mr. Defer will present in the plenary session the work ATR² has done concerning their aircraft.

¹ Cf. appended list

² Avions de Transport Régional

For the future, new aircraft will have to demonstrate their flying qualities in severe icing conditions. New certification requirements are being discussed to assess aircraft performance and handling in icing conditions and to address inadvertent severe icing encounters. In that respect, DGAC³ is working with the European Aviation Authorities (JAA⁴), the FAA⁵, the TCA⁶, industry and airlines pilots. Graham Weightman of the JAA has just presented the JAA's work (in the plenary session) and Eric Parelton of the JAA will present the JAA Notice of Proposed Amendment NPA 25F-219 in workshop "requirements for and Means of compliance in icing conditions".

To support this regulatory work, existing icing data will be analysed in order to improve our knowledge of severe icing. We are also working with our European partners in a research programme called Eurice. This programme is funded by European research centers and aircraft manufacturers and the European Commission which represents the European Union member States. CIRA of Italy will explain to you the details of this programme in the workshop called "Icing environmental characterization" and one called "Requirements for and means of compliance in icing conditions". This programme started in January 96 and will last 2 years.

At the same time, French aircraft design methods are being enhanced. Simulation tools are necessary because it would be too expensive and technically very difficult to experiment real aircraft in severe and rare natural icing conditions.

Aircraft manufacturers are modifying their calculations codes which they use to design their aircraft and to get aircraft certification. The modifications will take into account particular icing conditions on aircraft performance, such as:

- icing around 0° Celsius,
- super cooled large droplets and drops,
- ice roughness,
- ice deposit called "lobster tail".

The simulation of severe icing conditions (such as super cooled large droplets) is not an easy matter. Test centers (ONERA⁷, Centre d'Essais de Propulsion),

³ Direction Générale de l'Aviation Civile (French Civil Aviation Authority)

⁴ Joint Aviation Authorities

⁵ Federal Aviation Administration (USA)

⁶ Transport Canada Aviation

⁷ Office National d'Etudes et de Recherches Aéronautiques

the Ministry of Defense and DGAC are exploring all possible solutions. In that respect, Mr Prieur will present to you in workshop "requirements for and means of compliance with icing conditions" ONERA's icing wind tunnel in Modane, the modifications ONERA has made and what they plan.

This work should last 3 more years. It should be of high interest for many aircraft manufacturers in the world which use calculations codes developed in France.

ii. To develop airborne systems to detect severe icing conditions

Currently, aircraft can not fly in any icing conditions and there are operational limitations to enforce. Beyond these limitations, pilots should exit the icing environment. But it is not easy to do so. In practice, pilots often have trouble determining if the icing of the day is within or outside the aircraft operational limitations. Moreover, existing weather forecasting service is not totally reliable.

As a result, pilots need assistance and appropriate warning systems for severe in-flight icing conditions.

For helicopters, the need is to detect icing in advance, in front of the aircraft because the vast majority of helicopters can not fly safely in icing conditions. The idea of detection in front of the aircraft is quite revolutionary. We will define the feasibility of predictive ice detection systems and the scope of work.

For large aeroplanes, different organizations are taking initiatives :

- DGAC is working with the JAA to define appropriate requirements for airborne icing detection systems.
- French equipment manufacturers are developing systems to detect severe icing conditions. Work will focus on the detection of the presence of ice aft the protected zones and on the detection of the aerodynamic distortions. Special attention will be paid to the location of the sensors, the interface with the pilot and with the other systems of aircraft.

I believe that the future of ice detection systems for large aeroplanes lies in systems which can detect both in-flight icing and also ground icing which is also a very important safety and environmental issue.

Today, one of the most difficult questions to solve is the location of the sensors so that detection is the most representative and effective. To solve this question, we will improve our knowledge of severe icing conditions and we will use ad hoc simulation means.

In that field, Michel Le Pimpec of INTERTECHNIQUE will present in the workshop "Ice detection and ice protection" an article on ultrasonic detection of large droplets accretion. Mr Averous of AERAZUR will also present a paper called the "ice protection system for a new commuter aircraft".

iii. To improve present icing forecasting for the flight preparation and to develop an immediate weather forecasting service for severe icing situations

Pilots and air traffic controllers need weather forecasts to manage their flight or their traffic. Currently, needs for icing weather forecasts with a time scale of few hours are more or less satisfactory. For short time forecasts, needs are mainly satisfied thanks to pilots who exchange their real-time weather observation information through the air traffic controllers.

More systematic, accurate, and reliable information is required by pilots and air traffic controllers.

METEO FRANCE is already working on new severity indices in order to improve precision of current icing forecasts which are provided few hours before the flight. Validation of these methods should take one more year.

For very short time forecasts, METEO FRANCE is envisaging the development of an expert system which will help the weather forecaster in assessing the probability of occurrence of normal and severe icing. These icing forecasts will be based on statistical methods with data provided by airlines pilots, radars and satellites.

This work will last 3 or 4 years, including new training for weather forecasters.

Jean-Marie Carrière of METEO FRANCE has planned to take part in workshop on "Forecasting and avoidance". He will give more details about METEO FRANCE's on-going and planned activities.

iv. *To improve pilots' education and training on icing phenomenon and its consequences*

Icing is not a friend to aviation. Pilots must be well educated and trained to keep aircraft flying safely and avoid adverse icing conditions. Currently, educational and training programmes address the meteorological phenomenon. But aeroplanes pilots seems to be overconfident or inadequately informed about the capability of their aircraft to fly safely in icing conditions.

Educational and training programmes will be completed with more information on aircraft certification conditions. They will also deal with the consequences of icing on flight mechanics, flight performances, propulsion and equipment.

DGAC will define the general contents of new educational and training programmes for icing issues. They will modify regulations concerning examinations for commercial pilots licences, examinations and renewal of IFR rating, aircraft type rating programmes and airlines pilot training programmes.

Specific actions have already been taken for airlines using ATR. Work should be completed in the middle of next year.

v. *To improve circulation of information between meteorologist, air traffic controller and pilot*

There are three main sources and users of information on icing : meteorologists, air traffic controllers and pilots.

- a) The *meteorologist* is a *source* of information. He provides icing forecasts to air traffic controllers and pilots. He is also a *user* because he needs real observations of pilots and air traffic controllers to be able to validate his forecasts.
- b) The *air traffic controller* is a *user* of information from the meteorologist in order to regulate its traffic. He also *uses* information from the pilots who can provide real time observations of their weather environment. He is also a *source* of information because he informs pilots on the in-flight weather conditions.

- c) *Pilots are users of information when they prepare their flight and when they fly. They are also a source of information which is very useful for the air traffic controllers and for the meteorologists.*

It seems therefore very important to make sure that this chain of information between meteorologists, air traffic controllers and pilots is effective.

We have taken actions to improve this circulation of information.

- New procedures are experimented: When pilots identify moderate to severe icing conditions, they inform air traffic controllers and the air traffic controllers inform the meteorologists. The format of the information includes the aircraft type, the flight level, the icing type and, if possible, total and static temperatures. The information is then analysed by meteorologists. Information will be systematically disseminated through ATIS (Air Traffic Information System) and SIGMET warning messages for severe icing.

French regional airlines have already made their crews aware of the need to report to air traffic controllers on icing conditions. ATC services, weather forecasting services and the Ministry of Transport are defining a way to request systematic information from pilots.

- Educational and training programmes for meteorologists, air traffic controllers and pilots will be completed so that everyone is aware of all safety aspects and of the importance of its role in the system. Courses with all operators, at local level, and training on simulators are envisaged. Improvements have already been achieved in programmes for meteorologists and air traffic controllers.

Conclusion

I would like to conclude by reminding you how huge the job has been to keep present air transport safety in icing conditions at acceptable levels and how huge the job will be to improve further safety. The action plan I have presented today shows that many organizations in France commit themselves to this effort. We are taking concrete actions related to aircraft design, ice detection equipment, weather forecasting service, educational and training programmes, working methods between meteorologists, air traffic controllers and pilots.

These actions will provide solutions which meet safety needs for future air transport in France and which can meet the expectations of other States. The important progress we have made for the ten last years and your participation to this conference let me be optimistic.

The main challenge is scientific. Icing is a complex phenomenon. The threat is not always visible or predictable. But a better knowledge of severe icing conditions is a must.

Another challenge is of an economic nature because we need important funding to support all research needs. Synergy between all organizations in France and cooperation with our European and American partners have been developed. These efforts will have to be maintained at national and international levels for several years if we want to finalise and implement efficiently all necessary icing protection measures.

A last challenge I would like to point out is communication between different participants. Scientists, meteorologists, air traffic controllers, pilots, aircraft/equipment designers, aviation authorities do not use the same words to describe icing severity or they use same words to describe different things. This kind of communication is important so that everyone in the system can play their role efficiently. In that respect, DGAC will study, in 1996, the different languages and their correspondence and will contribute to facilitate mutual understanding.

This conference is also a good opportunity to encourage and facilitate mutual understanding. One key for the success of this conference depends on our efforts to understand each other.

It would be a great step forward for future aircraft flight safety in icing conditions if we could, during these 3 days, identify all the best ideas and solutions which could be implemented in the different activities which support air transport, at national or international levels, on a short or longer term basis.

I would like to thank the FAA for offering me this opportunity to meet you and I thank you all for your interest in air transport safety and for your attention.

***French Organizations Involved
in the Safety of Aircraft Flying in Icing Conditions***

Aircraft operators : Air France, Air Inter, Brit'Air, Fédération Nationale de l'Aviation Marchande, TAT

Aircraft and equipment manufacturers : Aérazur, Aérospatiale, Airbus Industrie, Dassault Aviation, Eurocopter, Groupement des Industries Françaises Aéronautiques et Spatiales, Intertechnique, Sfm Industries

Air traffic controllers : Direction Générale de l'Aviation Civile (Direction de la Navigation Aérienne)

Meteorologists : Météo France

Scientists and experts : Ministry of Defense, Office National des Etudes et des Recherches Aérospatiales, Laboratoire Atmosphérique de Météorologie Physique

Aviation authority : Direction Générale de l'Aviation Civile

Accident investigators : Bureau d'enquêtes-accidents

Update on Action/Research Ice Detection Study Freezing Rain/Drizzle Programme

**CLIFF BARROW
JOINT AVIATION AUTHORITIES/
U. K. CIVIL AVIATION AUTHORITY**

Abstract

This paper presents the CAA's concerns regarding the safety of aircraft flying in icing conditions, and describes associated actions and research in three general areas, namely the certification icing atmosphere, ice detection, and pneumatic boot systems. Research on the characteristics and probability of freezing rain/drizzle suggests that the probability of such conditions may be significant. Investigation has indicated that, in some incidents, the flight crew may have had difficulty in recognising icing conditions and were late in actuating the airframe de-icing system, and a more efficient ice detection systems may have been of benefit. Studies have confirmed concerns regarding the limitations of pneumatic boot de-icing systems and their use on large modern transport category aircraft. The CAA has been closely monitoring the FAA action on large droplet icing/roll control problems and, whilst supporting the general objective of addressing flight safety in these conditions, has some concerns regarding the programme and how it has been conducted to date. A comprehensive and harmonised approach to rulemaking is essential to ensure that not only future certifications but also, where appropriate, the re-assessment of existing in-service aircraft, are conducted thoroughly and equitably.

Objective of Presentation

The objective of this presentation is to explain the origins of the UK CAA's concerns regarding the safety of aircraft flying in icing conditions and describe the actions and research programmes instigated as a response.

The CAA's view of the recent FAA freezing drizzle/large supercooled drop programme is offered and ideas are put forward for determining the basis for future policy and rulemaking.

Origin of CAA Concern

In the late nineteen-eighties the CAA determined the need to examine the record of UK operations with respect to accidents/incidents (occurrences) associated with flight in icing conditions. Although these occurrences were not particularly frequent, a persistent pattern was apparent with two main areas, namely helicopter engine problems, and fixed wing turboprop aircraft encountering control difficulties in flight, being prevalent.

These incidents were the subject of investigation by the UK Aircraft Accident Investigation Branch (AAIB) and, as a result, recommendations were made to the CAA for further action.

Three general issues emerged from these recommendations:

- i. Is the existing certification icing atmosphere adequate?
- ii. Can crew alerting be improved by efficient ice detection systems?
- iii. Are existing pneumatic boot de-icing systems still acceptable on modern aircraft?

The CAA has therefore taken steps to address these questions by investigation and research.

CAA Action and Research

Icing Atmosphere

There appeared to be a factor common to several incidents in that they occurred in ambient temperatures close to 0 degrees C, affecting both helicopters and fixed wing aircraft. The two obvious questions were therefore; (a) did the certification testing adequately cover this temperature regime and; (b) do the certification requirements adequately address the 'real' icing atmosphere in these conditions?

The view that FAR/JAR 25 Appendix C has stood the test of time has been expressed on several occasions. However, the data on which it is based is now quite old and on this basis alone there appeared to be sufficient reason to re-examine its adequacy. Furthermore, there was at least circumstantial evidence that conditions related to freezing precipitation, rather than supercooled cloud alone, may have been present during some incidents. The CAA therefore decided in 1988 to initiate some research on the characteristics and probability of freezing rain/drizzle in the atmosphere. At

same time we were aware of the FAA programme to investigate the icing atmosphere and the commitment to include freezing rain in their studies. It therefore seemed worthwhile to contribute to the FAA programme with a view to longer term requirement activity.

A two year UK Meteorological Office study, conducted for the CAA, was completed in 1990 and a report issued which was made available to FAA. This looked at the characteristics and probability of freezing rain in the UK atmosphere throughout the altitude range using data from ground stations and radiosonde ascents. The conclusion was that the probability of such conditions may be significant compared to that generally assumed for the specified conditions in Appendix C.

Although the FAA appeared to have taken the decision not to proceed with requirement activity based on a reassessment of the certification icing atmosphere, we were encouraged that freezing rain, (or 'large drops'), was discussed in forums such as the FAA Tailplane Icing Workshop, and is the subject of a dedicated SAE AC-9C Panel.

As a follow on project the Met. Office has further defined the probability in terms of percentages of time in freezing rain at a given location and will soon produce a further report which will summarise the work and attempt to give, for example, number of miles flown per encounter with freezing rain.

In addition the CAA has contracted the Met. Office to examine the feasibility of developing a method to define a global aircraft icing environment using satellite data and models of clouds and precipitation. This programme has run into technical difficulties and has been terminated for the time being but the methodology and results of work up until cessation will be published by the CAA. A further proposal for research using this experience to develop icing forecasting methods is being considered.

Ice Detection Systems

Investigation of the turboprop aircraft occurrences indicated that, in some cases, the flight crew may have been late in actuating the airframe pneumatic boot de-icing system. This could have been because either they did not realise that the aircraft was in ice forming conditions, or because they did not judge that there was enough ice on the visible part of the aircraft to actuate the system. It appears likely therefore that an efficient ice detection system may be of benefit in timely recognition and action, particularly with

respect to protected parts of the airframe outside the visual field of the flight crew.

We are aware that the FAA has also been involved in intensive activity regarding ground ice detection for several years and although many of the technologies proposed are applicable to ground use only, others may be suitable for in-flight use. We are aware of industry activity on such systems including the possible integration of detectors in pneumatic boots and the results are encouraging.

The CAA completed a small study in 1992 which surveyed the existing available ice detection technology. In 1994 we contracted Loughborough University to conduct a more extensive study including a survey of operators and aircraft manufacturers to assess their experience with in-flight ice detection and their attitude to developing new systems. The results of this work were published as CAA Paper 95007 in 1995 and have been presented in several icing forums.

The main conclusions were that although there are obvious benefits in providing efficient ice detectors for in-flight use and several promising new technologies exist, flight crew are generally aware that the aircraft is in or is entering icing conditions before an ice detection signal occurs. A more fundamental issue was the operation and performance of pneumatic boot de-icing systems on turboprop aircraft.

Pneumatic Boot De-Icing Systems

Investigation of incidents involving turboprop aircraft had on some occasions resulted in the questioning of the suitability of existing technology pneumatic boot de-icing systems on modern aircraft. This included doubt concerning the flight crews' ability, knowledge, and experience in operating the system according to the Flight Manual procedures or in a manner which is the most efficient in removing the ice. The conclusions of the 1995 report were confirmation that such systems are perceived by the operators as unreliable and sometimes not particularly efficient at removing ice.

One particular problem is the confusion apparent with respect to the possibility of ice 'bridging'. There has been a general conception that if the pneumatic boots are actuated with too thin a layer of ice on the surface then, in some conditions, the ice may flex but not break away over the inflating boots. It would then be possible for the ice layer to continue growing, with obvious hazardous consequences, unless the flight crew became aware of the

situation and quickly left the icing conditions. While acknowledging that there are some conditions of icing where shedding by the boots is less efficient, there seems to be little evidence for the ice bridging phenomenon. Indeed, if it were a real possibility, it seems inevitable that it would occur regularly and be clearly recognised. It is possible that where bridging has been reported, the real problem could simply be poor ice shedding performance, perhaps in icing conditions not adequately investigated during certification test flying. In any case, some manufacturers' Flight Manuals specify operation of the boots in an 'anti-icing' mode, i.e., to be actuated continuously as soon as ice is apparent on any part of the airframe. We are not aware of any in-service problems associated with this procedure

There are several new technology systems in development which could replace pneumatic boots and these look promising with respect to increased efficiency ice shedding. However a realistic appraisal shows that there are problems with compatibility between these new ice protection systems and turboprop aircraft. The study concluded that the increased cost of installing and providing the required power to more efficient de-icing or anti-icing systems on turboprop aircraft is a basic problem both commercially and technically. The existing ice protection requirements are objective and performance based, (i.e., not prescriptive regarding the characteristics of the system), and it is therefore unlikely that new systems will be provided on new types in the foreseeable future and certainly not on existing in-service and newly manufactured turboprop aircraft.

The CAA has therefore contracted Loughborough University to perform a follow-up study to investigate the effect of different ice protection systems on a typical turboprop tailplane in terms of aircraft performance, aircraft operations, and Direct Operating Costs, using the pneumatic boots as a baseline. This study is expected to take two years.

Flight Crew Awareness/Education

The most immediate step that could be taken to improve the overall situation is the provision of information to flight crew where appropriate material can be compiled or already exists. The CAA has considered the production of a video but has not as yet made progress in this respect. However in June 1994 the CAA issued an Aeronautical Information Circular entitled 'Turboprop and other Propeller Driven Aeroplanes: Icing Induced Stalls'. This was compiled with reference to a study of FDR data from incidents which was conducted on behalf of the CAA.

Supercooled Large Drop Phenomenon and FAA Programme

The UK CAA fully supports a programme to investigate the need for and develop appropriate airworthiness requirements to address atmospheric conditions outside the existing Appendix C envelope. This support arises from our long held view that such conditions, even if confined to 'conventional' freezing rain alone, may occur more frequently than their omission from the requirements would warrant. The view during our research was that when evidence of such conditions and their probability of encounter was established, discussion could then take place on the appropriate way forward, first in establishing criteria for airworthiness requirements and then consideration of any justifiable retrospective action. Although airframe icing on aerodynamic surfaces has been the main concern, recurrent problems involving turboprop and turbofan engine rundown and also pitot icing have on more than one aircraft type indicated the need to adopt a more comprehensive approach. However, there was little evidence which indicated the need for immediate or precipitate action. Although there was a history of incidents there was inconclusive evidence linking any one to consistent unusual atmospheric conditions.

The Roselawn ATR-72 accident in October 1994 of course drew a line under previous activities. The CAA was impressed by the urgency and resources made available for the investigation. However, like some other authorities, the CAA did feel uncertain about the apparent confidence being given to the correlation between the estimated accident atmospheric conditions, wing ice shapes, and the icing conditions in the test icing plume behind the tanker. The CAA was also concerned regarding the rationale for applicability to other aircraft types. The absence of the NTSB report and conclusions in support of follow-up action was, we felt, a significant factor, although we were impressed by the openness and extent of information made available at the meeting in Washington in May 1995.

The CAA's concern, again in common with some other authorities, had two main components. Firstly, although of course a sensitive subject, and one which is fully understood could have delayed appropriate action, there was only limited opportunity for technical discussion of features relating to the accident aircraft type which may have contributed to the problem or its service history. The second was the policy of not considering service history in considering the extent of action needed on other types. It is obviously a special case when considering conditions outside the certification requirements but the real icing atmosphere has not changed. It seems logical to suppose therefore that aircraft with considerable service experience will

have already encountered similar conditions. If, however, the conditions are so infrequently encountered that they have not, any action that is taken must be properly justified.

Concerning the FAA NPRM action which requires identical additional Aircraft Flight Manual material for the list of applicable aircraft, there is opinion, justified in our view, that some manufacturers, even though having expended considerable effort investigating their own aircraft in accordance with FAA directions and having developed appropriate Flight Manual material, have not been given further opportunity to submit recommendations based on their own investigations.

Where Do We Go From Here?

Although experience, better instrumentation, and a more systematic approach to evaluation of handling and performance have contributed to icing certification in recent years, the issue of the icing atmosphere was one that many specialists considered overdue for review. One problem was the gathering of sufficient reliable evidence. Equally daunting was the prospect of determining and implementing rule changes. The evaluation of conditions even inside the Appendix C envelope is open to judgement and interpretation. The limitations of existing techniques in accretion modelling and laboratory simulation must be realistically assessed together with the obvious difficulties in encountering an adequate range of conditions during natural ice flight tests.

The CAA fully supports the forthcoming harmonisation activity on icing airworthiness requirements. The issue of the icing atmosphere will of course form a central part of these discussions. However, we believe it important to consider this in coordination with all aspects of icing certification and indeed beyond that into other areas such as operations and maintenance.

Without prejudging any outcome of this activity, it seems unlikely at this stage that freezing rain/drizzle could be addressed in the same way as the 'normal' conditions inside the existing appendix C envelope for the reasons of limitations in techniques as described previously. The results of the intense activity over the past eighteen months may however form a valuable basis for determining means of assessing recognition of such conditions and the ability of an aircraft to safely negotiate and exit or avoid them. It is extremely important to consider the implications of broadening application to all Part 25 aircraft. The possible extension into retrospective requirements, needs careful consideration.

In addition to the icing atmosphere the CAA supports discussion and appropriate action on all the other issues covered by the conference agenda. In particular a coordinated investigation into improved methods of ice protection and detection for turboprop aircraft is proposed.

Presentation by:

J.C.T. MARTIN

T. OWEN

TRANSPORT CANADA

Abstract

This paper presents some Transport Canada views on flight in icing. Some of the factors in recent accident and incidents are discussed together with measures which could be implemented to improve safety. These measures include improvements in equipment, certification and operational procedures. The continuing airworthiness of in service aircraft is also discussed.

Introduction

Canada's winter climate results in the need to efficiently and safely conduct aircraft operations in icing conditions. Operations are carried out in regions which experience a significant number of days with freezing drizzle and/or freezing rain. Canada is also one of the major manufacturers of turbojet and turbopropeller powered transport aircraft used in short haul operations. Canadair Regional Jets and de Havilland DHC-6, DHC-7 and DHC-8 aircraft are used extensively in Canada and throughout the world. Transport Canada has the responsibility for certification and continuing airworthiness of these aircraft. Transport Canada recognizes and shares some of the FAA's safety concerns with respect to certification and operational issues associated with inflight icing. Transport Canada's concerns include, but are not limited to, operation in Supercooled Large Droplets (SLD).

Background

Accidents and Incidents

From an overall look at the safety of aircraft operations in icing conditions, it is readily apparent that there have been a number of differing contributing factors. Leaving aside accidents due to attempted takeoff with contaminated aircraft surfaces, inflight icing accidents and incidents have been characterized as follows:

- i. Inflight icing causing loss of performance leading to a stall. The aircraft was usually being flown with autopilot engaged in Pitch or Vertical Speed mode and the crew were unaware of the icing (or underestimated it) and did not detect the deceleration to the stall. The stall was often characterized by a sudden and abrupt roll departure.
- ii. Inflight icing causing loss of longitudinal control (tailplane stall). This has usually occurred after selecting full landing flap and/or aggressive manoeuvring at close to flap limiting speed.
- iii. Inflight icing causing stall or loss of longitudinal control due to failure of the flight crew to properly operate the protection systems or failure of the systems. Either of these factors could have contributed to the occurrences noted in i. and ii. above.

Although there has been no final finding published by the NTSB, it appears that the ATR-72 accident at Roselawn in October 1994 may have been precipitated by a loss of lateral control due to failure of the ice protection system to protect the outer wing in severe icing conditions. The icing conditions encountered are believed to be outside FAR 25 Appendix C and hence were not considered during the aircraft certification process.

Questions Arising From Accidents

Review of the factors involved in recent accidents raises a number of obvious questions:

- i. Do flight crew need a method of detecting icing conditions other than visual, in order to properly operate the protection systems in a timely manner?
- ii. Do flight crew need a method of detecting ice accumulation on critical surfaces caused by failure of protection systems? The failure could be because of system component failure or lack of performance by the protection system in the icing conditions encountered.
- iii. Have present aerodynamic designs, which have been optimized for manufacturing and operating efficiency, become more susceptible to the adverse effects of ice accretion?
- iv. Is the icing environment defined by FAR 25 Appendix C adequate?
- v. Have past design practices and certification procedures, although considered satisfactory at the time, been adequate for new aircraft designs?

- vi. Are flight crews fully aware of the adverse effects of icing?
- vii. Has the reduced flexibility in avoiding or exiting adverse icing conditions due to a congested air traffic environment and the economic need to maintain operating schedules been a factor?

While there may be no completely accurate answers to these questions, Transport Canada considers that the responses may lead to developments in certification and operational procedures which result in improvements to the safety record.

Discussion of Issues

Equipment

Atmospheric Icing Condition Detection Systems

There are currently no certification requirements for atmospheric icing condition detection systems although such systems are incorporated in many transport aircraft as options. Without such a system, the crew is dependent on visual observation and temperature indication to determine when the aircraft is in atmospheric icing. In a high workload environment, especially at night, there may be a delay in identifying icing conditions. Transport Canada has required that the likely effects of probable delays in crew operating procedures be considered and the aircraft be demonstrated to be free from hazardous flight characteristics due to crew delays in activating protection equipment. This has resulted in the mandatory incorporation of icing detectors on some aircraft. Transport Canada believes that the incorporation of icing detectors is a valuable safety enhancement and that the certification requirements for detection systems should be reviewed.

With respect to icing conditions which exceed FAR 25 Appendix C, there is a need to develop an icing detection system which will alert the crew and enable the appropriate escape procedures to be executed (see Reference 1). Such a system would significantly decrease the crew operational workload and remove much of the subjectivity from determination of a possibly unsafe condition. In the longer term, it may be possible to develop a prediction system which gives some indication of the icing severity in front of the aircraft. Development of these devices should be encouraged.

Ice Accumulation Detection Systems

Many aircraft incorporate ice accumulation probes so that the crew may visually identify ice accumulation. However such probes can not tell whether a leading edge surface has been effectively deiced or anti-iced by the protection system. This is a significant problem with tail surfaces. Hazardous ice may be present due to system failures, or lack of performance of the system to cater for the particular icing environment encountered. An ice accumulation detector system which would alert the crew to this situation may be beneficial. Many such devices are being actively developed at present including devices which attempt to indicate when the aerodynamic characteristics of the surface become unsatisfactory whether this be from accumulated ice or contamination from other causes. Another concept is a performance monitoring system which could detect an unacceptable drag increase.

Although the requirement for such alerting systems must be considered in conjunction with overall ice protection system design, operating characteristics, reliability and performance, it appears that such systems could be beneficial for certain designs.

Ice Protection Systems

To date the most common anti-icing system has been thermal anti-icing using hot air from engine compressor bleed and the most common deicing system is pneumatic boots. In particular, pneumatic boots are standard on most turboprop aircraft. There have always been a number of concerns with respect to operation of pneumatic boots ranging from their reliability and maintainability, to their effectiveness in removing ice. There are inconsistencies in describing procedures for their use contained in AFMs and FCOMs (e.g. should boots be operated continuously or operated for single cycles when a certain amount of ice has built up?) These inconsistencies may have led many pilots to develop their own procedures based on experience. However these procedures may not always be the best, e.g. witness the continuing debate on "ice bridging" (see Reference 2).

Although improvements in boot deicer technology have been made, these improvements have been directed at reducing the operating cost of the system to achieve specific performance goals. The performance goals may have been adequate in the past, but the present operating environment and aerodynamic designs may require much more effective deicing systems.

Certification

FAR 25 Appendix C

FAR 25 Appendix C defines continuous maximum and intermittent maximum icing conditions in terms of cloud liquid water content, mean effective diameter of cloud droplets, cloud horizontal extent, ambient air temperature and altitude. This Appendix is used to define the critical icing environment for aircraft climb, cruise, holding, approach and go-around. Both the ice protection system performance and the accumulation of ice on unprotected surfaces must be considered in deriving critical icing cases.

There are two significant comments to be made with respect to Appendix C. Although the cloud horizontal extent is defined, the Appendix is not specific in defining the amount of time in continuous maximum and/or intermittent maximum icing conditions (e.g. in a holding pattern). The Appendix does not include the droplet size and liquid water content appropriate to freezing drizzle and freezing rain.

It has been accepted in the past that Appendix C does not include all expected icing conditions. Encounters with the more severe conditions were implicitly considered to be of low probability and short duration. It has not been clear that aircraft need to be designed for continuous operation in more extreme conditions than those specified in Appendix C.

Supercooled Large Drops (SLD), also known as Supercooled Liquid Droplets, include freezing drizzle and freezing rain. Prior to and since the ATR-72 accident, there have been many safe aircraft operations which, on a probability basis, have encountered SLD conditions. In one region of Canada, around St. Johns, Newfoundland, it is estimated that freezing drizzle conditions occur for approximately 5% of the time during the late Winter months (see Reference 3). The estimated number of scheduled operations each month is approximately 1600. Hence on a very simple statistical basis there are approximately 80 operations per month in an area with freezing drizzle conditions.

Quantitative data on the icing environment associated with freezing drizzle around St. Johns, have been collected by the Canadian Atmospheric Environment Service and the National Research Council during flights conducted in 1992 and 1995. Although this data set represents a limited number of observations and may not include extremes, it does provide a sound basis for further work in this area (see Reference 4).

In Phase 1 of the response to the ATR-72 accident, the FAA has stated that the environment of concern includes supercooled droplets with diameters ranging from 50 to 400 microns and a liquid water content of 0.4 g/m³. It is interesting to note that the St. Johns data show Median Volume Diameters (MVD) of up to 1000 microns but all encounters with MVDs greater than 40 microns had liquid water contents of less than 0.2 g/m³.

The statistical aspects of the defined icing environment must be carefully considered. While it would be inappropriate to assign a probability other than one, of encountering icing, it would also be inappropriate to assume that the most extreme conditions occur with the same probability as less extreme conditions. A clear understanding of the statistical representation is required in order to correctly define the reliability requirements and performance of the protection systems.

Clearly, one of the outcomes of this conference should be the agreement to quantify the icing environment which should be considered for aircraft certification, and incorporate any required changes into FAR 25 Appendix C.

Flight Characteristics

In the early 1980s, Transport Canada recognized that certification of the flight aspects associated with flight in icing was not well defined and was inconsistent between different manufacturers and different airworthiness authorities (see Reference 5). The search for operating efficiency was producing aerodynamic designs which were highly optimized (based on an uncontaminated wing) and which incorporated reduced protection to minimize engine power off-takes. The original icing requirements and procedures were developed around a philosophy of making sure the protection system worked and not how much protection was needed to ensure safe flight characteristics. The requirements and certification procedures did not keep pace with the changes in aircraft design. A certain design robustness has been lost which impacts on operations in icing.

One of the major difficulties encountered was that there was very little guidance material on how to comply with FAR 25.1419 which uses the term "...must be able to safely operate...". The basic premise of advisory material developed by Transport Canada and elaborated by the JAA in proposed AMJ 25.1419, was that the performance and flight characteristics requirements are applicable with the accumulated ice expected from normal system operation. However some of the details of the JAA proposal have been the subject of considerable comment and disagreement. Harmonization of the flight requirements for approval of

flight in icing conditions is now being tackled by an ARAC/JAA sponsored Flight Test Harmonization Working Group. Transport Canada appreciates the opportunity to be a member of this group and although early going was slow, there are now indications of significant progress.

Definition of Icing Conditions

For some time, Transport Canada has insisted on a standard definition of icing conditions to be used in the AFM. This definition arose out of some of the investigations following a B737 accident in Washington, DC. Notwithstanding that it appears to be a satisfactory definition and has been accepted by most of the major aircraft manufacturers for operation of engine anti-ice protection systems, this definition has not been universally adopted for operation of other anti-ice protection systems nor does it appear in any of the current advisory material. Indeed, in many cases, AFMs are silent on when to activate airframe anti-icing systems and are vague on when to activate deicing systems.

It is not appropriate to have a definition of icing conditions which is only appropriate to engine anti-ice protection systems. Transport Canada considers that a agreement on a consistent definition for inflight icing conditions, and incorporation of this definition into all AFMs and FCOMs would be a step forward.

Operational Issues

Given that review of certification of aircraft for flight in conditions exceeding FAR 25 Appendix C may be a lengthy and expensive process, and that technological solutions to some of the issues do not appear probable in the near term, safety improvements must be found in operational areas. Pilots must be provided with better tools to make safe operational decisions concerning operations in all icing conditions, but particularly when SLD is involved. It is imperative that AFMs and FCOMs provide clear, valid, consistent and operationally sensible guidance for flight in these conditions. Where limitations and abnormal procedures are necessary, they must be clearly stated. In turn, this material must be supported by both classroom and simulator training that emphasizes recognition of various icing conditions, proper use of anti-icing and deicing equipment, and essential Pilot Decision Making (PDM) activities, such as go/no go, climb/descend, turn around, continue, or divert. Crew Resource Management (CRM) training for icing situations is essential. This training should not be restricted to flight crew, but also given to dispatchers, who play a vital role in both dispatch and en-route decision making. Pilots and dispatchers must be provided with better forecasts and "nowcasts" of icing conditions on

which to base their decisions and must have the support of the Air Traffic Control system in permitting flexibility.

The Canadian record would tend to indicate that regular exposure to icing conditions leads to increased operational awareness by flight crews rather than, as one might expect, a more casual attitude. At any given time of the year there is probably somewhere where icing conditions exist. In the populated southern areas of the country, icing conditions of varying severity can be expected for at least six months of any year. All Canadian pilots operating under IFR are therefore exposed to icing conditions very early in their careers, and lessons learned are reinforced semi-annually. Canadian aircraft certification gives due consideration to the Canadian environmental imperatives, air carrier training programs emphasize winter operations, and proven operational procedures are employed. As a result, Canadian aircraft and Canadian air carriers have excellent records for safe operations in icing conditions. The winter weather systems in Canada's Atlantic provinces are recognized as highly conducive to icing in general, and SLD conditions in particular. Yet the Canadian regional carriers have achieved an outstanding safety record in operating DHC-8 aircraft in that region throughout the year. Transport Canada cannot point to any specific innovations in training and/or procedures that have contributed to this record, but believes it is due to the combination of aircraft certification, flight crew training, and continuous exposure to the icing environment. Operational safety depends on the cooperation of all involved, including airline management.

Transport Canada believes that operations issues are best addressed through operational measures and if necessary, operational rules. Conditions that are clearly hazardous must be addressed with unambiguous operating rules that simplify pilots' operational decisions and deal equitably with all aircraft subject to the hazard.

Continuing Airworthiness

The previous discussion has provided some of Transport Canada's thoughts for current and future certification requirements and procedures, as well as operational issues. However there is also the need to consider the airworthiness of the existing aircraft fleet, particularly with respect to SLD conditions.

Transport Canada has been somewhat concerned about the FAA's Phase 1 and Phase 2 programs with respect to turbopropeller powered aircraft, following the ATR-72 accident. It is recognized that the FAA had a safety concern and Transport Canada along with other airworthiness agencies, has attempted to

cooperate with the FAA by providing comments on the proposed test procedures contained in Phase 1. Hence it has been disheartening to note that the FAA did not appear to accept any of these comments, particularly with respect to service experience. Similarly we are now in the Phase 2 NPRM process which will add generic limitations, procedures and information to the AFMs of turbopropeller powered transport category aircraft. It is hoped that the FAA will give due consideration to the comments of Transport Canada (and others) as they pertain to Canadian manufactured aircraft.

Transport Canada continues to believe that service experience is a strong indicator of possible problems with in service aircraft. While it is not appropriate to wait for another accident to happen before undertaking continuing airworthiness action, neither is it appropriate to create a generic problem and impose a solution as a result of a problem which could be particular to one aircraft. If a generic operating problem is identified, then revised operational requirements are appropriate.

Conclusion

Transport Canada considers that the safety of aircraft operations in icing conditions can be improved through developments in equipment, improvements in icing certification requirements and procedures, and by improved operational procedures, increased crew awareness and training. The threat to safety from Supercooled Large Droplets (SLD) needs to be carefully considered for both future certifications and in service aircraft.

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Main Concepts for Modeling of Standardized Cloud and Analysis of Differences Between the AP-25 and FAR-25 Requirements Concerning Ice Protection

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Abstract

When developing Appendix C of AP-25 requirements for the Russian Federation, differences between Appendix C of FAR-25 (JAR-25) and ACJ 25.1093, ACJ 25.1419 were taken into account.

The standardized supercooled cloud model in Appendix C of AP-25 is based on statistical data obtained during aircraft flight tests in the former USSR. This paper will demonstrate the efficacy of using droplet mean arithmetic diameter for the standardized cloud model. The mean arithmetic diameter is taken equal to 20 μm for some purposes and is constant for various liquid water content values.

Concepts of Modeling of Standardized Supercooled Cloud

An analysis of the ice protection requirements given in FAR-25, JAR-25 and AP-25 reveals similarities between FAR-25 and JAR-25 and essential differences of both from AP-25. However, analysis of FAA Advisory Circular 20-73 (AC 20-73) and Means of Compliance for JAR-25 (ACJ 25.1093) shows that they contain corrections and expansions of envelopes in Appendix C of FAR-25 and JAR-25. Furthermore, sections ACJ 25.1093 and ACJ 25.1419 identify two methods to demonstrate compliance:

- the method based on experience in the United Kingdom and France;
- the method based on experience in the United States.

The two methods differ from each other essentially; the standardized supercooled cloud model for the first method is more severe than for the second one. These differences tell us that the standardized cloud model given in Appendix C of FAR-25 is not so good.

Using the experience of specialists from countries in which ice protection is considered a serious problem, we offer some criteria that should be taken into account when developing standardized supercooled cloud models:

- In flight, the ice thickness that may form on unprotected wing and empennage leading edges in icing conditions is for practical purposes not more than 75 mm (3 inches). Flight duration is usually not more than 30 minutes under the most severe conditions.
- Liquid water content and icing horizontal extent for ambient air temperature 0 to -5°C should be chosen using the first criterion. The mean flight speed can be taken to be 400 km/h.
- A natural cloud contains supercooled droplets with diameters ranging from several microns up to hundreds of microns (polydispersed aerosol flow). Therefore, a standardized characteristic size of cloud droplets should be chosen so as to relate the ice accretion zone for polydispersed aerosol flow in flight and the ice accretion zone calculated for monodispersed aerosol flow. The standardized characteristic diameter should be the same as the value used to calculate the ice accretion zone.
- The parameters of standardized cloud given in Appendix C should be the basis for the calculations for ice protection systems and ice formation, icing condition modeling, and tests in artificial icing conditions. During controlled tests in natural icing conditions, less severe count conditions than those in Appendix C may be used. These count conditions should be included in the Means of Compliance.
- Since the Means of Compliance and Advisory Circulars are advisory in nature, they cannot require a standardized cloud model to be more severe than in Appendix C.

We believe that it is desirable for Section 25.1419 of FAR-25 and JAR-25 to include requirements for aircraft that do not intend to fly in icing conditions, but that may enter these conditions inadvertently (night flights or day flights

on routes without good weather forecasts). First, ice detectors should be installed on these aircraft; second, it should be demonstrated that if the aircraft enters icing conditions, it can exit safely. The experience of aircraft operation in the Russian Federation (R.F.) in icing conditions shows that flight safety increases dramatically if aircraft are equipped with ice detectors and automatic anti-icing control systems.

Methods of Measuring Liquid Water Content and Cloud Droplet Size During Certification Tests of Airplanes in Icing Conditions.

An important requirement when testing in icing conditions is to obtain values for the main icing parameters: liquid water content (LWC), characteristic cloud droplet size, and ambient air temperature. In the R.F., LWC is measured using an electro-thermal device that measures the heat exchange intensity on a sensor exposed to cloud water droplet impact. The LWC device includes a sensor, an electric power supply unit, and a measuring unit. The sensor consists of an electrically heated rod on which an operational sensitive element is installed (figure 1). The operational sensitive element is made of metal wire with high specific resistance and high temperature resistance coefficients. The wire is 0.5 to 0.7 mm in diameter and about 100 mm long. The temperature of the operational sensitive element is specified to be between 160 and 200°C, which ensures the total evaporation of the water that is intercepted.

Recently electro-thermal LWC devices with operational and compensational sensors have been used. The sensors are kept at a constant temperature and the difference of supplied power is measured; this difference is proportional to LWC.

To measure cloud droplet size, the most common method is to collect droplets from the flow on glass coated with hydrophobic liquid and then microphotograph the droplets. Various types of hydrophobic liquids are used, such as polymetilsiloxan liquids in a wide range of temperatures (PMS-700, PMS-1000), which are siliconorganic polymers that exhibit only slight variations in viscosity with changes in temperature. In flight tests, impactors are used, as shown schematically in figure 2. The working surface of the glass is constructed to prevent the droplet form from changing shape due to blowing of the hydrophobic liquid (figure 3).

In addition to droplet impactors, measuring cylinders with diameters of 140mm are widely used, providing the opportunity to define the

characteristic cloud droplet size on the basis of the compact ice accretion zone. This method will be discussed later.

All the above-mentioned instruments are well known to U.S. specialists, since we have tried to use instruments similar to those used in the United States. The main difference in instrumentation is that we do not use optical measuring devices, since we have not been able to develop devices that would measure the entire droplet-size spectrum and work reliably under icing conditions, especially at temperatures below -10°C . However, R.F. researchers in cloud physics use optical devices successfully.

Features of Standardization of Characteristic Cloud Droplet Size

A cloud is a polydispersed aerosol flow that contains water droplets with diameters ranging from several microns up to several hundred microns. As shown in the literature [1, 2], the experimental distribution of droplet sizes with diameters from $4\text{--}8\text{ }\mu\text{m}$ up to $20\text{--}40\text{ }\mu\text{m}$ is well approximated by a γ -distribution as given by L. M. Levin:

$$n(r) = a r^{\alpha} \exp[-(\alpha + 1)(r/r_{ep})]$$

where r is the droplet radius, r_{ep} is the mean arithmetic radius, a is a normalizing factor, and α is a factor that determines distribution "width."

In particular, when $\alpha=2$, A. H. Khrgian and I. P. Mazin use this formula to describe a droplet-size distribution with diameters not exceeding $40\text{ }\mu\text{m}$. In the literature [3], the droplet-size distribution given by Langmuir shows a relationship between the mean diameter (d_i) representing a range of diameters and the relative water volume (V_i) of all droplets with diameters less than or equal to d_i .

To describe cloud droplet sizes one usually uses a characteristic diameter. In our opinion, the choice of characteristic diameter should take into account at least two requirements:

- it should define the functional relationship between the droplet impact zone, which is calculated for an aerodynamic profile in a monodispersed flow of aerosol, and the zone of accumulation of compact ice layer, which is measured during an experiment in a polydispersed flow of aerosol; and

- it should permit the accurate calculation of the water mass intercepted on the profile in a polydispersed flow of aerosol.

At the Flight Research Institute, special work was undertaken in 1976 to define the characteristic cloud droplet size, taking the above-mentioned conditions into account.

To define the relationship between the compact ice accretion zone and various characteristic cloud droplet sizes, testing was carried out under both artificial and natural icing conditions in a range of true air speeds from 100 to 160 m/s, altitudes from 600 to 5000 m, and ambient air temperatures from -5 to -20 °C. To carry out the investigation, a cloud droplet impactor, a microphoto set, and an electrically heated (periodically) cylinder with a diameter of 140 mm and a height of 250 mm were installed on the flying testbed Il-18. The cylinder was marked to enable researchers to visually determine the zone value of compact ice accretion.

The following method was chosen. In the icing region, cloud droplets were collected until the entire compact ice accretion zone formed on the cylinder. The zone usually formed in 3 to 4 minutes and did not change appreciably thereafter. The zone was measured and then the ice was ejected from the cylinder. A new cycle of droplet collection began with the first indication of ice formation on the cylinder and ended with the formation of the compact ice accretion zone. It should be noted that the cloud droplet impact zone consists of an ice accretion layer zone with well-defined boundaries (Q) and a zone in which discrete ice patches are observed at the beginning of the process (figure 4). In the second zone, the separate ice patches, falling within an "aerodynamic shadow" as the first zone develops, decrease noticeably in size over time due to sublimation and the "splitting" of ice patches. Therefore, the initial ice accretion zone is approximately equal to the zone of the largest impacting cloud droplets, but it diminishes to the compact ice accretion layer over time.

To analyze the formation of compact ice accretion zones on the cylinder (in polydispersed flow of aerosol), ice accretion zones on the cylinder were calculated for droplet sizes for monodispersed cloud for various airplane flight regimes. When treating the results of cloud droplet measurements, droplet size values were assigned to several groups, which taken together contain the whole range of droplet sizes. The number of groups and their boundaries were determined by taking into account the expected

measurement error and the fact that the larger droplets significantly influence median volume diameter.

The quantity of droplets n_i in group i was corrected with the help of local impact coefficients, each coefficient being calculated for the mean diameter of a group. On the basis of measured droplet-size spectra, the following characteristic values are calculated:

d_{cp} - the mean arithmetic diameter, defined by:

$$d_{cp} = (\sum d_i n_i) / (\sum n_i)$$

d_m - the modal diameter (the value d_i with the greatest frequency)

MVD (median volume diameter) - the droplet diameter that divides the total water volume in the droplet distribution in half.

In Table 1, data are given for compact ice accretion zones (Q) on a cylinder. The diameter d_p is calculated using Q for a monodispersed flow of aerosol, and the characteristic diameters d_{cp} , MVD, and d_m are obtained from measured droplet spectra. Comparing the diameters shows that a regular relationship exists between d_p and d_{cp} , but no regular relationship involving the other characteristic diameters is observed. The relationship between d_p and d_{cp} is shown in figure 5. These results are the basis of the conclusion that the mean arithmetic droplet diameter d_{cp} is strongly related to the boundaries of the compact ice accretion zone in polydispersed flow of aerosol. Droplets having diameters larger than d_{cp} fall on areas of the cylinder beyond the compact ice accretion zone and form only discrete patches of ice that disappear over time.

These results can also be considered from another point of view. When working with cloud droplet samples that include a whole spectrum of diameters larger than $4 \mu m$ (smaller droplets are not intercepted by the impactor), the small number of relatively large droplets exerts a strong influence on MVD, but a much weaker influence on d_{cp} . Large droplets ($200 - 300 \mu m$) are present in naturally occurring cloud droplet spectra and their formation in stratiform and cumuliform clouds is documented in the literature [4]. Therefore, MVD should be used to characterize droplet size distributions only if the spectrum is truncated to exclude large droplets, which makes it necessary to specify the upper boundary for the truncated spectrum.

In order to compare the formation process for the compact ice accretion zone on different aerodynamic profiles in flows of polydispersed and monodispersed aerosol, ice accretion zone data were used from a circular cylinder with a diameter of 140 mm, and from wing and stabilizer sections of an Il-62 airplane. The data were obtained with the help of a flying testbed Il-18 under natural and artificial icing conditions. The arithmetic droplet diameters were defined using compact ice accretion zones (Q) on the cylinder; these diameters in turn were used to calculate impact zones on the other profiles in monodispersed aerosol flow. The comparative data on compact ice accretion zones and impact zones are shown in figure 6. The comparison indicates that the best agreement is observed for zero degree angle of attack (AOA) of profiles. With an AOA of 4 to 6 degrees, there is a large difference between the experimental and the calculated zone, but a linear relationship between the size of the experimental compact ice accretion zone (S_{exp}) and the size of the calculated impact zone (S_{calc}) does exist:

$$S_{calc} \cong 1.8 S_{exp}$$

It can be seen from this equation that in this case the impact zone calculation had to be done with a smaller droplet size than d_{ep} . In recent years the method of impact zone calculation on aerodynamic profiles has improved, thanks to the introduction of the aerodynamic lift coefficient, giving improved agreement between calculated and experimental values for profiles for given angle of attack.

Initial State Before Development AP-25 25.1419

When developing Appendix C of AP-25, several features found through analysis of Appendix C of FAR-25 and of FAA AC 20-73 were taken into account:

- The functional relationship in Appendix C of FAR-25 between LWC and MVD is not confirmed by experiment. It is based not on statistical data on the joint variation of these variables, but rather on equality of intensity of water impact on a hypothetical surface for various droplet sizes and LWC's [5].
- It is not effective to characterize a standardized cloud model using MVD, because a truncated spectrum must be used, as explained above. This results in indefinite methods of treating experimental icing data.

- LWC values decrease versus MVD and horizontal icing extent. However, during special test flights in natural icing conditions Russian specialists found that the larger LWC values often did not decrease versus MVD and horizontal icing extent.
- FAA AC 20-73 recommends using an MVD of 40 μm or 50 μm to calculate the accretion zone and an MVD of 20 μm to calculate impact water intensity. However, the supercooled cloud model in which the flight safety must be confirmed in Appendix C of FAR-25 has no requirements to conduct tests in icing conditions with MVD of 40 μm or 50 μm .
- FAA AC 20-73 indicates decreasing LWC with increasing horizontal cloud extent (Appendix C of FAR-25) must be taken into account in calculating ice on unprotected surfaces, but not for calculations for protection systems [3].

Comparing the requirements in Appendix C of FAR-25 with the recommendations in FAA AC 20-73 shows that American researchers use different cloud models for calculations and for testing; it is known that test icing conditions may be considerably less severe than those used for calculations. As mentioned above, we drew the conclusion that it is effective to use d_{cp} as a standard, since this parameter provides a relation between the ice protection system calculation, applicable to monodispersed flow of aerosol, and experimental results in polydispersed flow of aerosol.

The standardized cloud model in Appendix C of AP-25 can be used both for calculations and for experimental confirmation of flight safety. The standardized icing conditions are simulated with the help of rigs or flying testbeds and the tests in natural icing conditions are carried out with icing parameters that may be less severe than the standardized ones.

During the development of Appendix C of AP-25, flight test results from the following airplanes in natural icing conditions were analyzed: An-124, Tu-144, Yak-42, An-74, Il-86, An-28, W-3. The relationship between LWC and horizontal icing extent for maximum icing duration (figure 11) was determined, with LWC values taken to be the maximum (with some reserve) from those values obtained during special flight tests of flight vehicles (figures 7,8,9,10). As shown in the literature [1], in stratiform and stratiform-cumuliform clouds with thicknesses of about 2000 m, the mean

LWC slowly decreases from a height of 600 - 700 m above the cloud base in the direction of the cloud base.

Such LWC variation is given in BCAR. Similar LWC variation near the ground is given in AP-25, but, in contrast to BCAR, the constant LWC value is maintained from the altitude of 500 m to the ground, not 300 m. This correction is accepted as there is the requirement in FAR-25 25.1093--the text of which is adopted in AP-25--that gas-turbine engines must operate 30 minutes at idle at sea level, with ambient air temperature in the -1 to -9°C range and LWC not less than 0.3 g/m^3 . Decreasing LWC versus altitude from 1200 m to 500 m and keeping it constant to zero altitude for horizontal icing cloud extent of 32 km, with ambient air temperature of -5°C yields an LWC value of 0.3 g/m^3 near the ground. In this case there is no discrepancy with FAR-25 25.1093.

Comparison of AP-25 and FAR-25 Requirements

Comparisons of Appendix C of AP-25 and of FAR-25 are presented in figures 11,12,13,14, and 15. As can be seen from figures 13 and 15, Appendix C of AP-25 exceeds Appendix C of FAR-25 at altitudes for which standardized icing conditions are considered. To compare standardized LWC values for AP-25 and FAR-25, it is necessary to use characteristic cloud droplet of comparable size. So in AP-25, mean arithmetic diameter is standardized at $20\text{ }\mu\text{m}$ and characterizes the entire spectrum of cloud droplet sizes. In FAR-25, MVD is standardized and characterizes the truncated spectrum of cloud droplets, i.e., droplets with diameters less than $50\text{ }\mu\text{m}$ [6]. Furthermore, in FAR-25 the standardized MVD value is not constant, but is a function of LWC.

Research on cloud droplet size distributions shows that if large droplets are not considered in calculating the mean arithmetic diameter, the value of d_{cp} for the truncated spectrum is smaller than the value of d_{cp} for the entire droplet size spectrum (natural icing). Let d_{\max} denote the maximum diameter of the truncated spectrum, d_{cp} denote the mean arithmetic diameter of the truncated spectrum, and $d_{cp\Sigma}$ denote the mean arithmetic diameter of the entire spectrum. Figure 16 and Table 2 illustrate the relationships among these variables.

Referring to Table 2, note that if we truncate the cloud droplet size spectrum at $d_{\max} = 50\text{ }\mu\text{m}$, then a $d_{cp\Sigma} = 20\text{ }\mu\text{m}$ corresponds to a value between $d_{cp} = .98 \times 20\text{ }\mu\text{m} = 19.6\text{ }\mu\text{m}$ and $d_{cp} = 0.82 \times 20\text{ }\mu\text{m} = 16.4\text{ }\mu\text{m}$. In that part of the droplet

size distribution where $d_i < 40$ to $50 \mu\text{m}$, which can be described by a logarithmic normal law, the relationship $\text{MVD} \cong 1.83 \times d_{cp}$ is observed [7]; then $d_{cp} = 16.4 \mu\text{m}$ corresponds to $\text{MVD} = 30 \mu\text{m}$ and $d_{cp} = 19.6 \mu\text{m}$ corresponds to $\text{MVD} = 36 \mu\text{m}$.

LWC values are given for comparison in figures 11, 12, and 14 according to AP-25 with $d_{cp\Sigma} = 20 \mu\text{m}$, and according to FAR-25 with $\text{MVD} = 30 \mu\text{m}$. LWC values with $\text{MVD} = 15 \mu\text{m}$ and $\text{MVD} = 20 \mu\text{m}$ are shown in these figures when LWC values for horizontal icing extent $L = 32 \text{ km}$ and $L = 5 \text{ km}$ coincide with LWC values in AP-25. An analysis of figures 11, 12, and 14 shows that LWC in AP-25 exceeds that in FAR-25 with comparable diameters, i.e., the icing conditions in AP-25 are more severe than in FAR-25.

In addition to FAR-25 requirements, it is advisable to consider advisory material on using FAR-25. As we mentioned before, in the literature [3] some recommendations are given on the use of Appendix C of FAR-25. In particular, figures 3 and 6, which give LWC correction coefficients for varying horizontal icing extent, are most important in defining the quantity of ice that can be accumulated on unprotected surfaces in a given period of time. However, in developing ice protection systems, to obtain LWC values, the FAR-25 requirements specify a constant value of horizontal extent of stratiform clouds (32 km) and cumuliform clouds (5 km) (i.e., figures 3 and 6 in Appendix C are not taken into account). An MVD of $20 \mu\text{m}$ is recommended to define the impact water intensity and an MVD of 40 to $50 \mu\text{m}$ to determine the accretion zones.

Therefore, if one takes the truncated spectrum of cloud droplet sizes with $d_{\text{max}} = 50 \mu\text{m}$, if this spectrum has an MVD of $40 \mu\text{m}$, then d_{cp} is approximately $20 \mu\text{m}$. In this case, we have approximately the same cloud model to confirm by experiment the accuracy of the calculation of impact droplet zones using the U.S. and R.F. methods. The absolute values of droplet diameters used in calculating the accretion zones are different, perhaps as a function of the calculation methods used. However, the absolute values of droplet diameters for calculating impact water intensity are the same.

At the present time in Western countries, there is one method often used for icing unprotected surfaces [8]. In particular, in 2 ACJ - 25.1419, which corresponds to the experience in the United States using FAR-25 requirements, it is pointed out that ice thickness on the most critical unprotected surfaces does not usually exceed 75 mm (3 inches). The thickness for surfaces is defined by calculation, but if this calculation cannot

be carried out, then the thickness should be specified as 75mm. We also note another difference between Appendix C of AP-25 and FAR-25: maximum short-duration and maximum intermittent icing. In the literature [8], it is pointed out that maximum intermittent icing means intermittent 5-km segments of horizontal flight under icing conditions (figure 4 of Appendix C of FAR-25) and 5-km segments in "dry" air (figure 17).

Analysis of figures 14 and 17 shows that the LWC value in AP-25 can be as much as twice that in FAR-25 for comparable characteristic diameters ($d_{cp} = 20 \mu\text{m}$ and $MVD = 30 \mu\text{m}$) for $L = 5 \text{ km}$. For cyclic-type anti-icing systems in normal operation, the conditions according to AP-25 will be more severe, but for unprotected surfaces the thickness of ice according to FAR-25 will exceed the thickness according to AP-25 by as much as a factor of 1.33. But on unprotected surfaces, more thick ice is formed under long-duration icing conditions than under short-duration conditions, so this difference is not fundamental. In figure 18, a comparison is given according to Appendix C of FAR-25 and AP-25 for ice formed on a visual indicator with midsection of about 20 mm under icing conditions with ambient air temperature $t = -5^\circ\text{C}$ and $t = -30^\circ\text{C}$. It is assumed that all water freezes where it lands on a surface, i.e., water does not blow away or shift (run back). The comparison shows that on a visual indicator ice is formed with a thickness of 105 mm under AP-25 conditions and 63 mm under FAR-25 conditions, with $MVD = 15 \mu\text{m}$, provided that the horizontal icing extent is equal to 200 km and $t = -5^\circ\text{C}$. Under FAR-25 conditions ($MVD = 15 \mu\text{m}$), average flight speed of 400 km/h, and maximum standardized horizontal icing extent of 600 km, the maximum ice thickness will be about 84 mm.

As for accumulation on wing tips and on the stabilizer, the ice formation intensity is less by a factor of 1.5 to 2 than that on the visual indicator. During flights of 200 km in standardized cloud, according to AP-25 the maximum ice thickness on these components will be about 70 to 50 mm, which corresponds well with method 2 of ACJ 25.1419. Under conditions according to FAR-25, ice thickness on these same aerodynamic components will be only 56-42 mm, even during a 90-minute flight.

Conclusions

An analysis of Appendix C of FAR-25 and AP-25 and FAA AC 20-73 and investigation of results used as the basis for developing Appendix C shows:

1. U.S. and R.F. specialists use different methods to determine the standardized cloud model.
2. The standardized cloud model in Appendix C of AP-25 can be used both for icing protection system calculations and for confirmation of safe airplane operation in icing conditions. The basis of this model is the following requirement: in the standardized accretion zone, a standardized amount of water must be caught.
3. The standardized cloud model in Appendix C of FAR-25 should be used mainly during controlled airplane flight tests in natural icing conditions; FAA AC 20-73 includes additional standardized cloud models for calculations and tests. The standardized cloud model in Appendix C of FAR-25 is based on the requirement that an equal amount of water must be caught on some hypothetical surface for various liquid water contents and cloud droplet sizes.
4. To confirm the accuracy of accretion droplet zone calculation and impact water intensity experimentally according to U.S. and R.F. methods, the same models of standardized cloud are used that are presented in Appendix C of FAR-25 and of AP-25. The absolute values of droplet diameter, which are taken into account in calculating the accretion zone, are different; the absolute values of droplet diameter, which are taken into account in calculating the impact water intensity, are the same.
5. The difference between standardized cloud models presented in Appendix C of FAR-25 and of AP-25 indicates that confirming safe airplane operation in icing conditions according to FAR-25 requirements is carried out under less severe conditions than according to AP-25 requirements. The parameter values for standardized clouds in FAR-25 and AP-25 are not based on specified probability of the joint appearance of all the standardized parameters; but rather on the probability of the joint appearance of two parameters

only, such as liquid water content and ambient air temperature, if horizontal extent is 32 and 5 km (long duration and intermittent icing).

Offers for Harmonization of Requirements

To harmonize the requirements of Appendix C of FAR-25 and AP-25, it is efficacious:

1. to develop a joint approach to create a standardized cloud model;
2. if it is necessary to carry out joint experiments in natural icing conditions, to determine the characteristic cloud droplet size using a coordinated test method;
3. to coordinate a joint approach to icing parameter measurements, icing protection systems calculation, and testing.

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Table 1. Data of compact ice accretion zone values on cylinder and characteristic cloud droplet sizes

No	H, m	V, km/h	t, °C	Q, degs	d _p , μm	d _{cp} , μm	MVD, μm	d _m , μm
Natural icing								
1	600	360	-5	20	11	8	150	8
2	3100	430	-10	30	11	14	65	8
3	1400	380	-7	35	16	16	30	8
4	1300	380	-7	50	24	22	45	16
5	1200	380	-15	20	12	9	110	8
6	1600	450	-11	35	15	13	42	8
7	1400	400	-12	30	14	11	32	8
8	1200	380	-9	55	26	25	50	12
Artificial icing								
9	5000	450	-20	65	28	28	70	8
10	3200	520	-11	65	30	33	107	20
11	5000	550	-20	68	30	29	92	8
12	6500	570	-30	65	25	23	73	4

H - altitude of flight

V - true air speed of flight;

t - ambient air temperature;

Q - compact ice accretion zone

d_p - diameter calculated from Q

d_{cp} - mean arithmetical diameter

MVD - median volumetric diameter (mean effective)

d_m - modal diameter

Table 2. Effect of Truncation of Droplet Spectrum on Mean Arithmetic Diameter

d _{max} , μm	70	60	50	40
d _{cp} — 100, % d _{cpΣ}	90 - 100	85 - 100	82 - 98	75 - 98

d_{max} - the maximum diameter of the truncated spectrum

d_{cp} - the mean arithmetic diameter of the truncated spectrum

d_{cpΣ} - is the mean arithmetic diameter of the entire spectrum

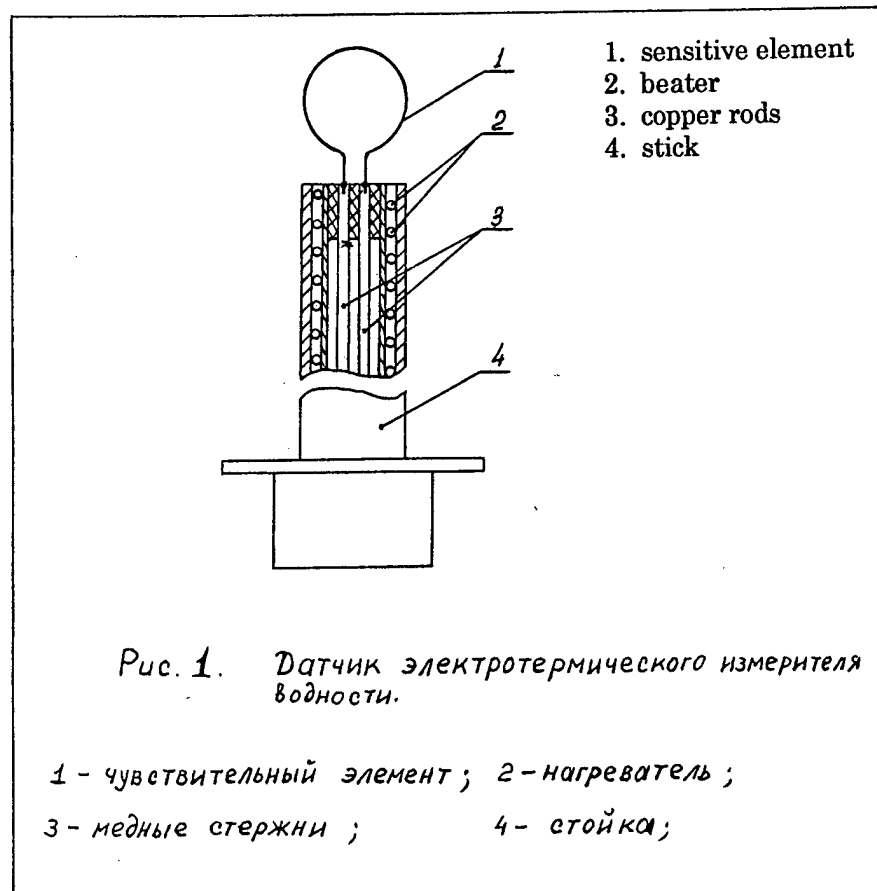


Figure 1. Sensor of electro-thermal LWC measuring unit.

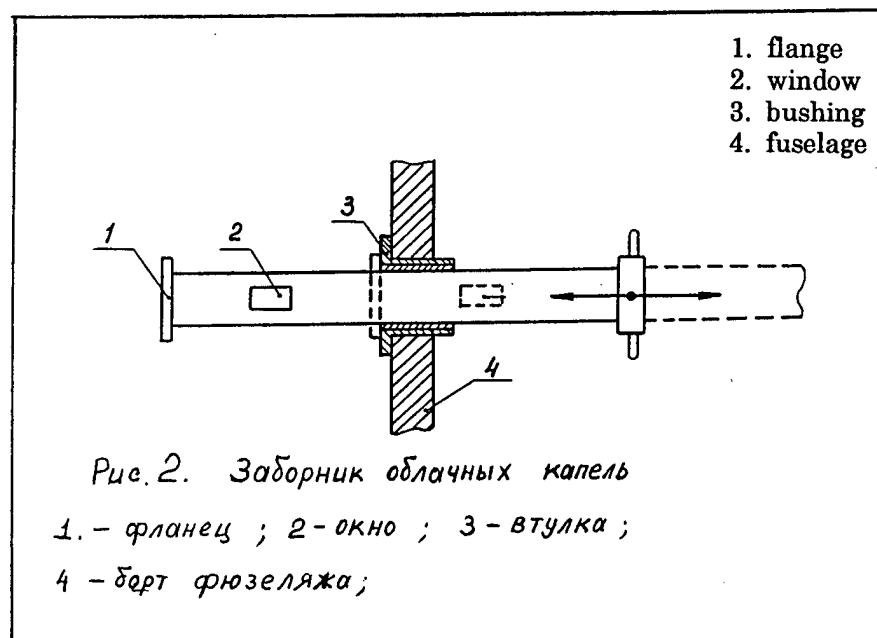


Figure 2. Cloud droplet impactor

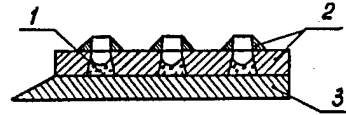


Рис. 3. Предметное стекло.

1. - гидрофобная жидкость; 2 - непрозрачная пластина;
3. - прозрачная пластина;

1. hydrophobic liquid
2. nontransparent plate
3. transparent plate

Figure 3. glass coated with hydrophobic liquid

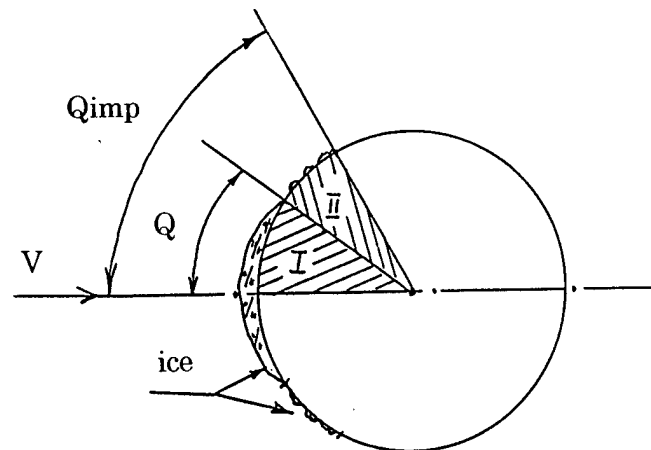


Рис 4. Границы зоны улавливания капель (Q_{ul})
и зоны отложения сплошного слоя льда. (Q)

I - зона отложения сплошного слоя льда;
II - зона с отдельными участками поверхности,
покрытой льдом.

1. compact ice accretion layer zone
2. discrete patches of surface coated with ice

Figure 4. The boundaries of droplet impact zone (Q_{imp}) and compact ice accretion layer zone (Q).

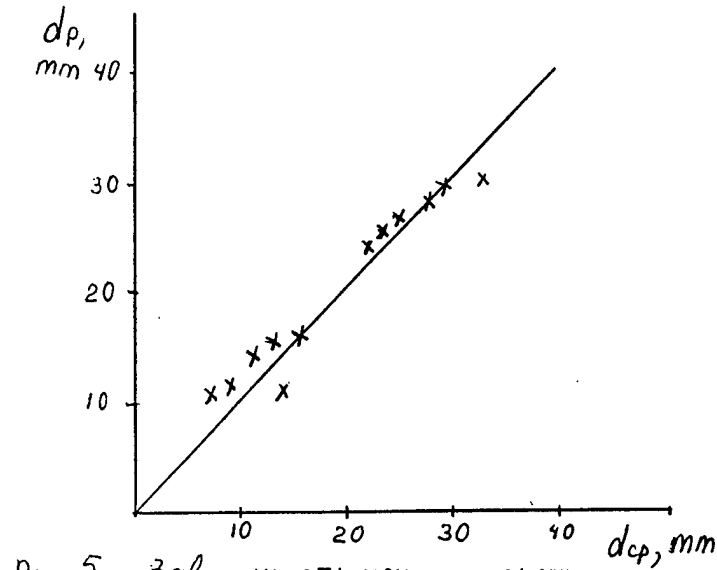


Рис 5. Зависимость между расчетным и среднеарифметическим диаметрами капель.

Figure 5. Relationship between calculated mean arithmetic droplet diameters.

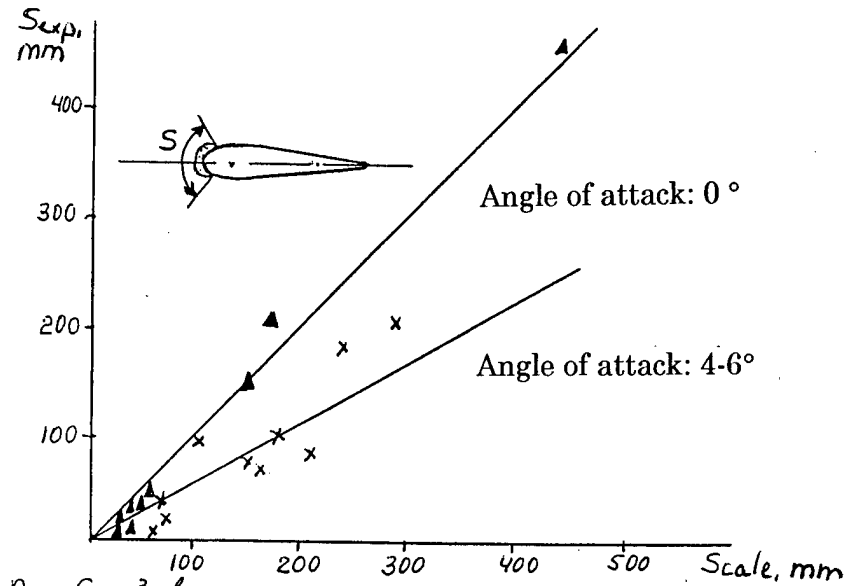


Рис 6. Зависимость между экспериментально полученной зоной отложения льда и теоретической зоной улавливания для отсеков крыла и стабилизатора самолёта Ил-62

Figure 6. Relationship between ice accretion zone obtained in experiment and the calculated theoretical impact zone for wing and stabilizer component of the II-62 airplane.

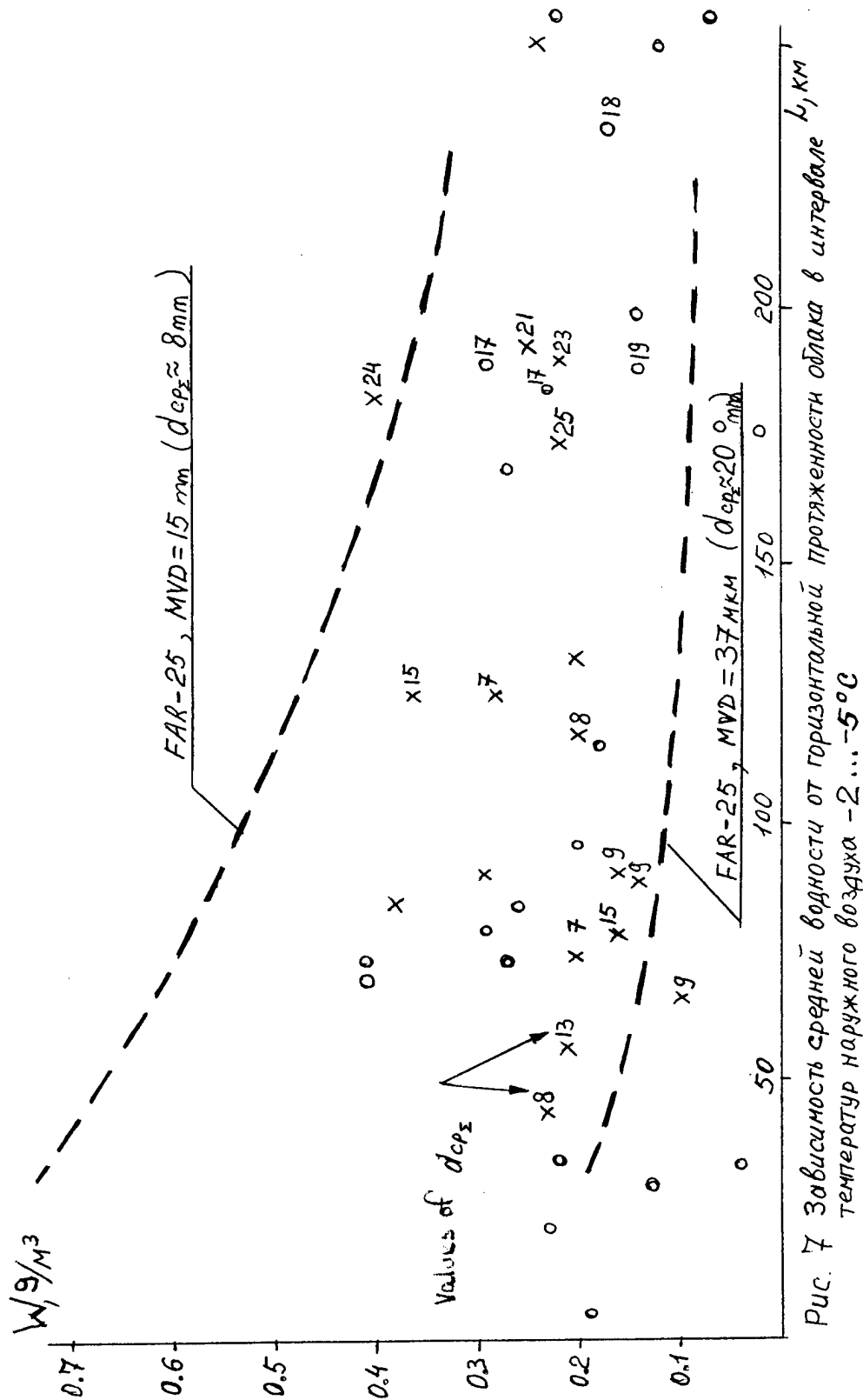


Рис. 7 Зависимость средней водности от горизонтальной протяженности облака в интервале температур наружного воздуха $-2 \dots -5^\circ C$

Figure 7. Relationship between mean liquid water content W and horizontal icing extent L in the ambient air temperature range of -2° to $-5^\circ C$. The numerical labels of the data points are the values of d_{cp} for those data points.

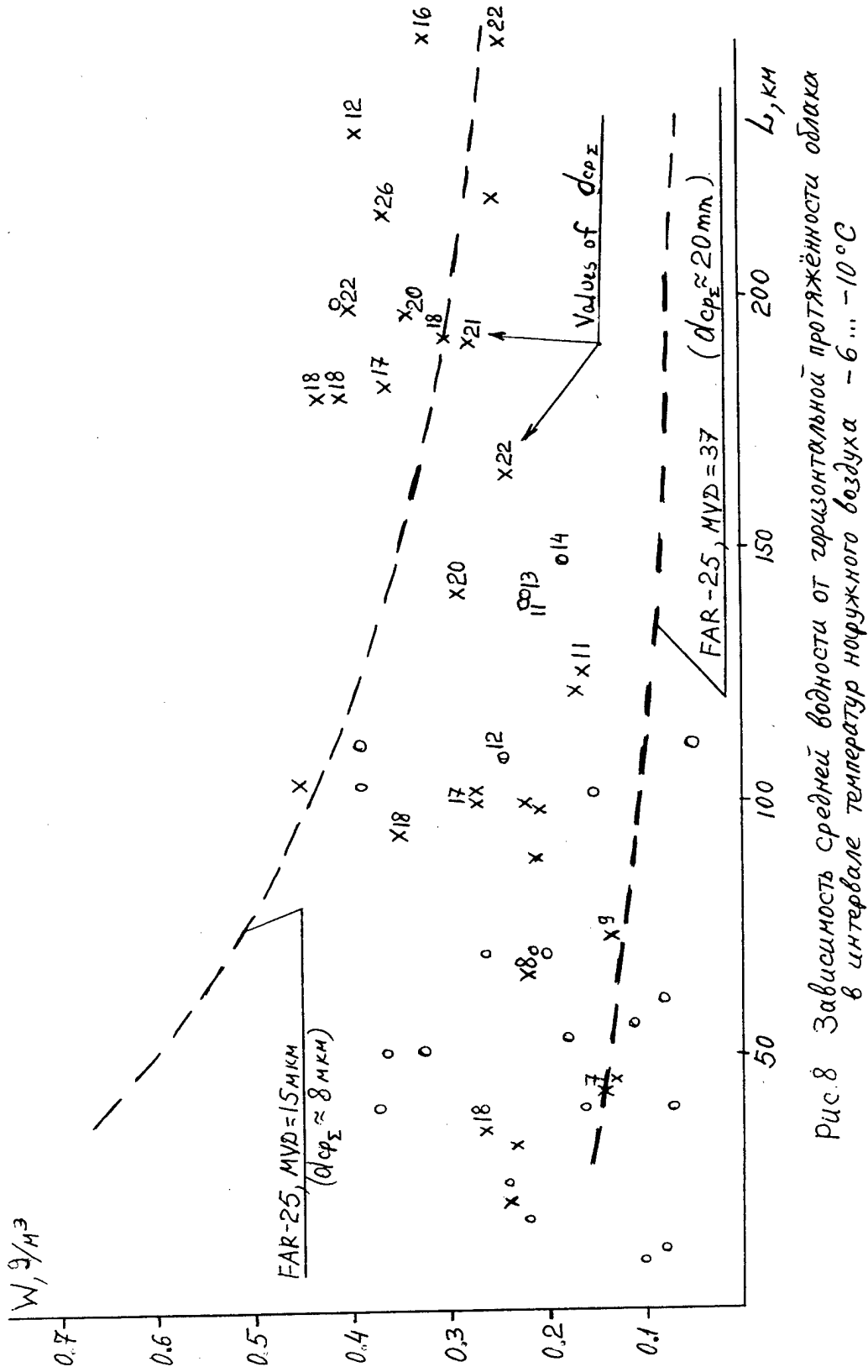


Рис. 8 Зависимость средней водности от горизонтальной протяжённости облака в интервале температур наружного воздуха $-6 \dots -10^\circ C$ the values of d_{cpz} for those data points.

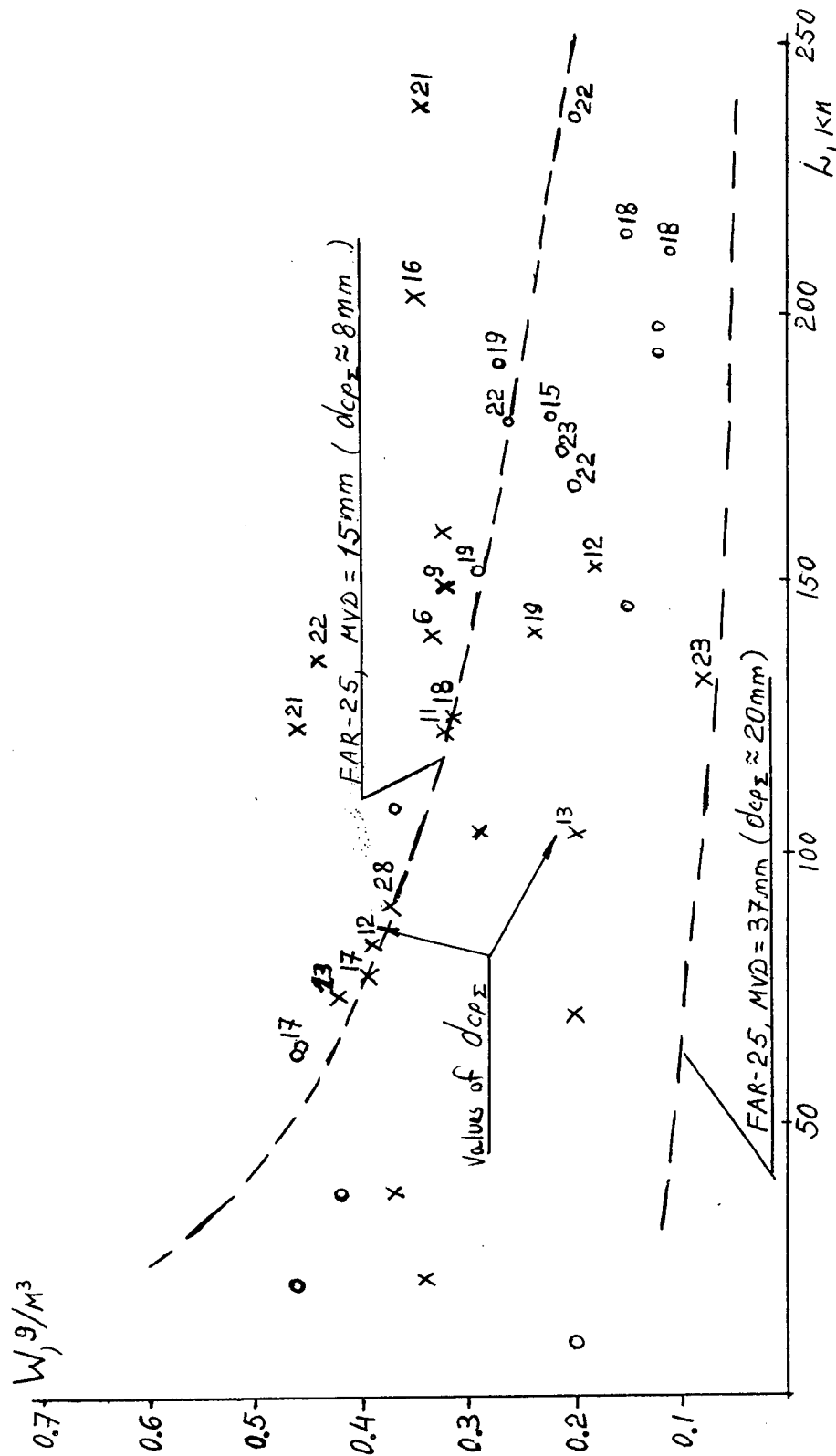


Рис 9 Зависимость средней водности от горизонтальной протяженности облака в интервале температур наружного воздуха $-10 \dots -15^\circ \text{C}$

Figure 9. Relationship between the mean liquid water content W and horizontal icing extent L in the ambient air temperature range of -11° to -15°C . The numerical labels of the data points are the values of d_{cpz} for those data points.

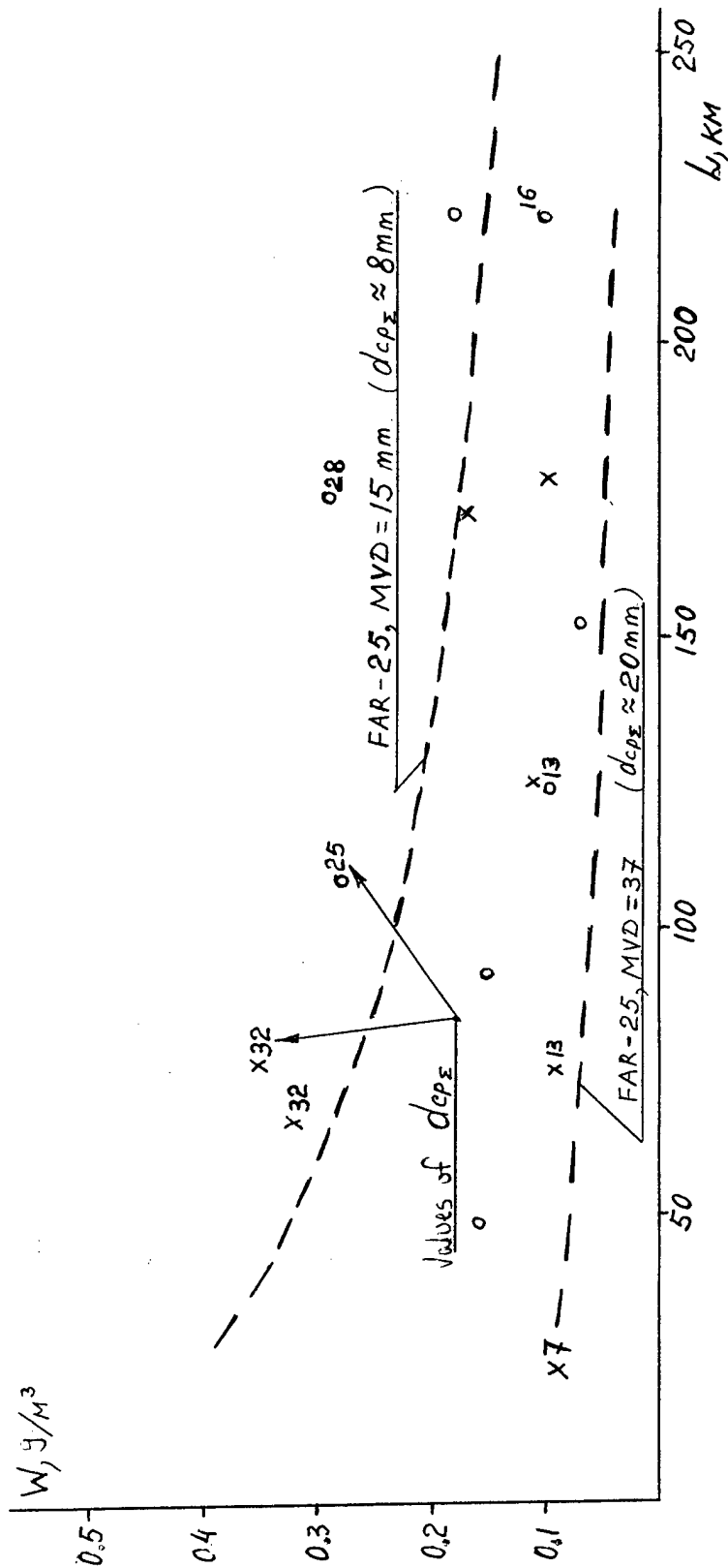


Рис.10. Зависимость средней водности от горизонтальной протяжённости облака в интервале температур наружного воздуха $-16...-18^{\circ}C$.

Figure 10. Relationship between the mean liquid water content W and horizontal icing extent L in the ambient air temperature range of -16° to $-18^{\circ}C$. The numerical labels of the data points are the values of d_{cpz} for those data points.

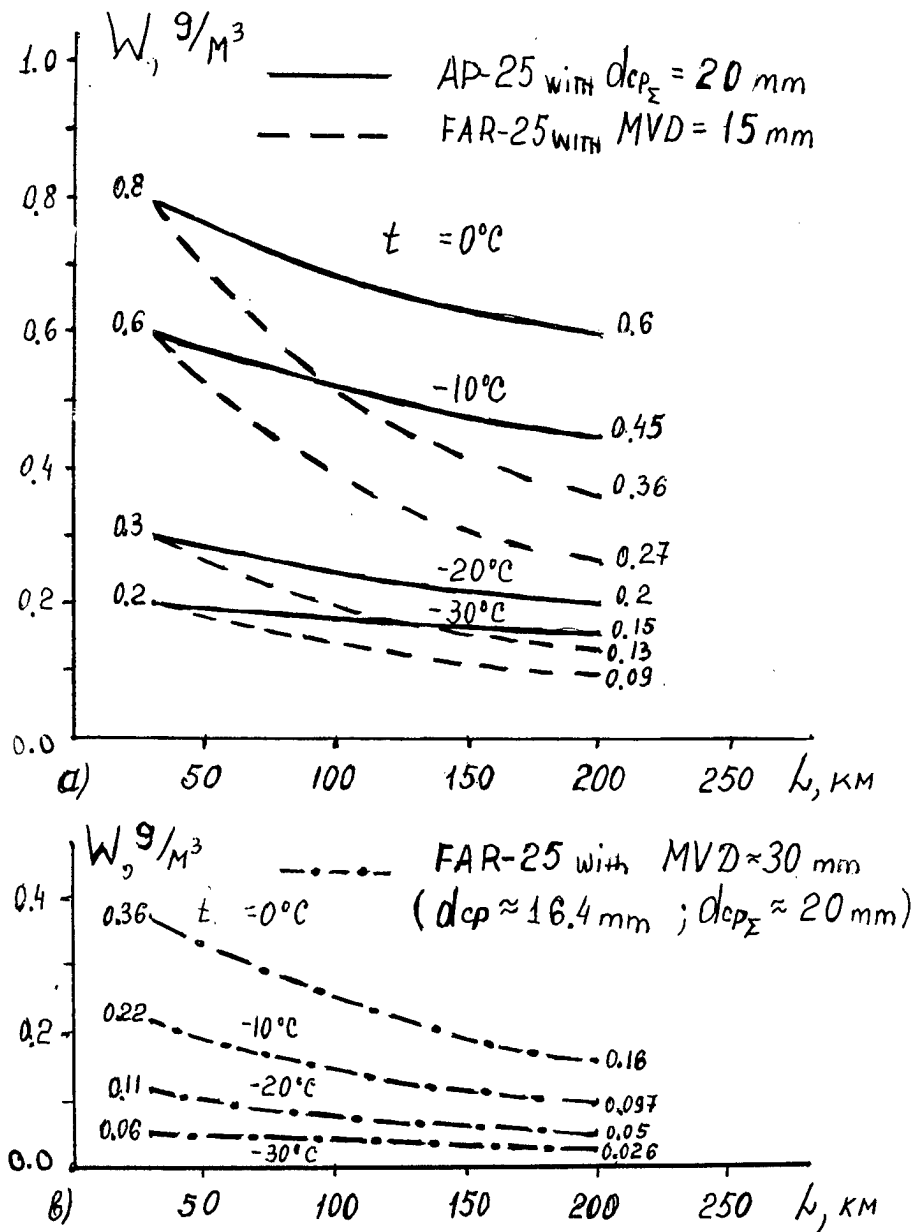


Рис.11 Зависимость нормируемой водности (W) от горизонтальной протяжённости (L) зоны обледенения по АП-25 и FAR-25 (длительное обледенение)

Figure 11. Relationship between standardized liquid water content W and horizontal icing extent L according to AP-25 and FAR-25 (long icing duration).

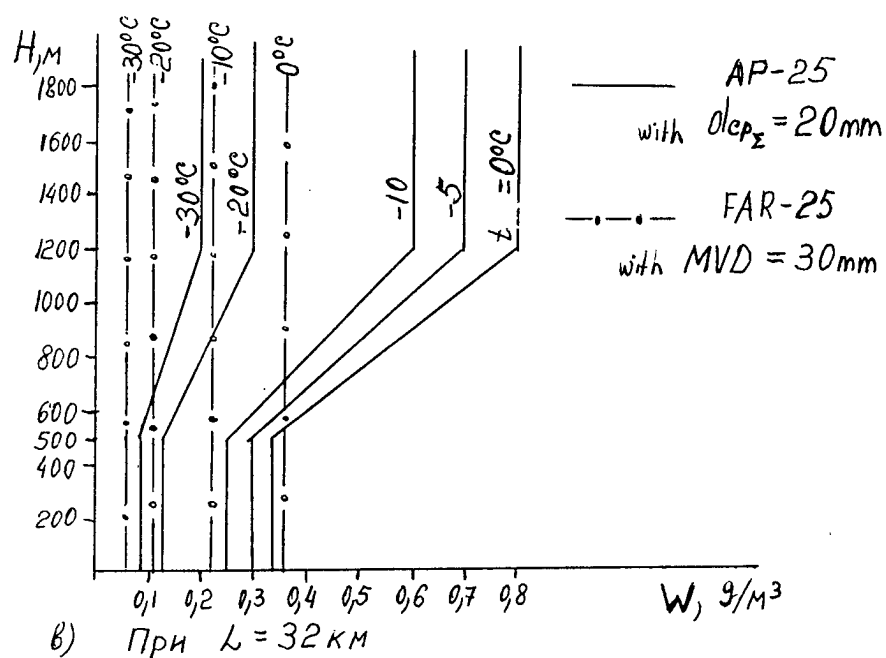
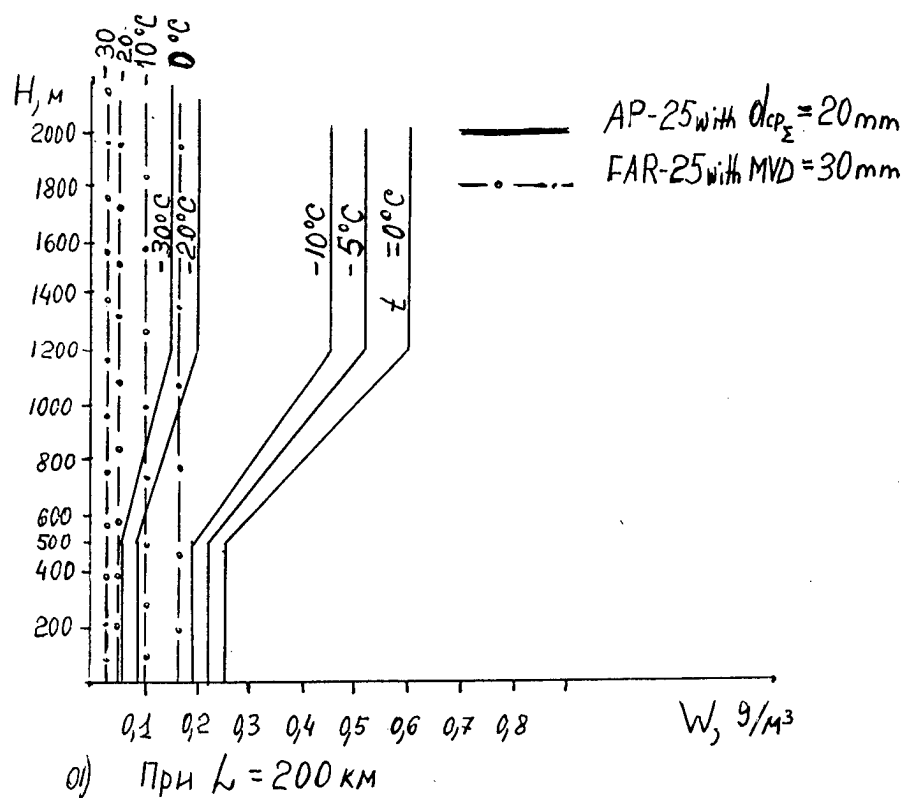


Рис 12. Зависимость водности от вертикальной протяжённости зоны обледенения (H).

Figure 12. Relationship between standardized liquid water content W and vertical icing extent H .

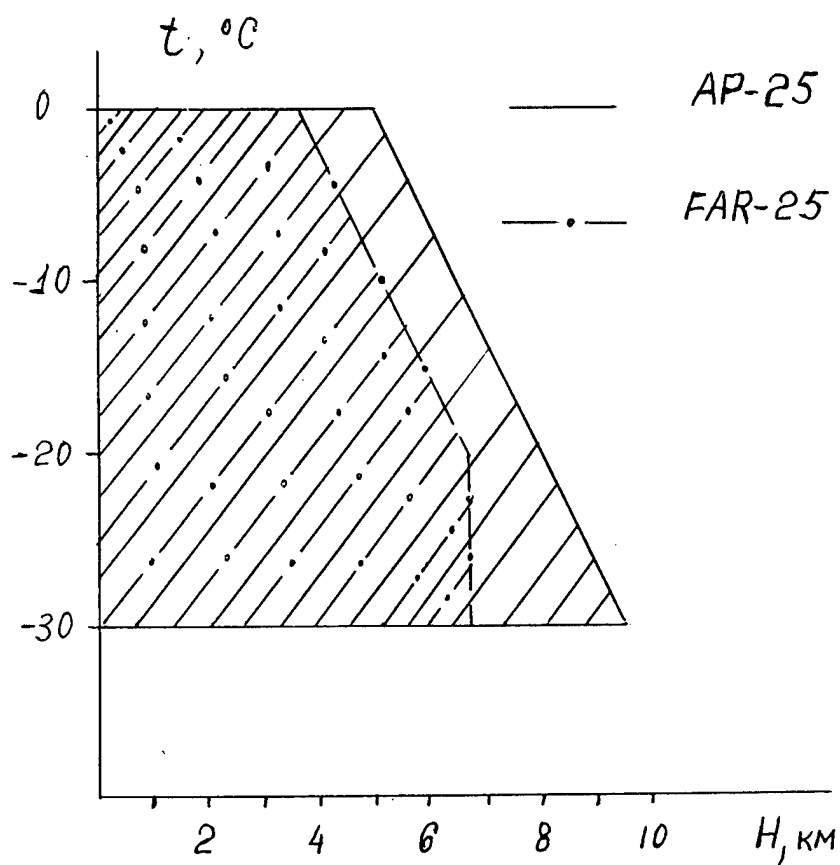


Рис 13 Зона возможного обледенения, определяемая высотой и температурой наружного воздуха для условий максимального длительного обледенения.

Figure 13. Possible icing zone defined by altitude H and ambient air temperature t for maximum duration of icing conditions.

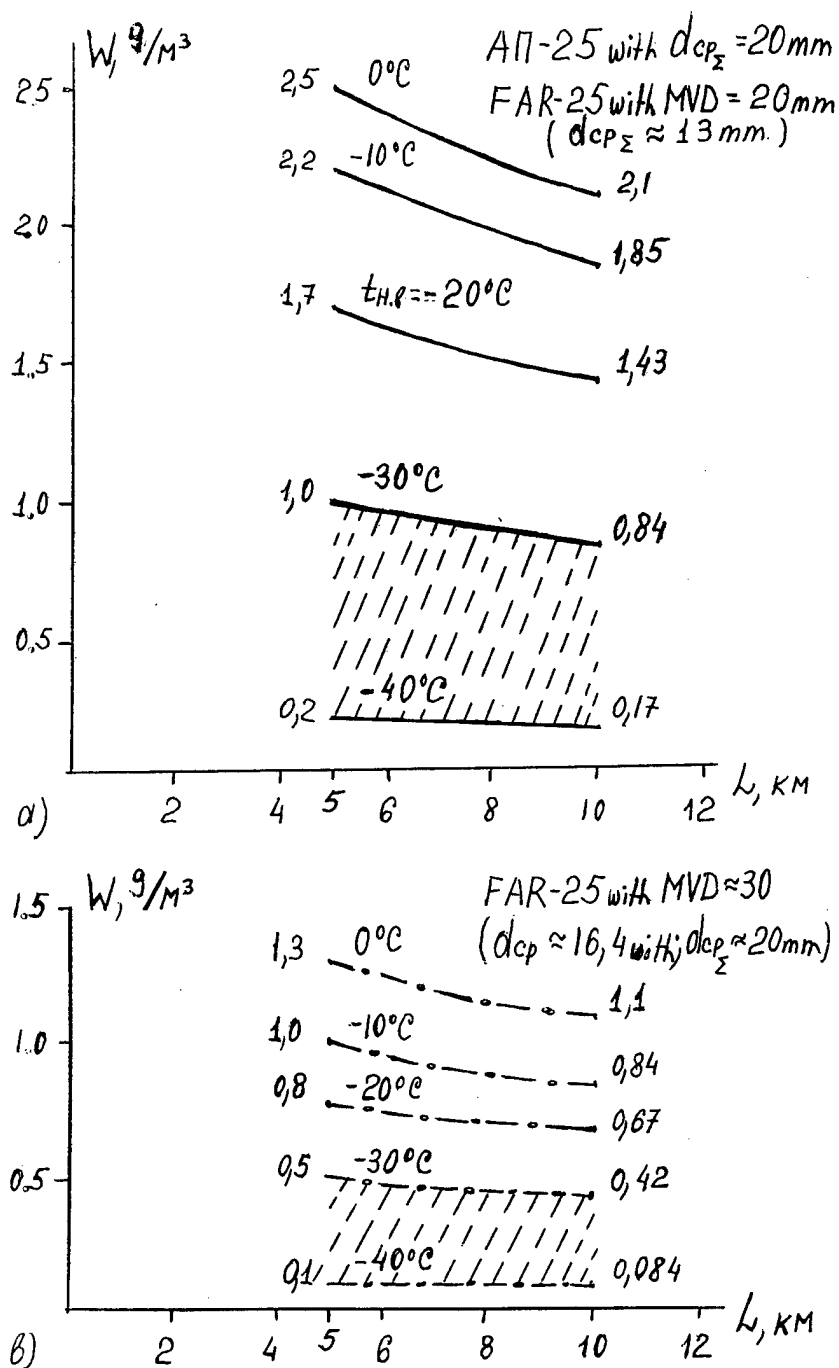


Рис 14. Зависимость нормируемой водности от горизонтальной протяжённости зоны обледенения по АП-25 и FAR-25 при кратковременном обледенении (по FAR-25 - перемежающееся обледенение)

Figure 14. Standardized liquid water content vs. horizontal icing extent according to AP-25 and FAR-25 for short duration icing (intermittent icing in FAR-25).

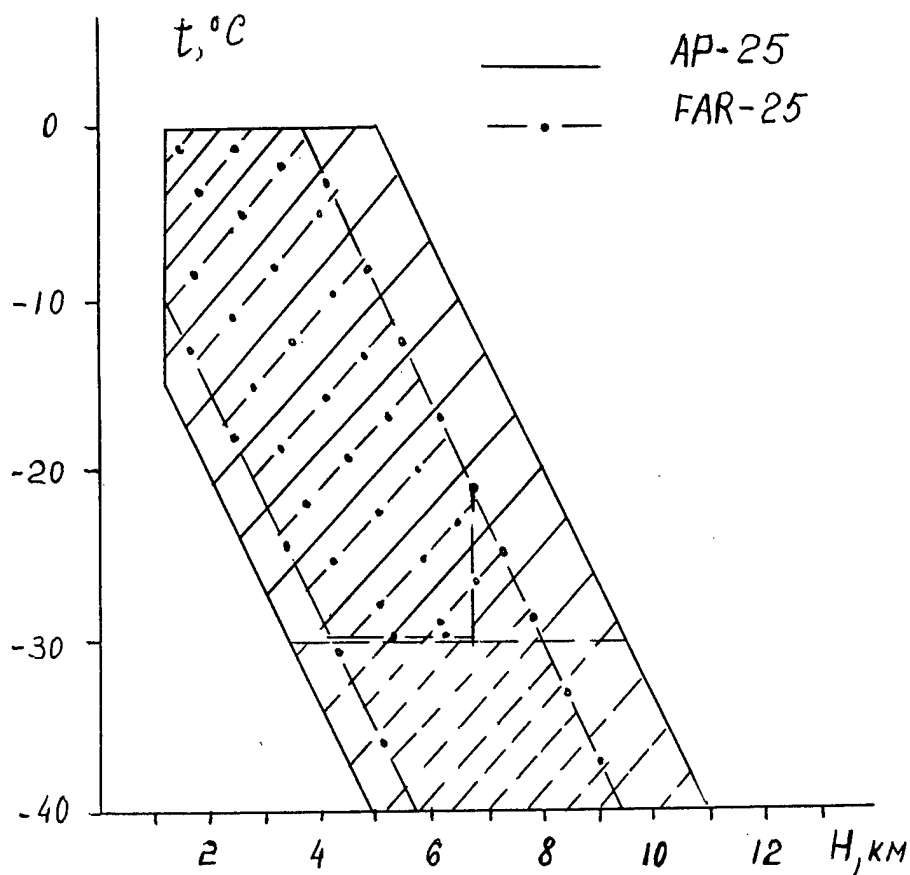


Рис 15 Зоны возможного обледенения, определяемая высотой и температурой наружного воздуха для условий максимального коротковременного обледенения.

Примечание: при $t_{н.в} = -30 \div -40^\circ\text{C}$ зону возможного расширения условий (по требованию заказчика)

Figure 15. Possible icing zone defined by altitude H and ambient air temperature t for maximum short duration icing conditions.
Note: for -30° to -40°C , possible expanded zone conditions are given.

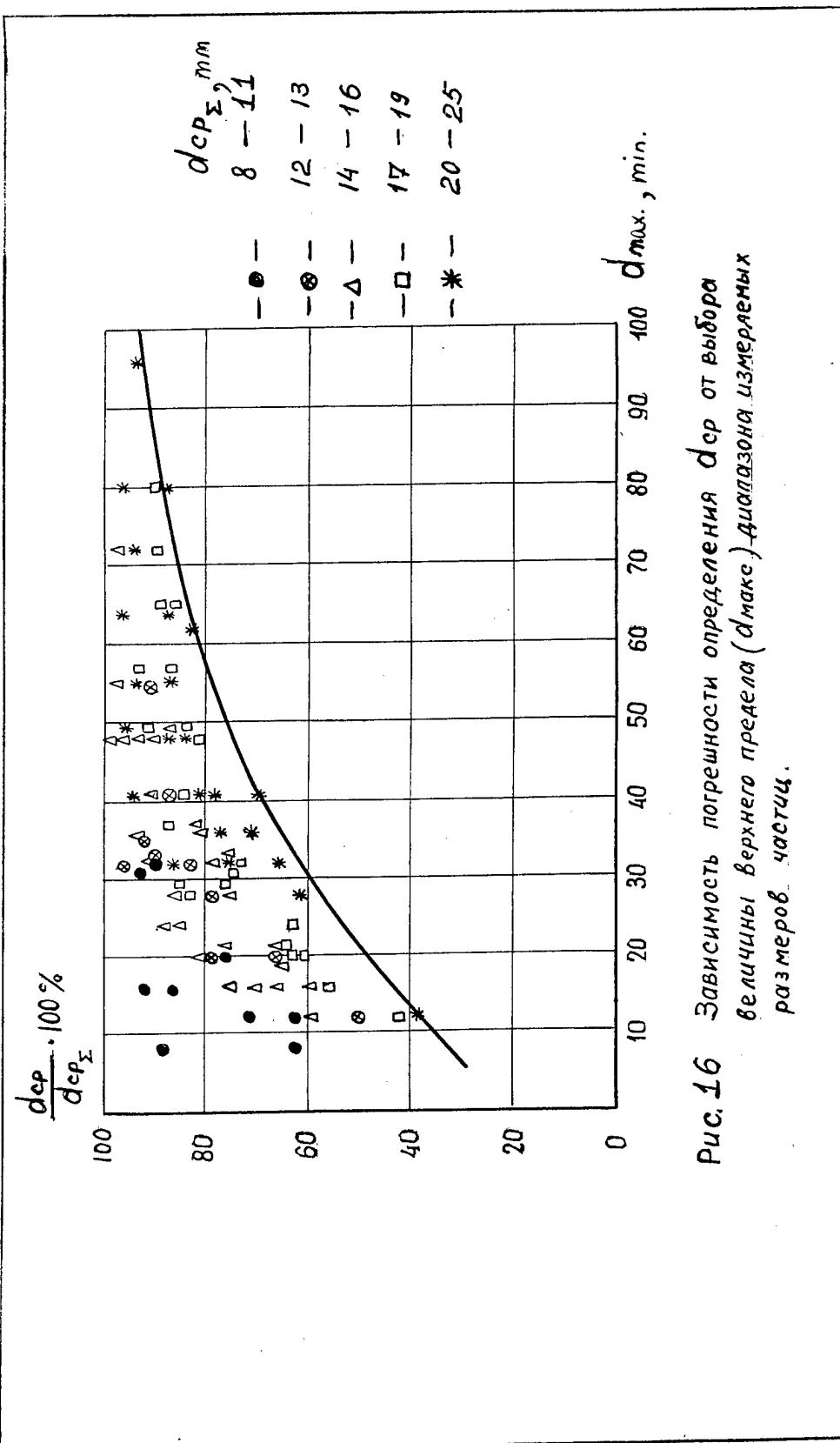


Рис. 16 Зависимость погрешности определения d_{cp} от выбора величины верхнего предела (d_{max}) диапазона измеряемых размеров частиц.

Figure 16. Relationship between d_{cp} errors and selected upper limits (d_{max}) of measured droplet size range.

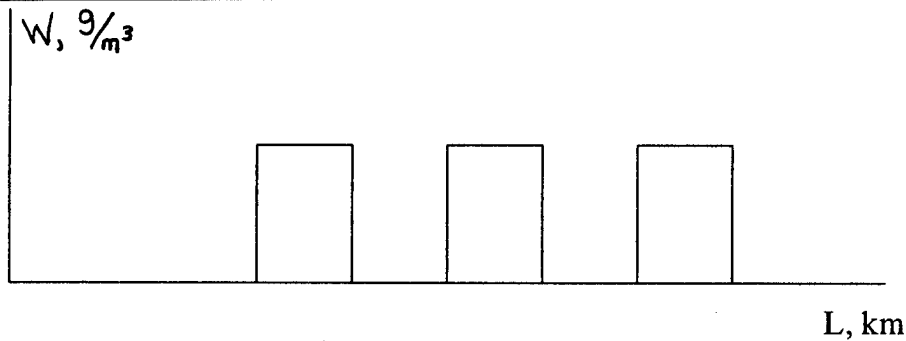


Figure 17. Graphic depiction of intermittent icing.

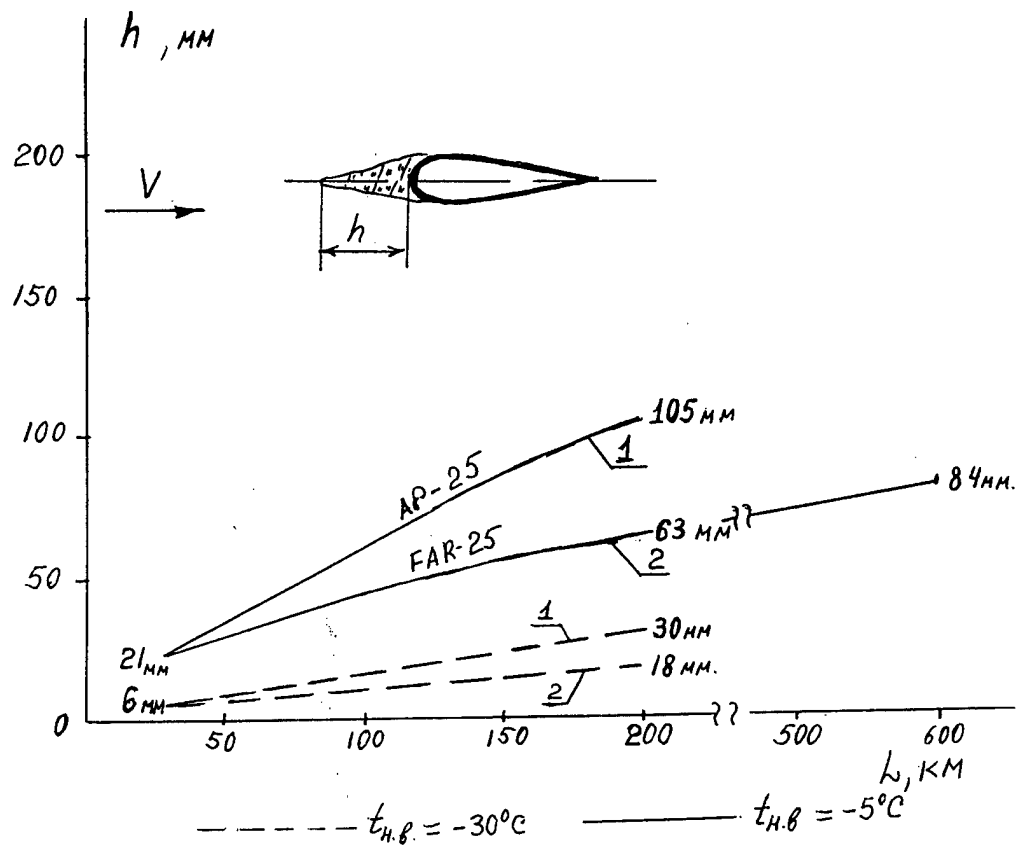


Рис 18. Сравнение условных толщин льда, которые могут образоваться на визуальном указателе в условиях обледенения:

1 - по АП-25 ($d_{ср\sum} = 20 \text{ мкм}$)

2 - по Приложению С FAR-25
MVD = 15 мкм ($d_{ср\sum} \approx 8 \text{ мкм}$)

Figure 18. Comparison of hypothetical ice thicknesses which can form on visual indicator in icing conditions.

Improving the Safety of Flight in Icing Conditions

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Abstract

The safety of flight in icing conditions can be improved by changing the existing aircraft icing certification requirements, operational procedures, regulatory language, and basic airman's information. The FAA should review these areas of concern and make appropriate changes to improve the safety of flight in icing conditions.

Body of Paper

The safety of flight in icing conditions can be improved by changing the existing aircraft icing certification requirements, operational procedures, regulatory language, and basic airman's information. There are some meteorology/forecast improvements to be made as well, but I will defer discussion of them to the experts.

Aircraft certification for flight in icing conditions should require consideration of all icing conditions known to exist, including freezing drizzle and freezing rain. If safe flight is not possible or cannot be demonstrated in some icing conditions known to exist, the manufacturer should be required to provide the flightcrew with positive means of detecting when such icing conditions have been encountered as well as procedures for safely exiting the icing conditions. Further, the regulatory language authorizing operator flight in certain icing conditions should not contradict the basic airman's information concerning icing conditions.

The existing FAA/JAA icing certification requirements, associated Appendix C icing certification envelopes, and advisory material do not require consideration of all icing conditions known to exist. The Appendix C envelopes have a maximum drop size of 50 microns MVD, which does not account for a variety of large drop conditions. For example, the original 1940s NACA icing research flights encountered drop sizes of up to 80 microns instrumentation could not provide the researchers with an accurate numerical characterization of the freezing rain encounters, they recognized the possibility and risk of such encounters. NACA subsequently proposed

inclusion of an aircraft icing design requirement for demonstration of flight in 1000 micron MED conditions as an approximation of exposure to freezing rain.

In the 1950s, statistical analysis of the 1940s NACA icing research data resulted in icing condition envelopes for a variety of probabilities. This statistical analysis did not include the estimated 1000 micron MED freezing rain encounters, presumably because of the lack of actual measured data. Nevertheless, the existing Appendix C envelopes appear to have been derived from the 10^{-3} probability envelopes presented in this statistical analysis.

From this point on, the subjects of freezing rain and other large drop icing conditions were primarily relegated to discussion in ADS-4 (the 1960s predecessor to the Aircraft Icing Handbook) and University of Wyoming icing research reports. The Safety Board's 1981 aircraft icing study recommended to the FAA, among other things, that they expand the Appendix C icing envelope to include freezing rain. The FAA responses to this recommendation and subsequent Safety Board follow-up letters through 1994, indicated that they believed the existing Appendix C envelope was adequate. Now that we've had the Roselawn accident, the adequacy of the Appendix C icing envelope as a representation of the natural icing environment in which people fly, and as a means of properly certifying the safety of flight in icing conditions, is once again a topic.

The Roselawn accident and subsequent research have shown that the near-freezing icing environment, even with certification-size drops, can result in accretions substantially different from, and in some cases more consequential than found in colder icing environments. We have since had numerous near-freezing in-flight incident investigations and pilot reports, some with flight data recorders and even some with photographs of the accretions. Other pictures were brought out because of past recollection, such as those shown by Wayne Sand at the last FAA icing conference. Further, review of several Part 25 airplane icing certification submissions show few or no data points within 3 degrees of the freezing boundary of the Appendix C icing envelope. More research and certification flight time should be spent on near-freezing icing characteristics, and analytical tools should be developed by research agencies to assist manufacturers in coping with this problem area during the design phase.

FAA icing certification specialists have also indicated that little attention is given to the algorithms used to generate the icing data supplied in

certification submissions, despite recent testing showing that instrumentation manufacturer and university algorithms can result in MVD values differing by a factor of 2 when using the same raw data input.

Once the Appendix C icing envelope is redefined to account for other known types of icing, comprehensive stability & control and performance criteria analogous to those required of a clean aircraft should be developed as the means of demonstration of safe flight throughout the icing envelope. These criteria should account for all known adverse effects of ice accretions and potential aggravating factors, including effects on hinge moment characteristics of all control surfaces, all permissible configuration changes, and subsequent effects on other systems such as an autopilot. If safe flight is not possible or cannot be demonstrated in portions of the revised Appendix C envelope, the manufacturer should be required to provide the flightcrew with positive means of detecting when such icing conditions have been encountered as well as procedures for safely exiting the icing conditions.

Visual accretion cues established in one or a limited number of icing conditions should not be accepted as means of detection of all unsafe icing conditions. Visual accretion cues at 100 microns MVD, 0.3 g/m^3 LWC, and -3° C TAT could be significantly different than those at 300 microns MVD, 0.1 g/m^3 , and -1° C TAT and it is unsafe to assume otherwise without testing. The continued development and miniaturization of icing parameter measurement instrumentation could provide aircraft manufacturers and pilots with a more reliable solution than visual accretion cues.

Once a pilot is given the means and is able to detect that icing conditions have been encountered for which the aircraft is not certificated to fly in, manufacturer and airworthiness authority-approved procedures should be in place that will assist in safe exit from those icing conditions.

The FAA Part 91 and 135 regulations contradict the basic airman's icing information provided in the Airman's Information Manual and other meteorological publications. Specifically, Parts 91 and 135 state that if an aircraft is certificated for flight into icing conditions, it may fly into any icing condition including severe icing conditions. The AIM and other publications define severe icing as that in which the aircraft ice protection systems cannot effectively remove the ice from the aircraft and exit from the icing conditions is required to continue safe flight. So the FARs authorize flight into severe icing conditions, which by FAA definition constitute a hazard to safe flight. The Safety Board's 1981 aircraft icing safety study and recommendations asked the FAA to remedy this contradiction, citing the confusion and

misleading nature, particularly since PIREPs use the subjective icing terminology *light/moderate/severe*. The FAA initially agreed to remedy the situation, but later reversed their decision and said that no contradiction existed. Perhaps this issue will be the subject of further discussion at this meeting.

Lastly, having knowledge that ice accretions on airfoils can reduce the AOA at which flow separation occurs and that ice accretions and their effects are sometimes less-than-predictable, it would be beneficial to require manufacturers to educate airworthiness authorities and operators on the characteristics of and recovery procedures recommended for any atypical aircraft stability and control characteristic found at AOA's normally beyond the stall protection system AOA thresholds, such as control surface hinge moment reversals. In doing so, if incidents occur and characteristics are recognized, flightcrews may be able to recover their aircraft and describe the situation, and airworthiness authority staff may be able to understand the true nature of the problem and assure appropriate corrective action.

Most of these issues are already being addressed by the airworthiness authorities, the ARAC process and other committee work such as will take place during this conference. I look forward to seeing these issues discussed, resolved or improved through these efforts and it is a pleasure to have the company of so many knowledgeable people working on their resolution.

NASA's Aircraft Icing Research in Supercooled Large Droplet Conditions

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Abstract

NASA Lewis Research Center has been studying supercooled large droplet icing since shortly after the crash of the American Eagle ATR 72 on October 30, 1994. This paper gives an overview of the supercooled large droplet icing research conducted at NASA Lewis. This includes research using the NASA Lewis Icing Research Tunnel, and the Lewis ice accretion code called LEWICE. Plans for flight research with the Twin Otter in the Great Lakes Region are also presented. Although much has been learned about supercooled large droplet icing by NASA and others since the accident, there is a critical need for further research. Future supercooled large droplet icing research should be a cooperative effort that is national/international in scope.

Introduction

NASA's aircraft icing program is conducted at the Lewis Research Center in Cleveland, Ohio. Figure 1 shows an aerial view of the center, located adjacent to the Cleveland Hopkins International Airport. In addition to its role in aircraft icing, Lewis is the Lead NASA Center for Aeropropulsion and the NASA Center of Excellence for Turbomachinery.

NASA's involvement in aircraft icing dates back to the 1940s when the Lewis Research Center was the newly established NACA (National Advisory Committee for Aeronautics) Aircraft Engine Research Laboratory (Dawson, 1991). All three NACA laboratories, Langley, Ames, and Lewis, joined together to mitigate the hazards of aircraft icing during World War II. The emphasis in those early days of icing research was to develop and test improved ice protection systems, and to better define icing environmental conditions. Initial development of a thermal anti-icing system took place at the Langley Research Center, and the testing of the ice protection system took place at the Icing Research Tunnel (IRT) at the Lewis Research Center and in flight tests.

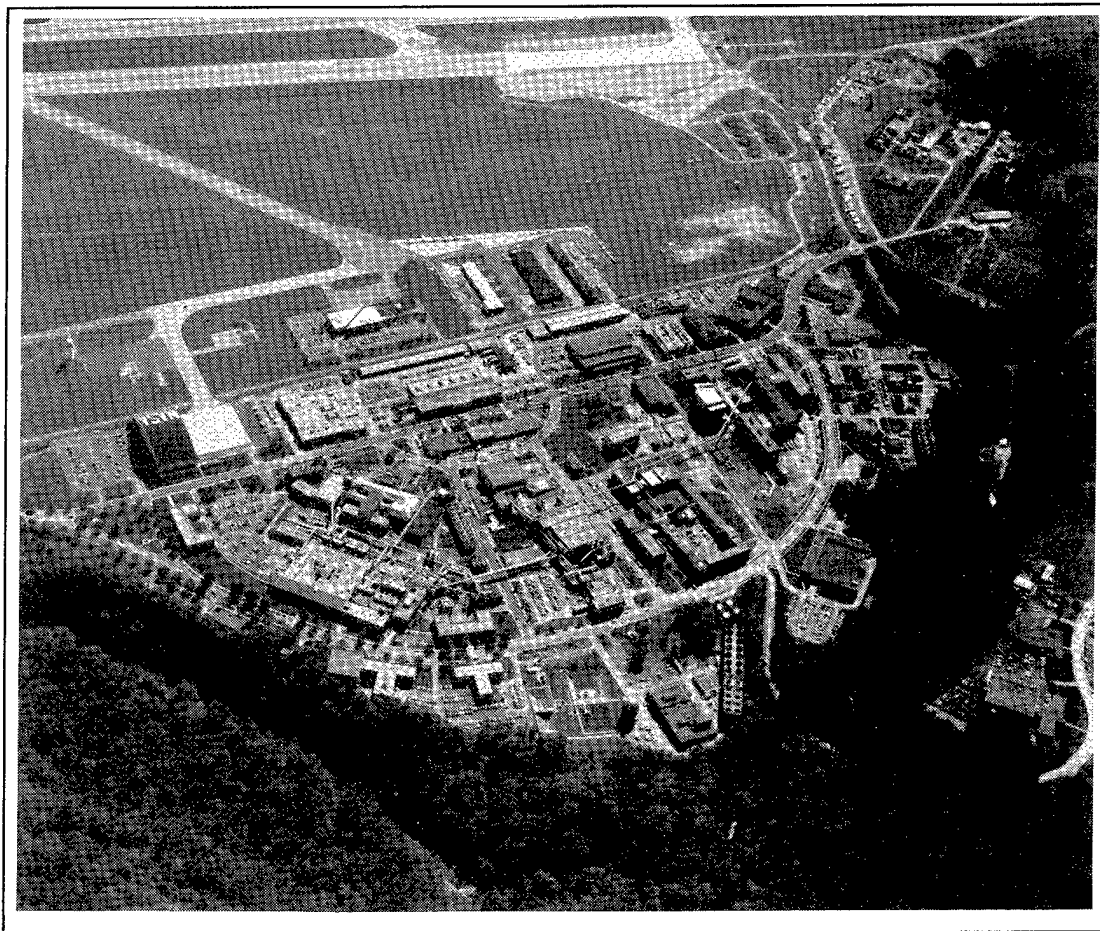


Figure 1. NASA Lewis Research Center in Cleveland, Ohio

In 1944, NACA began a flight program to characterize icing cloud conditions. This was a collaborative program between NACA Ames in the West, NACA Lewis Laboratory in the Great Lakes area, and the Air Force in the upper Mississippi Valley. The cloud characterization was intended to guide the design requirements of ice protection systems. Statistical analysis of these flight data eventually led to the FAA FAR-25 Appendix C icing certification envelope in use today.

Improvements in jet engines for civil aviation after the war caused a phasing out of the icing programs at Ames and Langley Research Centers. Even the icing research program at Lewis came to a close in 1957 when the IRT was officially closed, although a few industry hardware tests were allowed to be run in the tunnel. The icing program at Lewis was reinstituted in 1978 due to industry demand. Reviews of the Lewis icing

program up to 1991 can be found in Reinmann et al. (1982), Ranaudo et al. (1988), Reinmann et al. (1989), Potapczuk and Reinmann (1991), and Reinmann (1991). The current icing program that includes IRT testing, LEWICE code simulation, and icing flight research is described in the next section.

Eight days after the crash of the American Eagle ATR 72-210 Flight 4184 near Roselawn Indiana on October 31, 1994, NASA Lewis Research Center received a call from National Transportation Safety Board requesting assistance for the accident investigation. Two Lewis researchers served on the NTSB accident investigation team (Airplane Performance Group). The research performed at Lewis in support of the accident investigation included an IRT test of a wing section in near-freezing, supercooled large droplet conditions, simulations using the Lewis ice accretion code (LEWICE), and Navier-Stokes code analysis of airfoil performance degradations that could result in a control anomaly. These and other activities in support of the accident investigation has been reported to NTSB. This paper presents an overview of the supercooled large droplet (SLD) icing research performed at the Lewis Research Center since the accident investigation. The SLD icing research is described in the section following the one on the overall Lewis icing program.

Lewis Icing Program

Today's icing research program at NASA Lewis Research Center has the following goals. The first goal is to develop and transfer analytical and experimental icing simulation tools to help industry reduce the cost of icing systems design and regulation compliance. The second goal is to foster the development of ice-protection systems, including ice sensing, prevention, and removal. The third goal is to provide technical support for the needs of fixed wing, rotorcraft, and propulsion industries and for federal agencies to advance aircraft safety.

Aircraft icing research at Lewis emphasizes ground-based experimental simulations, computer simulations, and icing flight research. The Lewis Icing Research Tunnel is the primary testbed for experimental icing simulations. A tenth scale model of the IRT and nozzle test facilities are also used for more detailed analyses. LEWICE is the Lewis ice accretion code with compatible ice protection codes. Lewis also has capabilities to analyze aerodynamic performance penalties due to icing using Navier-

Stokes codes. The Twin Otter is the current Icing Research Aircraft. A brief description of the IRT, LEWICE and the Twin Otter are given below, along with information on Lewis programs.

The Lewis Icing Research Tunnel is the world's largest refrigerated wind tunnel for aircraft icing, with a test section that is 6 ft (1.8m) high, 9 ft (2.7m) wide, and 20 ft (6.1m) long. The IRT was proposed in 1942, and the construction was completed in 1944. Testing of ice protection systems has been an important focus of the tunnel work. Tests have also been conducted with wing sections, inlets, subscale models of fixed-wing aircraft and rotorcraft, and instrumentation and sensors.

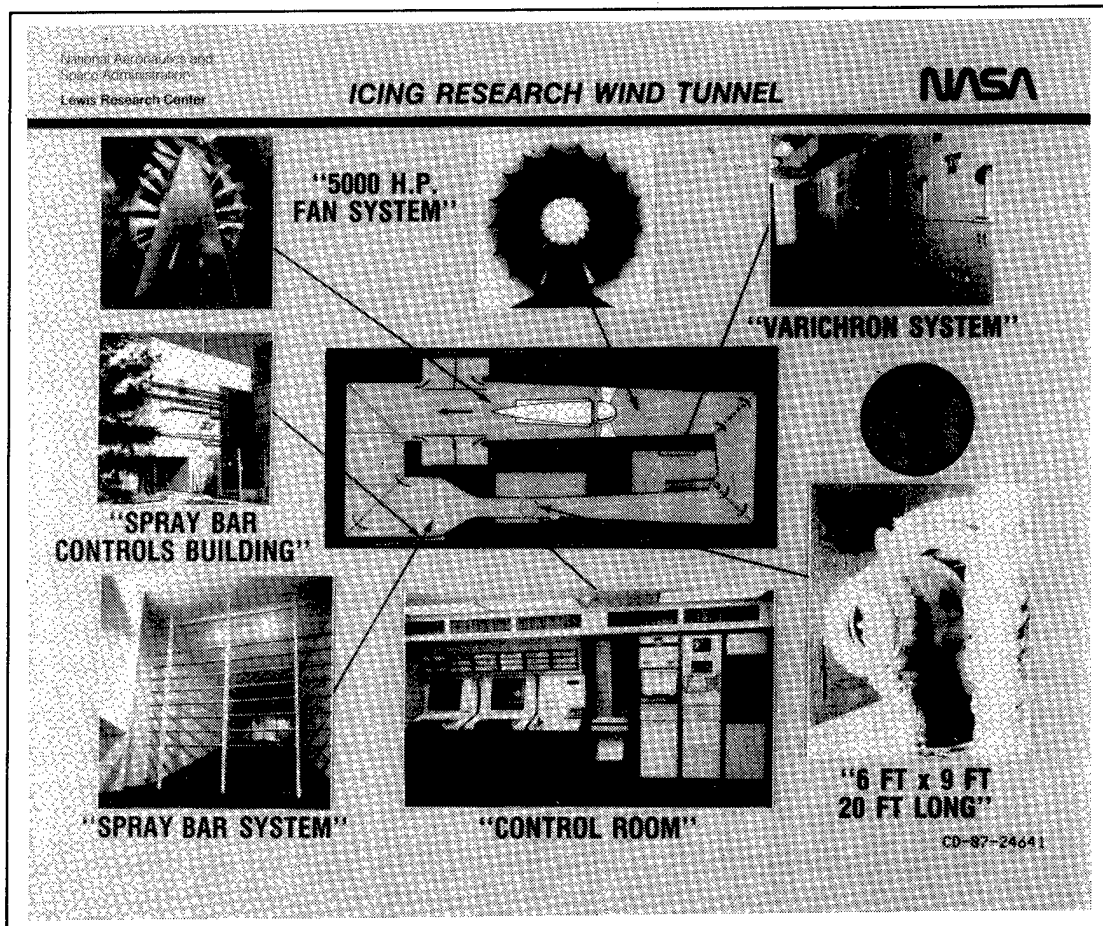


Figure 2. The Lewis Icing Research Tunnel

A schematic of the tunnel with some key features of the IRT is shown in Figure 2. The IRT provides a controlled environment that simulates icing conditions at representative flight speeds. It provides repeatable liquid water content, water droplet size, air temperatures, and speeds. The tunnel speed can be varied from 43 knots (22 m/s) to 373 knots (192 m/s) at air temperatures as cold as -40°F (-40°C). The liquid water content ranges from 0.2 g/m^3 to greater than 3.0 g/m^3 depending on air speed. The calibrated sizes of supercooled water droplet are intended primarily to cover the FAR-25 Appendix C envelope, with calibrated median volumetric diameters (MVD) from 15 μm to 40 μm . Point calibrations have been obtained for sizes smaller than 15 μm and larger than 40 μm . Calibrated SLD test conditions available in the IRT are discussed in the next section.

A continuing effort to improve test methodologies have resulted in development of new scaling laws and specialized imaging capabilities for the IRT. Unique imaging capabilities in the IRT include high speed photography, infrared imaging systems, and a sheet laser flow visualization system that uses the icing cloud as the seeding material. A five component force balance is also available in the tunnel to measure aerodynamic loads on test models. A new spray bar system, that will provide step function changes in the cloud water content and fast response time, is being planned (Irvine and Anderson, 1996).

LEWICE is NASA Lewis Research Center's signature code. LEWICE calculates the flow solution using a two-dimensional potential flow code, calculates droplet trajectories, and predicts ice accretion (Wright, 1995). LEWICE version 1.6, released in June 1995, is a two-dimensional code, although there is a quasi-three dimensional version as well. LEWICE can also be used with ice protection codes. LEWICE/ET and Antice are the codes that currently incorporate electric and hot gas heater models. There is as yet no code that models pneumatic boot de-icing systems. Aerodynamic performance simulations to analyze icing performance penalties are calculated with viscous flow codes that can handle ice shapes.

There is an ongoing effort to validate and improve the Lewis icing codes. Since LEWICE is a research code, improvements are incorporated into the code as more is learned about the icing phenomenon. IRT tests to generate validation data for thermal ice protection codes have begun and will continue into the next year. An effort is also underway to modernize the

droplet impingement database, with attention being paid to large droplet conditions as well as the FAR-25 Appendix C envelope (Papadakis and Bidwell, 1996).

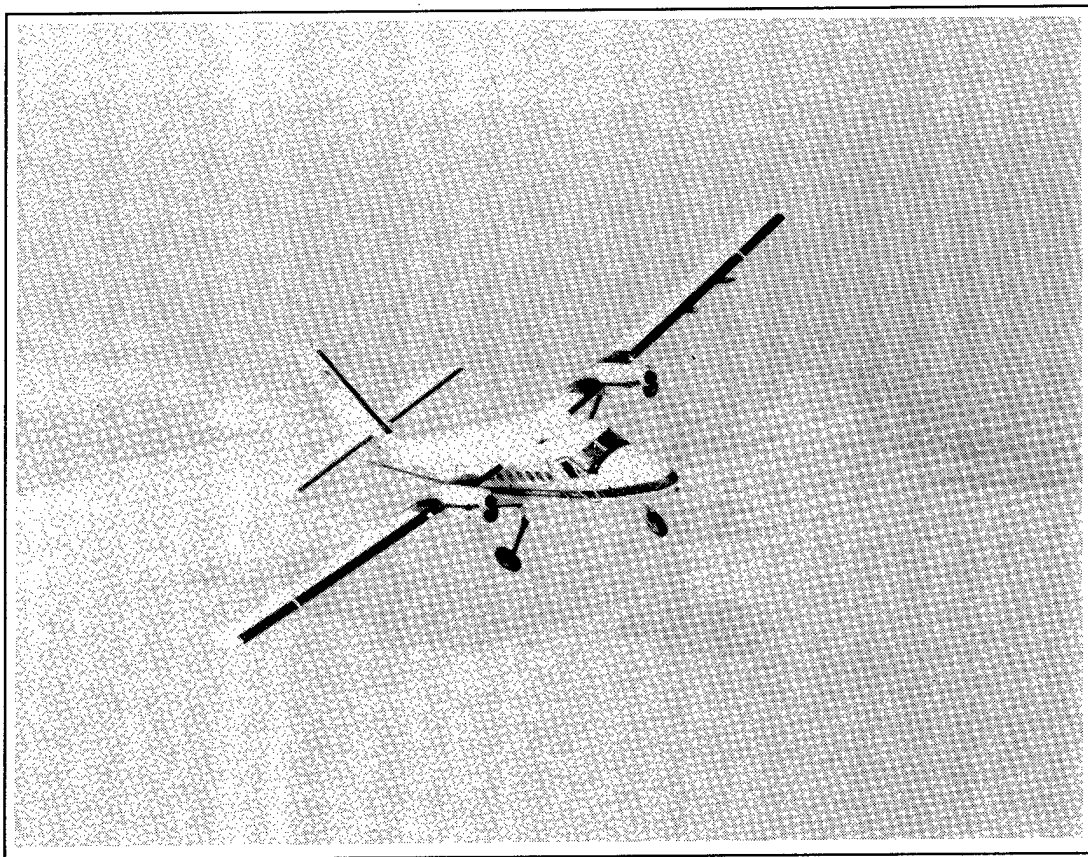


Figure 3. The Lewis Icing Research Aircraft

The current Lewis Icing Research Aircraft is the DeHavilland DHC-6 Twin Otter, a commuter class, twin engine turbo-prop airplane, which has been fully instrumented for in-flight icing measurements (Figure 3). The Twin Otter has been flown extensively in natural icing conditions, but it has also been flown in clear weather to study the effects of artificial ice shapes. Past flight programs have included performance, stability and control tests, ice protection system tests, ice accretion physics research, and instrumentation validation. The aircraft has two experimental sites: the first is the aircraft itself, and the second is the overhead hatch through which small experiments can be raised. The aircraft is protected with nonstandard anti-ice and de-ice systems.

Flight research data produced by the NASA icing flights go beyond cloud characterization to include documentation of corresponding ice accretion and aircraft/airfoil performance. Measurements of droplet size distribution, liquid water content, temperature, altitude and geographic location are used for cloud characterization. Measurements of air data, inertial data, flight control surface data, pilot force data, engine control and airplane mass allow for a complete characterization of aircraft state. Extensive imaging systems allow for documentation of ice accretion on wing upper surface, wing leading edge, and tail lower surfaces.

The Twin Otter research flights are an integral part of the NASA/FAA Tailplane Icing program currently under way at Lewis. Aerodynamic data will be generated around the tailplane, with and without artificial ice shapes, to better understand ice-contaminated tailplane stall. The ice shapes, generated from a series of IRT tests, will be first tested at an Ohio State University wind tunnel before the flight tests. Comprehensive flight data will be obtained during proposed certification test maneuvers, with and without ice shapes, and are being used to validate a computer simulation model.

In addition to the Tailplane Icing program, other major icing programs at NASA Lewis include the NASA/FAA Modern Airfoils program, the AGATE ice protection systems work package, rotorcraft icing, and icing research for NASA's vehicle-focused programs. The Modern Airfoils program is an IRT test program to broaden the current icing database to include modern airfoils and wings of interest to industry and FAA. Lewis leads the AGATE (Advanced General Aviation Transport Experiments) ice protection systems work package. AGATE is an industry/government/university consortium that seeks to revitalize U.S. general aviation through development and deployment of advanced technologies that support the small aircraft transportation system. Lewis is working in partnership with rotorcraft industry to better understand rotorcraft icing and ice protection options. The Lewis icing program also supports NASA's High Speed Research program that seeks to develop the technology base for the next generation supersonic civil transport.

Lewis Supercooled Large Droplet (SLD) Icing Program

The NASA Lewis SLD icing research program has the following objectives. The first objective is to experimentally simulate SLD icing in the Icing Research Tunnel. To meet this objective, the large droplet

capabilities of the IRT needs to be explored, and parametric studies of the SLD icing need to be performed in the controlled environment of the IRT to better understand the phenomenon. It is also important to address instrumentation issues in measuring the SLD environment. The second objective of the SLD program is to ensure that LEWICE adequately models SLD icing. An assessment of the presently available code for SLD conditions is a necessary step toward meeting the second objective, although any improvements to LEWICE will probably require development of a better physical model for SLD. The improved code will also need to be validated against IRT and flight data. The third objective of the SLD program is to gather sufficient flight data for SLD environment characterization and simulation verification. To meet the third objective, the SLD research flights must go beyond measuring cloud parameters to also capturing natural ice accretion and airfoil/aircraft performance characteristics.

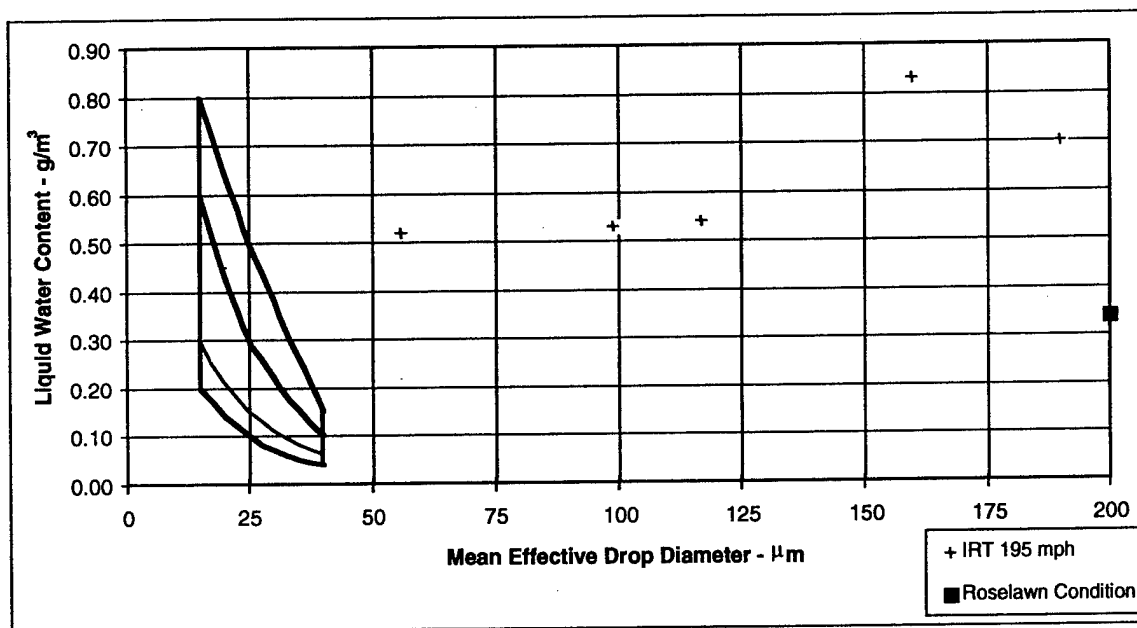


Figure 4. FAR-25 Appendix C Envelope and IRT SLD Test Conditions

The critical and urgent need for a SLD icing research program is illustrated with the figure above. Figure 4 shows a plot of the current FAR-25 Appendix C icing envelope between 15 mm to 40 mm. The 1994 Roselawn accident condition, as reported at the NTSB hearing in February of 1995, is shown at 200 mm. The five points marked as "IRT 195 mph" are the discrete calibrated points outside the Appendix C envelope that have been studied at the NASA IRT since the Roselawn

accident. Even with over fifty years of research and development at NASA and elsewhere, all the icing issues within the Appendix C envelope have not been completely resolved. It is not surprising that there is still much unknown about the SLD icing, with only about one year of research effort and five calibrated conditions that are so far from the Appendix C conditions.

This section presents an overview of what NASA has been able to learn during the past year's research into SLD icing. More detailed analyses and discussions are available in the referenced technical papers that are presented at the Working Group session at this conference.

SLD Studies in the IRT

The liquid water contents of the five large droplet calibration points shown in Figure 4 were obtained by using rotating cylinders. The drop sizes are calculated from a size distribution determined by a combination of the Forward Scattering Spectrometer probe and the Optical Array probe. SLD studies in the NASA Lewis IRT included a test entry with a model MS-317 wing section in support of the NTSB accident investigation, a Twin Otter wing section, and a NACA 23012 airfoil. Parametric studies were conducted with the Twin Otter and NACA 23012 entries. The possibility of scaling large droplet icing using smaller droplet sizes is also being explored. Measurement techniques used to measure liquid water content are also considered.

Four different techniques for measuring liquid water content (LWC) were evaluated in the NASA Lewis IRT for $LWC = 0.1$ to 1.25 g/m^3 (Ide, 1996). The techniques tested were the icing blade, single rotating cylinder, hot wire probes (Johnson-Williams and CSIRO-King), and integration of the droplet size distributions from the combined readings of the Forward Scattering Spectrometer probe and the Optical Array probe. A discussion of the data reduction algorithms for the optical array probes is presented in the work by Hobbs et al. (1996). The study by Ide (1996) showed good agreement between the icing blade technique and the two hot wire probes for the MVD range of 10 to 40 μm . There was also a good correlation between the icing blade and rotating cylinder techniques for MVD range of 15 to 160 μm . For the tunnel environment, the integrated liquid water content values from the droplet sizing probe were significantly higher than the liquid water content values obtained by the other techniques for all droplet sizes.

The large droplets in the IRT were shown to be supercooled (Miller et al., 1996). Droplet thermal analysis, time history of thermocouple measurements on an airfoil leading edge, and ice tracings with varying initial spray water temperatures all indicated that the larger droplets have sufficient time to reach thermal equilibrium and become supercooled. Figure 5 shows the ice tracings on a Twin Otter wing section when the spray bar water temperature was cooled from 185 °F (85 °C) to 72 °F (22°C). The repeatability of the ice tracings is one confirmation of large droplet supercooling.

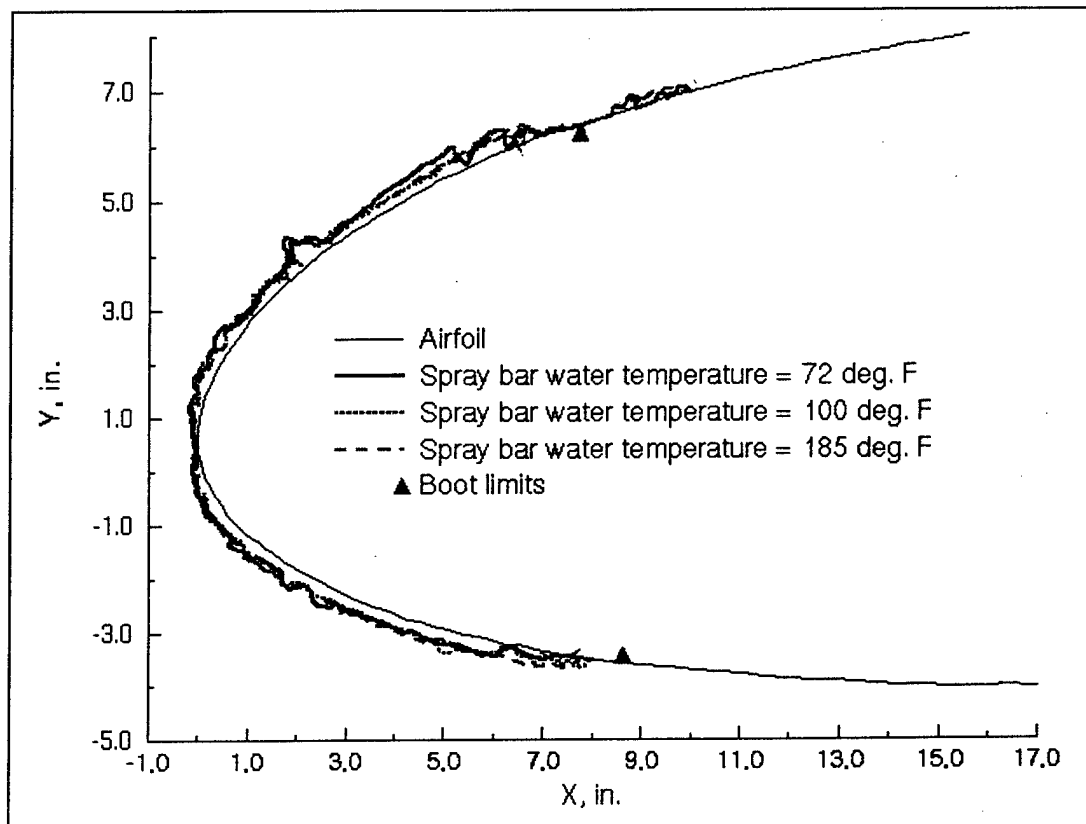


Figure 5. Ice Shape Repeatability Showing Droplet Supercooling

The IRT entries with the NACA 23012 and Twin Otter wing sections were the first parametric studies of the large droplet ice accretion and its effects on airfoils at near-freezing temperatures. The Twin Otter wing section results were reported in Miller et al. (1996), and the report of the NACA 23012 wing section is presented in Addy et al. (1996). Figure 6a shows the Twin Otter wing section installed for testing in the IRT. The

Twin Otter wing section is all aluminum in construction with a constant chord of 77.25 inches (1962.2 mm) and a 30% flap. The NACA 23012 wing section shown in Figure 6b is a single element, tapered section with the bottom chord of 73.8 inches (1874.5 mm) and 65.2 inches (1656.1 mm)

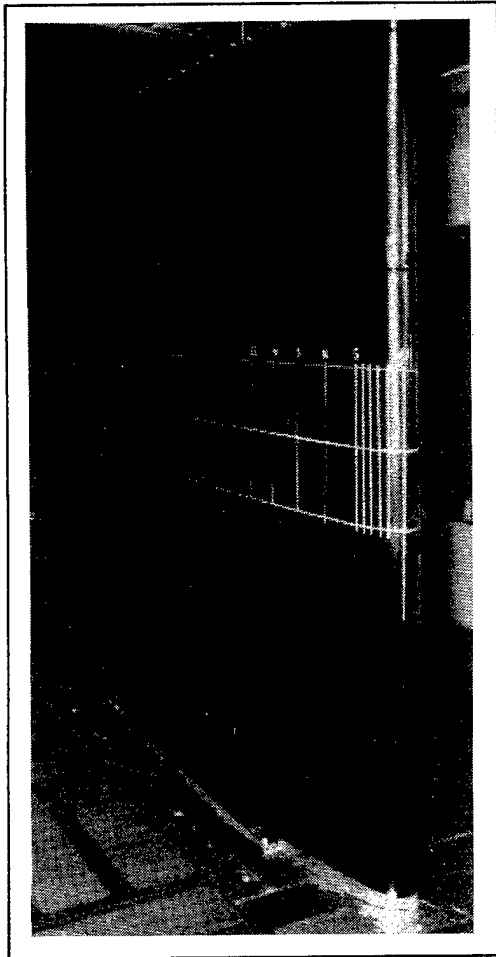


Figure 6a. Twin Otter Wing
Section in the IRT

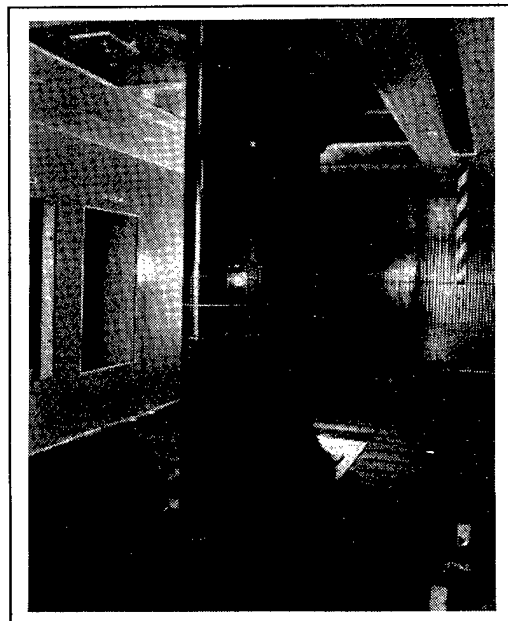


Figure 6b. NACA 23012 in the IRT

chord at the top. The NACA 23012 model has a composite leading edge. The parameters considered for the IRT studies (Miller at al., 1996, and Addy, et al. 1996) were air temperature, droplet size, angle of attack, airspeed, and pneumatic deicer boot cycling time. Because of the limited

number of calibrated SLD points, a parametric study of the liquid water content could not be undertaken at this time. Significant findings from these studies were that an ice ridge formed after the active portion of the deicer boot for the large droplet conditions tested, although the location, height, and spanwise extent of the ridge varied due to the random shedding of the accreted ice. Figure 7 shows one such ice ridge on the NACA 23012 airfoil. Increased angle of attack caused more ice to accrete on the pressure surface and less on the suction surface. Although no effect was seen at near-freezing temperatures, shorter boot cycle interval was shown to be more effective at removing ice at lower temperatures. Still, a ridge did build on the suction surface even with shorter boot cycles. The most significant finding of these studies was that temperature is a critical parameter in large droplet ice accretions. Largest performance degradations, i.e., lift loss and drag increase, were for temperatures near freezing.

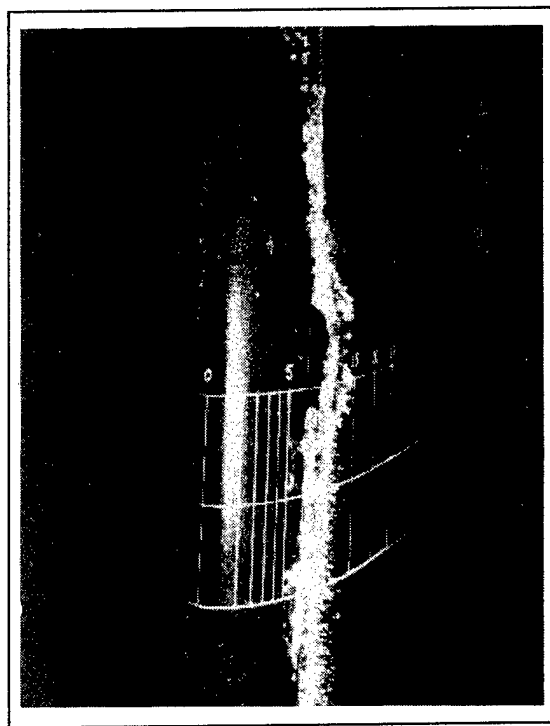


Figure 7. Ice Ridge Formation on NACA 23012

Scaling often becomes an important test consideration in tunnel simulations due to either the size of the model or limitations in tunnel capabilities. An effort to expand SLD capabilities of the IRT beyond the

current five calibration points would be a major undertaking, requiring possible break-throughs in nozzle technology and an extensive calibration effort. The option of using appropriate scaling to test large droplet conditions using spray capabilities within the FAR-25 Appendix C envelope is therefore very appealing. A first attempt at SLD icing scaling is reported in Irvine and Anderson (1996) and matches the changing droplet trajectory with an increase in droplet size. The AEDC scaling (Ruff, 1986) and the constant-Weber-number methods (Bilanin and Anderson, 1995) are used to study the feasibility of scaling a 200 mm droplet test with a 40 or 50 mm droplet test. Unfortunately, the constant-Weber-number method required extremely short spray times and a model that is much too small to be practical. The AEDC method also required the use of a model much smaller than has been previously validated with the scaling approach. An additional concern with the SLD scaling is that there is yet no method that can scale the thermal effects associated with near-freezing conditions that have been found to be so critical to large droplet icing. Further research is needed to adequately address scaling issues in tunnel simulation.

Numerical Simulations of SLD Icing

SLD computational activities at Lewis included analyses for a MS-317 airfoil, a regional transport, Twin Otter, and NACA 23012 airfoils. The MS-317 and a regional transport airfoil results were generated in support of the NTSB accident investigation. The Twin Otter and NACA 23012 airfoil results were generated for comparison with the Lewis test results of these airfoils in the Icing Research Tunnel. The numerical effort reported in Wright and Potapczuk (1996) uses LEWICE, the NASA Lewis ice accretion code, and ARC2D, a NASA Ames Navier-Stokes aerodynamics code, to model SLD icing and the resulting aerodynamic impact of such ice formation.

The LEWICE calculations for the Twin Otter and NACA 23012 airfoils, reported in Wright and Potapczuk (1996), give an initial assessment of LEWICE accuracy as compared to IRT generated ice shapes. Figure 8 shows a comparison of an 18 minute IRT ice tracing at 28°F with a LEWICE prediction. This is an excellent comparison for this case of 160 mm MVD. Other ice shape comparisons and a drop size analyses are included in the paper. Although LEWICE Version 1.6 (Wright, 1995) was shown to be a robust code for predicting droplet trajectories and ice accretions even at SLD conditions shapes without de-icer activation,

further research is needed to better understand droplet splashing and ice shedding/sliding phenomena.

The airfoil performance simulations in the paper (Wright and Potapczuk, 1996) compare clean wing flow fields of an MS-317, a regional transport,

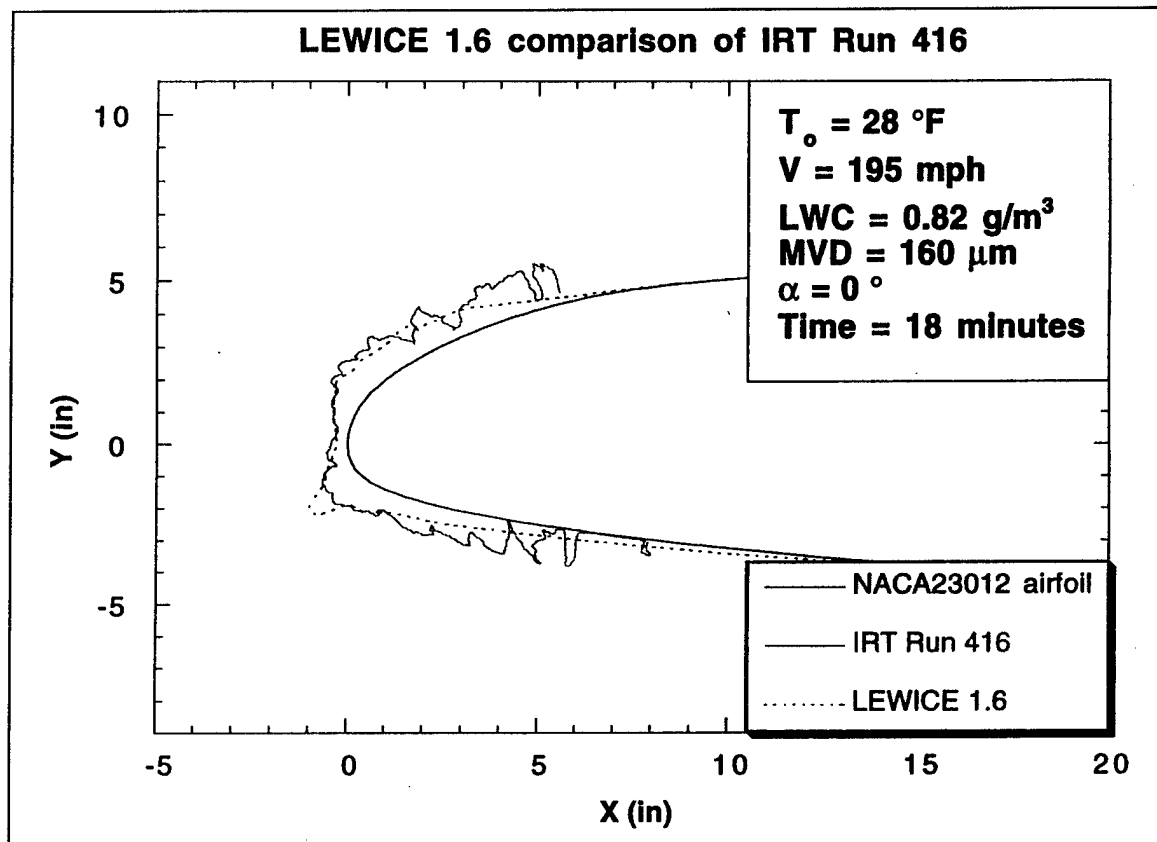


Figure 8. Comparison of LEWICE and IRT Ice Shapes

and a NACA 23012 airfoils with those with ice contamination. IRT generated ice shapes, LEWICE generated ice shapes, and an artificial obstruction were considered. Figure 9 shows the Mach number contours for a NACA 23012 airfoil with an IRT generated ice shape at Mach number of 0.28, Reynolds number of 9×10^6 , and an angle of attack of 6° . The ice shape used for Figure 9 is the ice shape from Figure 8. The flow field in Figure 9 shows an unsteady leading edge stall condition with vortex shedding from upper surface of the airfoil. Other results in the paper show how performance calculations can be used to contrast aerodynamics of real ice shapes to predicted or artificial obstructions. With further development, performance calculations can be used with

tunnel simulations to identify ice formation features that affect a particular airfoil's performance.

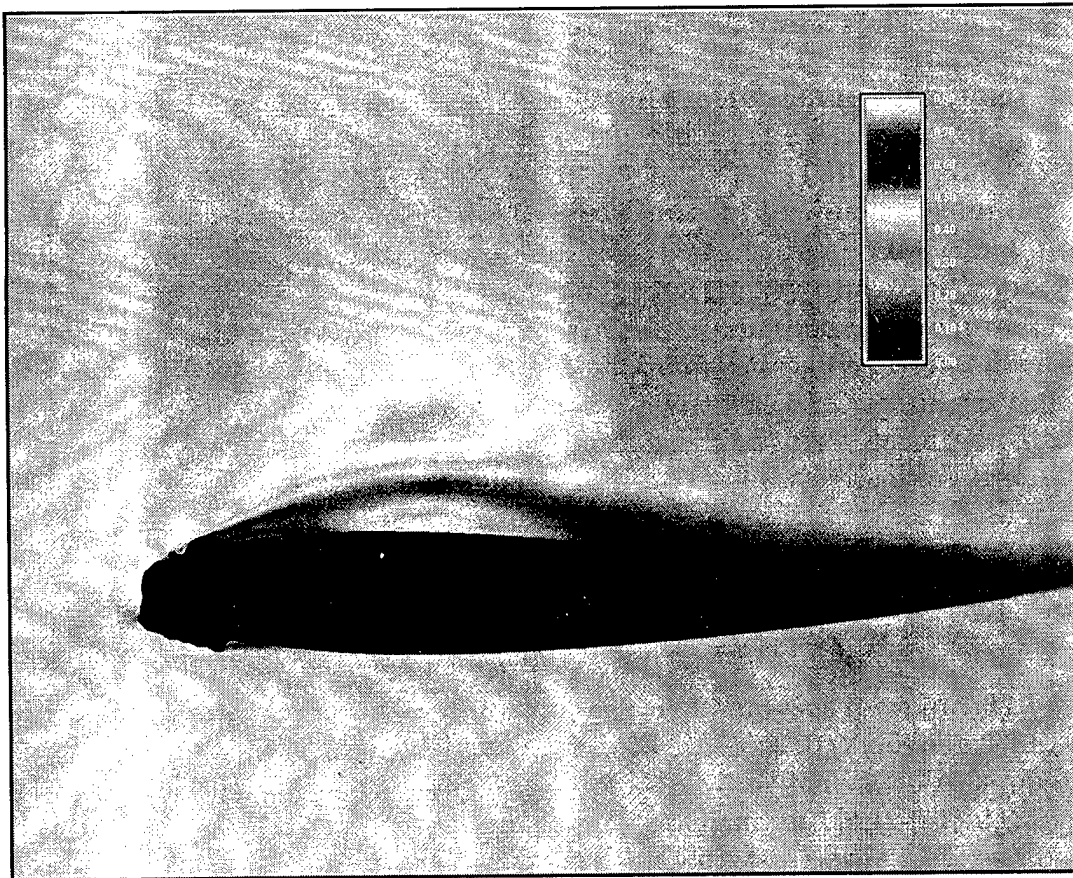


Figure 9. Aerodynamic Effects of an IRT Ice Shape

Planned SLD Research Flight Program

Although formal SLD flights have not yet taken place, planning for a SLD flight research program for the icing season 1996-1997 in the Great Lakes Region is well under way. The reason for the focus on the Great Lakes Region is because there is no documented SLD data for the region in which the ATR accident occurred. The likelihood of SLD conditions for the region is also considered to be high.

The goals of the planned SLD flight research program are unique. They include obtaining SLD cloud parameters of droplet size distribution, liquid water content, air temperature, location, and altitude as in previous flight programs to characterize FAR-25 Appendix C icing

conditions. But this program seeks to also document natural SLD ice accretions and to measure the effects of such ice formations on aeroperformance. Meteorological, icing, and performance data are all required to truly understand how SLD icing should be simulated, whether the simulation of choice is a tunnel test, computer simulation or ice tanker test. Icing simulation offers a safer and more cost effective alternative to natural icing flight tests.

Discussions for cooperation between NASA and NCAR (National Center for Atmospheric Research) have been initiated where NCAR would support NASA research flights with weather forecasting. NASA will in turn supply atmospheric data to NCAR for validation of SLD weather forecasting models. The cooperation needs to be broadened beyond NASA and NCAR to include all icing research organizations, if a complete characterization of SLD icing is to be achieved in a timely manner.

Conclusions

Significant findings from SLD icing research to date at the NASA Lewis Research Center have been reviewed in this paper. It has been shown that the Lewis Icing Research Tunnel is capable of simulating SLD icing, with even the larger droplets supercooled. Parametric studies in the IRT with a variety of airfoils showed temperature to be a critical parameter, with near-freezing temperatures being the most critical for performance degradation. Ice shapes and droplet trajectories calculated by LEWICE are also shown to be reasonably accurate for SLD conditions.

Further research is needed to improve NASA's icing simulation tools. Flight research is the most critical and urgent need in order to define the SLD environment and to obtain icing and performance data to improve simulations. Further research is needed to resolve the many issues that still remain with scaling the large droplet conditions. Understanding of the underlying physics of SLD icing at near-freezing temperatures is also needed to improve LEWICE modeling.

Times have changed a great deal since NASA Lewis Research Center first ran an icing test in the IRT. World War II is long over, and there is not the luxury of taking fifty more years to fully understand the hazards posed by SLD icing. For SLD icing research to properly impact aircraft safety, national and international cooperation is urgently needed.

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Advances in Forecasting Aircraft Icing

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PREDICTION, AVIATION WEATHER CENTER**

Abstract

The Aviation Weather Center (AWC), formerly known as the National Aviation Weather Advisory Unit (NAWAU), is responsible for issuing SIGMETs, AIRMETs, and Area Forecasts. One of the phenomenon for which SIGMETs and AIRMETs are issued is aircraft icing. For the past few months, meteorologists at the AWC have been honing new tools for forecasting aircraft icing with special emphasis on the supercooled large droplet (SLD) problem, also known as freezing drizzle/rain aloft. These tools have been applied directly to delineating areas of mixed or clear icing, which are formed from large droplets. As a result of this effort, enhanced AIRMETs, which reflect the more explicit forecasts of SLD, are being issued operationally.

Background

Forecasts of airframe icing are characterized by delineation of a threat area, in the horizontal and the vertical, for a given period of time. Furthermore, advisories are categorized by intensity. SIGMETs are issued for the occurrence of severe icing not associated with thunderstorms. In severe icing conditions, as defined in the *Airmen's Information Manual* the rate of accumulation is such that deicing or anti-icing equipment does not reduce or control the hazard. AIRMETs are issued for the occurrence of moderate icing not associated with thunderstorms. In moderate icing conditions, even short encounters are potentially hazardous and use of deicing or anti-icing equipment or diversion is necessary.

Since our beginnings in 1982, many aspects of our icing forecasting program have been based on concepts contained in the U.S. Air Force publication, AWS/TR-80/001, *Forecaster's Guide on Aircraft Icing* (the original version was published in 1964). This document defines ice accumulation on aircraft

as occurring in three types, rime, clear, and frost. Mixed icing is described as a mixture of rime and clear ice. It further comments that mixtures of rime and clear ice are quite common. The definitions indicate that droplet size is a key distinguishing factor in differentiating rime and clear ice. Therefore, we have treated mixed icing as a blend of large and small supercooled droplets.

The first step in any forecasting process is an analysis of current conditions. Upper air sounding data are analyzed for stability and moisture content at temperatures below freezing. An empirically derived frequency of icing for each layer is determined (AWS/TR-80/001). The bases and tops of the two layers with the highest probability of icing are determined, along with the type of icing, which is based on the lapse rate. Clear ice is indicated if the sounding is conditionally unstable, while rime is indicated if the sounding is absolutely stable. Our experience has been that probabilities greater than 40% indicate that moderate or greater icing intensities are likely assuming that satellite imagery indicates the presence of clouds.

Pilot weather reports (PIREPs) are another valuable diagnostic tool. Pilots are the only human observers within the icing environment and are used as a sort of "ground truth". Their reports are used to modify the vertical and horizontal extent of a diagnostic icing area.

Beginning in the mid 80's, numerical guidance used in the preparation of 12 hour forecasts of moderate icing was generated from forecasts of mean relative humidity, 1000-500 mb thickness, vertical velocity, and temperature advection. These empirically derived techniques incorporated data from research flights conducted by NASA Lewis in Cleveland. This guidance was routinely used as a basis for issuing AIRMETs, even in the absence of PIREPs. In contrast, SIGMETs for severe icing were (and still are) generally driven by PIREPs. However, we have issued them in association with areas of strong vertical motion, geographically forced upslope or lee effects in and around the Great Lakes.

Icing Forecasting Today

Since those early days, improvements in icing guidance has been achieved through improvements in the numerical models and application of improved algorithms to their output. Objective icing guidance, based on temperature and relative humidity, from several numerical models is now available (table 1). The ETA model is preferred by forecasters in most situations.

Table 1. NAWAU icing algorithm

CAT 2 - Higher Probability*	$-14 \leq T \leq -1^{\circ}\text{C}$	$\text{RH} \geq 75\%$	low levels: (w/in 900m) $-20 \leq T \leq 0^{\circ}\text{C}$ and $\text{RH} \geq 86\%$
CAT 1 - Lower Probability*	$-19 \leq T \leq 0^{\circ}\text{C}$	$\text{RH} \geq 60\%$	

*Can be lowered by one category if downslope winds stronger than -5 cm/s.

The contoured output depicts two categories (1=light, 2=moderate) at 6 hour intervals with bases and tops of the icing layer also available (figure 1). The category 2 contour provides the first guess for AIRMET thresholds at the valid time of the guidance panel. Category 2 icing is defined above 900m by temperatures between -1 and -14C inclusive and by relative humidity 75% or greater. Below 900m we look for temperatures from 0 to -20C and relative humidity 86% or greater. In addition, the category is reduced by one if downslope winds stronger than 5 cm/s exist.

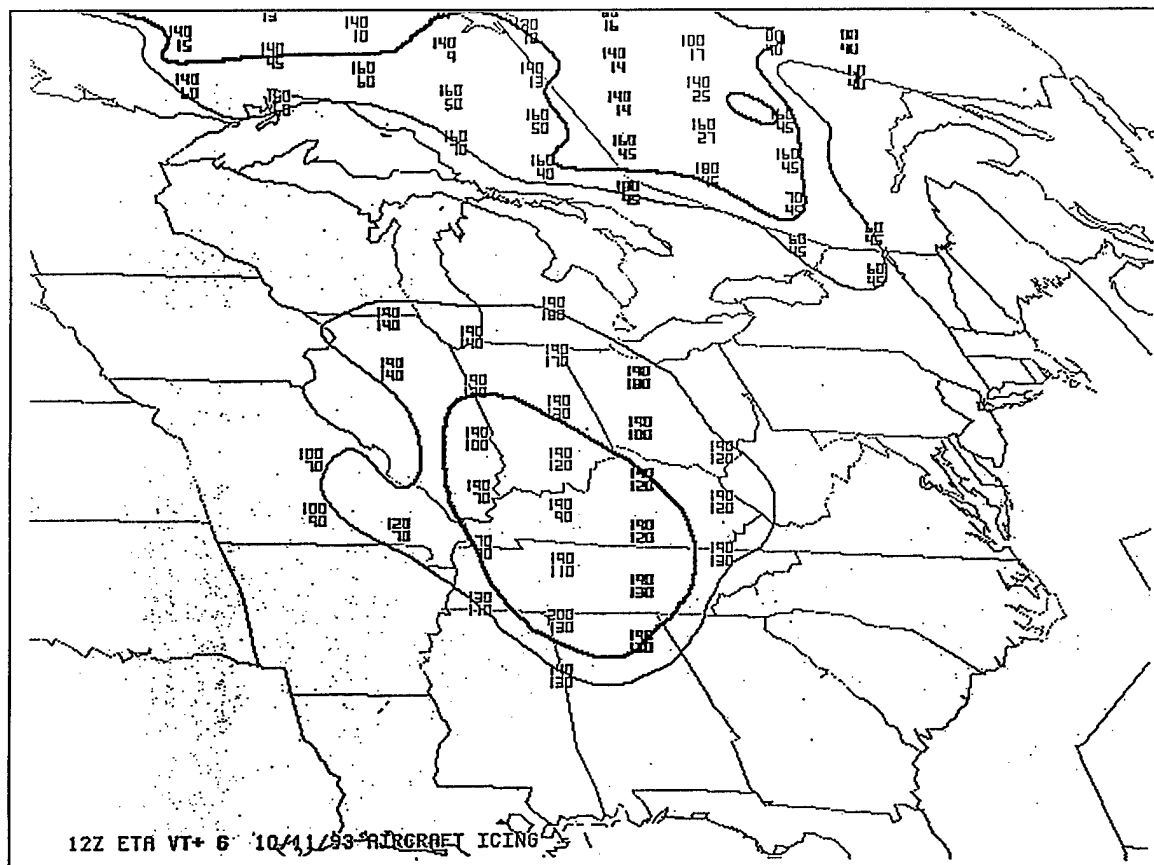


Figure 1.

Even with this level of guidance, our forecasters routinely included mixed icing in forecasts whenever we thought that large, precipitation sized supercooled droplets may be involved. We did not base these forecasts solely on surface reports of freezing drizzle or freezing rain (which are surface based phenomena). The forecast was worded "MDT RIME/MXD ICGICIP", which implied that we had a mix of cloud sized drops and precipitation sized drops at flight level. In the case of AIRMETs, these forecasts are commonly made even in the absence of pilot reports. SIGMETs are usually initiated following a pilot report of severe icing which suggests to us that the situation is potent enough to affect all categories of aircraft.

Forecasting Supercooled Large Drops

Following the NTSB hearing on the Roselawn, Indiana crash, it was clear that users wanted a more specific delineation of SLD. Recently, our Experimental Forecast Facility (EFF) meteorologists, have been working with the research community to develop techniques for forecasting large droplet icing regimes with greater accuracy. These techniques include the application of new algorithms to numerical model output in an attempt to highlight likely areas of supercooled large droplets.

Table 2. NCAR/RAP icing algorithm

Freezing Rain	$T \leq 0^{\circ}\text{C}$	$\text{RH} \geq 85\%$ w/ $\text{RH} \geq 80\%$ above $T > 0^{\circ}\text{C}$
Stratiform	$-12 \leq T \leq 0^{\circ}\text{C}$	$\text{RH} \geq 85\%$ w/ $\text{RH} \leq 85\%$ above $T < -12^{\circ}\text{C}$
Unstable	$-20 \leq T \leq 0^{\circ}\text{C}$	$\text{RH} \geq 56\%$ w/ $\text{Max_RH} \geq 65\%$ below in conditionally unstable layer
General	$-16 \leq T \leq 0^{\circ}\text{C}$	$\text{RH} \geq 63\%$

This collaboration between the EFF meteorologists and the National Center for Atmospheric Research/Research Applications Project (NCAR/RAP) scientists has resulted in further refinement of icing guidance characterized by specification of four different categories (table 2). Operationally we have found that the stable category corresponds most closely to rime icing, while freezing drizzle corresponds most closely to mixed or clear icing (figure 2). This development plus the new diagnostic, STOVEPIPE, developed by Ben Bernstein at NCAR (figure 3), suggested to us that it might be possible to construct more explicit forecasts of Supercooled Large Droplet (SLD) icing conditions.

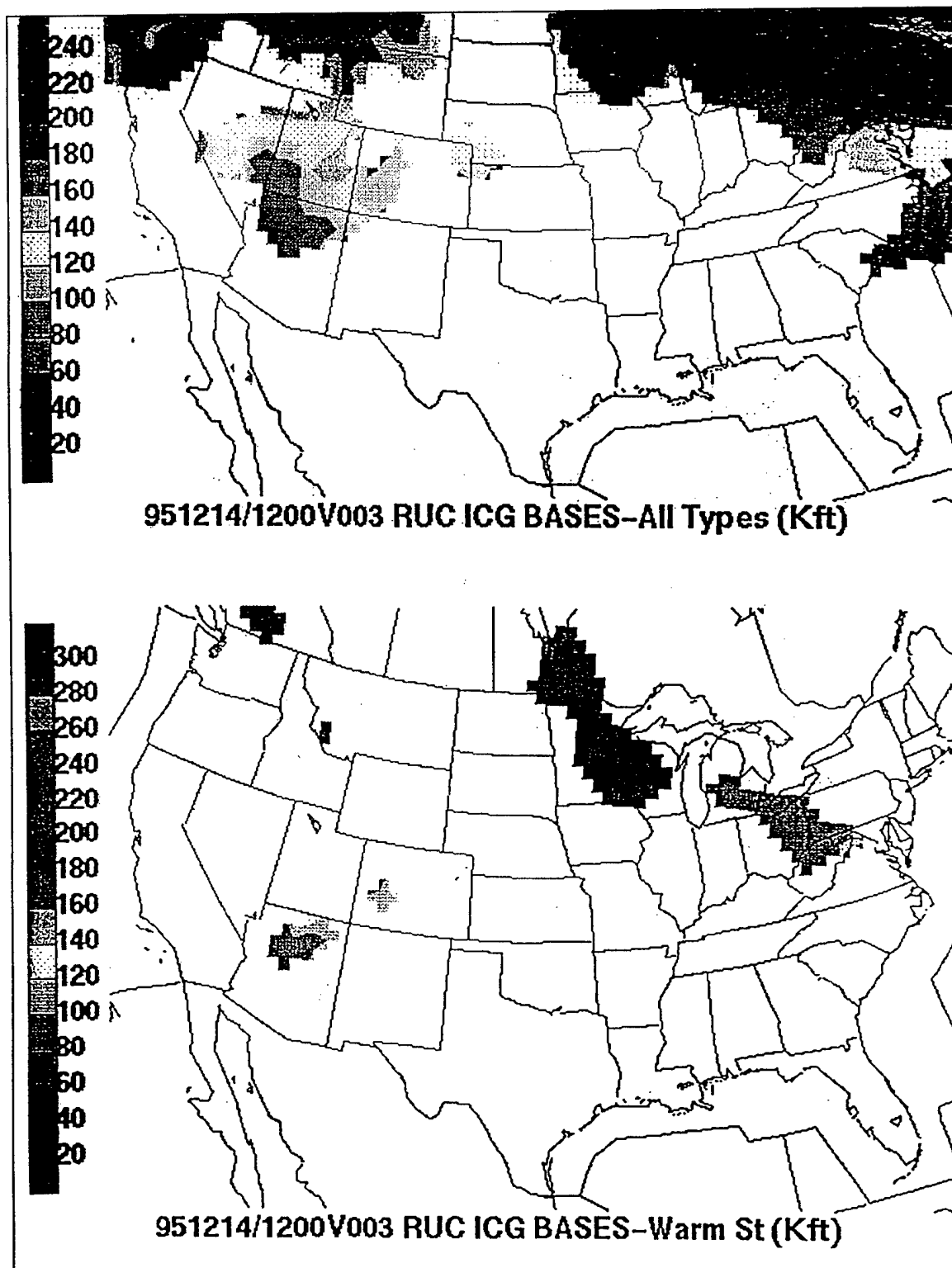


Figure 2.

Another icing forecasting tool recently developed within EFF (McCann) is derived from neural network artificial intelligence software. Using pilot reports as a means of identifying episodes of aircraft icing of varying intensity, then examining patterns of relative humidity, temperature, and equivalent potential vorticity, from which vertical motion can be inferred (Bohorquez and McCann 1995), the neural network program learns atmospheric pattern of icing and manufactures an algorithm that can be used to help forecasters. The resultant guidance derived from the Rapid Update Cycle Model (RUC) is available at three hourly intervals with 25mb vertical resolution (figure 4). Early experience is that it is good guidance for moderate or greater icing with some promise indicated for more intense icing conditions.

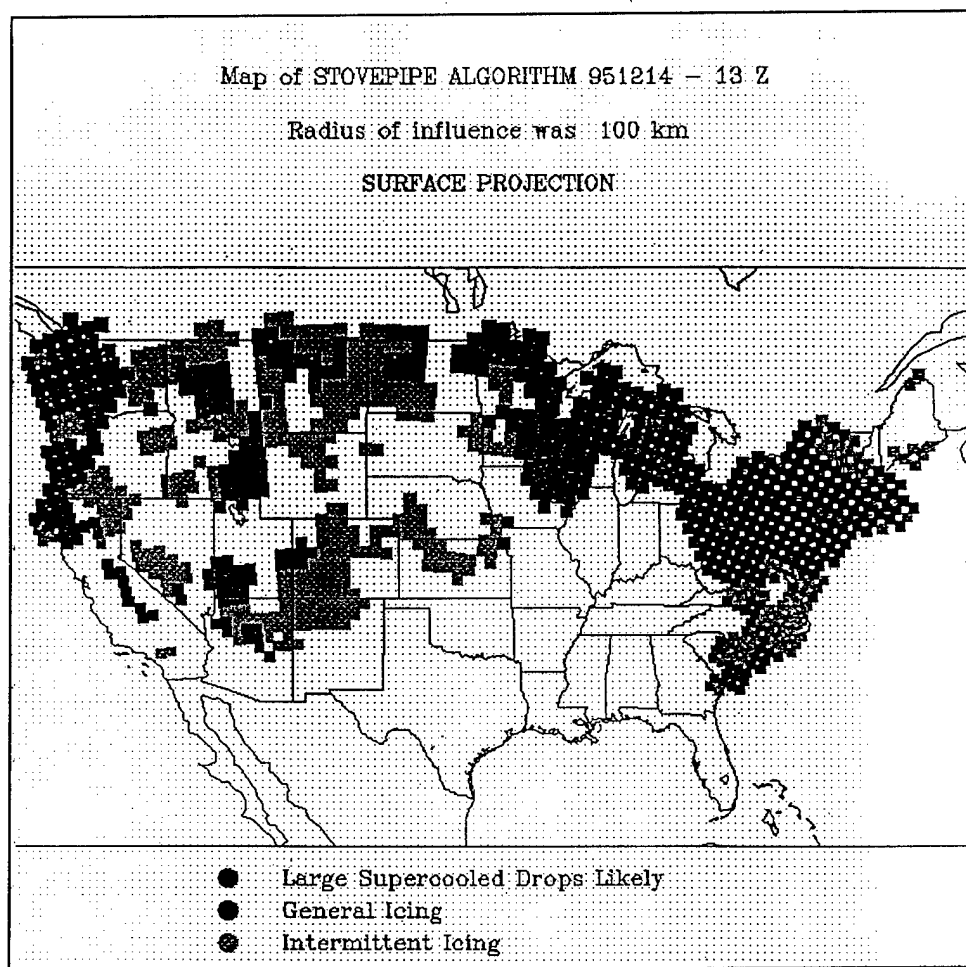


Figure 3.

Using these new tools, our experience has been that sometimes we can separate mixed or clear icing from rime and sometimes we cannot. If we cannot, then we use our "RIME/MXD ICGICIP" formulation for one area. In other situations we can successfully delineate the two categories. For example, a common case in the northwest, stratus trapped in the Columbia Basin might have rime icing with cloud sized droplets, while rime and/or mixed icing associated with an elevated moist layer may exist within a mixture of cloud and precipitation sized droplets. In this kind of case, we would issue a two tier AIRMET with possibly overlapping horizontal areas in the horizontal but separated in the vertical.

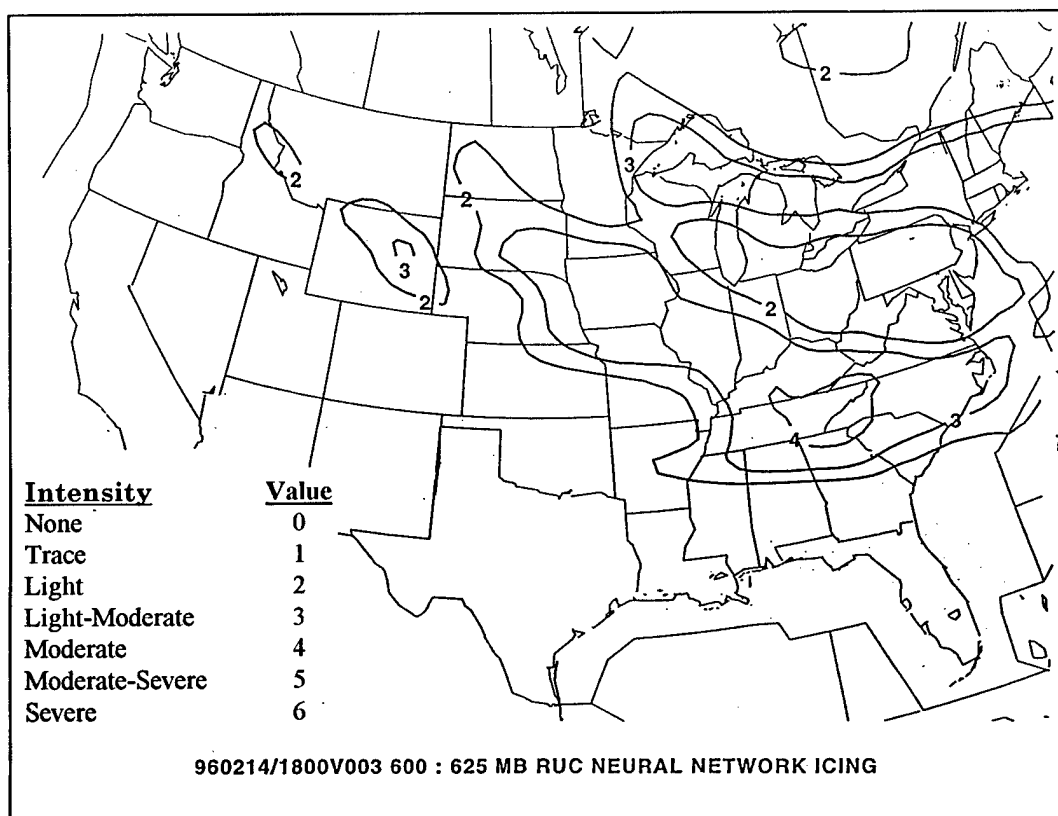


Figure 4.

In other cases we can separate the two areas in the horizontal as in the following case:

AIRMET ICG...WI IL MI IN LS LM LH
FROM YQT TO YVV TO DTW TO FWA TO CVG TO EVV TO DLH TO YQT

OCNL MDT MXD ICGICIP BLO 60 AND OCNL MDT RIME ICGIC BTWN
60 AND 150.

AIRMET ICG...ND SD NE KS MN IA MO WI IL KY
FROM YQT TO DLH TO EVV TO CVG TO HNN TO TRI TO OSW TO MOT
TO YQT
OCNL MDT RIME ICGIC BLO 150.

If, in addition, a portion of the area of the first AIRMET had severe icing conditions, then we would issue a SIGMET and put the usual reference at the top of the AIRMET bulletin.

Conclusions

Forecasting aircraft icing is making good progress which is consistent with the science available to apply to the forecasting problem. Especially noteworthy is the synergism derived from the cooperative efforts of the meteorologists of the EFF and those working in the research community. This partnership has already resulted in improved forecasts for pilots.

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Forecasting Large Droplet Icing: A Weather Briefing

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NATIONAL CENTER FOR ATMOSPHERIC
RESEARCH**

Abstract

As meteorologists enhance their understanding of large droplet formation, and work with the aviation community to appreciate their needs in this area, progress is being made in large droplet icing forecasting. Improvements in sensor technology and numerical weather forecast models have also aided rapid progress. A brief review of these improvements and recent research results related to large droplet icing are presented.

The Challenge of Forecasting Large Droplet Icing

In spite of some minor disagreements on definitions and terminology, the community is arriving at a consensus: large droplet icing is due to flight in clouds or precipitation containing droplets with diameters larger than $\sim 30\text{-}50\text{ }\mu\text{m}$ at temperatures below 0°C . The main problem in forecasting large droplet icing is that there is not any single process involved in large droplet formation. Thus, it becomes difficult to isolate those clues in the atmosphere that lead to identification of large droplets icing environments. There is, of course, the relatively simple case of freezing rain or drizzle created via melting of snow which requires a very specific and easily recognized temperature structure. However, large droplet icing can also exist without this structure and there are several processes--which may work alone or in combination--which can create this aviation hazard. Research has revealed some important factors, including but not limited to in-cloud turbulence, low cloud condensation nucleus concentrations, and parcel oscillation. However, the specific meteorological conditions associated with these can be subtle, difficult to analyze, and are not in general easily identified via the information sources available to the forecaster.

Available Tools

Information about the environment comes from sensors and numerical models. At this time there is neither an operational sensor nor model that can directly measure or predict where large droplet icing occurs with accuracy required for the job. The forecaster must therefore combine temperature, liquid water, humidity and wind information to assess likely locations of large droplets, or devise algorithms that allow a computer to do so. Knowledge of the conditions conducive to large droplet formation, gained through meteorological research, forms the basis of this assessment. The current operational models do not explicitly predict droplet sizes, but they are beginning to include the liquid water amounts.

Increased horizontal and vertical resolution of these models is allowing more physically-real representations of the atmosphere, both in terms of the model physics and the scales of information available to the user. Sensor data includes surface and upper air measurements of temperature, humidity and winds, as well as surface precipitation reports. New remote sensors, including NEXRAD and TDWR radars, wind profilers, and the NOAA GOES-8 and GOES-9 multispectral satellites, also can detect precipitation, temperature, water phase (ice or liquid), and droplet size. These data streams, however, are relatively new, and the meteorological research community is working to determine how to best apply the information provided by these new sensors to the large droplet icing forecast problem.

Highlights of Recent Research Results

The Forecasting/Avoidance Working Group at this conference will review recent advances in this area through a series of presentations. Some of the following will be included:

Recent versions of the National Center for Environmental Prediction include explicit cloud liquid water as output fields.

There is a strong correlation between icing pilot reports suggestive of large droplet icing and reports of freezing rain, freezing drizzle and ice pellets at the surface.

A balloon-borne liquid water measurement device has been developed and successfully deployed in research field programs; capability to add droplet sizing capability is being tested.

A strong statistical relationship has been found between wind shear at the tops of stratiform clouds and the presence of large droplets; radar-based techniques are being developed to exploit this for use in real-time large droplet detection.

Combinations of different wavelengths detected by the new GOES-8 weather satellite can be used to identify supercooled liquid cloud tops and provide droplet size information there.

New instruments designed for research aircraft use have been developed which provide increased resolution and accuracy of large droplet detection, counting and sizing.

Combinations of ground-based remote sensors, including a microwave radiometer, short wavelength radar and radio-acoustic sounding system, can be used to diagnose icing hazard altitudes, and provide liquid water content and droplet size information in drizzle conditions.

Measurements from a dual-polarization radar can identify and distinguish (freezing) drizzle from ice crystals.

Long-wavelength wind-profiling radars can be used to distinguish rain, drizzle and snow, and can in some circumstances provide drizzle drop size information.

In continental clouds, it appears that liquid water contents of 0.25 g m^{-3} are needed to allow direct collisional growth of cloud droplets to drizzle size on realistic time scales.

Data collected from a research airplane were used to devise a liquid water content-based severity index, which can be implemented using operationally-available model outputs.

A physically-based numerical weather forecast model technique, verified using satellite observations, shows promise for forecasting icing regions.

Forecasting techniques based on research results have been successfully transferred to the National Weather Service's Aviation Weather Center.

Future Prospects

Our approaches to the icing forecasting problem have been undertaken somewhat independently, even in the more restricted area of large droplet icing forecasting. Quantitative results on the strengths and weaknesses of various approaches are starting to come forth. The eventual goal ought to be the optimization of forecasting guidance products by combining information sources and analysis techniques. For example, surface precipitation reports could be combined with model output, NEXRAD or TDWR radar and/or satellite data, to utilize the strengths of each information source for a more accurate depiction or forecast of large droplet icing conditions.

As the meteorological community implements forecast improvements, it becomes more difficult to assess those improvements with the verification data sets available. So far pilot reports of clear or mixed icing, of moderate or greater severity, have been used as surrogates for large droplet icing conditions. This is a rather poor surrogate at best. More efficient or comprehensive means of reporting large droplet icing, including training of pilots to recognize that hazard, are needed. Field research efforts should be continued in order to gather the detailed data sets needed for progress in forecasting research.

Summary

Forecasting large droplet icing is inherently difficult. Yet, progress is being made both in transferring knowledge from the research to the operational realm, and in expanding the knowledge base by exploring the processes responsible for large droplet formation, as well as the means by which to diagnose or predict those processes. Conferences such as this are valuable for encouraging ongoing communication among researchers, forecasters, dispatchers, rule-makers, airline companies, and airframe and de-icing equipment manufacturers.

To close, I would like to suggest three issues for consideration during the Working Group discussions:

- i. Continuation of research on large droplet formation
- ii. Support for improvements in sensor techniques and model improvements

- iii. A clear path for implementation of new forecast techniques in an operational setting

Acknowledgments

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Presentation by:

WILLIAM SCHULTZ GENERAL AVIATION MANUFACTURERS ASSOCIATION (GAMA)

Introduction

The members of GAMA sincerely appreciate FAA's invitation to present industry remarks at this conference opening plenary. Many experts in the field of ice protection system design and certification from our companies are here to proactively support the several concurrent workshops that will soon get underway. The objective of this presentation is to briefly highlight some relevant facts and to make recommendations for consideration at this important conference.

GAMA companies design and manufacture many of the aircraft products operating throughout the world today and have a long and successful history of designing and applying ice protection systems. As we embark on this conference, let us recall that the origin of these safe designs extends back to documents and authoritative sources such as the Bureau of Flight Standards Release Number 434, NACA Technical Notes TN-1855, 1904, 2569, and 2730, The Britannia Studies, Technical Report ADS-4, CAR 4b, and many others. From the earliest designs up through today, there's been a continuum of icing protection system development and application. Considerable research has been conducted not only on new hardware concepts but also on the atmosphere. It has been a while, however, since an organized effort has been made to look at the whole scope of matters affecting inflight icing safety. It is appropriate, therefore, to review all aspects of this subject in an atmosphere of open and factual communication and understanding. Let's share our expertise and outline a well based plan of action. To assist this process, let me share some brief comments on design rules, recommendations on supercooled large droplets, the advanced general aviation transport experiment, and conference opportunities.

Design Rules

Indeed, manufacturers must design and equip aircraft products so they can be safely operated in the intended environment. A variety of equipment is available to effectively protect aircraft products for the flight icing environments defined in the regulations as maximum continuous and intermittent maximum. It is also recognized that certain extreme conditions may be found in the environment for which the airplane is not designed. Products could be designed to cope with nearly any situation, however, comprehensive cost-benefit analyses and product safety objectives help define the most appropriate product configuration and operating procedures. Thus, we design and equip aircraft products for safe operation in the flight icing conditions presently defined in the regulations. This excludes severe icing and large hail which are alternatively and appropriately handled through a broad range of operational procedures.

We understand that a researcher recently said that the icing environment has become more severe. I don't believe this is true based on the extensive icing atmospheric research that has been conducted over the past ten years. However, the amount of flight activity has certainly increased in recent years and is expected to further increase in the future. Thus, more emphasis appears to be needed on the operational elements affecting flight safety.

Also, a comment was recently made by a member of the FAA icing team suggesting, based upon some limited analyses, there may be more accidents and incidents attributable to icing conditions than originally believed. Industry recommends that FAA share such information for evaluation at this conference and/or involve industry in post conference data analysis. Safety in the icing environment depends upon all elements of the equation remaining intact and if any element needs extra attention, we conferees should recommend rebalancing the equation. GAMA's position is that the current environmental criteria contained in the design regulations is fully adequate for safety.

Supercooled Large Droplets

Now turning attention to SLD, industry has several specific recommendations for consideration at this conference. To begin, research and actual field experience show the frequency and extent of SLD is highly limited. SLD is not a new discovery as some profess because it is

discussed in the oldest environmental characterization documents and has been with us throughout the entire history of aviation. Experience shows most airplanes tolerate a limited exposure to SLD conditions. With minimum crew vigilance, airplanes exposed to SLD can proceed to exit severe icing conditions and safely continue flight and landing. Safety could be enhanced, however, if flight crews have better information about the location and extent of SLD icing conditions. We know that weather forecasting accuracy will eventually improve and hope to learn the nature and schedule for such improvements at this conference. While on the subject of forecasting, industry must call upon FAA to clearly define the meaning of the terms "forecast" and "known" icing conditions. FAA help is needed because NTSB's current legal decision is that "known" icing conditions exist whenever temperatures below freezing and visible moisture are forecasted. Per NTSB, all that's needed is a forecast because it seems NTSB equates "forecast" with "known."

Another area where a pilot could take advantage of additional safety information is through appropriate indications that the airframe is encountering severe icing. Pilot training and increased awareness is needed to enable proper use of this information and its integration into his or her overall safety management of the airplane.

Another recommendation involves the FAA setting of standards for pilot use in reporting SLD encounters and to make these a part of PIREP training materials. Pilots and ATC should also become more interactive in the exchange and flow of vital weather information. Industry believes that ATC should take on the role of a critical weather information clearing house and thus fill a significant safety void in today's operating system.

Last week FAA issued numerous AD's against turboprop commuter airplanes for the purpose of revising airplane flight manuals to prohibit flight in freezing rain or freezing drizzle conditions, to limit or prohibit use of various flight control devices, and to provide pilots with recognition cues and procedures for exiting severe icing conditions. Industry strongly believes that a more complete and balanced approach for attaining appropriate safety objectives should be evaluated and recommended by the attendees at this conference.

Advanced General Aviation Transport Experiment

As we look to the near future and hopeful introduction of means for improving operating safety in icing conditions, we find there is an existing

Advanced General Aviation Transport Experiment program which is placing an emphasis on the development and integration of new technologies into the regulatory and aircraft operating system. The Ice Protection System Workpackage is one of several parts of the overall program, and the concepts and methodologies employed in this workpackage may have some relevance at this conference. The AGATE plan is to enhance airplane protection and detection systems and to combine them with improved weather data link reporting systems, automatic ATC systems, cockpit information integration and display, and pilot training to improve the potential for expanding aircraft utilization and improving operational safety in icing conditions. This balanced approach should likewise be considered at this conference. AGATE is a consortia of NASA, FAA, U.S. aviation companies and academic institutions. Several members of the AGATE Ice Protection Systems Workpackage are present at this conference and they are invited to introduce appropriate suggestions so long as the consortia agreement is maintained.

Conference Opportunities

With all the expertise assembled at this conference, we should jointly look forward to sharing new ideas, factual information and synergistic creativity. The authorities and industry must work in partnership to produce the best plan for future action and the industry should be involved in any post conference plan refinement and implementation. Industry would also appreciate receiving information on how the FAA icing committee works and how best to interact with this relatively confusing part of the FAA system.

Thank you.

Roselawn Main Lessons

GILBERT DEFER
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Abstract

The rational increase in icing certification rules developed with the French DGAC in 1988 to increase safety were suddenly brought into question by the Roselawn accident.

This presentation describes the experimental work performed by ATR-Aerospatiale in order to understand the effects of what was (and still is) left outside the aircraft certification: icing induced by Supercooled Large Droplets (SLD).

It shows what we have learned about how to recognize these rare conditions, characterizes their main potential dangers, which appear strongly dependent upon aircraft angle of attack during ice accretion, and discusses possible course of actions.

Introduction

An aircraft accident always strongly impacts public opinion, but is also of great concern to the manufacturer.

ATR Previous Approach to Icing-Related Issues

In an effort to reconcile operational practices, airworthiness requirements, and relevant aircraft systems, ATR had promoted (together with DGAC) a very comprehensive and rational approach to the icing certification.

The objective was to obtain an identical level of safety whether operating in a non-icing or icing environment, both in terms of performance and controllability.

This approach was based on the characteristics of the de-icing/anti-icing equipment used and took into full consideration the icing environment as

defined by applicable requirements (Airworthiness or Operational), which, by the way, leads to leading edges ice build-ups only.

Practically, the losses of aerodynamic capabilities inherent to these kind of accretions were scrupulously taken into account, to the worst practical build-ups. Flight envelope definition and protections were adapted (lower max AOA, higher minimum operational speed) to provide the same margins for both the spoiled (iced up) and clean aircraft.

This new approach to certification (which is now imposed by the JAA) has been shown to adequately cover all "leading edge" accretion cases, including tailplane stall issues.

The Post-Roselawn Accident Investigation

The loss of control on the roll axis could not be initially understood: having quickly eliminated all other possible aircraft failures or malfunctions as unable to produce such a roll upset, we started, with the help of U.S. scientists--FAA, NASA, and USAF at Edwards--a comprehensive research program to better understand the effects of what was (and still is) simply not included in aircraft certification requirement: the Supercooled Large Droplets (SLD), which were quickly suspected to have been present in the accident area.

In addition to wind tunnel testing, this research effort has been developed on three main experimental axes:

1. Artificial icing tests behind the USAF tanker at Edwards.
2. Definition of ice imitators (ice shapes), based on Edwards test results, capable of reproducing and hence understanding the accident scenario.
3. As the knowledge and means of recognition of SLD developed (mainly because of the USAF tanker testing), flight test experience of real, natural SLD accretions.

Artificial Icing Tests Behind the KC 135

In spite of their unavoidable limitations (see Appendix 1), this series of tests was absolutely fundamental in several respects:

First, flying the artificial icing cloud with droplet size at the upper limit (and even a little more) of the "Appendix C" environment showed indeed that ice developed on the leading edges only and that the boots performed their

intended function, giving no possibility for the roll upset to develop in the flight conditions of the ill-fated flight at Roselawn.

Second, and probably most important, the opportunity to fly in an artificial cloud incorporating SLD (measured 4 to 5 times greater than the maximum specified in Appendix C) gave us for the first time the ability to positively identify the consequences of prolonged operation in these conditions.

We have widely disseminated the information associated with the cues observed which allows more specific identification of SLD accretions.

Third, through several icing runs in this artificial SLD environment, the process of ice accretion could be observed, with the following main features :

SLD do not impinge on the boots only, but will develop accretions aft the protected area.

SLD-induced accretions appear strongly dependent upon the mean AOA during the accretion.

At usual (positive) values of AOA, the overwing impingement is limited to about 9 percent chord, while the underwing impingement will extend as far as 30 to 40 percent chord. At unusual (negative) values of AOA (as will happen when flying close to VFE, flaps extended), the overwing accretion reaches 14 percent chord while the underwing remains practically clean.

Ice ridges tend to develop on both sides of the leading edge in the positive AOA case, and much more aggressively on the upperwing in the negative AOA case: it takes minutes (at least 10) for these ridges to reach a critical height of 1/2 inch. Thereafter, they will grow more quickly, but are then self-limited in height to about 3/4 inch, as dynamic pressure blows them off in a very random pattern, finally building up a jagged, sawtooth-like spoiler.

Flight Test With SLD Accretion Simulators

Returning to Toulouse with the knowledge described above, we tried to replicate the shapes observed during the Edwards icing runs, within a "tanker-generated" SLD cloud. It was not practical to restore the ice accretions observed exactly, but based on wind tunnel results that were run in parallel, we tried to mimic the ice ridges observed, in terms of basic shape, height, and chord wise location.

After a limited number of tests centered on "Flaps O" ridges, which were unable to duplicate the very low AOA at which the roll upset materialized, we concentrated on the "Flaps 15/VFE" ridges and were then successful in defining shapes which:

Produced a very small drag increase (at least before airflow separation occurred) as apparent in the last minutes of holding of the accident aircraft at Roselawn.

Triggered an airflow separation leading to roll upset very similar to the accident scenario at similarly low values of AOA.

We then flew repeatedly, with these shapes, the Roselawn upset entry conditions. We reached the following conclusions:

When AOA is slowly increased above the critical local AOA value of 6° , a very unsteady airflow separation (visualized by tufts) appears behind the SLD ice shape.

This airflow separation may change the aileron aerodynamic balance abruptly and strongly in a random manner.

The roll control forces required to hold the wheel may vary rapidly and can exceed the AP roll servo maximum torque: this will lead to AP trip out and rapid self deflection of the roll control (eventually to the stop).

There is a lot of variability in the aircraft behavior and pilot forces required to recover: a good example of this variability is that out of many identical upset entries, the yoke could be left free before bank angle reached 80° , which sometimes occurred in slightly less than 2 seconds, and sometimes in more than 13 seconds. In all cases flown, recovery has always been possible, by one pilot alone using only the yoke, and without the need to reduce AOA quickly (flaps extension not required).

Flight Test After Natural SLD Encounters

Once the stigma of SLD were known, it became possible to find some "genuine" cases, even if, as expected, they are pretty rare, and mainly of a very limited extension, particularly in the vertical plane. Within Europe, the best "chance" to find them is close to the top of turbulent stratocumulus, with static temperatures just negative, i.e., Total Temperatures just positive. This

also gave us the opportunity to revisit one older flight test that the Edwards results indicated was on SLD.

The main interest of flight test in real SLD is of course that, contrary to the results of the tanker tests (and also of the flight tests performed with the ice simulators for the wing only), we can see the global effect of SLD, including effect on tailplane.

Because of the difficulty of finding such conditions, only the most usual cases of positive AOA (flaps 0°) accretions have been experienced.

The main results of these flight tests are as follows:

The first important effect is a very strong parasitic drag, which becomes apparent a few minutes after SLD encounter begins.

This drag increase is typically five times greater than the drag increase created by "Appendix C" worst ice shapes. It is measurable from the cruise condition, and if altitude is maintained, it is strong enough to bring the airplane towards a premature stall after several more minutes. (Around flight level 170, typical deceleration rates of 7 to 9 kt per minute at cruise power may be recorded).

Discussion

The large amount of work that we carried out to understand and hopefully eradicate the conditions that led to the Roselawn accident gave us a better understanding of the SLD environment, which was omitted (and is still omitted) from the certification requirements.

It is quite obvious that what we have learned, based on a limited sample of the SLD world, shows that the "rational icing certification approach," although it covers adequately the vast majority of icing occurrences, is unable to address these rare conditions.

There are probably other kinds of icing that fall in the same category, like heavier icing rain (droplets up to 1500 microns, i.e., upper limit of SLD) and even also some other outer wing accretions like "runback shapes" at slightly positive impact temperatures, which may be very "fragile", but may become temporarily "devastating" as they could slide along the wing according to NASA icing tunnel results.

It is also obvious that these rare "overwing shapes" cannot be treated by any "envelope" approach, and that "negotiating" some maximum droplet size above the 40 microns of Appendix C is not going to provide practical solutions.

At this stage, the best course of action appears to be as follows :

For the short term:

To be practical, accept the fact that airplanes with unpowered flight controls, relatively little spare power in the intermediate altitudes, and mechanical ice removers on leading edges may be less resistant to SLD than large jets able to cruise at FL390 at $M = 0.80$ or more with servocontrols and hot air de-icers. (This does not mean that the turboprops are inherently less safe, as there are several other areas where they indeed show their genuine advantage: resistance to windshear/microburst may be the best example).

Remind and make clear to the aviation community (pilots, ATC, dispatchers, etc.) that there are weather conditions that may occasionally exceed any aircraft capabilities in the icing field: this is nothing new in aviation. As everybody accepts that structural integrity cannot be guaranteed in the worst CB, one must accept that some rare icing encounters, like the SLD, must not be sustained for a significant period of time.

In order to never leave space for the worst overwing ice ridges to develop, prohibit flight in icing conditions with flaps extended and speed sustained near the maximum (VFE), and increase the boots chordwise on the upper side of the wing, ahead of the ailerons.

Develop the knowledge of visual cues to recognize readily SLD environments and take steps to leave it before drag increments make any escape difficult: ATC cooperation will be required to facilitate altitude changes, which are frequently the most effective course of action.

For the medium term:

Encourage manufacturers' flight test teams to experiment during icing certification flights with real SLD encounters in order to provide the operators with first-hand descriptions of SLD diagnosis and means of recognition. It must be stressed that looking for the ugly double horn shapes--supposedly the worst ice shapes for handling--is not the best way to find the really bad SLD: OAT conditions are, in particular, very different.

Develop suitable detectors (surface, aerodynamic performance, etc.) to help crews better recognize and quickly exit the SLD environment.

For the longer term:

Define new rules for minimum coverage of de-icers and their performance, particularly for icing cases with OAT close to freezing.

Conclusion

SLD may be detrimental to safety more rapidly than other, much more frequently encountered icing occurrences--including the much larger "worst case" ice build-ups.

SLD conditions must be addressed by everyone in the aviation community.

SLD can strike insidiously: avoiding the roll upset is an absolute must and should be easily achieved (no prolonged flight in icing conditions at negative AOA). But the huge increase of drag pushing towards premature stalls must not be neglected: it is then important to know, recognize, and avoid or escape those rare occurrences.

It is important also to stay modest and avoid any "Titanic syndrome" by recognizing that although technological advances may enhance crew awareness, they cannot replace it.

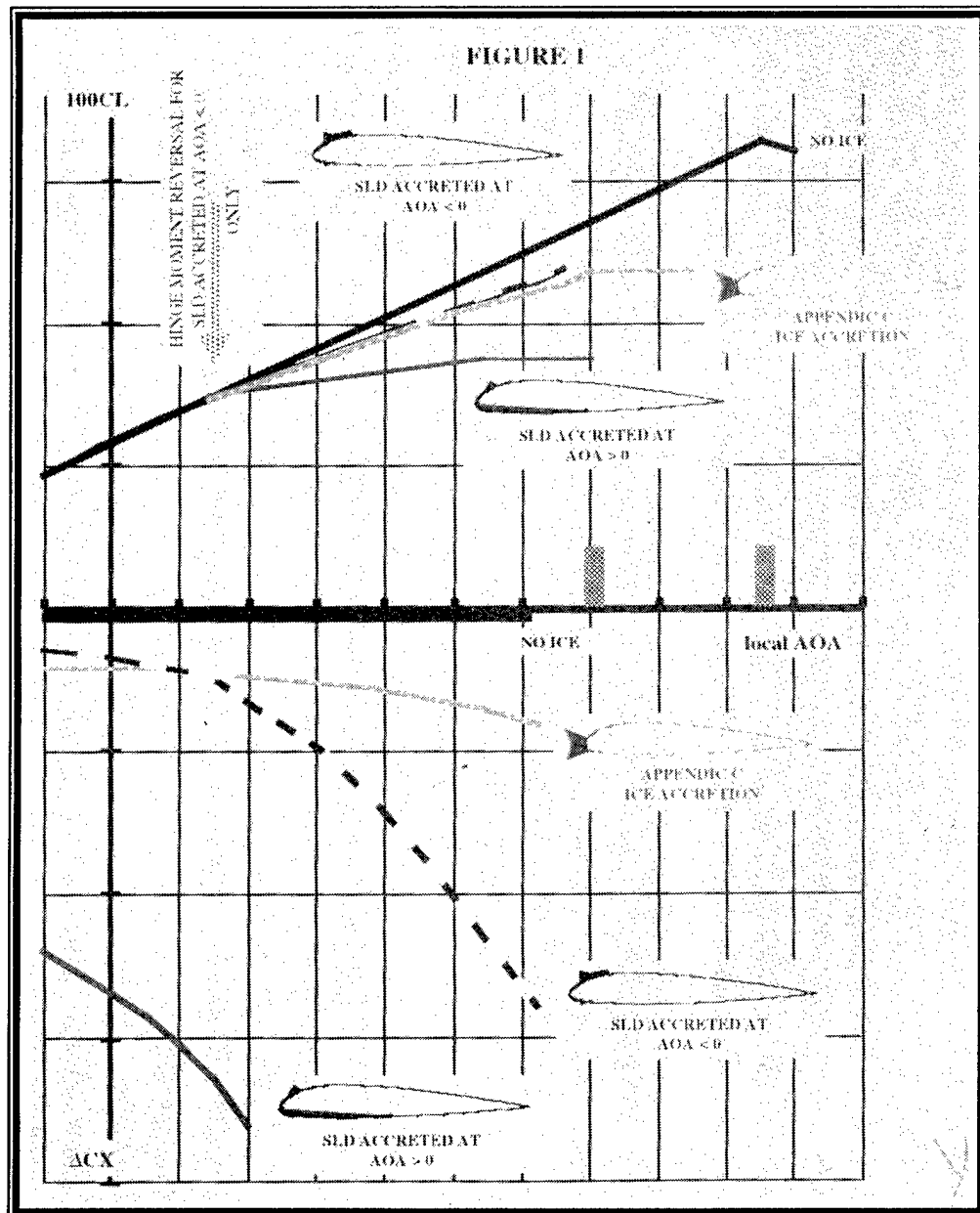
Appendix 1

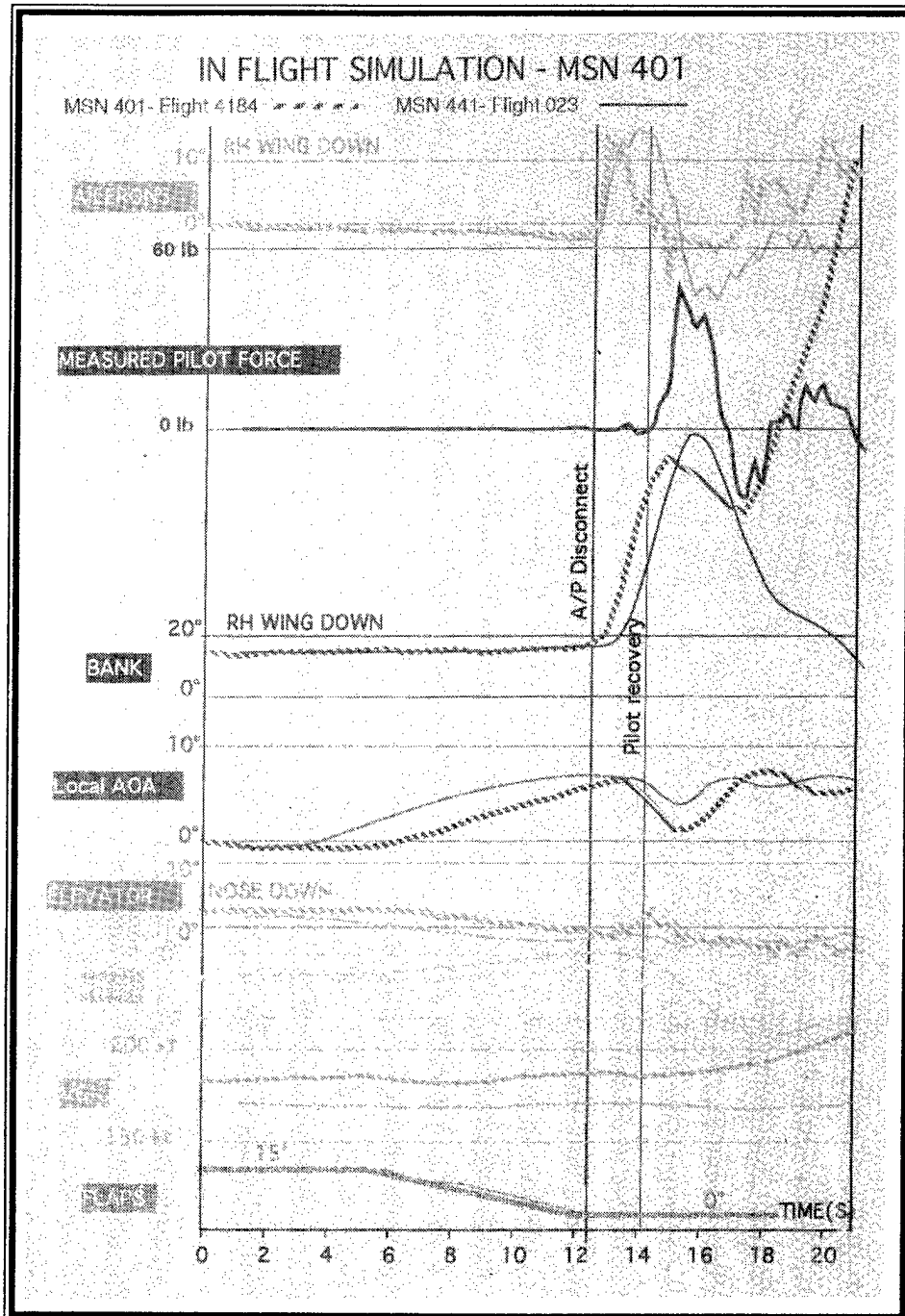
KC 135 Tanker Icing Tests: Main Limitations

1. Cost is high.
2. The artificial cloud is not governed by tanker-controlled parameters only. In our experience (two campaigns), at least the relative humidity of the air mass in which the test takes place may affect the nature of ice build-ups.
3. Cloud dimensions are small (useful diameter of about 2 to 3 meters).
4. Droplet size and distribution vary rapidly with distance between the "water sprayer" and the airfoil segment to be exposed. This means that:
 - a) The position behind the tanker must be held with a "tiring" accuracy.

- b) There are parts of the receiver airplane that physically cannot be placed usefully in the artificial cloud (e.g., ATR tailplane).
- 5. The size of droplets, although significantly above the Appendix C maximum, is apparently limited to 200 μm (Median Volumetric Diameter).
- 6. The downwash of the KC 135 is fairly powerful and aggravated by the need to push inner engines to get enough P2 to avoid icing of the spray ring: this makes it impossible to stay in the artificial cloud without large ailerons and rudder deflection.







Inflight Structural Icing: An Operational Analysis and Global Approach

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Introduction

In December of 1994, shortly after the accident at Roselawn, Indiana, the Air Line Pilots Association formed the Inflight Icing Certification Project Team. This team was tasked with monitoring the FAA's Special Certification Review of the ATR series aircraft. In addition, it was tasked with developing recommendations for changes in both certification and operating rules with regard to inflight structural icing. The team integrated activities which had already begun in the Flight Test Harmonization Working Group, a part of the ARAC, and the SAE AC-9C Subcommittee on Large Droplet Icing.

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The following paper is a study of the system used to design, certificate and operate in structural icing conditions that is in use today. The paper contains recommendations for needed change.

It is the author's opinion that this system led directly to the accident at Roselawn.

1.0 Statement of the Problem

1.1 With regard to flight in icing conditions, there is a serious disharmony between the criteria used for certification of an aircraft and the criteria used for the dispatch and operation of that aircraft.

When the aircraft is certificated, the only requirements under the FAR are to examine the capabilities of the ice protection systems, and then only in a limited icing environment defined by 14 CFR Part 25, Appendix C. Certification does not envision operation outside the icing envelope defined by Appendix C. However, there is no requirement for manufacturers to provide a means for the pilot to discern whether his aircraft is in an environment which is outside of the certification envelope. Furthermore, there are no operating limitations in the FARs designed to preclude the dispatch and operation of an aircraft into an icing environment that exceeds the criteria used for certification of the ice protection systems. Indeed, present FARs and other operational guidance issued by the FAA leave the impression that at least certain operations in severe icing, freezing rain and freezing drizzle are acceptable.

1.2 The present requirements of FAR Part 25 do not explicitly specify handling and performance standards of the aircraft in any icing environment.

This has led to an inconsistent approach to examining the handling and performance effects of ice accretion. Further, the lack of specific handling and performance standards has allowed a failure to communicate to pilots differences between dry wing handling and performance qualities and those of a contaminated wing.

1.3. The icing environment defined by 14 CFR Part 25, Appendix C, does not address the freezing drizzle/freezing rain environments.

Recent research suggests that these environments may occur at a frequency greater than previously accepted, and significant enough to appear regularly during the icing seasons in some geographic locations. This frequency, coupled with presently accepted and often erroneous assumptions regarding both the formation and the forecasting of freezing rain/freezing drizzle, may compromise safe operations.

1.4. There is a complete lack of an objective index describing inflight icing severity.

Each of the four presently used descriptive terms defined in the Airman's Information Manual requires from one to four subjective determinations. Each requires pilot observation under varying conditions of visibility. The subjectivity of the index reflects the complete lack of real-time measurement technology. At best, the index can only be used to describe structural icing relative to a particular airframe/system combination. This makes it very nearly useless for the communication of icing conditions to pilots operating different airframe/system combinations. Yet the index is also used for both forecasting and pilot reporting. Finally, because of the reliance on pilot observation, the index fails to account for lifting surfaces not visible from the cockpit.

1.5. Presently available methods for the forecasting of inflight icing are not capable of useful resolution in space, time, or parametry.

The present technique for enhancing the resolution of these forecasts requires actual detection of icing conditions. The detection of hazardous inflight icing relies completely on the penetration of aircraft into these conditions.

2.0 Background

2.1 Certification Criteria

The cloud physics criteria used for the design and certification of ice protection systems, and for the development of representative ice shapes required for handling and performance evaluation, are contained within Appendix C of 14 CFR Part 25. The requirements for the ice protection system are referenced in FAR 25.1419 AND FAR 23.1419. The recommended standards for handling and performance evaluation are contained within the FAA Aircraft Icing Handbook. Requirements for handling and performance certification proposed by the JAA are contained within NPA 25F-219.

2.1.1 Appendix C

The parameters generally measured today when considering liquid droplets in the atmosphere are a) mean volumetric diameter (MVD - expressed in microns, or one thousandth of a millimeter), b) liquid water content (LWC - expressed in grams per cubic meter, or gm^{-3}), and c) static air temperature.

Appendix C provides two envelopes referencing these parameters. The first is the Maximum Continuous requirement, which specifies continuous ice

accumulation over a 17.4 nautical mile encounter. The relationship of droplet diameter to liquid water content varies from 15 microns at 0.60 gm^{-3} to 40 microns at 0.15 gm^{-3} . The second condition is the Maximum Intermittent requirement, which specifies a short, 2.6 nautical mile encounter with potentially more hazardous droplet sizes exhibiting significantly higher liquid water content. The maximum droplet size contemplated by this condition is 50 microns.

It is important to understand the meaning of the term “mean volumetric diameter”. This term indicates a statistical function which places one half of the mass of liquid water under consideration within droplets smaller than the MVD, and the other half of the mass within droplets larger than the MVD.

The use of the term MVD implies the presence of a droplet size distribution schedule, or curve. Presently, there are two approaches to developing such curves. The first is to develop them statistically, using the assumption of a monomodal, or single bell curve, distribution. This was done many years ago in the form of the Langmuir-Blodgett droplet distribution curves. The second approach is to actually measure droplet populations in clouds and precipitation. While still demanding careful interpretation of the recorded data, the equipment used today can present a much better picture of droplet distributions than that used during the development of Appendix C.

In cases of freezing drizzle, this actual measurement has revealed that a *bimodal* (two modes) distribution may exist, which is not described by the Langmuir-Blodgett assumption. The bimodal distribution contains two concentrations of liquid water; the major concentration remains characterized by Appendix C parameters. The second concentration, however, is characterized by SLD, or supercooled large droplets, which exceed the droplet size parameters defined by Appendix C.

Indeed, Appendix C describes droplet diameter with the term mean effective drop diameter (MED) instead of MVD. Mean effective drop diameter was used with rotating multicylinder measurement devices, which are obsolete. The observations made with this equipment required an assumption of distribution to be made in order to interpret the data; this assumption was derived from the Langmuir curves. These very assumptions virtually prevented the detection of large droplets. The contemporary equipment, consisting of a series of particle measuring probes, uses the MVD term. The particle measuring probes are used to actually measure and count the droplets sampled, thus leading to an actual distribution.

The MED of any given cloud or rain parcel has been hypothesized to be within 10% of the corresponding MVD. However, definitive work on this correlation has not been done.

It can be seen that any variation on the mean droplet diameter term does not truly characterize the cloud. What is important is the droplet distribution curve, and the resulting characterization of the large droplet population. Hidden behind a relatively nominal, Appendix C mean droplet diameter may, in some types of cloud, be a significant population of droplets whose sizes well exceed Appendix C.

2.1.2 Ice Protection Systems

FAR 25.1419 is located in Subpart F of Part 25 under the subheading "Safety Equipment". It appears to provide only criteria for the certification of airframe ice protection systems. In its present form, the rule allows for optional icing certification, and sets forth some basic testing requirements for the system should icing certification be elected. It does not specify a complete matrix of configurations versus parameters, but does require testing "in the various operational configurations."

The rule requires that the airplane be "able to operate safely" within both the continuous maximum and intermittent maximum icing conditions of Appendix C, and it requires that an analysis be performed to establish that the ice protection system is "adequate".

Curiously, the rule does not appear to contemplate anything less than a complete removal of ice from the protected surface.

2.1.3 Handling and Performance Evaluations

There does not presently exist any explicit regulatory requirement regarding the criteria to be used when evaluating the handling and performance characteristics of the airplane in icing conditions. Generally aircraft have been expected to have unchanged characteristics in Appendix C icing conditions, but the required tests have been incomplete and varied from one aircraft to another. The FAA has used protocols described in advisory circular 20-73 for many years.

The JAA has proposed something which addresses this issue in the form of NPA-25F-219; Flight Characteristics in Icing Conditions.

2.1.3.1 Ambient Conditions

FAR 25.101 specifies that airplanes must be able to meet the applicable performance requirements of Subpart B in “ambient atmospheric conditions”. There is no stipulation of inflight icing conditions as not being ambient; indeed, icing conditions are a substantial minority of the prevailing atmospheric conditions during the winter season, and are probably no less ambient than clouds encountered in static air temperatures of less than zero Celsius. Icing conditions must therefore be considered ambient for the purpose of evaluating the performance characteristics of the airplane, however this is not explicitly stated in FAR 25.

FAR 25.143 specifies the flight conditions during which the airplane must be safely “controllable and maneuverable.” The rule makes no reference to any atmospheric conditions at all; perhaps by omission implying that such controllability and maneuverability should be expected in all ambient atmospheric conditions which might be encountered. At the very least, an aircraft must be controllable, in any conditions that may be encountered, with appropriate limitations on length of exposure where hazardous conditions can be recognized and exited.

The JAA, in NPA-25-219, defines Appendix C as the ambient atmospheric conditions to be considered. It further states that

“Operation in icing conditions must be regarded as a normal operation for an aeroplane for which certification for flight in icing conditions is required. The general objective of the proposed AMJ is to maintain the same minimum standard of safety as in non-icing conditions and consequently no credit can be given for the probability of encountering icing conditions.”⁶

2.1.3.2 Current FAA Interpretive Material

The most current FAA provided interpretive material pertaining to transport airplanes is contained in Advisory Circular 20-73, the latest version of which was issued in 1971. This document provides information on the types of ice protection systems, design factors such as meteorological data, design analysis techniques, and test methods and procedures for icing certification. Paragraph 32(c) of the document describes testing procedures for natural and dry air flight tests. This paragraph states that “the tests should also provide the means by which the buildup of ice on running wet and unprotected surfaces can be evaluated with respect to...the lift, drag and controllability of the airplane.”² It

goes on to state that "The natural icing tests should demonstrate that no hazardous accumulations of ice occur which could cause an unsafe condition to develop when icing is encountered."²

However, the AC makes it clear in Chapter 5, Summary of Recommended Procedures for Type Certification, that the "*airframe manufacturer should submit a design analysis which has as its prime objective...the prediction of performance of protective systems for those areas of the airplane for which he has certification responsibility.*"² (italics added). This objective does not address aircraft handling and performance characteristics.

The FAA has also produced, as an engineering reference, the three part FAA Aircraft Icing Handbook. In Chapter V, Paragraph 2.12, this document states that with regard to icing effects on the stability and control problem, "Normal stall and stability and control warnings do not exist in these situations, and the loss of stability and control can be sudden and final."³

The Handbook uses a generic airplane as a certification example. In Chapter V, Paragraph 3.2.3, Stability and Control, the Handbook says, "No attempt will be made in this section to develop the equations and analysis techniques needed to evaluate ice formation effects on aircraft stability. It is an important area that requires more attention than can be given to the subject at this time... Ice formations affect pitching moments and also the ability of the horizontal and vertical stabilisers to control aircraft attitude... Flight tests at these (landing) speeds become quite hazardous, and the effects on stability and control are mainly determined by analysis and by the judgment of experienced test pilots."³

This leads one to believe that operations with any ice accretion are anything but nominal. Further, this statement is difficult to reconcile with the guidance cited above from Advisory Circular 20-73, particularly, "The natural icing tests should demonstrate that no hazardous accumulations of ice occur which could cause an unsafe condition to develop when icing is encountered."²

The emphasis on pitching moment, empennage surfaces and landing speeds leaves unaddressed the question of roll control in any configuration.

This particular language from the Aircraft Icing Handbook illustrates the absence of any standardized requirements for the examination of stability and control with ice formations accreted, whether naturally or artificially. One has to wonder whether the "experience" associated with the test pilot includes enough experience beyond the limits of Appendix C, as well as enough line operations experience, to make a judgment regarding the ability of the airplane

to be operated safely at the very edge of the Appendix C environment in nominal line operations.

One also has to wonder why, if analysis and the judgment of the test pilot lead to the conclusion that an unsafe condition does not exist, the flight test cannot be conducted to verify those conclusions. Indeed, this language makes it seem that the hazardous flight test is left to the line pilot.

2.1.3.3 NPA-25F-219

This proposal has been developed by the JAA in an effort to recognize the need to provide guidance on flight testing for the investigation of flight characteristics, i.e., handling and performance, in icing conditions dictated by service experience.

The NPA is an outgrowth of Special Conditions developed by the French DGAC for the certification of turboprop aircraft in icing conditions. The NPA is not intended to be regulatory, but to provide advisory material.

Perhaps the most significant proposal put forth in the NPA is that, since 25.1419 requires that the airplane must be able to operate safely in the continuous maximum and intermittent maximum icing conditions of Appendix C, then “the impact on flight characteristics and performance should be determined for flight in icing conditions”.⁶ Further, the NPA states the intention to use Subpart B of FAR Part 25 as a guide to determine the appropriate flight conditions to be considered.

In addition, the NPA contained several other significant points.

- i. Limited, qualitative handling evaluation in natural icing condition
- ii. A more detailed investigation with artificial ice shapes involving:
 - a) A demonstration of adequate stability and control with the most critical ice shapes pertinent to each flight phase and related configuration. This would include longitudinal and lateral control capability, static longitudinal and lateral/directional stability and dynamic stability.
 - b) A demonstration of the safety of normal procedures for change of configuration.
 - c) The above investigation of longitudinal controllability focused on the potential for ice contaminated tailplane stall using a specific flight test known as a zero-G pushover.

- iii. No reduction in maneuvering capability to stall warning in icing conditions from that required of the "clean" airplane, applicable to airplanes which demonstrate a stall speed increment of 5 knots or 5% V_{s1g} , whichever is greater.
- iv. A stall warning which has sufficient margin to prevent an inadvertent stall under any form of ice accretion. The stall warning margin should not be less than that demonstrated for the clean airplane.
- v. Stall handling characteristics which are not so "violent or extreme as to make it difficult to effect a prompt recovery and to regain control of the airplane using normal piloting skills."⁶
- vi. A stall speed increase, in the takeoff configuration, of no more than 5 knots or a drag increase of more than 5%, without adjustment of Airplane Flight Manual take-off data.

2.1.3.4 Exceedance Conditions

Exceedance conditions refer to icing conditions beyond that contemplated by the applicable design criteria. Freezing drizzle (ZL) and freezing rain (ZR) are two examples of such conditions. The FAA Aircraft Icing Handbook (AIH) defines freezing drizzle as exhibiting a droplet size in the 200 to 500 micron range. Freezing rain is defined as exhibiting droplet sizes of approximately 1000 microns by the same reference.

Because these terms are presently defined as surface observations, recent development of terminology in the industry has led to the term supercooled large droplets (SLD) to define airborne icing environments whose droplet size distribution contains conditions not considered by Appendix C. This includes airborne ZL and ZR.

Small droplets such as those contemplated by Appendix C have small moments of inertia. They tend to impact the wing in an area close to the stagnation point. Those droplets entering the flowfield ahead of the wing and offset from the immediate area around the stagnation point are easily displaced. They tend to follow the streamlines and avoid impinging on the wing.

Large droplets such as freezing drizzle have large moments of inertia. They are harder to displace, so do not follow the streamlines quite as well as the smaller droplets. Large droplets in the immediate area of the stagnation point impinge there just as do the small droplets. However, those offset from the stagnation point may not be displaced in advance of the wing and thus may impinge at greater distances from the stagnation point than small droplets. It is these

droplets which may impinge at points aft of the protected areas, leading to an ice buildup that causes early turbulent flow or complete flow separation in spite of a functional ice protection system.

A second type of exceedance icing occurs when the liquid water content exceeds that specified by Appendix C. In this case, accretion aft of the protected areas is not likely. However, the accretion rate may be so high that the ice protection system cannot shed the ice fast enough. In the case of an hot wing system, the required heat transfer may exceed the ability of the powerplants to produce adequate bleed air. This type of exceedance is commonly known as "severe" icing under the present AIM definitions.

A range of droplet sizes may also exhibit runback, a process in which the heat transfer required to freeze the droplet on the wing takes sufficiently long enough for the droplet to flow aft on the wing before freezing. This process is typically limited to the temperature bands near freezing. Particularly insidious is the possibility of small droplets (Appendix C) impinging at total air temperature values above freezing, then running back to a point along the chord at which aerodynamic cooling has depressed the temperature below freezing. In this case, the positive total air temperature may mislead the flight crew into thinking that icing is not a threat, when in fact it is.

For many years the industry has proceeded along the logic that the severity of an icing environment was open ended. It seems to make sense that the larger the droplet, the worse the icing threat. Thus, freezing rain is considered more critical than freezing drizzle, etc.

The result of this is the concept that no aircraft can be protected against all types of inflight icing. There does not appear to be any combination of droplet sizes and liquid water contents that represent a peak in the severity of the envelope.

However, recent work by Wright⁵ on the capabilities of the NASA LEWICE code raises some interesting questions. There is a previous lack of good data on the splash and breakup characteristics of large droplets on a wing. However, preliminary consideration suggests that large droplets may break up prior to impingement when they are accelerated by the bow wave ahead of the leading edge. This may result in a considerable reduction in the size of the droplet which actually impinges.

Wright also points out that large droplet splashing is not yet well understood. There would appear to be a considerable mass loss due to splashing, resulting in less ice accretion than might have been previously thought. Both of these concepts need further investigation. It would be interesting and useful to develop knowledge of these phenomena with a view toward determining an airfoil-specific critical icing environment. Such an icing environment would produce a particular airfoil's most severe ice accretions; environments less severe and more severe would produce less critical effects.

Presently, the FAA Aircraft Icing Handbook advises that the probability of encountering conditions which exceed Appendix C is 10^{-3} . Stated another way, this means that for every one thousand hours of operation in icing conditions, one hour will be in conditions beyond Appendix C. This probability is based on aggregate data for the conterminous United States; the probability in regional environments may be somewhat greater.

This probability defines the exposure of an aircraft to an environment within which the probability of a catastrophic event is not well understood nor controlled through design or operating practice. It is an unacceptably high exposure, particularly insidious because the flight crew has no way of discriminating between exceedance and nominal icing conditions.

Green and Bracken have reported that since January of 1995, 73% of the ATR pilots surveyed who operate in the central and eastern United States have experienced at least one occurrence of side window icing, a certificated visual cue which does not occur until conditions are well beyond Appendix C. 11% of those surveyed had experienced at least five encounters; 2.5% had experienced at least 10. They further noted a significantly higher percentage of reports along an axis from Chicago to Dallas, with the greatest number in the north central region of the country. ⁴

2.1.4 Detection

The traditional approach to ice detection has been somewhat digital, i.e., the aircraft is either accreting ice or it is not. The collateral assumption is that the pilot will first operate the ice protection systems, and then monitor the situation to determine if the ice protection systems are adequately removing the ice accretion or not. If not, then appropriate steps must be taken to change routing or altitude in order to find conditions less hazardous.

Little or no attention has been paid to how the pilot monitors the function of the ice protection systems. In 1996, the authors stated in their paper, *Tools for the Management of Inflight Icing in the Twenty-First Century*,

“Today, many main wings are not visible from the cockpit, and the most insidious collector of ice, the tailplane, never has been. Glaze ice has been shown to be visibly undetectable to someone looking directly at the wing in broad daylight; and, of course, this whole method of detection must be used at night.”⁵

In short, the pilot today has no approved, tested, or even reliable method of detecting exceedance conditions. The reliance on visual observation is so compromised by design and ambient conditions as to make it meaningless.

2.2 Forecasting

The requirement for accurate forecasting of inflight icing is the ability to detect the presence of supercooled liquid water, and to provide a quantification of the associated liquid water content and droplet size. Unfortunately, the present database used for developing forecasts does not include these parameters. Furthermore, an essential ingredient of icing, cloud cover, is also not available in the database. The result is that the forecaster must infer the presence of icing from other data that is available.

The present inference is often so weak that it must cover very broad geographic areas in order to be effective at all. In doing so, the probability that an icing forecast will not actually translate into icing becomes so high as to depreciate the value of such a forecast to near zero in daily operations.

The only input which can locally strengthen the validity of the icing forecast is a pilot report. However, these reports are dependent on the subjectivity described above. They are also dependent on other social factors. At the time of this writing, research has begun to show that, beginning with the Roselawn accident, pilot reports of inflight icing (and particularly of freezing rain or drizzle encounters) for the 1994-1995 season declined substantially with respect to the nominal volume established between 1990 and 1994.

In any event, the pilot report at present requires the aircraft to actually encounter the icing. This represents a type of active sampling of a hazardous environment which rapidly leads to some degree of overconfidence on the part of the recipient of the pilot report. To begin with, the pilot making the report obviously survived the encounter, thus automatically biasing the risk

assessment that can be made with the report. Furthermore, the spatial and temporal mobility of icing leads to a sizable body of reports that negate the forecast, i.e., "nil icing". There is nothing in the research to suggest that, ten miles or ten minutes away from such a report, severe icing is not present. In fact, quite the opposite may be the case. Yet, any number of nil icing reports can easily be construed by all to permanently disable the forecast.

Possible solutions to this situation fall under two approaches. First, the presently active approach is to enhance the ability to infer icing from the data available. Some of these algorithms, which are used with output from numerical weather forecast models, are fairly sophisticated and are proceeding along the track to validation and implementation. However, they still rely on a somewhat complicated inference.

A second possibility is to improve the weather forecast model physics so that concentrations of supercooled liquid water can be explicitly calculated. Alternatively, detection capabilities might be developed so that the elements required for inflight icing can be detected in real time. The research community has advanced this latter concept as applicable to the terminal area; since the area around the airplane is more or less a continuously moving terminal area, it would be interesting to see if such a technology could be brought aboard the aircraft and used as a method of predictive detection.

In the final analysis, the forecast must have adequate resolution to warrant specific changes to operational planning, and it must be sufficiently validated to instill pilot/dispatcher confidence in the probability of occurrence.

2.3 Operations

2.3.1 Icing Severity Index

Virtually any and all discussion of operations in icing conditions takes place with reference to the terms defined by the icing severity index in paragraph 521 of the Airman's Information Manual. These terms are used by most of the few FARs which cover operations in icing conditions; they are used for the purpose of issuing pilot reports of inflight icing; and they are used by aviation meteorologists when issuing forecasts, AIRMETS and SIGMETS for icing conditions.

The Airman's Information Manual publishes the following icing severity index:

AIM Para 521 Descriptive Terms

- 1) *Trace* - Ice becomes perceptible. Rate of accumulation is slightly greater than the rate of sublimation. It is not hazardous even though deicing/anti-icing equipment is not utilized unless encountered for an extended period of time (over 1 hour).
- 2) *Light* - The rate of accumulation may create a problem if flight is prolonged in this environment (over 1 hour). Occasional use of deicing/anti-icing equipment removes/prevents accumulation. It does not present a problem if the deicing/anti-icing equipment is used.
- 3) *Moderate* - The rate of accumulation is such that even short encounters become potentially hazardous and the use of deicing/anti-icing equipment or flight diversion is necessary.
- 4) *Severe* - The rate of accumulation is such that the deicing/anti-icing equipment fails to reduce or control the hazard. Immediate flight diversion is necessary.

It can be seen that this index is entirely subjective, being dependent on the aircraft type, on the type of ice protection system in use, the specific system, proper operation of the system, and the crew making a determination as to the ability of the system to manage the ice accumulation. Moreover, the time periods cited are arbitrary.

Indeed, it is remarkable how paralytic the index is in its function. By their very definition, the terms describe icing as it manifests itself on the particular type of aircraft from which the pilot report is being issued. Hence, extrapolation of the information to another aircraft is difficult at best; and the use in forecasts, which are not airplane specific, hints at a separate set of definitions not available to pilots.

What is most interesting to consider about this type of index is the definition of severe icing. To begin with, the aircraft must penetrate the area before the icing severity can be rated under this system. Further, the system requires that the crew be able to evaluate the ice protection system's ability to manage the ice. It is well understood today that, due to their relative thinness, tailplanes are more efficient collectors of ice. As such, they may be considered a critical design point for ice protection equipment. However, due to its position relative to the cockpit, severe icing of the tailplane is impossible to detect visually, even though it will likely meet the criteria for severe icing before the main wing does. This index apparently does not contemplate ice contaminated tailplane stall (ICTS).

Severe by definition is icing which exceeds the ability of the ice protection system to reduce or control the hazard. If we encounter exceedance icing, that beyond Appendix C, then as a matter of course we have no design or test data describing the capabilities of the system in that environment. We must then consider those capabilities to be unknown, therefore, nil until proven otherwise. So we must consider exceedance icing to be severe based on the absence of system performance data for this environment. Yet the severity index definitions, as presently written, do not contemplate Appendix C at all. Thus, any icing that exceeds the criteria used for design and evaluated in certification must be considered severe.

A succinct summary of the present severity index's limitations is stated in the author's 1996 paper, *Tools for the Operational Management of Inflight Icing for the Twenty-First Century*:

"If we step back and consider the spatial and temporal mobility of icing conditions, the aircraft specific variability of such relevant parameters as AOA and TAT, and the interpretive variability, both linguistic and cultural, of the official terminology, then the severity of the dilemma becomes clear. It can become literally impossible for one pilot to extrapolate the severity of any particular icing report or forecast to his specific aircraft, at his specific location, at one specific time."⁵

2.3.2 Operating Rules

2.3.2.1 FARs

The following references appear in the FARs with regard to operating in icing conditions:

91.527(b)

Except for an airplane that has ice protection provisions that meet Section 34 of Appendix A, or those for transport category airplane type certification, no pilot may fly -

- (1) Under IFR into known or forecast light or moderate icing conditions; or
- (2) Under VFR into known light or moderate icing conditions; unless the aircraft has functioning deicing or anti-icing equipment protecting each rotor blade, propeller, windshield, wing, stabilizing or control

surface, and each airspeed, altimeter, rate of climb, or flight attitude instrument system.

91.527(c)

Except for an airplane that has ice protection provisions that meet Section 34 of Appendix A, or those for transport category airplane type certification, no pilot may fly an aircraft into known or forecast severe icing conditions.

135.227 (b)

Except for an airplane that has ice protection provisions that meet Section 34 of Appendix A, or those for transport category airplane type certification, no pilot may fly -

(1) Under IFR into known or forecast light or moderate icing conditions; or

(2) Under VFR into known light or moderate icing conditions; unless the aircraft has functioning deicing or anti-icing equipment protecting each rotor blade, propeller, windshield, wing, stabilizing or control surface, and each airspeed, altimeter, rate of climb, or flight attitude instrument system.

135.227 (d)

Except for an airplane that has ice protection provisions that meet Section 34 of Appendix A, or those for transport category airplane type certification, no pilot may fly an aircraft into known or forecast severe icing conditions.

121.629 (a)

No person may dispatch or release an aircraft, continue to operate an aircraft enroute, or land an aircraft when in the opinion of the pilot in command or aircraft dispatcher (domestic and flag carriers only) icing conditions are expected or met that might adversely affect the safety of flight.

Both Part 91 and Part 135 give a clear implication that transport category aircraft, or Section 34 Appendix A aircraft, *can* operate into both forecast and known severe icing conditions. Yet this cannot be considered consistent with the AIM definitions of severe icing.

Aircraft that do not meet the requirements of the transport category, or Appendix A of Section 34 (or its present day equivalent), do not have ice protection equipment that is designed to cope with Appendix C conditions. To simplify the discussion, we might assume that such aircraft have no ice protection at all. For this type of aircraft, an encounter with trace, light or moderate icing, as defined in the AIM, leaves open an option consistent with the aircraft's equipage. In the case of either trace or light icing, the non-equipped aircraft need only avoid exposure for more than one hour. In the case of moderate icing, the definition uses the terms "the use of deicing/anti-icing equipment or flight diversion is necessary." The only option open to the non-equipped aircraft is obviously the latter, flight diversion.

Hence, prohibiting non-equipped aircraft from severe icing is a logical extension of this thinking. The definition for severe offers no options to the non-equipped aircraft; it does not even contemplate aircraft that are not equipped with ice protection.

The point here is that the definition of severe icing offers no options to the transport category aircraft, either. The definition makes it clear that the ice accretion has exceeded the ability of the ice protection equipment, and that *immediate* flight diversion is necessary. It is not a conditional definition; there is no safe or correct way to operate in severe icing. The time sensitivity suggested by the term "immediate" correctly conveys the notion that this is not a safe place to operate an aircraft.

Yet 91.527(c) specifically states that transport category aircraft are *excepted* from the prohibition on operation in known or forecast severe icing. Here the system confounds itself. Operation in severe icing is an unsafe practice. But because information on icing conditions is near totally dependent on aircraft penetrating the condition and reporting it, aircraft must be allowed to fly in severe icing if only to continuously sample the condition to confirm whether it is still "severe" or not.

While stumbling around this conundrum, the language of this regulation subtly conveys to pilots and operators the notion that, as long as one is equipped under the transport category, etc., operation in severe icing is not an unacceptable risk.

2.3.2.2 JAR OPS

The following references appear in the Joint Aviation Regulations which are scheduled to go into effect in 1998:

SUBPART D - OPERATIONAL PROCEDURES

JAR-OPS 1.345 *Ice and other contaminants*

- (a) An operator shall establish procedures for the ground anti-icing and de-icing and related inspections of the aircraft.
- (b) A commander shall not commence take-off unless the external surfaces are clear of any deposit which might adversely affect the performance and/or controllability of the of the aeroplane except as permitted in the Aeroplane Flight Manual.
- (c) A commander shall not commence a flight under known or expected icing conditions unless the aeroplane is certificated and equipped to cope with such conditions.

SUBPART K - INSTRUMENTS AND EQUIPMENT

JAR-OPS 1.675 *Equipment for operations in icing conditions*

- (a) An operator shall not operate an aeroplane in expected or actual icing conditions unless it is certificated and equipped to operate in icing conditions.
- (b) An operator shall not operate an aeroplane in expected or actual icing conditions at night unless it is equipped with a means to illuminate or detect the formation of ice. Any illumination that is used must be of a type that will not cause glare or reflection that would handicap crew members in the performance of their duties.

It is interesting that 1.345(c) probably sets forth the most explicit guidance available. Obviously, it prohibits operation in known or expected freezing drizzle or freezing rain, since no aircraft is certificated or equipped to cope with those conditions. The question then must be, do the flight crew, the operator, and the local authorities understand this? If so, how can this regulation be complied with, if the flight crew have no means of discriminating between icing conditions for which the aircraft is certificated and equipped and those for which it is not?

2.3.3 Kinds of Operation

Each aircraft is certificated for one or more “kinds of operation” under FAR 25.1525. In Section 2 of the Airplane Flight Manual, Limitations, these kinds of operation are set forth. Typically, for a transport category aircraft, they will include operations such as “night” and “IFR”, among others. If the aircraft is certificated for icing under 25.1419, then “icing”, or “flight in icing conditions”

will be stated. There has not usually been any condition attached to the term "icing"; the fact that "icing" means Appendix C icing is not stated. Yet the approval for operation in "icing" is a different sort of approval than that for operation at "night". Night conditions are more or less digital; it either is dark or it isn't. Icing conditions, on the other hand, are analog. To one degree or another, they are open ended, and for the purpose of certification, we have only examined a subset of the whole. In other words, it only gets so dark. There is no known equivalent plateau for icing conditions.

2.3.4 Ground Deicing Programs

Flight Standards Information Bulletin - Air Transport (FSAT) 95-29, *Operations During Freezing Drizzle and Light Freezing Rain*, dated October 17, 1995, is the basis for current airline pilot deicing training. It discusses operations in these conditions and not only specifies emphasis on "takeoff considerations when operating during freezing drizzle or light freezing rain conditions", but also contains recommendations for "air carriers electing to operate in light freezing rain or freezing drizzle". Pilots are provided holdover data for deice/anti-ice fluids when exposed to both freezing drizzle and light freezing rain. This data was developed in a strong effort to achieve a practical program for complying with the "clean wing" provisions of FAR 121.629. Yet the FSAT, and the resulting training programs, convey the clear inference that, after proper fluid application, lifting an aircraft off the runway in these two conditions is not a problem. Indeed, the program and holdover data do provide assurance that, at brake release, the wing is clean. However, once airborne, the aircraft is in an environment that exceeds Appendix C.

FAA statements in the FSAT, such as "air carriers electing to operate in light freezing rain or freezing drizzle", lead to the inevitable conclusion that such operation is approved and therefore safe. This conclusion, and the documents that led to it, are not at all consistent with current knowledge about freezing precipitation or with recent accident histories. The fact is that there has not yet been a coordinated investigation of the icing environment between the ground and 1000 feet AGL, which is generally understood to be the floor of Appendix C data.

So while exceptional industry effort in recent years has brought approved training programs, approved operational programs, and a wealth of knowledge to the cockpit regarding how to achieve and maintain a clean wing up to brake release, no such effort has been developed regarding the maintenance of a clean wing after brake release. Once the aircraft rotates, and the fluids are sheared off, the aircraft enters a sort of intellectual void where operations in freezing

precipitation are elective, and until reaching 1000 feet, the actual icing environment has not been well characterized.

2.3.5 The Operational Conundrum

FAR 121.629(a) provides language that is remarkably conservative yet simultaneously subjective. As a result, the difficulty in applying such conservative language (...in the opinion of the...expected or met...that might adversely affect...) is overcome by taking often considerable liberties when forming the requisite opinion. The subjectivity of the rule is greatly enhanced by a lack of clear information specifying a quantified hazard with regard to icing; by the lack of spatially, temporally and parametrically accurate forecasts; and by a very substantial variety of opinion within the industry about what type of icing may or may not "adversely affect" the safety of flight.

The rule may actually be the precise embodiment of the disharmony between certification and operating rules cited in the statement of the problem at the beginning of this paper. There is an absence of quantified handling and performance evaluations during icing certifications. There is an absence of any certification consideration of conditions which exceed Appendix C. There is an absence of any means to discriminate exceedance conditions from Appendix C conditions while in flight. There are regulatory exceptions which infer approval to operate in severe icing. There is AFM limitations language that does not reflect the actual limitations used in certification. There are FAA issued documents, approved training and approved operations programs which state that operations in known freezing precipitation are elective. All of these factors unite to form a disjointed body of knowledge and rules regarding structural icing which bars from the pilot access to any consistent and knowledgeable approach to forming the opinion required by 121.629(a). The industry has virtually guaranteed that this opinion will be a blind one. Yet, at the end of the day, after the accident, it will be the pilot's incorrect opinion which is castigated...not the industry's misleading and selective approach to certification and operation.

3.0 A Global Approach

The process of designing a system for safety revolves around controlling the probability of a catastrophic event and the exposure to that event. The event itself, and the design, operating and natural factors which form the chain leading to it, must be understood and anticipated. The resultant risk of a catastrophic event must be evaluated in terms of acceptable risk to the society which uses the system. The acceptable risk dictates the degree of control over the exposure and probability which must be exercised. The cost of exercising

that control as a percentage of the value the system delivers to the society dictates whether the system is useful or not.

The accident at Roselawn, Indiana in 1994 was such an catastrophic event. The investigation into this accident has illustrated the absence of a systematic approach to controlling the exposure to, and reducing the probability of, such an event. Rather, the approach has been compartmentalized, with each part of the industry more or less operating in a vacuum, assuming that the other parts would fill in the remaining gaps. This compartmental approach has failed to keep pace with the expansion of the industry and the advance of technology. In the early days of air transportation, operations in icing conditions were understood to lie beyond the scope of design and certification. While this quickly proved to be economically inconsistent with the idea of all weather operations, many segments of the industry cling to the precept and assume that the rest of the industry does as well. Today, the probability of exceeding the design icing envelope is simply calculated as 10^{-3} , as if no effort was needed to control this exposure and the resulting potential for catastrophe.

Thus, any comprehensive approach to insuring safe operations in icing conditions (an approach which will henceforth be referred to as a "global approach") begins with this probability of a catastrophic icing encounter and its control. A complete solution to the problem of inflight icing requires a coordinated effort that is specifically designed to 1) reduce the exposure to an icing environment within which continued safe flight cannot be assured, and 2) reduce the probability within that environment of a catastrophic event.

A rethinking of how this problem is approached might be characterized by five fundamental points:

- i. An operationally realistic icing environment must be characterized, perhaps differentiated by geographic region, with data used to develop both a probabilistic distribution of icing severity and a graduated, parametric method of describing icing severity.
- ii. Ice protection and flight control design technology must then be evaluated on a cost benefit basis to determine in what portion of the above severity distribution the dry wing handling and performance qualities of FAR 25 Subpart B can be maintained. This portion of the distribution can then be defined under FAR 25 as the nominal icing environment.

- iii. The remainder of the severity distribution can then be identified as the exceedance environment. If aircraft are not equipped with forward looking, predictive icing detection equipment adequate to prevent inadvertent encounters with the exceedance environment, they must be able to experience exceedance icing, detect it, and retain adequate control and performance for enough time to safely exit this condition. Each icing certificated aircraft must have a probability of encountering catastrophic loss of flight control in the exceedance environment that is no higher than that accepted for any other loss of flight control function. This probability is managed largely through design.
- iv. Operating rules must then be developed which are specifically designed to 1) cause the air craft to be operated in accordance with the limits of its icing certification, and 2) reduce the exposure to the exceedance environment.
- v. The tools necessary to comply with these operating rules, such as operationally useful forecasts, real-time ground or satellite based detection, and on-board reactive and/or predictive detection, must be developed and required for air carrier operations.

3.1 An Operationally Realistic Icing Environment

The characterization of the icing environment forms the fundamental basis for the requisite design requirements, certification criteria, and operating rules. Within that characterization lies a distribution of icing severity against frequency. How often are the conditions really bad? This severity distribution is arguably the most critical piece of information necessary to develop policy.

The term “operationally realistic” is intended to define a different approach to the characterization of the icing environment than that used with Appendix C. Whereas Appendix C used an aggregate of data taken in various parts of the forty-eight conterminous United States, this approach would examine icing on a regional basis. This concept is based on the observation that icing severity and frequency vary greatly by region, and operation largely within certain regions greatly increases the chances for a given aircraft encountering exceedance icing.

Anecdotal evidence has long suggested that a number of regions worldwide may exhibit icing environments more severe than those described by a broad-based, aggregate nominal. Recently, the Canadian Freezing Drizzle

Experiment reported by Cober, et al., in 1995 identified at least one region in which conditions which exceed Appendix C were not difficult to find.¹ As discussed above, Green and Bracken noted a higher concentration of side window icing reports from ATR crewmembers in the north central region of the United States.⁴

The short haul aircraft operates in a limited regional environment. If that particular region tends to exhibit conditions frequently more severe than the aggregate nominal conditions used to characterize a broad icing environment, such as Appendix C, then the resulting severity distribution will present that aircraft with a much higher exposure to the exceedance environment.

Yet it is precisely this higher exposure with which the short haul pilot, operating within one region and often one airmass, must deal in daily operations, and which therefore must be addressed by design, certification and operations policy.

Finally, the parametric data gathered during this work, combined with the resultant icing severity distribution, can be used to develop a graduated parametric icing severity index. The index must refer specifically to the temperature, liquid water content, and droplet size distribution of an icing environment. It must cover the known range of icing severity, making a particular effort to offer a scope capable of describing the exceedance as well as the nominal environment. Presently, the index defined in Paragraph 521 of the AIM suffers the limitations of subjectivity described above, as well as leaving the exceedance environment (defined as "severe icing") more or less open-ended, beyond the descriptive scope of the index.

The development of a graduated parametric index is critical to the success of work to harmonize the industry's approach to inflight icing.

3.2 The Certification Icing Condition

By the absence of a limited set of handling and performance criteria for an iced wing, which would supersede FAR 25, Subpart B, the clear implication is that present certification expects no ice on an aircraft with a normally functioning icing system. This is simply not realistic, and indeed current testing is done with ice shapes representing residual and intercycle ice on protected areas as well as nominal ice on unprotected areas. However, without specific criteria, the suitability of handling and performance in these tests is left to the judgment of the individuals involved. Thus, a major part of

a global solution is to design and certificate the complete, normal operating envelope for dry wing characteristics in a specific portion of the icing severity distribution, treating this portion as the nominal condition. This nominal condition must include a large enough portion of the severity distribution to enable unchanged operations in the majority of icing conditions that can be expected in any region.

Where this proves impractical, the operating envelope must be further limited to one in which dry wing characteristics can be attained in the nominal icing condition. Adjustments to the operating envelope must be implemented either automatically (such as stall warning/avoidance system icing bias) or with minimal implementation required by the flight crew.

Precisely what portion of the severity distribution within which dry wing characteristics can be maintained will largely be a function of the technology used by the ice protection system.

Technologies such as a fully evaporative ice protection system and irreversible flight controls appear, from the incident history, to be very effective in managing a large portion of the icing severity distribution. By its very nature, the fully evaporative system probably comes as close to preserving dry wing characteristics in icing conditions as can be achieved. However, these systems are expensive to manufacture and operate, and are typically found only on larger aircraft, and then only when some other characteristic of the design has more or less precluded the use of less expensive approaches (its pretty hard to design a pneumatic deicing boot that works with a leading edge slat).

Another example of a technology which may greatly help retain dry wing characteristics is the product known as NO-ICE. This thermal mesh is bonded to the skin, possesses no significant thickness, requires very low power density and yet is capable of anti-icing a significant area forward of the flight control surfaces, whether they be ailerons or elevators. NO-ICE appears to represent the kind of cost effective technology that can be used to retain dry wing characteristics across a useful portion of the icing severity distribution.

In the final analysis, it may be possible to certificate different airframes, flight control designs and ice protection systems to the maximum severity that those particular components and configurations are capable of managing. Thus, a large airframe with a fully evaporative anti-ice system

coupled with irreversible flight controls may be certificated for a more severe environment than a small airframe using pneumatic deicing with reversible flight controls. In any case, more capable aircraft should not be restricted from more extreme conditions if their capability can be demonstrated and confirmed in certification. There is also no need to require all aircraft to be able to operate in the maximum conditions and pay the price that such a capability requires. A certification process that recognizes differences in capabilities, yet maintains a minimum capability to ensure normal operations in the vast majority of conditions, would give credit for existing capabilities, encourage additional technologies, and result in operating rules which recognize the specific capabilities of each airframe.

3.3 The Exceedance Icing Condition

The remainder of the severity distribution can then be identified as the exceedance environment. This is the icing environment within which dry wing characteristics cannot be maintained within the minimum practical operating envelope. Consequently, it is an icing environment within which continued flight is not acceptable.

The exceedance environment itself does not necessarily foster an immediate catastrophic event. The threat held within the exceedance environment is the probability of a catastrophic loss of control, either longitudinal or lateral, or a catastrophic loss of performance. Control of exposure to the exceedance condition itself provides the best strategy for avoidance of an event. However, in the absence of an effective predictive detection system, an aircraft will have to enter exceedance conditions to detect them. This fact mandates that, while continued flight in exceedance conditions is not acceptable, limited exposure must be anticipated and considered in design, certification and operation.

The probability of a single event, the catastrophic loss of lateral or longitudinal control, or a catastrophic loss of performance, is minimized primarily through design. The exposure to that event, by operating in the exceedance environment, is primarily minimized through operating procedures.

There are two directions in which one may depart the certification envelope; one is to exceed maximum droplet size, and the other is to exceed the maximum liquid water content.

The continuum of the exceedance environment is not well understood in terms of the effects that it has on an airfoil. For example, a condition characterized by small droplet diameters and high liquid water content will result in accretion very near the stagnation point on the leading edge. If the liquid water content exceeds the design criteria, then an exceedance condition may exist. Since the problem created by high LWC is generally one of accretion rate, this type of exceedance is very much a function of exposure time. The management of this exceedance condition would therefore focus on control of the exposure time.

On the other hand, a condition characterized by large droplet diameters and low liquid water content will result in accretion at some point aft of the stagnation point. The precise percent of chord aft of stagnation is a function of droplet size. The effect of this accretion on handling and performance characteristics is a function of chord location and protrusion into the boundary layer. It may take very little time to accrete just the right size ridge at precisely the right chord location to cause a serious event. Because the problem caused by droplet size exceedance is less a function of ice quantity than it is ice location, it is less a function of time than of droplet size. Thus, the simple management of exposure time would not provide a direct control over this problem.

Nonetheless, exposure time is perhaps the only variable over which the flight crew has direct control. While minimizing exposure time in a Supercooled Large Droplet (SLD) environment may not directly control the critical variable, it does place a statistical control in effect. Obviously, the less time the aircraft operates in the SLD environment, the less probable a catastrophic event becomes. This, combined with the direct control that exposure time has over the threat found in high liquid water content environments, makes exposure time a significant factor in controlling the probability of an event.

The design for operations in the exceedance environment must consider that the probability of a loss of flight control be no greater than that accepted for any other flight control malfunction. This probability is best defined in FAR 25.1309, which describes the requirements for aircraft equipment, systems and installations. 25.1309(b)(1) and 25.1309(b)(2) state:

“(1) The occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable, and

(2) The occurrence of any other failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions is improbable.”

Advisory circular 25.1309-1A defines “improbable” and “extremely improbable” as:

”(2) Improbable failure conditions are those having a probability on the order of 1×10^{-5} or less, but greater than on the order of 1×10^{-9} ,

(3) Extremely Improbable failure conditions are those having a probability on the order of 1×10^{-9} or less.”

If a design critical exceedance environment cannot be defined, then a maximum exposure time must be defined. Within such a maximum exposure time, the probability of a flight control anomaly must be consistent with the standards set forth in 25.1309. This maximum exposure time must also be commensurate with a flight crew detecting and adjusting the flight path in a normal manner to depart from the conditions.

ATR appears to have had some success in this concept with the retrofit of an extended chord deicing boot following the Roselawn accident. The sizing of the protected area on the wing must not be limited to certification (Appendix C) impingement, but rather must be a function of a precise determination of the point on the wing at which ice accretion will adversely affect flight control balance. During the post-Roselawn investigation work, ATR identified a chord position at which ice accretion could sufficiently disturb the flow field to cause aileron hinge moment reversal. This position was slightly aft of the Appendix C impingement limits; by protecting this area, the manufacturer has provided a degree of safety margin beyond the Appendix C conditions. Thus, by removing the cliff at the immediate edge of Appendix C, the manufacturer has reduced the probability of a catastrophic event immediately after encountering exceedance icing conditions.

3.4 The Operating Rules

After the work described in (3.1) through (3.3) above has been completed, we reach a situation where

- i. The icing environment has been characterized

- ii. The frequency distribution of icing severity within this environment has been defined
- iii. The portion of this frequency distribution within which dry wing handling and performance characteristics can be maintained using feasible and cost effective technology has been identified as the nominal condition
- iv. The point on the severity distribution has been identified which has a probability of occurrence corresponding to that accepted for other flight control/lifting capability failures
- v. An exceedance envelope is defined
- vi. This exceedance envelope is investigated for design critical time period in which combinations of parameters produce critical effects on handling and performance.
- vii. The question of whether a design critical, or peak severity, icing condition exists has been resolved

At this point, operating rules can be defined which insure that the assumptions used in design and certification are implemented and maintained. A parallel objective of the operating rules must be to minimize exposure to the exceedance environment.

Such rules must use terminology that is specifically consistent with that used in design and certification. Further, such rules must reference parameters which are objectively identifiable to the flight crew, and must reference operating procedures which are practical for all phases of flight.

3.5 The Operating Tools

In the final analysis, the pilot exists to provide a human interface between the preformatted structure inherent in the engineered product and the dynamic assembly of natural variables presented by the operating environment. Operating rules represent a code by which the human being can effect this interface. The human being, however, cannot provide any type of interface which requires sensitivity and response resolutions which exceed human capabilities.

For example, if the pilot cannot detect a 200 micron water droplet, there is no way he or she can use any operating rule to avoid the 200 micron water droplet.

Thus, it is useless to provide the pilot with operating rules designed to control exposure to a high risk exceedance environment when there is no method of discriminating ambient icing from exceedance icing while operating the aircraft. It is useless to provide such operating rules when no quantified description of the icing severity distribution, and the portion of it which is protected, exists in the operating literature available to the pilot. It is economically senseless to provide such operating rules while at the same time failing to provide a high resolution forecast of icing conditions along the route of flight.

The pilot is a necessary link between the engineered product and the natural operating environment. He or she cannot, however, universally accommodate the failure of the engineering to anticipate statistically significant environments which pose serious risk.

4.0 Implementation

There is an immediate need for change in the way the industry approaches inflight icing. While considerable work must be done in order to best address this problem, flight operations in icing conditions are being conducted routinely today. Thus, two parallel programs must be initiated. One would accomplish the research toward a better characterization of the icing environment as has been described in 3.1 above. This would lead to better definition of the nominal icing environment, a better understanding of the probability of exceeding that nominal condition, and better operating rules designed to control that probability. The other would implement immediate actions designed to 1) control the probability of exposure to conditions which exceed Appendix C today, using existing terminology, and 2) reduce the probability of a loss of flight control function in any icing environment, using existing technologies.

4.1 Development of the "Operationally Realistic" Icing Environment

The program to accomplish this must be conducted and coordinated internationally. It is essential that data from all climates which support icing conditions aloft be included in this investigation. It would be particularly useful to include data from nations which formerly comprised the Soviet Union, as they have extensive operational experience in this type of condition which has yet to be appreciated by the West. The program must have the specific goal of characterizing the most critical icing environment likely to be experienced by commercial aviation. The characterization should be based upon the distribution of severity both measured and calculated.

As a collateral goal, this program should use the collected data and severity distribution to arrive at a useful icing severity index, specifically graduated to describe the complete distribution of severity using standard icing parameters.

4.2 Definition and Implementation of an Interim Nominal Icing Environment

While this paper strongly advocates an original characterization of an operationally realistic icing environment as described above, this is a long term goal. Today, the best data available remains that contained within Appendix C. All contemporary design work has been accomplished relative to this data, and it forms the natural and indeed the only basis for immediate consideration.

Whether it was intended to be or not, it is also a de facto nominal condition. While the definition of severe icing clearly describes an exceedance condition, in which the ice protection equipment cannot cope with the accretion, the definition of moderate icing implies that the use of ice protection equipment is an alternative to flight diversion. Moreover, FAR 25.1419 specifies that the airplane be able to "operate safely" in both sets of Appendix C conditions. Thus, operations in icing up to severe are tolerated and, indeed, routine in terminal areas with high traffic volume.

Two programs must be initiated in order to fully define Appendix C as a nominal condition under FAR Part 25. First, all new designs must be certificated to the relevant standards of Part 25, Subpart B in either natural or artificial icing conditions. Second, existing designs must be evaluated under this same criteria. Where an existing design is found to be unable to comply with any relevant standard of Subpart B, the degradation in handling and/or performance qualities must be clearly described in the Airplane Flight Manual.

4.3 The Control of the Probability of Loss of Control or Lift

As described in section 3, the probability of encountering exceedance conditions is currently accepted as 10^{-3} . These conditions are prerequisite to a catastrophic loss of control or lift. However, beyond the results obtained during the FAA Phase II investigation of 1995, there is little data available to describe handling characteristics in any conditions beyond Appendix C. Even this investigation was arguably ad hoc, a quickly developed "first look" at the environment beyond Appendix C. So it becomes essential to develop operating rules and the tools to comply with them in order to substantially reduce the probability of a

catastrophic event such as that experienced at Roselawn. This is best done by minimizing the exposure of aircraft to conditions which exceed Appendix C.

4.3.1 Operating Definitions and Rules

The authors would like to propose the following changes to definitions and operating rules, which we believe would have an immediate effect on the probability of encountering, or at the very least continuing to operate, in exceedance conditions:

1. **The AIM paragraph 521 definition of severe ice be changed to read:**

“Severe - The rate of accumulation is such that the deicing/anti-icing equipment fails to reduce or control the hazard, or the accretion is occurring aft of the protected surfaces. Immediate flight diversion is necessary.”

2. **The language of FAR 91.527(c) and 135.227(d) be altered and amended as follows:**

“Except for an airplane that has ice protection provisions that meet Section 34 of Appendix A, or those for transport category airplane type certification, no pilot may fly an aircraft into ~~known or~~ forecast severe icing conditions. No pilot may continue to fly an aircraft into severe icing conditions once the pilot has observed those conditions.”

3. **All Airplane Flight Manuals be revised, in section 2, “Kinds of Operation”, to include the following or similar language when approval for operations in icing conditions has been granted:**

“Flight in icing conditions as defined by FAR 25 Appendix C”

4. **All Airplane Flight Manuals be revised to include, in section 2, Limitations, the following language:**

“Warning: Flight in observed or reported freezing drizzle or freezing rain is not approved”.

5. **FAR 121.629 be amended to include language already used in the JAR-OPS. It should read,**

“No person may dispatch or release an aircraft, continue to operate an aircraft enroute, or land an aircraft under known or expected icing conditions unless the airplane is certificated and equipped to cope with such conditions or when, in the opinion of the pilot in command or aircraft dispatcher (domestic and flag carriers only) icing conditions are expected or met that might adversely affect the safety of flight.”

6. **A revised FSAT regarding ground deicing programs be issued, which is consistent with the language in (4) above, and which deletes all description of operations in freezing precipitation as an elective.**

The FAA has recently endeavored to begin this process by issuing several Airworthiness Directives which finally and clearly indicate the limits of icing certification. Thus, the “kinds of operation” approval in the AFMs of these aircraft now indicate that operation in freezing drizzle or freezing rain is not approved.

These ADs were limited to specific turboprop aircraft. If we evaluate the respective abilities to manage the ambient icing described by Appendix C, and to provide a stable margin of exceedance beyond Appendix C, it is intuitive that turboprop aircraft are less capable than turbojets. However, no aircraft should operate in an icing condition which exceeds that for which it has specifically been certificated. Thus, no aircraft should presently be intentionally operated in freezing rain or freezing drizzle, or in any icing condition which exceeds Appendix C. It follows that one operating rule which would eliminate some encounters with the exceedance environment would be to rescind the de facto approval of operations in freezing rain and freezing drizzle put forth by FSAT 95-29.

Finally, the FAA should take extensive action, as part of this immediate program, which discourages or even prohibits airborne holding while actively accreting ice, unless the aircraft is equipped with an approved method of detecting the exceedance environment. The very definition of maximum continuous icing contained within Appendix C indicates that icing is typically a localized event; thus the 17.4 nautical mile horizontal extent. It is known that as horizontal extent increases, sustained high values of liquid water content become less and less probable. Airborne holding, which sets up extended flight within a short horizontal extent, is the perfect way to exponentially increase the exposure to an exceedance condition. Discouragement and/or prohibition of such holding, perhaps in conjunction with a return to a ground stop program while

icing conditions prevail, could not help but impact the probability of exposure to exceedance conditions.

4.3.2 Operating Tools: Reactive Detection Systems

However, ALPA argued in its comments on the respective NPRMs that the FAA was essentially implementing a rule as described in paragraph 3.5 above, without including the tools described in paragraph 3.6 as essential to the pilot's ability to comply.

Thus we arrive at the single most important step which may be accomplished today in order to control exceedance encounters: the requirement for certificated equipment or techniques which identify the edge of Appendix C. No pilot can take any action in order to avoid the exceedance environment if he or she cannot distinguish that environment while in flight, short of the suspension of operations during all icing conditions.

There are ample technologies available: aerodynamic monitoring, pulse-echo ice detection located aft of the Appendix C impingement limits, vibrating diaphragm ice detection similarly located, or, at the very least, a visual cue such as that presently provided by ATR.

The Roselawn accident demonstrated a number of significant factors. Foremost among these is that very little ice accretion is necessary to generate a catastrophic handling event. Data gathered from the Roselawn accident DFDR indicates no appreciable drag rise, thus no airspeed decay or requirement for additional power. There is no reason to believe that the aircraft must be or will be laden with ice before such an event occurs.

Furthermore, in cases where by design, such as a high wing arrangement, or by lack of visibility, such as night or IMC conditions, there is no reason to believe that the flight crew is capable of high resolution visual discrimination of ice accretion patterns on the wing. There may be no traditional warning of an impending handling event whatsoever. Yet today, with the exception of the ATR, no aircraft exists which is equipped with any flight tested techniques for the identification of the SLD subset of exceedance conditions.

Thus, a phased program must be initiated which will lead to certificated equipment or techniques which identify the edge of Appendix C becoming mandatory in order to either obtain or maintain icing certification. This technology, which can be referred to as reactive ice detection, is not at all beyond reach. It must be considered a prerequisite for icing operations. Until such time

as this program is complete, the pilot's judgment while operating in icing conditions is essentially removed from any program designed to control the probability of exposure to exceedance conditions.

4.3.3 Industry Coordinated Training Aid

The absence of a unified, consistent approach to the problem of in flight icing has predictably led to the absence of consistent pilot training on the subject. Airline training programs typically offer little training in meteorological or aerodynamic factors, preferring to focus on operating policy and airplane specific procedures. The result is that many pilots have widely varied but frequently inaccurate ideas about icing. There has been little effort to correct this, and the failure to communicate knowledge regarding everything from the limits of certification to common weather systems associated with icing continues unabated.

A special effort should be made to develop training syllabi and material which are accurate and complete. This type of package, which has already been developed by Boeing with regard to rejected takeoffs and is being developed by the Flight Safety Foundation with regard to Controlled Flight Into Terrain accidents, could be made available to operators seeking to improve their flight crew's understanding of the problem of inflight icing and how they can manage it with existing tools. This program, if developed cooperatively within the industry, could be of immeasurable use to flight crews attempting to cope with both an inadequate regulatory system and a very unpredictable weather phenomena. Training is not a substitute for a global approach to resolving the icing problem; yet, in the short term, it would be very effective in reducing the probability of another accident.

5.0 Conclusion

Today, the system in use for the management of inflight icing is nothing less than an ambiguous afterthought which strongly implies the industry's discomfort in addressing a problem that does not neatly and predictably interface with the pre-formatted structures of an engineered product. This system led directly to the accident at Roselawn, Indiana and indeed may be implicated in numerous other accidents as well. It must be changed.

The principal focus of this change must be to control the probability of a catastrophic loss of control or lift. This probability must be no greater than that accepted for loss of control or lift due to either system or structural failure. Reduction of this probability is best accomplished by reducing exposure to the

exceedance environment, and designing for nominal flight control function in all icing environments.

A second but no less integral focus is the assurance of dry wing handling and performance characteristics within the nominal icing environment.

The need for immediate change, coupled with the need for considerable original research, requires a program featuring two parallel elements. One is the characterization of an operationally realistic icing environment, which then leads to design, equipment, and operating rule development which meets the goals described above. The other element is the interim development of certification protocols and operating rules based on the existing icing environment characterization, Appendix C, which meets these goals to the extent possible with today's knowledge.

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Presentation by:

WALTER S. COLEMAN REGIONAL AIRLINE ASSOCIATION

The Regional Airline Association is grateful to be represented at the International Conference on Aircraft Inflight Icing. I am also very pleased to note that the regional airlines have several representatives participating in this conference.

RAA and its member airlines recognize the value of identifying a single topic and assembling knowledgeable and industrious individuals to address and resolve the task at hand. This is not a new issue. Inflight icing has been an issue from the time that flight was attempted into visible moisture. The existence of this conference acknowledges that there is more we can achieve in addressing the phenomena of inflight icing. What is more important is that this conference also indicates that we believe that we have the potential for refining our understanding and applying new tools to achieve our safety and efficiency objectives.

This forum also has the potential to follow in the successful footsteps of other similar industry efforts which addressed specific aviation issues. Some of the finest work that has been accomplished in achieving improvements in aviation safety and efficiency has come from the collective efforts of numerous organizations and individuals who have an intense interest in improving aviation. There are several examples which stand out. Some of those are:

- i. *The Joint Government Industry Task Force on Flight Crew Performance.* There were several products from that effort, one of which was the Advanced Qualification Program.
- ii. *The Windshear Training Aid.* This was begun by Boeing, supported by many, and has been extraordinarily successful both in reducing accidents and even encounters with the windshear phenomena.
- iii. *The Ground Deicing Conference.* One of the largest gatherings in the United States on a single operational and safety issue.

- iv. Others include study and training materials resulting from the application of collective resources addressing Rejected Takeoffs, Wake Turbulence and Controlled Flight Into Terrain.

That list is extraordinary for several reasons. The results represent the collective efforts of a wide array of organizations. The conclusions were driven by consensus. And, most important, they succeeded in their objective. We seek the same in this effort.

I would like to examine the issue we have before us for the next few days. Airlines and other aviation organizations have, as a characteristic of their operations, an expectation that their aircraft will depart at a pre-determined time and safely fly a pre-determined and efficient route. One of the benefits that could come from this conference would be the acquisition of tools for the accurate identification of the location and intensity of inflight icing so that go/no-go and routing decisions can be made.

This may be one of the most important issues we address here if we make the following presumptions: The existence of the weather phenomena that cause inflight icing will always be present. There will continue to be an expectation from the traveling and shipping public that scheduled air carriers will operate on the published schedule. And, there will be a concurrent expectation from the traveling and shipping public, from the air crews, from FAA and from certificate holders that the operations will be safe and not be exposed to known dangers. What is the answer to this? The answer is to accurately locate severe icing and avoid it.

This identify-and-avoid strategy is not intended to ignore other aspects of this conference, including the FAA icing certification requirements. Regardless, however, of possible changes to the certification standards, if the information available indicates severe icing, avoiding that encounter, no matter what certification criteria have been applied, would remain the prudent course of action

Advice to airmen on avoiding icing conditions and what action to take if icing conditions are encountered is and has been a part of every airline's training program. As you know, last Thursday the FAA issued airworthiness directives (AD) addressing this issue. The AD provides language for inclusion in the *Airplane Flight Manual* on actions the aircrew is to take if severe icing is encountered. It is the view of many operators and airframe manufacturers that this was a very curious use of an airworthiness directive.

In examining the language in the ADs, there are two elements of this FAA action which are perplexing. One is the use of an AD as the vehicle rather than adding or reinforcing a training requirement. The other is why, when reading the advice carefully, FAA did not elect to apply the information and the requirement to all airmen, including amending the *Airman's Information Manual*. Perhaps this group would find it beneficial to endorse wider dissemination of the guidance issued last week.

What is our objective here this week? I am confident that the participants will carry out the charge that has been presented and examine the several aspects of crew training, certification, weather products, and flight management.

I would like to propose that, for those in the business of providing safe and reliable scheduled service, perhaps the most beneficial result would be to increase our understanding of the inflight icing phenomena, identify new tools for accurately locating where inflight icing could affect our flight operations, and deliver that information to aircrews, dispatch offices, and ATC facilities to enhance the basis for decision making.

Introduction to Working Group Reports

At the closing plenary session on the afternoon of May 8, co-chairs gave reports on behalf of each working group. These reports highlighted the recommendations which had achieved a consensus (or, if a vote was necessary, a majority) within the working groups. Recommendations called for some action, usually by the FAA, but sometimes by industry, the research community, the international community, or some combination of the above. If a proposition discussed in a working group achieved a consensus, but did not explicitly call for specific action, it was referred to as a consensus item. (The line between recommendations and other consensus items was not always sharp.) Finally, if there was a significant amount of time devoted to discussion of an issue, but no consensus emerged, it was listed as a non-consensus item.

The recommendations, other consensus items, and non-consensus items are listed near the beginning of the working group reports without explanation or comment so that the entire list can be quickly read or scanned. However, for some recommendations or items, the working group co-chairs have provided additional explanation as to their meaning or significance, the amount of attention they received, or how strong a consensus they enjoyed. Thus, a background section follows the lists of recommendations and items for each working group. For four of the five working groups, the format is simply to repeat selected recommendations or items followed by explanatory text. The Working Group on Icing Environmental Characterization addressed a number of technical issues not widely familiar within the industry; therefore, more extended background material was provided by the co-chairs of this working group.

The formal papers presented within each working group may be found in Volume II of the conference proceedings.

Working Group on Ice Protection and Ice Detection

CO-CHAIRS:

DAVID SWEET, BF GOODRICH AEROSPACE

CHARLES MASTERS, FAA - WILLIAM J. HUGHES

TECHNICAL CENTER

The Ice Protection and Ice Detection working group objectives were to examine:

- 1) Determination of ice protection systems appropriate to specified aircraft characteristics and icing environment.
- 2) Detection of icing conditions.
- 3) Use of specially located/designed ice detectors or of aircraft-specific "cues" to recognize Supercooled Large Droplets and other inflight icing conditions.

The sessions were well attended, with an average group size of 80-90 attendees.

The working group's recommendations, other consensus items and non-consensus items follow. In the background section, the co-chairs provide an explanation in italics in all but two instances.

RECOMMENDATIONS

- 1) Characterize Supercooled Large Droplet (SLD) icing environment.
- 2) Accelerate development of technologies which remotely assess icing conditions (airborne, ground based, space based).
- 3) Improve the air transportation system to decrease the probability of a catastrophic icing event.

- 4) Establish cooperative research efforts and methodologies to define aircraft critical ice accretion characteristics.
- 5) Establish cooperative research efforts to characterize Part 25 Appendix C exceedance environment (includes SLD).
- 6) Promote the use of ice detection systems to provide icing information about critical surfaces. Visual cues, if adequate, should be considered as a solution.
- 7) It is essential that an icing environment severity index be developed as a generic scale.
- 8) Coordinate research activities internationally.
- 9) Aircraft manufacturers and users should investigate the feasibility/cost/operational benefits of installing a combination of ice detection, supplemental ice protection, and operational procedures for protection to safely exit from uncertified type icing conditions for their aircraft.

CONSENSUS ITEMS

- 1) There needs to be an international definition of SLD conditions.
- 2) Flight crews need to be notified when critical areas of their aircraft are abnormally* accreting ice.

*Icing severity index for exceedance.
- 3) The aircraft manufacturer or modifier needs to define aircraft specific critical areas for SLD.
- 4) Research needs to be carried out to determine realistic limits for exceedance to Part 25 Appendix C for all forms of precipitation.
- 5) Critical ice formations need to be defined which consider the effects of ice protection systems through a cooperative research effort.

- 6) Candidate technologies exist to directly and indirectly (aerodynamic performance monitors) sense in-situ ice accretions, including SLD accretions, as currently characterized.
- 7) Candidate ice protection technologies exist which can remove SLD ice accretions as characterized today.
- 8) Encourage development of cost-effective helicopter ice protection technology.

NON-CONSENSUS ITEMS

- 1) Ice detection systems should be REQUIRED on all aircraft certified to Appendix C.
- 2) Flight crews need to be notified when they are operating in conditions for which their aircraft are not protected in critical areas.
- 3) Wide-area ice detection is preferred over spot sensor in near freezing conditions.
- 4) It is essential that an icing environmental severity index be developed as a generic scale. Aircraft/helicopters could be certified to meet certain levels* on this scale dependent on aircraft type and its on-board devices.

*See recommendation #7 for severity index.

BACKGROUND ON RECOMMENDATIONS

- 1) Characterize the SLD icing environment.

This recommendation addresses the need to sufficiently characterize the SLD environment for design and evaluation of ice protection systems.

- 2) Accelerate development of technologies which remotely assess icing conditions (airborne, ground based, space based).

This recommendation focuses on the need to sense, from a distance, inflight icing conditions such that the aircraft could maneuver to avoid these conditions. This would be especially true for those aircraft with minimal or no ice protection and for all aircraft in SLD conditions. This approach is analogous to that of the "storm scope" currently installed on many aircraft to identify thunderstorm conditions so that they can be avoided. This recommendation was enthusiastically supported by all; however, it was realized that possible technological advancements may be needed to achieve the requisite results. Although an aircraft mounted sensing system was the focus of the discussion, uplinking of data to flight crews from ground based systems such as the NEXRAD Weather Radar with special SLD detection/processing algorithms or from satellites was not ruled out. The U.S. Army Cold Regions Research Engineering Laboratories (CRREL) is pursuing the development of such technologies through a Small Business Innovative Research (SBIR) announcement.

- 3) Improve the Air Transportation System to Decrease the Probability of a Catastrophic Icing Event.

The purpose of this recommendation is to improve the overall reliability of the air transportation system such that a catastrophic icing event becomes extremely rare. Factors to be considered include weather forecasting, dispatch criteria, air traffic control when icing is present or forecast, in-situ ice sensing, ice protection equipment, operational procedures, pilot (crew) training, FAA inspection and oversight, etc. It is envisioned as a reliability study of the entire system such that factors requiring improvement can be readily identified and addressed.

- 4) Establish cooperative research efforts and methodologies to define aircraft critical ice accretion characteristics.

Current methodologies to define ice accretions in terms of their effects on aircraft performance (C_L , C_D , pitching moments, and handling qualities) vary. Ice accretion codes have not been validated for various icing conditions, including SLD. However, the effects of critical ice accretions on airfoils are wide ranging.

Standardized critical areas for protection require that critical ice shapes be defined in terms of size, roughness, shape, and location on the critical areas of the aircraft/airfoil. The working group viewed this as a government/industry effort employing national laboratories, academia, aircraft manufacturers, and regulatory authorities, both domestic and foreign.

- 5) Establish cooperative research efforts to characterize Part 25 Appendix C exceedance environment (includes SLD).

This recommendation calls for the establishment of cooperative R&D efforts on an international basis to characterize those icing conditions outside of FAR 25 (27,29), Appendix C envelopes. This included mixed conditions, ice pellets, freezing ground fog, SLD (freezing rain and drizzle), ice crystals, and supercooled cloud conditions (LWC, MVD, altitude, horizontal extent, temperature) that exceed the Appendix C envelopes. This effort should also focus on inflight icing near 0°C ($\pm 2^\circ\text{C}$) within the Appendix C envelopes.

- 6) Promote the use of ice detection systems to provide icing information about critical surfaces. Visual cues, if adequate, should be considered as a solution.

There was much discussion about the need to sense ice accretions on critical airfoil surfaces which may be out of view of the flight crew. These can include the horizontal stabilizer and upper surface of the wing (especially on high wing aircraft). In-situ ice detectors were deemed appropriate for sensing these ice accretions. However, in some cases, critical SLD accretions are indirectly indicated by the buildup on other surfaces such as side windows and spinner domes. It was proposed that such cues be given consideration as a means of detecting SLD accretions.

- 7) It is essential that an icing environment severity index be developed as a generic scale.

The working group felt very strongly that all icing conditions were not equal and that certain aircraft had greater capabilities to withstand icing conditions than others, although they may all be certified for flight into known (Appendix C) icing conditions.

The group felt that due to emerging technological advances in weather sensing and forecasting, information on different levels of icing severity would soon be available to the pilot. Also, the aircraft could be equipped with some type of ice accretion rate/severity measuring sensor (electronic or manual). Thus, aircraft could be certified to different levels of icing severity, and operation in known conditions which exceed the certification level could be avoided or quickly exited. The question of what to do with aircraft currently certified to FAR 25, Appendix C was raised. One answer (not unanimous) was that the Appendix C conditions could be designated as a middle or upper range icing severity level. Aircraft certified for higher levels of severity would have to show compliance for these higher levels. This recommendation is in consonance with recommendation 5, which addressed definition of the FAR 25 Appendix C exceedance environment.

8) **Coordinate research activities internationally.**

Ongoing R&D activities in many areas to ensure safe aircraft operations in or exiting of SLD conditions need to be coordinated internationally to preclude duplication of efforts and ensure maximum return for resources. It was pointed out that some countries may have advanced capabilities in certain areas. To avoid a duplication of effort, cooperative international efforts (especially for government laboratories) should be encouraged. Several countries are independently developing ice accretion codes (it is realized that some of the code development work is supported by industry and may be proprietary; however, joint cooperative activities should be coordinated where possible), and some countries may have significantly more data on SLD conditions than others.

9) **Aircraft manufacturers and users should investigate the feasibility/cost/operational benefits of installing a combination of ice detection, supplemental ice protection, and operational procedures for protection to safely exit from uncertified type icing conditions for their aircraft.**

This generic recommendation calls for the conduct of a feasibility/cost/benefit analysis by the aircraft manufacturers in

conjunction with their customers to determine if it is practical to provide their aircraft with ice detection and limited protection capabilities such that the aircraft could safely exit from all inadvertent encounters with icing conditions outside the Appendix C envelopes. Operational procedures to accomplish this exit would also be addressed. From the discussions, it was not clear who or how this feasibility/cost/benefit analysis would be initiated.

BACKGROUND ON CONSENSUS ITEMS

- 1) There needs to be an international definition of SLD conditions.

This consensus item repeats recommendation number 1 but stresses that there should be an internationally agreed to characterization of SLD conditions.

- 2) Flight crews need to be notified when critical areas of their aircraft are abnormally accreting ice.

This addresses the need to warn the pilot that he is operating in conditions which exceed the icing conditions or icing severity index to which his aircraft was certified. This consensus item is in consonance with recommendation 7 which addresses a need for an icing severity index.

- 3) Research needs to be carried out to determine realistic limits for exceedance to Part 25 Appendix C for all forms of precipitation.

Current exceedance limits for a combination of all variables that constitute the FAR 25 Appendix C envelopes are selected at the 99.9 percent level. Are these limits practicable for other forms of precipitation or should they be at some higher level?

- 4) Critical ice formations need to be defined which consider the effects of ice protection systems through a cooperative research effort.

What are the conditions that must be considered for residual ice resulting from activation of ice protection systems and equipment? What levels of ice ridges behind boots are allowable

without unacceptable degradation in control effectiveness or other aerodynamic performance? What level of ice (ice roughness) is allowable in key lift producing areas of the airfoils following the activation of ice protection equipment?

- 5) Candidate technologies exist to directly and indirectly (aerodynamic performance monitors) sense in-situ ice accretions, including SLD accretions, as currently characterized.

Current sensors employing a variety of technologies (mechanical vibratory, impedance change, ultrasonic/w UHF characteristic impedance monitoring, optical, etc.) and aerodynamic performance monitors were deemed to have the capability to sense SLD conditions as it was defined for the screening of turbopropeller aircraft for SLD icing, i.e., MVD of 170 microns, LWC of .82 g/m³, and duration of 60 nm. Additional R&D to develop sensors to detect SLD was not deemed essential.

- 6) Candidate ice protection technologies exist which can remove SLD ice accretions as characterized today.

Current ice protection technologies have the potential (exists) that can protect against SLD conditions (as currently defined). These include pneumatic boot ice protection systems with extended coverage (chord wise) and electrothermal heater blankets. Also, low adhesion surfaces have been shown to enhance performance of primary ice protection systems against SLD conditions.

- 7) Encourage development of cost-effective helicopter ice protection technology.

The working group was reminded that at this time certification of helicopters for flight in icing conditions suffers primarily due to the lack of a cost effective ice protection system. For over a decade, the only helicopter certified for flight in known icing condition has been the Aerospatiale Super Puma helicopter, although there have been several starts of icing certification efforts by several rotorcraft manufacturers. It was stressed that the key to overcoming this limitation was the development of a cost-effective helicopter ice protection system, and the helicopter

should not be forgotten in the endeavors by the aviation industry to accommodate the SLD problem.

BACKGROUND ON NON-CONSENSUS ITEMS

- 1) Ice detection systems should be **REQUIRED** on all aircraft certified to Appendix C.

There was much discussion on this topic, both pro and con. It was resolved with a vote in which the majority opposed making this equipment a requirement. The primary argument against requiring ice detectors was that most pilots know when they are in icing conditions, based upon cues unique to their specific aircraft. The primary argument in favor of requiring ice detectors was that the pilot may be busy with other activities and require a "heads-up" reminder.

- 2) Flight crews need to be notified when they are operating in conditions for which their aircraft are not protected in critical areas.

At the present time, exact methods of detection of all conditions outside of Appendix C have not been developed. However, future sensor developments (airborne, ground based, and WX satellite) may fill this void. If so, this requirement could be revisited at that time.

- 3) Wide-area ice detection is preferred over spot sensor in near freezing conditions.

Several members of the working group indicated that due to runback, sliding, and non-uniformity of ice accretions in near freezing conditions, large area sensors to cover most of the upper wing surface areas were preferred over spot sensors.

Working Group on Requirements for and Means of Compliance in Icing Conditions (Including Icing Simulation Methods)

CO-CHAIRS:

THOMAS BOND, NASA LEWIS

ERIC PARELON, JAA (DGAC-F/CEV)

JOHN DOW, SR., FAA AIRCRAFT

CERTIFICATION SERVICE

The working group objectives were to examine:

- (1) The applicability, limitations, and validation of icing simulation techniques, including icing and wind tunnel, icing tankers, analytical codes, and flight with artificial ice shapes.
- (2) The icing effects on aircraft aerodynamics, performance, and stability and control.
- (3) Compliance with certification standards or aircraft "safe exit capability" requirements by means of flight in measured natural icing conditions and the use of icing simulation methodologies.

The sessions were well attended with an average group size of 130-140 attendees.

The working group's recommendations and non-consensus items follow. (There were no consensus items apart from the recommendations for this working group.) Recommendations and other items with an asterisk are repeated with an explanation in italics by the co-chairs in the background section which follows.

RECOMMENDATIONS

- 1) Create an ad-hoc working group to identify validation requirements as guidance material for computer codes, icing tankers, and icing tunnels

in the harmonization activities. Develop and publish guidance material, including limitations for validating prediction tools/simulation facilities, through a coordinated effort between research/industry/regulatory authorities.

- 2) Set up a steering committee for coordination of in-flight icing activities, including recommendations from this conference.
- 3) Industry recommends that future harmonized rules provide sufficient details and guidance to allow consistent certification practices (some areas of NPA 219 are currently subject to interpretation):

The following topics should be addressed accurately:

- ◇ Critical ice shape assessment.
 - ◇ Validation of simulation tools.
 - ◇ Flight test techniques.
 - ◇ Instrumentation issues.
- 4) Recommend standard terminology and definitions for icing conditions. Harmonize language between operational and certification areas, for example, the severity level of icing conditions.
 - 5) Require in certification a means to detect icing conditions that exceed the 14 CFR part 25 Appendix C icing envelope and require appropriate Airplane Flight Manual /Airplane Operating Manual information, including exit procedures.
 - 6) Require handling and performance adequate for recognition of and exit from the exceedance envelope.
 - 7) Recommend that the FAA not make compliance with FAR 25.1419 mandatory because some manufacturers postpone icing certification until after type certification due to seasonal constraints for natural icing testing.
 - 8) Prior to considering the expansion of Appendix C:
 - ◇ Characterize the Supercooled Large Droplet (SLD) environment.
 - ◇ Provide a means to detect SLD.
 - ◇ Use uplinking/nowcasting for weather updating.

- ◇ ATC take an active role in transmission and dissemination of SLD weather information.
 - ◇ International research community develop validated SLD computational capability and accurate prediction tools/simulation facilities for near-freezing temperatures. Make international comparison between all improved codes.
 - ◇ Provide educational/training information on SLD to support safe operations.
 - ◇ Add appropriate language to Airplane Flight Manual/Airplane Operating Manual.
- 9) FAA/Industry should review data from the FAA Phase II icing tests to determine if there are significant correlations which can be shared for future use and to identify realistic ice shapes due to SLD. Look at parameters such as airfoils, pressure distribution, aileron design, etc. Manufacturers indicated a willingness to contribute data.
 - 10) Long-Term Activity - Recommend review of the design philosophy of automatic autopilot disconnection (e.g., is it acceptable to have the autopilot disconnect based on external disturbances?).
 - 11) Recommend Appendix C be reevaluated, modernized, and made more user friendly; no change to the icing environment defined by Appendix C is required. (See the work of Dr. Richard Jeck, FAA Technical Center.)
 - 12) Harmonize Part 23.1419 and Part 25.1419 (except for the 61 knot stall speed requirement).
 - 13) Recommend the development of reliable ice detectors that indicate the icing severity.
 - 14) Recommend development of predictive sensing of icing conditions.
 - 15) Provide a publicly available icing tanker.
 - 16) Recommend FAA accept principle of certification to less than full envelope such that with adequate detection systems rotorcraft manufacturers can certify to that icing envelope.
 - 17) Develop and validate propeller icing performance code.

NON-CONSENSUS ITEMS

(Items with an asterisk are repeated at the end of this section with explanatory text.)

- 1) If tests are needed to show adequate handling qualities, recommend use of SLD ice shapes replicated from tanker or icing tunnel tests in short-term (code outputs currently in question).
- 2) Recommend a common definition of when the airframe anti-ice systems must be activated.
- 3) Require essentially unchanged controllability and performance in Appendix C environment.
- 4) Consider Part 33, 35 for exceedance icing conditions.
- 5) All aircraft should meet the same requirements; recommend ADs similar to the recently issued icing ADs also be issued for all airplanes.
- 6) Recommend ADs not be issued on large jet transports because of the absence of adverse service history.
- 7) Address SLD issues with a priority on airplanes with unpowered flight controls that were not covered by Phase II.
- 8) Recommend that the NASA Lewis Icing Research Tunnel (IRT) be able to simulate the entire Appendix C envelope, including low liquid water content.

BACKGROUND ON SELECTED RECOMMENDATIONS

The above recommendations identified with an asterisk are repeated here with explanatory text.

- 1) Create an ad-hoc working group to identify validation requirements as guidance material for computer codes, icing tankers, and icing tunnels in the harmonization activities. Develop and publish guidance material, including limitations for validating prediction

tools/simulation facilities, through a coordinated effort between research/industry/regulatory authorities.

The limits of reliability for computer codes, icing tankers, and icing tunnels have not been addressed in a harmonized and definitive manner. This recommendation, if adopted, would ultimately provide guidance to establish appropriate procedures so that the limitations of analytical tools and ice simulation facilities would be identified.

- 2) Set up a steering committee for coordination of in-flight icing activities, including recommendations from this conference.

This recommendation is intended to ensure that the various groups working on icing issues are aware of the different groups' activities and communicate with each other.

- 3) Recommend standard terminology and definitions for icing conditions. Harmonize language between operational and certification areas, for example, the severity level of icing conditions.

One example often cited is the confusion between the Aeronautical Information Manual (AIM) and Title 14 Code of Federal Regulations (CFR) part 91. The AIM defines icing levels of trace, light, moderate, or severe. Severe icing is defined as:

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

Thus, severe is defined in terms of the capability of the ice protection system as related to a specific icing environment. Title 14 CFR part 91.527(c) which only applies to large and turbojet-powered multiengine airplanes which are not covered by parts 121, 125, 129, 135, and 137 states:

"Except for an airplane that has ice protection provisions that meet the requirements in Section 34 of Special Federal Aviation Regulation No. 23, or those for transport category airplane type certification, no pilot may fly an airplane into known or forecast severe icing conditions."

This recommendation, if adopted, would ultimately clarify the apparent paradox which suggests that part 91 allows flight into icing conditions more severe than the airplane ice protection system is able to control for certain airplanes.

- 4) Require in certification a means to detect icing conditions that exceed CFR Part 25 Appendix C icing envelope and require appropriate Airplane Flight Manual/Airplane Operating Manual, including exit procedures.

The icing conditions defined in Appendix C include a maximum continuous condition and an intermittent maximum condition. The icing conditions are defined by parameters of mean effective diameter (approximately equivalent to median volumetric diameter), temperature, liquid water content, and horizontal extent. These conditions are representative of nearly all icing conditions likely to be encountered. However, there are occasions when icing clouds can be encountered which will exceed one or more of the icing certification parameters. Pilots are not able to readily identify when one or more of the parameters of the icing condition exceeds either the Appendix C icing envelope or the capability of the ice protection system and may remain in the condition until the airplane suffers noticeable degradation in performance or handling characteristics. This recommendation, if adopted, would ultimately provide some means for the pilot to know when a condition exceeding key parameters of Appendix C exists so that immediate action can be taken.

- 6) Require handling and performance adequate for recognition of and exit from the exceedance envelope.

Presently the handling requirements for part 25, Appendix C conditions, are under study by an Aviation Rulemaking Advisory Committee (ARAC).

Part 23 handling requirements are addressed in §23.1419. Neither part 23 nor part 25 address handling characteristics outside certification conditions. This recommendation, if adopted, would ultimately result in the generation of minimum standards for performance and handling characteristics for icing conditions outside of the current Appendix C icing envelope.

- 7) Recommend that the FAA not make compliance with FAR 25.1419 mandatory because some manufacturers postpone icing certification until after type certification due to seasonal constraints for natural icing testing.

and 25.1419 currently allow certification of an airplane without ice protection provisions.

- 8) Prior to considering the expansion of Appendix C:
- ◇ Characterize the Supercooled Large Droplet (SLD) environment.
 - ◇ Provide a means to detect SLD.
 - ◇ SLD environment treated like flight into thunderstorms; avoid if possible, if encountered.
 - ◇ Develop improved meteorological prediction capabilities.
 - ◇ Use uplinking/nowcasting for weather updating.
 - ◇ ATC take an active role in transmission and dissemination of SLD weather information.
 - ◇ International research community develop validated SLD computational capability and accurate prediction tools/simulation facilities for near-freezing temperatures. Make international comparison between all improved codes.
 - ◇ Provide educational/training information on SLD to support safe operations.
 - ◇ Add appropriate language to Airplane Flight Manual/Airplane Operating Manual.

This recommendation specifically addresses expansion of Appendix C. However, it is understood to apply to the extension of the icing certification envelope in any format whether it is a change to Appendix C as it is currently defined or the addition of a supplemental appendix, i.e, appendix "x."

- 9) FAA/Industry should review data from the FAA Phase II icing tests to determine if there are significant correlations which can be shared for future use and to identify realistic ice shapes due to SLD. Look at parameters such as airfoils, pressure distribution, aileron design, etc. Manufacturers indicated a willingness to contribute data.

During Phase II, manufacturers generally used a 1 inch high, ¼ round shape to screen airplanes. Four manufacturers used the United States Airforce (USAF) Icing Tanker to obtain

representative ice shapes. Additionally, there have been flights in measured natural freezing drizzle conditions using an instrumented research airplane. All of these may be evaluated to determine if correlations can be made.

- 11) Recommend Appendix C be reevaluated, modernized, and made more user friendly; no change to the icing environment defined by Appendix C is required. (See the work of Dr. Richard Jeck, FAA Technical Center.)

Alternate formats for the presentation of Appendix C have been proposed and may provide an easy method for determining when a flight test point satisfies the Appendix C conditions.

- 12) Harmonize Part 23.1419 and Part 25.1419 (except for the 61 knot stall speed requirement).

Presently part 23 has defined performance and handling characteristics from Subpart B as a requirement for certification for flight in icing conditions. Part 25 has no such requirement at this time but is being studied by ARAC. This recommendation, if adopted, would lead toward uniformity between the parts.

- 14) Recommend development of predictive sensing of icing conditions.

The FAA has adopted a policy of allowing inadvertent exposure to SLD icing conditions to the point where ice accretion can be observed before the pilot takes steps to exit the condition. Predictive sensing of icing conditions would provide the pilot with identification of an icing environment before the airplane is exposed to the condition.

- 15) Provide a publicly available icing tanker.

The USAF Icing Tanker used for the simulated SLD testing of 4 airplane types was retired on April 31, 1996. There currently is no other means to test entire aircraft in a simulated freezing drizzle environment.

- 16) Recommend FAA accept principle of certification to less than full envelope such that with adequate detection systems rotorcraft manufacturers can certify to that icing envelope.

Some parts of the icing envelope are difficult for rotorcraft to show compliance. This recommendation, if adopted, would ultimately result in rotorcraft being certificated to less than full Appendix C conditions provided that a reliable means of detecting the ice environments so that the pilot would know that he has exceeded the icing envelope.

BACKGROUND ON SELECTED NON-CONSENSUS ITEMS

The above non-consensus items identified with an asterisk are repeated here with explanatory text.

- 2) Recommend a common definition of when the airframe anti-ice systems must be activated.

This recommendation was felt to be impractical for all airplanes due to unique configuration dependent characteristics.

- 3) Require essentially unchanged controllability and performance in Appendix C environment.

Manufacturers felt this requirement was not practical.

- 4) Consider Part 33, 35 for exceedance icing conditions.

If airframes are to be subjected to exceedance conditions, then the regulations covering engines and propellers should similarly be addressed.

- 8) Recommend that the NASA Lewis Icing Research Tunnel (IRT) be able to simulate the entire Appendix C envelope, including low liquid water content.

Presently, the NASA Lewis Icing Research Tunnel is not capable of replicating some parts of the Appendix C icing envelope due to technical reasons.

Working Group on Icing Environmental Characterization

CO-CHAIRS:

GEORGE ISAAC, AES (CANADA)

RICHARD JECK, FAA, WILLIAM J. HUGHES

TECHNICAL CENTER

The working group objectives were:

- 1) Survey current knowledge of atmospheric icing environments, especially for supercooled large droplets (SLD).
- 2) Survey the status of instrumentation for measurement of icing environments.
- 3) Recommend possible interim characterizations of the SLD environment.
- 4) Recommend necessary long-term research to characterize the SLD environment.
- 5) Recommend research to improve instrumentation for measuring SLD.

The sessions were attended by an average of 40-50 participants.

The working group's recommendations, other consensus items, and non-consensus items follow. In view of the fact that this working group addressed a number of technical issues not widely familiar within the industry, an extended background section was provided by the co-chairs of this working group.

RECOMMENDATIONS

- 1) Circulate "trial" SLD dropsize distributions to PMS probe users to assess differences in LWC and dropsize processing methods.

Voluntary basis.

FAA Tech Center coordinate effort.
Short-term urgency.

- 2) Consolidate all available data (esp. airborne) on ZR and ZL.

Organized by AES of Canada and FAA Tech Center.

Data to include:

- > Final dropsize distributions.
- > Other (tbd).

Suggested sponsor: FAA.

Urgency: Within 1 year.

- 3) Reach agreement on standard instruments LWC meter(s), reliable in SLD droplet range (50 to 2000 microns).

Test and compare in NASA IRT.

Urgency: This summer.

- 4) Compile a global ZR and ZL climatology.

Cooperative effort of many individual countries.

Coordination?

Completed within 2 years.

- 5) Convene a workshop for SLD characterization.

Sponsor: ICAO, WMO, AMS, EC, or FAA (or some combination).

Within 2 years.

- 6) Need to conduct field projects to obtain SLD data.

In Great Lakes Region because high frequency of ZL, ZR, and lack of measurements aloft.

- > Sponsors: FAA, NASA, AES/NRC.

In Europe.

- > Sponsor: EC.

- 7) Encourage basic research on formation mechanisms for ZL.

Long-term research effort.

8) Characterize SLD environment for operations:

Solicit cooperation of operational aircraft in carrying probes (LWC and droplet); possibilities include:

- > Canada: DFO, DND, TC, etc.
- > U.S.: Coast Guard, etc.

Solicit cooperation of designated pilots in reporting of visual cues.

9) If the Appendix C envelope is to be revised or supplemented to encompass SLD, a special committee should be formed to address a number of issues, including:

Should there be a separated, independent envelope for SLD?

What variables should be used:

- > MVD, 80% VD, dropsizes distribution (5 bins).
- > LWC.
- > Altitude.
- > Temperature.
- > Horizontal extent.

Should mixed phase conditions be included in a revision?

Should it be tied to a severity index?

Can it incorporate terminology common to operations?

CONSENSUS ITEMS

- 1) International cooperation needed (e.g., EURICE).
- 2) Global climatology of ZR and ZL (starting point).
- 3) Definition of SLD - "any droplets larger than 50 microns diameter."
"SLD LWC" - LWC in dropsizes larger than 50 microns diameter.
- 4) Need common language/definitions for:

Certification, operations, forecasting, PIREPs.
- 5) Formation of ZL not well understood (nor horizontal extent).

- 6) Characterization of SLD environment needed to support:
Flight operations and forecasting.
Test and simulation.
Design.
- 7) Need a standard instrument for:
LWC (esp. SLD).
Dropsize distribution.
- 8) Need a consistent procedure for calibrating, processing, and reporting drop size and LWC data.
- 9) Develop remote sensing devices for SLD (ground-based, airborne, and satellite).

Microwave radiometers.
Multiparameter radars.
Lidars.
- 10) Manufacturers need better information for design purposes information on probe selection/installation.
- 11) If there is a need to revise or supplement the Appendix C envelope to include SLD, WE NEED MORE DATA!
- 12) Mixed-phase (solid and liquid) conditions not yet discussed.

NON-CONSENSUS ITEMS

- 1) Revise Appendix C Envelope (SLD and <50 microns).
- 2) Need for compact instrument package.

BACKGROUND

The Icing Environmental Characterization Working Group was focused almost entirely on what has been called "supercooled large droplet" (SLD) icing conditions. SLD includes ordinary freezing drizzle and freezing rain,

but also the more recently recognized problem of SLD aloft at aircraft holding altitudes.

There are three major application areas, each of which requires a different set of information or a different degree of certainty about the atmospheric variables involved. The following table shows these three categories:

The Different Needs for Information on Freezing Rain (ZR) and Freezing Drizzle (ZL)

Flight Operations (Dispatch Decisions, Inflight Escape, and Avoidance)

Where Does ZL and ZR Occur?

What altitudes?

What temperatures?

What geographic regions?

What time of year?

What weather situations?

What vertical cloud distributions?

What phases of flight are affected?

Test and Simulation (Icing Wind Tunnels, Airborne Spray Tankers, Computer Modeling)

What are representative or desirable test values of:

LWC and dropsizes?, or

LWC distribution and dropsizes?

Outside air temperature?

Exposure duration in different phases of flight?

Design for Certification

What are probable maximum (e.g., 99%) values of:

LWC and dropsizes?, or

LWC distribution and dropsizes?

Outside air temperature?

Exposure duration in different phases of flight?

Basically, dispatchers and pilots need to know the gross features of SLD conditions so that they can avoid or escape it. Aircraft test and evaluation

engineers need more detailed information, such as the range and representative values of the dropsizes, water concentrations, and air temperatures to be expected in SLD encounters so they can simulate it.

Finally, if the icing certification requirements are changed someday to include designing for SLD conditions, then presumably the worst case values of dropsizes, water concentrations, and temperatures will have to be known with a greater degree of certainty (such as, to the 99th percentile limit) than they are today.

The recommendations issued by this Working Group touch on all three of these areas of need. The recommendations presented in the final plenary session of the Icing Conference were numbered more or less in the order in which the subjects were discussed, and this also partially reflects the urgency they were considered to have. The recommendations appear renumbered and in a different sequence below, being grouped in several logical categories.

Recommendations on Instrumentation.

There were several needs that were obvious to researchers who have been trying to measure SLD with modern, electro-optical dropsizer spectrometer probes. These needs center around the long-recognized problem of trying to correct, or adjust, recorded dropsizer distributions for systematic measurement errors. These errors include: (a) Serious undercounting of the smaller droplets, due to probe response limitations (*Hobbs et al*); (b) Possible artificial broadening of the real size distribution due to optical effects in the droplet imaging process (*Korolev et al*).

There are at least two means of compensating for the undercounting of droplets. These make use of correction factors during the data processing step in which recorded droplets counts are converted to the number of droplets per unit volume of sampled air during flight. The manufacturer of today's most popular probes, Particle Measuring Systems, Inc., recommends a correction procedure in the owner's manual. Independent studies by some of the long-time probe users have resulted in an alternate recommended procedure. Other users may have devised other correction factors based on their own experience.

Unfortunately, it has been shown recently that these several correction schemes can all give different results for the same initial SLD size distribution (*Lawson et al; Ide*). Unacceptably large disagreements in computed MVD's and water concentrations can arise this way. In this

situation, nobody knows how much artificially introduced error is in published SLD results!

One reason that this discrepancy is still unsolved is that there has been no reliable, independent LWC meter known or available for use as a standard of comparison for the dropsize-computed LWC's. A suitable LWC meter that is used simultaneously with the droplet probe(s) would provide a "calibration" point. This would help decide which correction scheme is most reliable.

These problems have vexed cloud physics researchers for some time now, but the problem has now come to affect the aircraft icing community in a serious way. Recently, as a result of the Roselawn accident, attempts have been made to modify droplet spray systems in icing wind tunnels and on airborne spray tankers to produce SLD-sized droplets. Logically, it is desirable to simulate naturally occurring SLD size distributions, LWC's, and MVD's. But if the "corrected" size distributions, LWC's, etc., for both the natural and spray droplets can vary by as much as a factor of two, then it is obviously difficult to know if you are simulating realistic SLD conditions or not! Furthermore, if policy or test decisions have to be made *now* based on the best guess for "corrected" LWC's and MVD's, and if these LWC's and MVD's are eventually found to be in error one way or the other, then there could be unpleasant consequences as a result of the original decisions.

Therefore, it was clear that several immediate steps could be taken to assess the seriousness of the correction scheme problem and to make long-overdue progress on finding a suitable and reliable bulk-LWC meter for SLD conditions. These recommendations are as follows:

- 1) Circulate "trial" SLD dropsize distributions to PMS probe users to assess differences in LWC and dropsize processing methods.

This will allow all interested researchers to use their preferred correction scheme, whatever it may be, on the same initial size distribution and compare the results. The spread in computed LWC's, MVD's, etc., will serve to gauge the seriousness of the problem. This will probably not answer the question of which correction scheme is the best, but it will indicate the possible range of disagreement in computed results.

This comparison exercise is not expected to require much time or effort on the part of the participants. It should be easily worked

into their already existing data processing routines for their computer. Therefore, it is suggested that the exercise can be done voluntarily by interested participants. They will recognize that the results will be of benefit to them and to all participants, as well as to cloud physics researchers at large.

Someone must organize the exercise, simple as it may be. Because of the immediate benefit to the FAA and because of the interest that already exists at the FAA Technical Center, it is recommended that the FAA Technical Center lead this effort.

Obviously, this is an urgent requirement---little or no progress can be made on trusting SLD measurements until the scope of the problem is understood. This is a logical and easy way to make that assessment.

- 2) *Reach agreement on standard instruments LWC meter(s), reliable in SLD droplet range (50 to 2000 microns).*

This is intended to help answer the long-standing and urgent need for an independent, bulk-LWC meter which can serve as an absolute reference for LWC measurements and as a standard of comparison for LWC's computed from recorded dropsize distributions in the SLD size range. Presently, commonly used hot-wire LWC sensors are suitable only for ordinary cloud droplets. They lose sensitivity to droplets larger than about 40 μ m or so. Icing rate meters are sometimes used as substitute LWC meters, but their designs are not very suitable for accurate LWC measurements for all occasions. What is needed is a research grade LWC meter that is sensitive to droplets of all sizes to be found in SLD conditions.

It was pointed out by Working Group participants that one or more of the LWC meters recently developed by different organizations may indeed fill the need. Therefore, the recommendation was made that these new LWC sensors be tested and compared in a suitable facility, such as the NASA/Lewis Icing Research Tunnel, where adjustable and repeatable SLD conditions can be produced. Hopefully, one or more of these new LWC meters will be found suitable and reliable for use in wet wind tunnels at least, if not on research aircraft. At least the

SLD LWC in the test section of the tunnels could then be mapped and calibrated with some confidence. In addition, correction schemes for SLD dropsizer spectrometers could then be tested by comparing dropsizer-computed LWC's to those measured by a standard LWC meter that has been accepted by the users.

This is another urgent problem---little or no progress can be made on SLD measurement accuracy and reliable wet wind tunnel calibration until confidence can be had in the LWC and dropsizer data. Because several candidate LWC meter systems seem to be available and ready for evaluation in SLD conditions, it is recommended that the tests be done as soon as possible. Mid 1996 was recommended as a target date.

Recommendations on the Collection of SLD Data.

The following recommendations divide along the three categories of need indicated in the table:

- 3) Consolidate all available data (especially airborne) on freezing rain (ZR) and freezing drizzle (ZL).

This was considered to be the most urgent of the data collection recommendations. Several research organizations have already obtained some data on SLD aloft from past research campaigns using aircraft outfitted with cloud physics probes. It is logical to collect together and analyze what is already available as expeditiously as possible. Analyses of available data may help determine what new data is needed. It would also guide measurement campaigns that may be undertaken for other purposes anyway, but which could also obtain SLD-type data whenever the opportunity arises.

The data to be collected certainly must include SLD dropsizer distributions. There was not time for the Working Group to decide precisely which other variables should be collected too; but they would most likely include LWC, temperature, altitude, horizontal extent, and probably a number of others. It was left to the collective participants to work out the details on that.

This effort may require considerable time and expense for the participants, depending on how much data they have to offer and how much work is involved in preparing it for use. Because most of the known sources of SLD data are in North America, and because SLD is obviously a North American problem, it seemed logical to expect the U.S. Federal Aviation Administration (FAA) to fund this data assimilation project. Both the FAA Technical Center and the Canadian Atmospheric Environment Service (AES) were suggested as a possible joint organizing team for this work. No effort was made to estimate a likely cost, but it would certainly be far less expensive than launching new measurement campaigns to obtain the same amount of data.

Because the data already exist, and because of the importance of evaluating it, this recommendation was given high priority too. Realistically though, the additional complexity involved in organizing and funding such a project would no doubt take some time. In addition, it may be wise to wait for the initial results of Recommendation 1 before participants are asked to spend time and money preparing their data. Nevertheless, it was recommended that such a project get underway within a year.

4) Compile a global ZR and ZL climatology.

Two of the papers at the Conference (Jeck; Strapp et al.) show that good climatologies of freezing rain and freezing drizzle at the surface now exist for the United States and Canada. These climatologies (based on archived surface weather records) are necessary for depicting where SLD problems exist geographically. As far as we know, no similar climatologies have been published for Europe and Asia. It seems necessary to call for studies of the weather records there, too, in order to better determine where the SLD-prone areas lie. In other words, how do we know where and how bad the problem may be if nobody has done a survey?

It seemed logical that such surveys ought to be the responsibility of the individual countries that may be affected. Perhaps the national weather bureaus or a university within each country could perform the necessary research.

The Working Group did not have any recommendation on who should organize and coordinate this project.

This project was considered to be rather urgent, too, because airlines and pilots need to know in what geographical areas the SLD problems can occur and with what frequency. The climatologies would also point out which geographical areas are attractive for conducting inflight measurement campaigns of SLD conditions by interested research groups. The Working Group hopes that climatologies can be available within 2 years.

5) Conduct field projects to obtain SLD data.

Because of the relatively recent awareness of SLD as a possible inflight icing problem, not much scientific research has yet been directed to it. Although non-trivial amounts of SLD data have been collected over the past 10 years by interested researchers, only a few geographic locations have been sampled. Freezing drizzle has been sampled by research aircraft on the upslope side of the Sierra Nevada mountains in California (Ashendon and Marwitz), in Colorado (Lawson and Politovich), and the area around St. Johns Newfoundland (Cober et al). A few freezing rain cases have been sampled by research aircraft near Kansas City, Missouri, and in North Dakota (Stith, et al.). No SLD measurements have yet been attempted in the Great Lakes region of the U.S. where the Roselawn accident occurred and where the climatology shows SLD to occur most frequently in the U.S.

For these reasons it is logical to call for more data, especially in a geographic region that is known to have potentially serious SLD conditions and yet has not been sampled. The SLD problem presumably exists in parts of Europe, too, and, therefore, data need to be obtained there as well.

In the U.S., it is natural to expect the FAA, and possibly NASA, to finance such data collection efforts that are directly related to aircraft icing. In Canada, the logical funding organizations seem to be the Atmospheric Environment Service (AES) or the National Research Council (NRC). In Europe, a possible sponsor is the European Commission (EC) under the leadership of the EURICE project (Amendola & Mingione).

No time schedule was suggested for these efforts, but it is known that an aircraft icing field campaign involving the NASA, NCAR, and the FAA and employing cloud research aircraft is already being planned for the Great Lakes area in the Winter of 1996-97. This will automatically include attempts to measure SLD conditions whenever possible. It is hoped that SLD measurement campaigns in Europe will start as soon as possible.

- 6) Encourage basic research on formation mechanisms for freezing drizzle.

A distinction is made here between rain and drizzle. The formation process for classical freezing rain is well understood but the formation process for drizzle is not. Widespread or stratiform rain results from snowflakes or other ice particles falling into a "warm" ($T > 0^{\circ}\text{C}$) layer of air and melting to become raindrops. If these raindrops fall into another, subfreezing layer of air before they hit the ground, then they can freeze on contact with subfreezing surfaces (aircraft, trees, wires, etc.) and become freezing rain. This is called the classical freezing rain process. Freezing drizzle can form the same way, but the droplets are smaller for various reasons. But recent studies have revealed that 30 percent or more of freezing drizzle cases occur entirely in subfreezing air---that is, no melting layer is involved at all! This means that drizzle can often form in some other way, and this is thought to be through a collision-coalescence growth process among the ordinary cloud droplets. This has been called the non-classical freezing drizzle process by some researchers.

The problem is that no one knows for sure what can trigger the non-classical drizzle production process; and therefore, no one knows how to always tell when and where it will occur. This is obviously a problem for both weather forecasters and pilots. If forecasters don't know what all the causes are, how can they forecast it? If no one knows how to recognize drizzle-prone cloud conditions, how can pilots avoid it?

Although this may seem like more of a forecasting and flight operations problem rather than a characterization problem,

formation is an important part of characterization too. So this recommendation touches all three areas of concern---forecasting, flight operations, and characterization.

For these reasons, the Working Group strongly encourages basic research, especially on the non-classical formation processes.

No specific sponsors were suggested for this research, and it is realized that a long term research effort will probably be involved. It is known that several research groups are already interested and working on the problem.

Recommendations on Details of Characterization:

7) Convene a workshop for SLD characterization.

The Working Group discussions revealed that there was no clear consensus on exactly what variables were most important for including in a characterization of SLD conditions. The table shows that there are different types of information and different degrees of detail that may be needed by different users.

There was general agreement that LWC was obviously an important variable, but should it cover the whole range of droplets present (cloud and SLD) or just the SLD dropsizes? Should the LWC be further divided into drizzle sizes and raindrop sizes? And what about MVD---is it useful or even valid for designing for SLD conditions (Levchenko & Sophin)? It became clear that while cloud researchers (who populated most of this Working Group) could speculate on what they think is needed by design engineers or other users, they really didn't know for sure what variables all the possible users really need.

For these reasons, it was decided that an international workshop on this specific topic is needed to bring together representatives from all potential contributors and users of an SLD characterization. Then the requirements and possibilities could be discussed at more length and in more detail and with more preparation than was possible in the present Working Group.

Logical sponsors that were suggested for such a workshop are: The International Civil Aviation Organization (ICAO), the World Meteorological Organization (WMO), the American Meteorological Society (AMS), the European Commission (EC), the U.S. Federal Aviation Administration (FAA), or some combination of these.

The Working Group recommended that such a workshop be convened within 2 years.

8) Characterize the SLD environment for operations by:

Soliciting the cooperation of operational aircraft in carrying probes (LWC and droplet);

Soliciting the cooperation of designated pilots in reporting visual cues.

This is the idea of using scheduled or other frequently flying aircraft as vehicles for carrying sensors that automatically record icing-related data for later use in research or that automatically relay real-time, inflight icing conditions to ground stations for use by forecasters, dispatchers, pilots, and air traffic controllers. This idea has been around since the 1950's at least; and it resurfaces periodically but, for various reasons, little has been done about it.

Actually, there are at least two precedents for engaging commercial airliners and government aircraft to carry research sensors on board. One was conducted in the 1950's by icing researchers from the Lewis Flight Propulsion Laboratory in Cleveland, Ohio, (Perkins, 1959). They arranged to install automatically-recording, pressure-sensitive icing rate meters on 72 commercial and military airplanes. The civil airplanes were scheduled aircraft operating on domestic and overseas airways. The military aircraft were weather reconnaissance planes on routine patrols over wide areas of the Pacific and Arctic oceans. Altogether, the researchers obtained data from 3200 icing encounters over several icing seasons.

More recently, a small FAA-funded project called CASH (Commercial Aviation Sensing Humidity) has been underway for a couple of years. It is a pilot project to test the feasibility of obtaining frequent and high resolution vertical measurements of relative humidity from sensors installed on commercial airliners. It is hoped that such measurements will help forecasters locate cloud layers routinely and, thereby, help locate and forecast icing conditions with better spatial precision.

The Working Group re-introduced the idea of doing the same thing with more direct sensors of icing conditions.

Working Group participants suggested that if it is too difficult to involve commercial airlines in this kind of adventure, then perhaps government operated aircraft would be an acceptable substitute. Flight operations on available government aircraft may not provide the frequency or geographical coverage that could be obtained from the civil commuter fleet, but it may be easier to get a program started and obtain some data on icing conditions on a more-or-less routine bases.

In the U.S., perhaps the Coast Guard patrol aircraft would be available, for example. In Canada, the Department of Fisheries and Oceans, the Department of National Defense, and Transport Canada may be willing to have some of their aircraft retro-fitted for this purpose.

Many questions still remain about funding, logistics, airline interest and cooperation, liability concerns, and others. The Working Group did not have time to consider these questions but still proposed the recommendation as a worthy task.

The second part of the recommendation may be easier to do, and much sooner. It arose after hearing about the just-completed survey conducted by the Air Line Pilots Association (Green and Bracken). They sent questionnaires out to 700 or more ATR pilots to find out how often they had seen the side window icing cue that appears to occur in SLD icing conditions. Green also reported that for any pilot-observing campaign, much better reporting is obtained if specifically named pilots agree to serve as

designated observers and reporters. The success rate is much better this way than simply broadcasting an appeal to pilots in general for special observations and reports.

- 9) If the Appendix C envelope is to be revised or supplemented to include SLD, a special committee should be formed to address a number of issues, including:

Should there be a separated, independent envelope for SLD?

What variables should be used?

Should mixed phase conditions be included in a revision?

Should it be tied to a severity index?

Can it incorporate terminology common to operations?

The concern here is similar to that behind Recommendation 7. Namely, cloud researchers can devise any number of data presentations and include all sorts of variables, but what will the users of the of the envelopes really want, need, and find most useful? Before the researchers spend a lot of time on this problem, they want guidance from the airframe designers or other potential users of any new characterization of SLD icing variables.

References

Perkins, P.J., 1959; "Summary of Statistical Icing Cloud Data Measured over the United States and North Atlantic, Pacific, and Arctic Oceans During Routine Aircraft Operations", Memo Report 1-19-59E, NASA Lewis Research Center, Cleveland, Ohio 44135.

All of the following references are to papers that were presented at the Conference and can be found in Volume I or II of the Conference Proceedings.

1. Amendola & Mingione, "EURICE: European Research on Icing Environmental Characterization".
2. Ashendon & Marwitz, "Supercooled Large Droplet Distributions in the Natural Environment and...Water Spray Tanker".
3. Cober et al, "Analysis of Aircraft Icing Environments Associated with Supercooled Drizzle".

4. Green & Bracken, "An Investigation of the Prevalence of Icing Conditions which Exceed FAR Part 25, Appendix C".
5. Hobbs et al. "Comparison of Two Data Processing Techniques for Optical Array Probes".
6. Ide, "Comparison of Liquid Water Content Measurement Techniques in an Icing Wind Tunnel".
7. Jeck, "Representative Values...in Freezing Rain and Freezing Drizzle".
8. Korolev et al, "On the Accuracy of PMS Optical Array Probes".
9. Lawson et al, "Some Instrumentation Effects on...Drop Size Distribution in Freezing Drizzle".
10. Lawson & Politovich, "Freezing Drizzle...Over the Park Range in Colorado".
11. Levchenko & Sophin, "Main Concepts of a Standardized Supercooled Cloud Model..."
12. Stith et al, "In Situ Measurements of Aircraft Icing".
13. Strapp et al, "Canadian Climatology of Freezing Precipitation,...".

Working Group on Forecasting and Avoidance

CO-CHAIRS:

MARCIA POLITOVICH, NCAR

MYRON CLARK, FAA FLIGHT STANDARDS SERVICE

The working group objectives were to examine:

- 1) Current icing forecasting techniques and procedures.
- 2) Present research programs on icing forecasting.
- 3) Operational requirements for forecasting.
- 4) Avoidance techniques and the impact of icing forecasting on flight operations.

The sessions were well attended with forty pre-registered members and an average group size of 50-60 attendees.

The working group's recommendations, other consensus items, and non-consensus items follow. An explanation in italics by the co-chairs is provided in the background section for all recommendations and items.

RECOMMENDATIONS

- 1) FAA should encourage rapid prototyping of experimental products for limited operational use.
- 2) The FAA should endorse efforts in numerical weather forecast model development in the areas of prediction of cloud, cloud water, supercooled water, and eventually droplet size distribution with emphasis on a rapid implementation path and distribution mechanism.
- 3) FAA should fund technology transfer activities to foster development of operational sensors.

- 4) FAA needs a system-level analysis of operational forecast needs in order to focus research, define effective implementation strategies, and develop system architecture.
- 5) ASOS program should continue the development and implementation of freezing rain and freezing drizzle sensors, and stations that augment ASOS reports should routinely report this information.
- 6) The dispatcher should be provided with products that will permit full compliance with FAR 121.601c.
- 7) The recommendations from this conference should be shared with international aviation community through ICAO and other international agencies and forums.
- 8) The FAA should convene another working group meeting to address, specifically, icing severity definitions and icing severity index issues.
- 9) Standard terminology for large droplet icing should be developed and applied.
- 10) Ice accretion when reported by an aircraft should be confirmed with ATC as "Magic Words:"
 - ◇ "Trace" and "Light" always should be reported to the controller,
 - ◇ "Moderate" reports require action by ATC, and
 - ◇ "Severe" represents emergency action needed.
- 11) Review and clarify ground observer reporting rules for precipitation type, especially freezing precipitation.
- 12) The FAA should continue funding basic research to develop accurate icing detection and forecasting products.
- 13) Conduct one or more intensive field programs to collect comprehensive data sets to verify icing forecast and detection methods.

CONSENSUS ITEMS

- 1) The current PIREP system is flawed. It needs and deserves improvements. There are several issues:

- ◇ Stress to pilots the importance of accurate reporting, including null reports.
 - ◇ Enable a more efficient insertion of PIREPs into the system so they may be distributed in near real-time and archived for later use.
 - ◇ Make in-house PIREPs collected by airlines available to researchers and AWC forecasters, after de-identification.
 - ◇ There exists a fear of reporting weather conditions for which aircraft are not legally certified.
 - ◇ Develop special collection programs in cooperation with pilots.
- 2) Verification is vital for model and sensor outputs and for icing end-products to evaluate quality and enable improvements.
 - 3) The aviation community must be made aware of all severe icing conditions (such as icing associated with high LWC and ambient temperatures near freezing) as being as significant as icing associated with supercooled large droplets.
 - 4) Icing severity should be revisited:
 - ◇ User needs.
 - ◇ Definitions for pilot reporting.
 - ◇ Meteorological definitions (i.e., ICAO).
 - 5) Ensure that recommendations coming from this conference are integrated with user requirements.

NON-CONSENSUS ITEMS

- 1) Centralize all aviation weather forecasting activities within the National Weather Service's Aviation Weather Center.

BACKGROUND ON RECOMMENDATIONS

- 1) FAA should encourage rapid prototyping of experimental products for limited operational use.

This practice is being followed today. As new techniques and algorithms are developed, tested, and validated, they are being

evolved into products for field operations as expeditiously as is feasible.

- 2) The FAA should endorse efforts in numerical weather forecast model development in the areas of prediction of cloud, cloud water, supercooled water, and eventually droplet size distribution with emphasis on a rapid implementation path and distribution mechanism.

Recommendations 2, 3, 12, and 13 primarily deal with continued research in the field of aircraft icing; there is no argument with the merit of these recommendations. The controlling factor in the degree of support that FAA can give these activities is driven by the funding available in any given fiscal year. The major challenge for the federal government is establishing the correct priorities for funding this future work.

- 3) FAA should fund technology transfer activities to foster development of operational sensors.

See comment following recommendation 2.

- 4) FAA needs a system-level analysis of operational forecast needs in order to focus research, define effective implementation strategies, and develop system architecture.

These recommendations 4 and 7 will become action items in the Icing Conference Action Plan which will be published in the near future. The Office of Systems Architecture will be tasked to do the analysis and implementation strategies to achieve a viable and efficient system architecture.

- 5) ASOS program should continue the development and implementation of freezing rain and freezing drizzle sensors, and stations that augment ASOS reports should routinely report this information.

This recommendation is redundant since the development of freezing rain sensors has been completed by the NWS and the freezing rain sensor is currently being deployed as an integral component of ASOS. Augmenting stations are required to report FR and FZ whenever those conditions are observed.

- 6) The dispatcher should be provided with products that will permit full compliance with FAR 121.601c.

This recommendation is beyond the scope of this working group.

- 7) The recommendations from this conference should be shared with the international aviation community through ICAO and other international agencies and forums.

See comment following recommendation 4.

- 8) The FAA should convene another working group meeting to address, specifically, icing severity definitions and icing severity index issues.

Recommendations 8, 9, and 11 had broad support (including the working group chairs) for inclusion in the Conference Action Plan. Icing severity index issues are complex and need to be addressed from the perspectives of operations and the science of meteorology. Standard definitions for the aircraft icing environment should be developed, including "harmonization" with the international community through ICAO, and then promulgated throughout the aviation community world-wide.

- 9) Standard terminology for large droplet icing should be developed and applied.

See comment following recommendation 8.

- 10) Ice accretion when reported by an aircraft should be confirmed with ATC as "Magic Words:"

- ◇ "Trace" and "Light" always should be reported to the controller,
- ◇ "Moderate" reports require action by ATC, and
- ◇ "Severe" represents emergency action needed.

This recommendation was fully supported by the working group for incorporation in the Conference Action. It does have operational and procedural implications that reach beyond the Forecasting and Avoidance Working Group.

- 11) Review and clarify ground observer reporting rules for precipitation type, especially freezing precipitation.

See comment following recommendation 8.

- 12) The FAA should continue funding basic research to develop accurate icing detection and forecasting products.

See comment following recommendation 2.

- 13) Conduct one or more intensive field programs to collect comprehensive data sets to verify icing forecast and detection methods.

See comment following recommendation 2.

BACKGROUND ON CONSENSUS ITEMS

- 1) The current PIREP system is flawed. It needs and deserves improvements. There are several issues:
 - ◇ Stress to pilots the importance of accurate reporting, including null reports.
 - ◇ Enable a more efficient insertion of PIREPs into the system, so they may be distributed in near real-time and archived for later use.
 - ◇ Make in-house PIREPs collected by airlines available to researchers and AWC forecasters, after de-identification.
 - ◇ There exists a fear of reporting weather conditions for which aircraft are not legally certified.
 - ◇ Develop special collection programs in cooperation with pilots.

Although this item achieved consensus, it was seen by the co-chairs as so broad as to be beyond the purview of the conference.

- 2) Verification is vital for model and sensor outputs and for icing end-products to evaluate quality and enable improvements.

There is some validation and verification in progress today primarily being conducted by the research groups involved in icing forecasting and algorithm development. Could there be

more and would it be useful? -- Yes, but given current fiscal constraints, the co-chairs do not anticipate extensive increase in present activities. (Re: Paper in Vol. II by Barbara G. Brown).

- 3) The aviation community must be made aware of all severe icing conditions (such as icing associated with high LWC and ambient temperatures near freezing) as being as significant as icing associated with supercooled large droplets.

The point of this item is that the aviation community must recognize that there are a number of atmospheric conditions which can create a severe icing environment.

- 4) Icing severity should be revisited:

- ◇ User needs.
- ◇ Definitions for pilot reporting.
- ◇ Meteorological definitions (i.e., ICAO).

There was extensive discussion of this topic and nearly unanimous agreement that there is much to be done in this area to alleviate the confusion and misunderstanding in the aviation community regarding icing terms and definitions. Note that there are several recommendations from this working group on the subject of icing severity and terminology describing the icing environment.

- 5) Ensure that recommendations coming from this conference are integrated with user requirements.

This statement was directed to the conference leaders and is self-explanatory.

BACKGROUND ON NON-CONSENSUS ITEMS

- 1) Centralize all aviation weather forecasting activities within the National Weather Service's Aviation Weather Center.

There was extensive discussion on this topic. The "pro" being the thought that by centralizing the forecasting, full and more immediate advantage could be taken of research developments in

forecasting techniques and procedures. The "con" was the opinion that by centralizing, the forecasting loses the accuracy in the forecasters "knowing the territory." In truth, icing forecasts are all generated in a centralized office at the Aviation Weather Center in Kansas City, Missouri; so the non-consensus as far as icing forecasting is concerned is rather moot. As noted, the group did not reach a consensus.

Working Group on Operational Regulations and Training Requirements

CO-CHAIRS:

ROBERT BRAYTON, CONTINENTAL EXPRESS

KATHERINE HAKALA, FAA FLIGHT STANDARDS

The working group focused on the following issues:

- 1) Dispatch and operational procedures relating to severe icing conditions for all aircraft.
- 2) Flight crew and dispatcher training to recognize and avoid, or exit from, severe icing.
- 3) Use of PIREPs and icing reports for real time decision making and future research in support of ongoing technology development.
- 4) Connection between pilots, dispatchers, and ATC regarding obtaining and disseminating severe icing information.
- 5) Support of on-going severe icing, ice detection, and protection technology.

The sessions were well attended and comprised of representatives of aircraft manufacturers, U.S. and international airlines, pilot and dispatcher associations, airline organizations, government, and individuals.

The working group's recommendations and non-consensus items follow. (There were no consensus items apart from the recommendations for this working group.) Recommendations are consolidated under the subheadings of weather reports and forecasts, ATC, dispatch, flight crew, training, reporting/PIREPs, technology, aircraft certification, and regulations and guidance material. Recommendations and other items with an asterisk are repeated with an explanation in *italics* by the co-chairs in the background section which follows.

RECOMMENDATIONS

Weather Reports and Forecasts

- 1) Need accurate depiction of icing location for preflight planning, avoidance, and exit procedures.
 - ◇ Need plain language terminology for icing reports.
 - ◇ Need new products for accurate forecasts of severe conditions and predictions of severe ice.
 - ◇ Need accurate information to include emphasis on vertical distribution (temperature).

ATC

- 2) Emphasize severe icing in recurrent training for controllers.
- 3) Priority handling should be applicable to all aircraft requesting diversion for severe icing.
- 4) Clear, concise information in PIREPs must be passed to/from flight crews and dispatchers.

Dispatch

- 5) Recognize that dispatch includes both preflight and inflight decisions.
- 6) Need accurate forecasts and timely pilot reports in order to make real time, informed decisions regarding the safety of flight.

Flight Crew

- 7) Use manufacturer recommendations for operation of ice protection equipment. Research the ice bridging issue.

Training

- 8) Educate all pilots and dispatchers on weather conducive to severe icing, icing certification, icing subjects.
- 9) Develop common terminology including "priority handling."

- 10) Encourage coordination among manufacturers, operators, associations and organizations, research communities, pilots, and international community for development of training aids, pictorials, visual training aids, and advisory material.
- 11) Need recurrent winter operations training updated with new information and technology.
- 12) Update advisory circulars or guidance material on severe icing.
- 13) Develop FAA/industry training aid on in-flight icing.

Reporting/ PIREPs

- 14) Incorporate use of PIREPs and reporting procedures particular to icing into training programs.
- 15) Develop company procedures for requesting PIREPs information in icing conditions.
- 16) Improve PIREPs coordination between ATC and FSS and company/one call for all.
- 17) Modify NASA's ASRS program to include severe icing/ support funding.
- 18) Support use of partnership programs such as ASAP to capture icing data. Forward pertinent data to the ASRS system.
- 19) Update PIREPs icing information to include precipitation type and altitude.

Technology

- 20) Need reactive ice detection equipment that identifies ice accretion aft of protected surfaces.
- 21) Support the development of predictive onboard/airborne ice systems.
- 22) Aircraft manufacturers should provide data to simulator manufacturers to help replicate the icing environment.

- 23) Fund NASA to expand capabilities to keep pace with manufacturing/industry needs.
- 24) Encourage use of ASD (aircraft situational display) for dispatch.
- 25) FAA to fund research for the characterization of the icing environment.
- 26) Emphasize communication and cooperation in the international research community to define, resolve, and disseminate severe icing findings to industry in an established time frame.

Aircraft Certification

- 27) Review MMEL restrictions in ADs.

Regulations and Guidance Materials

- 28) Modify severe icing definition to include ice accretion aft of protected areas.
- 29) Recommend review and harmonization of FAA regulations pertaining to icing conditions.

NON-CONSENSUS ITEMS

- 1) Icing severity index.
- 2) Prohibition of operations in severe icing as defined by the AIM and in freezing rain and freezing drizzle.

BACKGROUND ON SELECTED RECOMMENDATIONS

- 7) Use manufacturer recommendations for operation of ice protection equipment. Research the ice bridging issue.

The question of whether or not ice bridging during the operation of pneumatic boots is a valid consideration was discussed. The

group recommended further research on this issue. In the interim, it was emphasized that the manufacturer's recommendations for operation of deicing equipment should be used.

- 9) Develop common terminology including "priority handling."

There should be a clear understanding of pilot and controller roles when clearance is requested for exiting icing conditions.

- 17) Modify NASA's ASRS program to include severe icing/ support funding.

The working group discussed whether there should be a single data collection source for reporting icing safety issues. The Regional Airline Association (RAA) had initiated a program to collect reports of unusual icing encounters. It was recommended that the RAA's program be wrapped into the ASRS system. The ASRS system was selected as it is an established and recognized reporting system. It was recommended that the report format be modified to collect specific technical data related to icing encounters.

- 18) Support use of partnership programs such as American Airlines Safety Action Program (ASAP) to capture icing data. Forward pertinent data to the ASRS system.

The partnership for safety programs, including the ASAP program, are used as a means to address safety problems and identify potential safety hazards. The intent of these programs is to increase the flow of safety information to both the air carrier and the FAA and include incentives to encourage employees to disclose information and identify possible violations without fear of legal enforcement sanctions. The group recommended that pertinent icing reports obtained through the partnership programs would be forwarded to the ASRS system.

- 24) Encourage use of ASD (aircraft situational display) for dispatch.

Refers to the use of ASD including weather display in the dispatch centers as a tool for flight planning, arrivals at airports, and advisories to crews.

- 27) Review MMEL restrictions in ADs.

This recommendation refers to recently issued ADs on airplanes with pneumatic boots and unpowered flight controls. The ADs required revision of the MMEL to delete relief for the ice detection lights when operating in icing conditions. There were questions as to which lights were affected by the ADs.

- 28) Modify severe icing definition to include ice accretion aft of protected areas.

The Aeronautical Information Manual (AIM) defines severe icing as the rate of accumulation is such that deicing/anti-icing equipment fails to reduce or control the hazard. Immediate flight diversion is necessary. The definition has been interpreted not to encompass icing in those areas that are not protected by deicing/anti-icing equipment.

- 29) Recommend review and harmonization of FAA regulations pertaining to icing conditions.

This includes review of Sections 91.527, 135. 227, and 121.341 and the JAA regulations and review of the definition of severe icing and its application in the operating rules.

Closing Remarks

ANTHONY J. BRODERICK ASSOCIATE ADMINISTRATOR FOR REGULATION AND CERTIFICATION FEDERAL AVIATION ADMINISTRATION

Thank you, Dan. Let me congratulate you and your colleagues for what was clearly a very worthwhile meeting. It was impressive hearing, during the last two hours, how much ground you covered in the last few days. What I heard convinced me that there was a tremendous amount of productive energy behind each of the five working groups and an interesting symmetry to some of the recommendations as well.

Before I begin, I would like to remind everyone of the job announcement posted on the board outside. I understand a number of you expressed quite a bit of interest in the National Resource Specialist Position in Icing. We are interested in hearing from those of you who are interested in the job. We want to get some of the best people we can working on this program. This is a key position in our minds; so please don't forget us if you think you would like to be involved. As it indicates on the job announcement, there is not a particular location requirement. So that should solve some of the big problems we have today with moving.

One of the things I heard a lot about in the last couple of hours was recommendations for funding this or funding that. I have to tell you that after spending the last couple of days fighting for budgets, we have to figure out innovative ways to make do with the budget realities of the world. One of the groups mentioned we need to have a public icing tanker continuously available. I agree with that, would love to have it; I don't know how we are going to figure out how to fund that kind of thing. It is something I think we all have to keep in mind.

Looking at what we hope to see come out of this conference, I think it is probably fair to say that this certainly isn't the end of the effort; it isn't even the end of the beginning. Maybe we can consider it the beginning of something that I suspect it is going to continue for more than a few years, probably stretching into the twenty-first century. We can develop a really

productive period of learning with and from each other for the improvement of our understanding of the important things that affect aviation safety in an icing environment.

I was interested in seeing the commonality of cries for better definitions throughout all of the working groups - better definitions for everything from the characterization of the supercooled liquid drops to what is meant by severe icing conditions. It is not really surprising, I suppose, when you look at the age of the actual language in our regulations. Looking at those words literally many decades later with different technologies, different backgrounds, and, indeed, almost all of us different people, we cry out for better specificity and better definitions. Better sensors and better predictive capabilities were requested throughout the working groups, and this is certainly something we need to try to develop. Better forecasting and better observation tools are available today, and certainly better computational tools as well. But all of that, as you know, takes time, sponsorship, and a lot of effort.

I was interested to note that almost whenever there was consensus in discussion about Appendix C, people urged that revision to that part of the regulations be approached with caution and that a lot of work be done before making changes. I infer that the concern is that the changes that we might make without the right information could be for the worse, not for the better; and I think that's very, very good advice. We certainly are going to take all of the advice that is contained in the report-outs of the five working groups and work with it over the coming months. As I said the other day and reaffirm now, we intend sometime probably late this summer to provide a response to the recommendations and findings of this conference.

When you think about all of the recommendations and findings that you heard, including the non-consensus items, we are going to have to form a group, as several working groups asked, to boil them down to some actionable materials. There is a lot of overlap in them, and I don't think it's fair to just list all seventy-five or so and say Yes, No, and this is when it is going to be done. So, we'll have to form a steering group of some kind working certainly within the FAA across all the disciplines within the agency and with other government agencies within the United States as well as other governments and companies from other countries. I also think it is fair to say that probably in 18 months, we ought to have another gathering of a group this large to see where we've come and what

think it is fair to say that probably in 18 months, we ought to have another gathering of a group this large to see where we've come and what kind of progress has been made and where we ought to go. By that time, maybe we will be closer to the end of the beginning and really have an idea of where these programs are going to go. I don't think it will be the FAA alone that will be steering this program; in fact, we are probably going to do less steering than setting of requirements. We certainly are going to need cooperation from a lot of other agencies.

The only thing I can tell you is that we will work hard to try and do what we can with the limited resources we have available over the next couple of years to address these issues. We certainly want to address the issue of coordination and cooperation with all of you. I heard a number of recommendations about things like enforcement action when you report an icing condition - among pilots and controllers and dispatchers. There are a lot of things like that which we can work on without a lot of expenditure of contract dollars or research dollars. We will try to do that. We will also try to do our best not only within the agency but also to help people in other agencies allocate monies to research that will advance our knowledge in these areas.

So once again let me thank you very much for your attendance. I especially thank those who traveled long distances to come here. I hope you have found it as worthwhile as we have. I can assure you of our continued interest and cooperation with you in the years to come in these programs. Thank you.

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