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NATIONAL ICING FACILITIES REQUIREMENTS INVESTIGATION

F. R. Taylor
R. J. Adams
SYSTEMS CONTROL, INC. (Vt.)

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2326 S. Congress Avenue, Suite 2-A
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16. Abstract

An analysis of National Icing Facilities requirements was performed at the request of the Federal Aviation Administration. This effort consisted of a five-month investigation to determine the scope and character of current and future icing facilities needs. This investigation included current aircraft needs as well as facilities that might be required for icing research, development and certification testing through the year 2000.

The information used for this study included all icing certification regulations for both fixed wing airplanes and rotorcraft. These regulatory requirements for icing certification were supplemented by a comprehensive analysis of current and future aircraft operational requirements. This independent facility requirements assessment was then compared to a previously published NASA review of icing facilities capabilities.

The conclusion was reached that the need for an inventory of National Icing Facilities currently exists and will become intensified in the next decade. The technical characteristics of these facilities were described and it was recommended that a joint FAA/NASA/DOD Task Force be established to formulate and spearhead the development of a National Icing Facilities Program.

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1.0 EXECUTIVE SUMMARY

The need for icing test facilities for research, development and certification purposes has recently been identified by FAA, NASA and DOD. This need stems from the difficulty in performing, and the imprecise results of, tests in natural icing conditions. To begin to resolve these problems, the FAA took the lead within the U.S. Government to define the requirements for icing simulation facilities. Through several national coordination meetings, with representatives from both industry and government, the FAA began to focus upon the real issues of icing research, development and certification, and has partially quantified icing facility needs and requirements. This report provides an in depth analysis of icing facilities' needs to support projected future research, development and certification needs for all aircraft types, military and civil, fixed wing and rotorcraft.

The method of approach used to determine icing test facility needs included an assessment of the impact of future aircraft developments, assessment of test requirements stipulated by existing FARs, and an examination of research needs which might dictate the type, quality and quantity of icing simulation facilities. Once the basic facilities requirements were established, the existing icing test facilities were assessed to determine whether or not these facilities could support those needs. Where shortfalls in facility capabilities were identified, rough order of magnitude cost estimates for facility modification or construction costs to meet the requirements were made.

The key results of this effort are summarized as follows:

- The technical requirements for national icing test facilities have been defined.
- An array of facility types is needed to support existing and future research, development, and certification testing. This array includes icing wind tunnels, ground based and in-flight icing simulators, test-bed aircraft and analytical prediction techniques.
- The array of national icing facilities should allow simulation of various icing conditions to include: supercooled clouds, snow, freezing rain and drizzle, and mixed conditions.
- Civil and military growth trends indicate a large number of new aircraft development programs in the next 20 years that will impose excessive workload upon existing icing test facilities.
- Existing icing test facilities, if properly modernized, can accommodate a significant portion of the projected workload. However, further duplication of some facility types: e.g., inflight simulators, may be needed to accommodate projected workload.

- Analytical techniques require development and refinement to reduce future testing requirements, and to avoid expensive redesign and retest.
- Simulated icing test technology needs advancement, including technology for icing scale model testing, to reduce the need for very large test facilities and to make more efficient utilization of existing facilities.
- A National Icing Facilities Task Force is needed to formulate and guide a national program. To assure that icing test facility priorities are given adequate visibility among the many other national needs, the task force should be composed of high level representatives from the National Aeronautics and Space Administration (NASA), Department of Defense (DOD), and FAA.

General Facility Characteristics Derived from the Investigation

The demand for National Icing Facilities is based on the need to test entire aircraft (up to and including the business jet category) and large components of transport category aircraft in a simulated icing environment. These facilities are needed today and the demand will increase rapidly through the year 2000, based on the current development of fuel efficient turboprop and turbofan powered small transports and the third generation helicopters (light, twin turbine, IFR helicopters such as, Bell 222, Sikorsky S-76).

A review of projected aircraft characteristics and operational capabilities through the year 2000 resulted in the following broad specifications for icing test facilities requirements:

- Airspeed range from 0(hover) to 350 knots TAS
- Altitude range from sea level to 29,250 feet pressure altitude
- Temperature range from +32° F to -40° F.
- Test Duration from 1 hour at 1 gm/m^3 to 20 minutes at 3 gm/m^3
- Minimum Test Section Length of 98 feet

Results of this investigation revealed 61 icing test facilities in North America. Many of these facilities are privately owned and can not be considered suitable as National Facilities. After analysis and review of the publicly owned facilities the following were considered candidates for inclusion in an array of facilities that would comprise National Icing Facilities for research, development and certification.

1) Icing Research Tunnel - NASA LeRC
2) Altitude Wind Tunnel - NASA LeRC
3) Engine Test Facilities - USAF AEDC, USNAPC
4) Climatic Chamber - McKinley Climatic Lab

5) Ottawa Spray Rig - Canada NRC
6) Inflight Tankers - U.S. Army HISS
- USAF KC-135
- USAF C-130

7) Test Bed Aircraft

Specific Icing Test Facility Improvements

An overall requirement exists for an inventory of National Icing Test Facilities. This inventory can be developed through a coordinated program of renovation and improvement of existing facilities, as well as limited provisions for new facilities. The recommended improvements and facilities needs are outlined as follows:

- Improved Inflight Tankers with the following characteristics:

Cloud Size	75' wide x 24' high
Airspeed Range	40-350 knots TAS
LWC Range	.04 - 2.8 gm/m^3
Adjustable droplet size range (MDD)	15 - 50 microns
Test Endurance	1 hr at 1 gm/m^3 20 min at 3 gm/m^3
Altitude Range	SL to 30,000 feet Pressure Altitude

- Ground Based Icing Simulators, (e.g.; Ottawa Spray Rig)

Cloud Size	75' wide x 24' high
LWC Range	.04 to 2.8 gm/m^3
Adjustable Droplet size range (MDD)	15 - 50 microns
Freezing Rain and Snow Capability	Parameters to be defined.

- Icing Wind Tunnels - several icing wind tunnels are needed to cover both low and high airspeed ranges and to provide research and certification data for aircraft components, ice protection systems and entire aircraft. The following specific recommendations resulted from this study:
  - Improve the capabilities of the existing NASA Lewis Icing Research Tunnel
  - Rehabilitate and improve the capabilities of the NASA Lewis Altitude Wind Tunnel

- The tunnels should possess the following combined or individual characteristics:

LWC Range	.04 to 2.8 gm/m^3
Adjustable droplet size range	15 to 50 microns
Temperature Range	+32°F to -40°F
Freezing Rain, snow & mixed test condition capabilities	Parameters to be defined

- Icing Research Test Bed Aircraft are needed to:
  - Test advanced ice protection systems.
  - Expand basic understanding of the conditions of natural icing.
  - Develop standardized instrumentation for use in icing certification testing.
  - Determine the effect of solar radiation and humidity on ice accretion and shedding.
  - Correlate the results of natural versus simulated icing tests.
  - Correlate analytical prediction results.
- Engine test facilities should be improved to have the following characteristics

LWC Range	.04 - 2.8 gm/m^3
Adjustable MDD Range	15 - 50 μm
Temperature Range	+32 to -40° F
Altitude Range	0 - 29,250'
Snow, Freezing Rain and mixed condition capability	Parameters to be defined

- Icing Test Chambers (e.g. McKinley Climatic Lab) need improvements to eliminate several factors which limit their use. The recommended improvements are:

Cloud size	75' wide x 24' high
Airspeed Range	0 - 70 knots TAS
Minimization or elimination of wall effects and other related air circulation problems	

Establishment of a National Icing Facilities Task Force

The subject of National Icing Facilities Requirements is quite broad and encompasses a multitude of capabilities, each with one or more associated problems. For this reason, as well as to satisfy a demonstrated need of the aircraft manufacturers and operators, it is recommended that a National Icing Facilities Task Force be established. A summary of the compelling forces which require the formation of this Task Force are presented in Section 4.2. The purpose of this Task Force would be to establish a National Icing Facilities program plan designed to be used by the Task Force in developing, managing and funding the icing facilities requirements.

2.0 INTRODUCTION

2.1 BACKGROUND AND OBJECTIVES

This analytical investigation of National Icing Facilities requirements was designed by the Federal Aviation Administration as a result of two previous intra-government and joint government and industry symposiums on the subject of aircraft icing simulation. A primary outcome of the symposiums was the recommendation that the FAA "take the lead" in defining the technical requirements for National Icing Test Facilities for research, development and certification. While much technical information was available with which to form a basis for the establishment of national facilities, the FAA recognized several important shortfalls in the available data. Specifically, there existed a need for quantification of the user demand on icing facilities based on: numbers of future (projected) aircraft developments, research requirements, and the impact of changing Federal Aviation Regulations (FARs). Additionally, the broad scope of qualitative improvements to existing facilities to provide the resources to support the projected workload was not known. The FAA determined that a necessary first step in defining the requirements for the national icing facilities was to perform an investigation which would fill the existing informational gaps and tie-in much of the previously published work in the icing field.

The scope of the work performed in this program was limited to a five month technical effort. The reasons for this somewhat short time frame were to expedite the flow of information establishing the needs and to integrate with the R&D planning process currently underway to define the need for and support the early formation of a joint FAA/NASA/DOD Icing Facilities Task Force.

The investigation results reported herein were limited to, and relied heavily upon, previous published work performed by NASA, the FAA and industry. The method of approach for this investigation included the steps shown in Figure 2.1 The investigation was initiated by reviewing all existing and proposed icing certification regulations for normal and transport category fixed wing aircraft and rotorcraft. This review was crucial to the establishment of facilities design/improvement criteria since the certification procedures and atmospheric conditions form the foundation upon which aircraft manufacturers will base their designs. Preliminary data from the certification requirements review was fed into both the facilities assessment and the aircraft operational requirements analysis. The facilities assessment was based primarily upon the previously published NASA work in this area (Reference 4). NASA had compiled detailed lists of icing facilities in North America and Europe. The capabilities of these facilities were analyzed insofar as their ability to meet the research and certification needs and the aircraft development testing needs established by the aircraft capabilities survey.

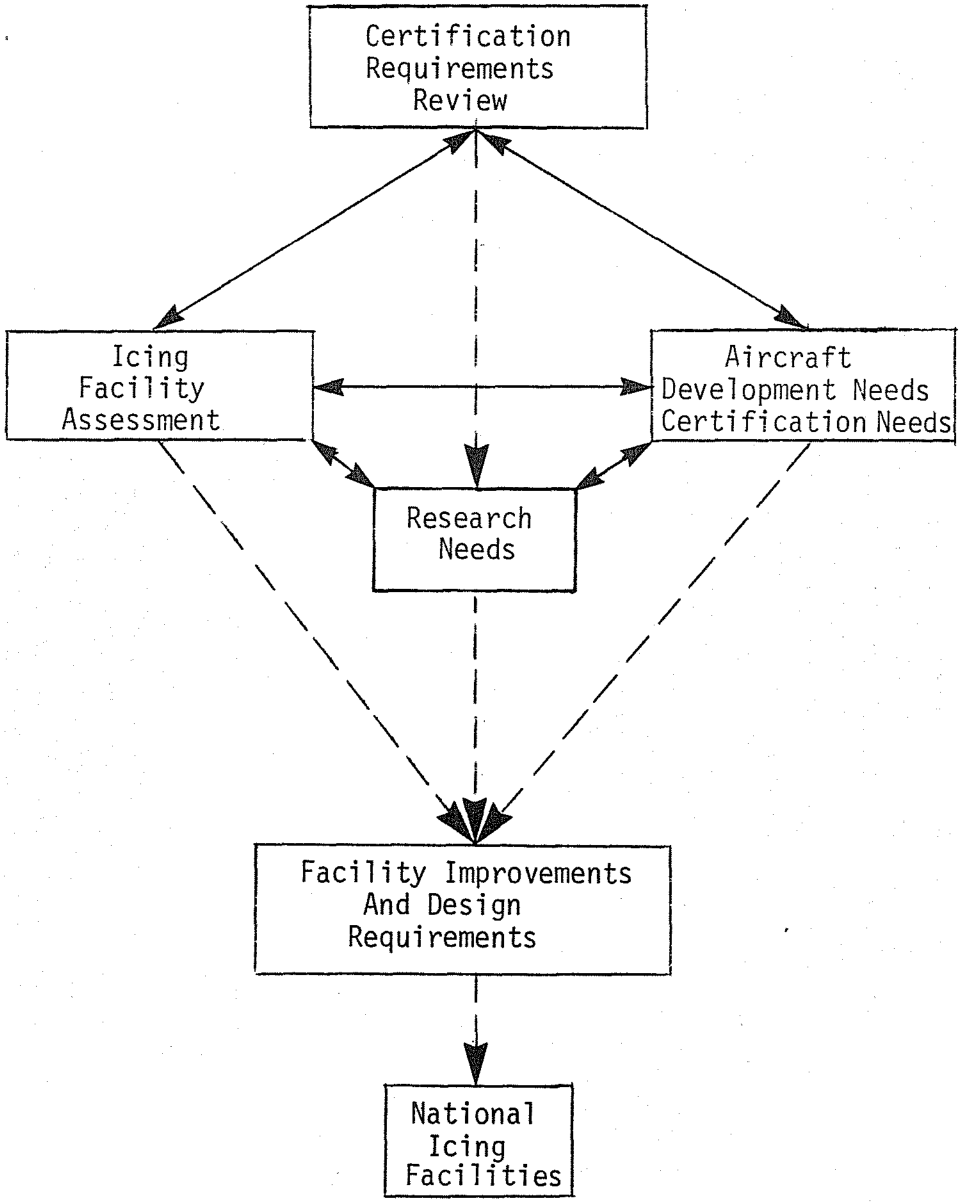


Figure 2.1 Overview of Methodology

The aircraft capabilities survey included a review of operational requirements for:

a) Civil Transports
b) General Aviation
c) Helicopters
d) Military Aircraft
e) Advanced Technology Concepts

The literature search and statistical analysis included review of published technical reports, aircraft performance handbooks, technical articles and airframe manufacturer data, for the purpose of establishing the range of parameters within which current and proposed aircraft would operate. Based on this assessment, National Icing Facility operational criteria were developed. These criteria were then compared to existing facilities and certification requirements. From this iterative process, a detailed set of recommended national facilities was developed. As a part of these recommendations, improved capabilities and new facility requirements were developed. Finally, an attempt was made to collate all of the above information into a recommended family of National Icing Facilities. This program included a rough order of magnitude estimate of the costs and schedules necessary to provide this national capability. These estimates were developed through a consensus of the organizations involved with operating, maintaining and modifying those facilities designated as desirable for the National Icing Facilities Program.

2.2 DETAILED METHOD OF APPROACH

The specific steps utilized to develop National Icing Facilities Requirements are discussed in this section. Each of the four program tasks is reviewed in terms of its primary objectives, data sources and method of analysis.

2.2.1 TASK 1: Review Icing/Icing Related Facilities

The objectives of this task were:

1) To review icing/icing-related facilities
2) To assess the potential of existing facilities for meeting current and future aircraft research, development and certification requirements

The method of analysis used to achieve these objectives included overlaying and comparing icing simulation capabilities of all the various facilities and comparing these aggregate capabilities with the FAR requirements, advisory information published by the FAA, and Notices of Proposed Rulemaking. This answered the question of the current shortfalls in facility designs as far as they apply to certification testing. The next step in this analysis was to perform a facilities capabilities vs aircraft operational requirements study. This answered both the R&D needs as well as any unique, aircraft specific, certification requirements. From these two comparisons, a list of facility design or operational shortfalls was developed.

The primary data sources for this task were:

1) Reference 4: NASA Lewis Research Center, "Survey of Icing Simulation Facilities in North America"
2) Reference 3: FAA-CT-80-210, "Helicopter Icing Review"
3) Reference 1: Minutes of National Icing Facilities Coordination Meeting, Sept. 1980
4) References 6-29: Technical Journals

2.2.2 TASK 2: Assess Aircraft Needs for Icing Research

The objectives of this task were:

1) To review current and projected U.S. civil and military aircraft developments through the year 2000
2) To assess aircraft needs for icing research, development and certification testing
3) Determine the impact of those needs on criterion for National Icing Facilities.

The major thrust of this task focused on categorizing the vast number of aircraft to be reviewed and then developing performance limits and operational regimes based on the operational and dimensional profiles of each category. Statistical operating and dimensional envelopes were developed for each category and then compared to the current icing simulation capabilities from Task 1 and the icing certification criteria from Task 3. From this twofold comparison, a determination of icing test facility requirements was developed as it directly related to current and future aircraft demand for these facilities.

2.2.3 TASK 3: Review Icing Related Documentation

The objectives of this task were:

1) To review icing-related Federal Aviation Administration documentation
2) To assess FAA certification requirements with respect to existing and non-existing icing facilities

The specific documentation addressed in this task included: Parts 21, 23, 25, 27, 29, 33 and 35; Advisory Circulars 20-73, 20-92, 20-93, 20-107, 60-9 and the Rotorcraft Regulatory Review Program Notice No. 1; Proposed Rulemaking (Reference 11). In addition, a detailed, independent assessment was made of Reference 3, "Helicopter Icing Review" as it related to icing certification requirements. The FAR certification procedures and rules from these documents were compared to the facilities capabilities from Task 1 to determine recommeneded facility improvements.

2.2.4 TASK 4: Project Icing Facilities Needs, Costs and Development Schedules

Of the four tasks, this was by far the most difficult to accomplish in an accurate manner. The scope of this effort did not allow sufficient time for indpeth facility design tradeoff studies, operational cost vs benefit studies or detailed (original) improvement costs and schedules. For this reason, only rough order of magnitude estimates of costs and development schedules were made to form a basis for future planning of facilities.

3.0 ICING FACILITIES REQUIREMENTS ANALYSES

Aircraft icing research, development and certification are three areas which will be of major concern to operators, manufacturers, researchers and regulatory agencies in the 1980s. The reasons for the increased activitiy and renewed concern are directly related to the dynamic growth of air transportation in general and to the strong demand for icing certification facilities generated by the rapid growth in four specific areas. These areas, and the aircraft which are key elements to their current and future growth include:

Commuter Aviation	Turboprops and advanced fuel efficient turbofan designs
Business Aviation	Executive turbojets and turboprops
General Aviation	Single and multi-engine
Civil Helicopters	Third generation equipment

The growth in aviation, and especially in these four segments of aviation, has created a "demand push" for icing test facilities for research, development and certification of advanced aircraft. The purpose of this effort was to review existing aircraft requirements for icing test facilities (both now and through the year 2000), and to relate those requirements to the capabilities and shortcomings of exisiting icing test facilities.

The current facilities available for icing test and evaluation include:

1) Natural icing tests
2) Inflight simulation
3) Ground based spray rigs
4) Icing wind tunnels
5) Climatic chambers

Each of these types of icing test facilities can provide the necessary data for only limited applications. For example, existing wind tunnels are not large enough for testing entire helicopters with the rotor systems in motion; spray rigs and tankers have limited cloud size and large variance in liquid water content and droplet size, etc. The only means currently available for reliable icing certification tests are in the natural icing environment. However, even this approach has limitations for the following reasons. First, in the U.S., natural ice occurrences are limited to a few months each year. Second, finding the types of ice desired for a sufficient amount of test time may take years since the natural icing meteorological conditions can not be controlled. Third, the entire process can be extremely expensive.

Due to the current state of the art in aircraft design and operation and the non-existence of a suitable set of icing test facilities or procedures, it was deemed appropriate by the Federal Aviation Administration to review the entire problem of "National Icing Facility Requirements". This investigation was in response to the FAA's need. The analysis presented in the following sections attempts to review and quantify the facilities needs from the viewpoints of certification requirements, current and future aircraft operational needs, icing test facilities requirements for future aircraft research and development, facility design improvements and new facility needs. The analysis begins with a thorough review of existing Federal Aviation Regulations, advisory material, proposed regulatory reforms and specific atmospheric test requirements. This is followed by an in-depth analysis of the stable of U.S. civil and military aircraft both in 1980 and forecast through 2000. From this analysis, the operational icing test facility needs are defined in terms of airspeed, altitude, temperature, size, etc. Finally, the existing facility capabilities and shortcomings are reviewed relative to those needs derived from certification and/or operational requirements.

3.1 ICING CERTIFICATION DOCUMENTATION REVIEW

3.1.1 Introduction

The material in this section summarizes the results of a detailed review of existing icing and icing related documentation. In accordance with the Statement of Work, the review initially addressed FAR Parts 21, 23,25,27,29,33,35; Notice for Proposed Rulemaking (Ref.11); and other pertinent FAA Advisory Circulars and Technical Reports. A review of the documents showed that several of them, Parts 21 and 35, did not discuss icing certification procedures and were therefore eliminated from further review. The remaining FARs were analysed to determine their impact on future icing certification requirements.

The purpose of this documentation review was to determine the necessary certification testing requirements which have either a direct or implied impact on existing or future icing facilities requirements. This was necessary to substantiate the need for improving existing icing facilities and to specify the extent to which new National Icing Facilities may be required. Currently, it is felt that the certification criteria should play a key role in developing these needed facility requirements. However, there are also unique facilities requirements needed for icing research and development testing (Ref. 1).

The following treatment of the documentation review and analysis is comprised of five important parts. This section presents the background within which certification criteria are currently developed as well as introducing the major certification issues and the relationship between certification regulations and various aircraft types. Section 3.1.2 discusses fixed wing ice protection documentation and the different facility requirement impacts for normal (aerobatic and utility) vs transport categories. Section 3.1.3 compares rotorcraft icing regulations to the fixed wing discussion and evaluates proposed new rotorcraft ice protection regulations. Finally, Section 3.1.4 provides a comprehensive statement of the atmospheric icing conditions required for certification. These requirements are the underlying cause of many icing facility design and improvement requirements. Section 3.1.5 briefly summarizes the FAA advisory material relevant to icing certification.

There are currently a multitude of diverse regulations, procedures and criteria for obtaining certification for flight into areas of known icing conditions. The applicable rules have evolved with the aircraft operational capabilities and with the certification process itself. There are many ways of analyzing the icing certification documentation. These could include the manufacturer's viewpoint, the regulator's viewpoint, the pilot's viewpoint and even the passenger's viewpoint. However, none of these limited perspectives are independently useful for the current analysis. This is due to the fact that the current analysis is broader in scope than any of these singular perspectives is capable of addressing. The question to be investigated here (and hopefully answered) is: How do the current certification documents impact the icing test facilities already in existence or planned for the future? In order to answer this question, it is necessary to step back and examine the documentation from the combined viewpoint of all these groups affected by the certification criteria. Then, from this perspective the criteria must be dissected and reduced to the most basic technical requirements that can be related to icing test facility improvements or new designs.

The first step in this sorting out process involves the development of an understanding of which FARs impact each aircraft type and what subjects they address. FAR Parts 25 (App C) and 33 apply across the board to all aircraft types. Part 35 addresses engine airworthiness certification and contains specific requirements for icing certification. Part 25, Appendix C presents the detailed Atmospheric Icing Conditions (cloud characteristics, ambient temperatures, altitudes, etc.). This material will be presented in its entirety in Section 3.1.4. Of the remaining FARs, Parts 23 and 25 address normal category and transport category fixed wing icing certification, respectively. Section .1093 provides induction system criteria and Section .1419 provides ice protection certification criteria. In an analogous manner, Parts 27 and 29 address normal and transport rotorcraft categories, respectively. However, at the current time, icing certification criteria is provided for induction systems only. The ice protection issue for rotorcraft is currently addressed in Reference 11, which will be incorporated as 27.1419 and 29.1419, if enacted as proposed. Table 3.1 lists the FARs which will most significantly impact icing certification. While other sections do address ice protection criteria, they do not impose requirements which will greatly influence icing certification in the future. The crux of the regulation review, therefore, resolves into the differences and similarities between Parts 23.1419 and 25.1419 for fixed wing ice protection outlined in Reference 8. The next section presents the review of fixed wing criteria.

3.1.2 Fixed Wing Ice Protection Certification Requirements

The first impression derived upon reviewing these FARs is one of subjectivity. Whereas most certification criteria, as for example autopilots, avionics, flight control, systems, etc., are previously defined

Table 3.1 Applicability of Icing Certification FAR's to Fixed Wing and Rotorcraft

FAR Part No	SECTION	CONTENTS	AIRCRAFT TYPES AFFECTED			
			FIXED WING		ROTORCRAFT	
			Normal, Utility	Transport	Normal	Transport
23		Airworthiness Standards	✓			
	.929	Propeller Deicers	✓			
	.1093	Induction System Icing Protection	✓			
	.1403	Wing Icing Detection Lights	✓			
	.1416	Pneumatic Deicer Boot Systems	✓			
	.1419	Ice Protection	✓			
25		Airworthiness Standards		✓		
	.929	Propeller Deicers		✓		
	.1093	Induction System Deice and Anti-icing		✓		
	.1419	Ice Protection		✓		
	APP C	Atmospheric Icing Conditions	✓	✓	✓	✓
27		Airworthiness Standards			✓	
	.1093	Induction System Icing Protection			✓	
29		Airworthiness Standards				✓
	.877	Ice Protection				✓
	.1093	Induction System Icing Protection				✓
NPRM		Ice Protection			✓	✓
33		Airworthiness Standards: Aircraft Engines	✓	✓	✓	✓
	.67	Fuel and Induction System	✓	✓	✓	✓

and only limited deviation from specific steps are allowed, the icing certification criteria are much more general. This may be a recognition of the difficulty of obtaining precise, prespecified icing data, or it may be a means of allowing certification data collection and evaluation responsibility to be placed at the regional level. Whatever the case, the current certification criteria for fixed wing aircraft are as follows:

3.1.2.1 Fixed Wing Normal, Utility and Aerobatic Aircraft Ice Protection Criteria

Compliance with FAR 23.1419 is required for certification with ice protection. This regulation states the following requirements:

> *a) The recommended procedures for the use of the ice protection equipment must be set forth in the Airplane Flight Manual or in approved manual material.*
>
> *b) Analysis must be performed to establish, on the basis of the airplanes's operational needs, the adequacy of the ice protection system for the various components of the airplane. In addition, tests of the ice protection system must be conducted to demonstrate that the airplane is capable of operating safely in continuous maximum and intermittent maximum icing conditions as described in Appendix C of Part 25 of this chapter.*
>
> *c) Compliance with all or a portion of this section may be accomplished by reference, where applicable because of similarity of the designs, to analysis and tests performed for the type certification of a type certified aircraft.*
>
> *d) When monitoring of the external surfaces of the airplane by the flight crew is required for proper operation of the ice protection equipment, external lighting must be provided which is adequate to enable the monitoring to be done at night.*

These criteria have some potential shortcomings which must be given serious consideration. First, no definition is provided in paragraph (b) of the number of acceptable "tests", the duration of each test or the pass/fail criteria for any data to be collected. Second, the question of the relative importance of natural icing tests vs inflight tanker tests vs wind tunnel tests is not addressed. Third, no recognition is made of the vast differences between classes of aircraft within this category. Finally, FAR Part 23 is void of references to any hazardous icing conditions other than the super-cooled cloud. Other such conditions which could adversely affect safe aircraft operations are snow, freezing rain, hail, and mixed icing conditions. An icing certification process with neither the requirement nor the means to test under these conditions leaves out an essential element of the total icing hazard.

3.1.2.2 Transport Category Aircraft Ice Protection Criteria

Compliance with FAR 25.1419 is required for certification of transport aircraft with ice protection. This regulation states the following requirements:

> a) *If certification with ice protection provisions is desired, compliance with this section must be shown.*
>
> b) *The airplane must be able to safely operate in the continuous maximum and intermittent maximum icing conditions determined under Appendix C. An analysis must be performed to establish, on the basis of the airplane's operational needs, the adequacy of the ice protection system for the various components of the airplane.*
>
> c) *In addition to the analysis and the physical evaluation prescribed in paragraph b) of this section, the effectiveness of the ice protection system and its components must be shown by flight tests of the airplane or its components in measured natural atmospheric icing conditions and by one or more of the following tests as found necessary to determine the adequacy of the ice protection system:*
>
> 1) *Laboratory dry air or simulated icing tests, or a combination of both, of the components or models of the components.*
>
> 2) *Flight dry air tests of the ice protection system as a whole, or of its individual components.*
>
> 3) *Flight tests of the airplane or its components in measured simulated icing conditions.*
>
> 4) *For turbine engine powered airplanes, the ice protection provisions of this section are considered to be applicable primarily to the airframe. For the powerplant installation, certain additional provisions of Subpart E of this part may be found applicable.*

Unlike FAR 23.1419, the ice protection certification process is more precisely defined. This regulation states, once again, the need for compliance with FAR Part 25 Appendix C meteorological criteria. However, the regulation further specifies that the effectiveness of the ice protection must be evaluated in a specific manner, i.e., flight tests in natural ice supplemented by at least one or more of the alternative tests specified. But, as with the FAR 23 criterion, no reference is made to testing in other hazardous icing conditions. This omission is of some concern because it allows flight in icing conditions that are not thoroughly defined. Research is currently underway at both the FAA and NASA to better define the total icing environment.

The genesis of the difference in these two regulations is interesting and pertinent to this review since it impacts the facility requirements for transport category fixed wing aircraft and since it impacts the development of proposed rotorcraft ice protection certification procedures. The distinction between normal and transport category aircraft stems from the premise that greater margins of safety must be insured in those cases where the largest numbers of persons are involved (Reference 11) in air travel. In the case of airplanes, certification in the normal category is based entirely on the number of seats available to passengers. Any aircraft having a seating configuration of nine or less seats may be certified in the normal category, and must meet the airworthiness standards set forth in FAR Part 23. These standards require less rigid safety requirements for aircraft certified in that category, taking into account not any decreased operational hazards to the smaller aircraft, but rather the social and economic implications of a catastrophic failure of the aircraft system.

The selection of nine seats as a cutoff beteen normal and transport categories is not apparently based on any referenceable statistical data. Although it is not within the scope of this paper to investigate the reasons for the nine passenger cutoff, it can be stated with some certainty that the economic implications of providing the same high level of operational safety of the large aircraft to smaller aircraft could prove so costly as to inhibit the growth of that sector of aviation. Thus some tradeoff for cost, at the expense of safety was necessary, bearing in mind the technological state-of-the-art.

Conversely, with regard to aircraft with passenger seating configurations in excess of nine seats, wider margins of safety are required. Airplanes in this category must meet the airworthiness standards as described in FAR Part 25. Those standards define the minimum safety requirements for air transport of large numbers of passengers, and represent the realization that catastrophic failure of aircraft carrying large numbers of passengers can have a very wide ranging impact on not only the passengers and crew, but also on the public perception of the aircraft manufacturing and air transport industry as a whole. Thus, the economic penalties inherent in the enhanced safety standards, are far outweighed by the potential for loss of life, property and public trust which could result from a failure.

In summary, the review of fixed wing FARs applicable to ice protection has shown that:

1) FAR 23.1419 defines the necessity for tests to demonstrate the capabilities and limitations of the ice protection system but does not prescribe explicit test procedures or criteria.

2) FAR 25.1419 specifies the necessity and the means for obtaining ice protection certification (i.e., natural icing tests plus some combination of simulated tests).

3) Both normal and transport category fixed wing aircraft must satisfy FAR Part 25 Appendix C meteorological criteria.

4) Neither normal nor transport category airplanes are required to undergo testing in other hazardous icing conditions.

The impact of these four findings on icing test facility requirements are as follows. First, FAR Part 23 does not explicitly require natural or simulated icing tests. Second, FAR Part 25 recognizes the necessity of data from other sources and consequently impacts icing facilities requirements for transport aircraft. In particular, facilities are needed which can provide data for large components, models of components and the entire aircraft to satisfy the stated need for:

a) Laboratory dry air or simualted icing tests

b) Flight dry air tests of the ice protection system

c) Inflight simulated icing tests of the airplane or its components

Additionally, omission of the need for testing in other hazardous icing conditions, has obviated the requirement for simulation facilities to duplicate those conditions. Currently, investigations are underway by FAA and NASA to determine the requirements for icing testing in conditions other than the super cooled cloud (FAR 25, APP C). Should the assessment be made that these conditions must be tested, additional facilities, or modifications to existing facilities, must be made in order to provide the means for that testing.

Finally, the commonality of FAR 25 Appendix C icing criteria has a direct impact on icing test facility design. This impact will be discussed in depth and quantified in Section 3.1.5.

3.1.3 Rotorcraft Ice Protection Certification Criteria

The demarcation between normal and transport category rotorcraft is currently somewhat different than that for airplanes, although the rationale for the demarcation remains essentially the same. Normal category rotorcraft are presently defined as those rotorcraft with maximum weights of 6000 lbs or less. Although this criteria does not specifically address passenger seating, technological development of helicopters in the foreseeable future, at the time FAR Part 27 was incorporated, precluded the large seating configurations in rotorcraft under 6000 pounds. It should be noted also, that at the time Part 27 was incorporated, the helicopter industry was still in its infancy in comparison with the fixed wing industry, and a minimum of restrictions were desirable in order to promote this sector.

Unlike transport category airplanes, different certification requirements exist for the two sub-categories of transport rotorcraft. Category. A transport rotorcraft are all multi-engine rotorcraft which are in excess of 6000 pounds and which demonstrate adequate performance capabilities for continued safe flight in the event of engine failure. Category B transports are those large rotorcraft in excess of 6000 pounds and less than 20,000 pounds for which landing is assumed in the event of engine failure.

Any rotorcraft in excess of 20,000 pounds normally must be certificated using Transport Category A criterion, however, certification under the less stringent Category B standards is possible dependent upon the expected mission of the particular rotorcraft.

As discussed previously, the FAR's analogous to Parts 23 and 25 for fixed wing aircraft are contained in FARs Parts 27, 29 and the NPRM (Ref. 11).

For both normal and transport category rotorcraft, the current FAR Parts 27 and 29 address ice protection characteristics of the engine only, because of the multitude of roles which the engine may assume in various other aircraft applications. Ice protection standards, per se, are not outlined for the airframe and airfoils themselves as Part 27 rotorcraft are normally restricted to VFR flight only, and hence cannot legally encounter natural atmospheric icing conditions.

The proposed rotorcraft ice protection certification criteria of the NPRM has a potentially dramatic impact on rotorcraft icing test procedures and test facility design criteria. For this reason, the contents of that proposal will be discussed in detail. The proposal for FAR 27.1419 ice protection for normal category rotorcraft is as follows:

> *a) If certification with ice protection provision is desired, complicance with this section must be shown.*
>
> *b) The rotorcraft must demonstrate the capability to safely operate in the continuous maximum and intermittent maximum icing conditions determined under Appendix B of Part 29 of this chapter within the rotorcraft flight envelope. Analysis must be performed to establish, on the basis of the rotorcraft's operational needs, the adequacy of the ice protection system for the various components of the rotorcraft.*
>
> *c) In addition to the analysis and phsical evaluation prescribed in paragraph b) of this section, the effectiveness of the ice protection system and its components must be shown by flight tests of the rotorcraft or its components in measured natural atmospheric icing conditions and by one or more of the following tests as found necessary to determine the adequacy of the ice protection system:*
>
> > *1) Laboratory dry air or simulated icing tests, or a combination of both, of the components or models of the components.*

2) *Flight dry air tests of the ice protection system as a whole, or its individual components.*

3) *Flight tests of the rotorcraft or its components in measured simulated icing conditions.*

d) *The icing protection provisions of this section are considered to be applicable primarily to the airframe and rotor systems. For the powerplant installation, certain additional provisions of Subpart E of this part may be applicable.*

e) *A means must be identified or provided for determining the formation of ice on critical parts of the rotorcraft. Unless otherwise restricted, the means must be available for night time as well as day time operation. The rotorcraft flight manual must describe the means of determining ice formation and must contain information necessary for safe operation of the rotorcraft in icing conditions.*

EXPLANATION (excerpted from "Rotorcraft Regulatory Review Program, Notice No. 1")

Recent IFR certification and operation of normal category rotorcraft make icing certification a logical follow-on. Normal category rotorcraft must be able to opeate safely in the natural icing environment if certification with ice protection provisions is desired. The icing environment in which normal and transport category rotorcraft must operate is the same. Appropriate icing criteria identical to that of proposed §29.1419 is therefore proposed for Part 27 rotorcraft. See the explanation for proposed §29.1419 in the following text.

Furthermore, the proposed ice protection criteria for transport category rotorcraft (FAR Part 29.1419) is identical to proposed FAR Part 27.1419. This essentially recognizes the recent growth of the normal category of rotorcraft and the upcoming demand for full IFR certification including icing certification. The details of the rationale are stated in the explanation for FAR Part 29.1419 as follows:

> *This proposal implements existing FAA policy. The current §29.877 implies that certification of helicopters with limited ice protection or in an icing environment somewhat less severe than the most severe defined natural conditions is feasible. Contrary to the intent of the recodification, which was essentially a format change, this implication was inadvertently included during the change from CAR 7 to Part 29. This implication is also contrary to current policy.*
>
> *Considerable exchange has taken place through various mediums, including the regulatory review meetings in New Orleans and Washington, D.C., relative to the possibility of limited icing certification or to some type of operational evaluation similar*

to that currently authorized by Special Federal Aviation Regulation (SFAR) 29-2 for helicopter IFR.

The possibility of limited icing certification has been carefully considered. The difficulty in forecasting the severity of icing conditions as well as the difficulty in relating the effects of reported icing conditions among different types of aircraft, and in particular between fixed and rotary wing aircraft, makes certification for limited icing conditions improbable at this time. Other concerns also militate against limited icing certification. Limited approvals have been made in other operating situations where the pilot has control of the limiting conditions. However, such is not the case with icing. Also, with limited ice protection or with a limited environmental approval, critical situations beyond the capability of the rotorcraft to operate safely may be readily encountered without viable escape alternatives.

The possibility of authorizing an operational icing evaluation similar to that permitted in SFAR 29-2 for IFR has been given serious and careful consideration. The situation in which SFAR 29-2 was approved is not comparable to the present situation regarding icing. There was considerable basis and experience with IFR certifications before SFAR 29-2 was approved; no helicopters have been certified in the U.S. for operation in icing. The limitations involved in an SFAR 29-2 operation are controllable by the pilot; the icing environment is not. The same concerns which apply to limited icing approvals are pertinent in the case. A limited icing operational approval by the United Kingdom Civil Aviation Authority has been suggested as a basis for rulemaking by the FAA. The United Kingdom approval is contingent on operation in a specific geographical area with unique environmental conditions which always provide an escape route in the event excessive icing conditions are encountered. Such a unique case would not be applicable to this proposal. The FAA must consider a much broader spectrum of conditions and applications for certification criteria. Therefore, limited icing approval is not included in this proposal.

On the other hand, the state-of-the-art in helicopter ice protection as displayed in military and foreign helicopter tests has shown that certification of helicopters in icing to the level of safety of fixed wing aircraft is feasible. It is therefore proposed to replace the existing §29.877 with essentially the same icing environment criteria that has been used for certification of fixed wing aircraft in §25.1419, with minor changes to adapt it to rotorcraft. The changes to convert §25.1419 to the proposed §29.1419 consist of:

a) *Substituting the word "rotorcraft" in place of "airplane" throughout the section;*

b) *Changing reference to Appendix C of Part 25 in paragraph (b) to Appendix B of Part 29:*

c) Adding the words "within the rotorcraft flight envelope" in paragraph (b) in order to recognize the inherent altitude limitations of helicopers with regard to the altitude envelope of Appendix B;

d) Deleting reference to turbine engines in paragraph (d), since Subpart E of this part addresses both reciprocating and turbine engines; and

e) Adding a new paragraph (e) which contains a requirement for a means of indicating or of identifying the formation of ice on the critical parts of the rotorcraft. This is necessary as it would not be possible to visually ascertain the formation of ice on critical parts such as rotor blades or engine inlets in order to activate ice protection systems. Information for safe operation of the rotorcraft in icing conditions must also be included in the Rotorcraft Flight Manual.

f) Adding Appendix B.

At the rotorcraft review conferences, the suggestion was made to defer rule making pending completion of ongoing icing research and development (R&D). Considerable R&D has been completed with FAA participation. This R&D has established the basic feasibility of operating helicopters with adequate ice protection systems in a natural icing environment. With this recognized, much of the R&D is now oriented toward refining techniques and reducing the time and cost associated with icing testing. The proposed rules simply define the icing environment, and the FAA sees no reason to defer rule making for icing certification in light of increased usage of helicopters in IFR and projected icing certification plans. A suggestion was also made at the rotorcraft review conference that the icing environment (Appendix C to Part 25 or Appendix B as proposed for this Part) should be reassessed since it was defined by NACA 25 or 30 years ago.

Numerous icing certifications and years of operational experience with fixed wing aircraft have verified the soundness of the natural icing envelope, even though it was defined many years ago. This proposal recognizes that helicopters have a need to operate in the same basic environment as their fixed wing counterparts, excpet for high altitude portions of the envelope exclusive to the fixed wing aircraft.

It is obvious that the ice protection requirements of NPRM (Ref. 11) represent a quantum jump in the substance of the rotorcraft requirements certification versus those which are currently in use today. Not so obvious, however, are the increased icing certification requirements of normal category rotorcraft versus the requirements for normal category airplanes.

The NPRM goes to great length to justify the necessity of applying the same standards of safety to both normal category rotorcraft and airplanes and it presents compelling arguments for the adoption of the basic standard. However, an important inconsistency lies in the differences between icing certification requirements for normal category airplanes and rotorcraft. If, as is stated in the NPRM, and effort is made to apply the same basic standard to airplanes and rotorcraft of the same category, the certification requirements for the two should be the same. Since the proposal makes requirements for normal category rotorcraft essentially the same as for transport category airplanes, and identical to those for transport category rotorcraft, the same standard is not being applied. This would seem to indicate a belief that normal category rotorcraft are inherently less safe in ice than the same category airplanes. However, this assumption is not born out by the remainder of the applicable FARs. A more likely assumption is that sheer volume of expected future IFR (and thus an increased number of icing encoutners) operations by normal category rotorcraft increases the likelihood for potentially fatal encounters, and thus normal category rotorcraft merit icing protection equivalent to transport category rotorcraft. If this is the case, it is logical to apply a similar test to normal category airplanes. Since increased numbers of IFR rated GA pilots, and increased usage by those pilots of the National Airspace System in actual instrument meteorological conditions is a fact, it appears that upgrading of normal category airplane requirements is now necessary to afford crew and passengers the same level of icing protection as is being proposed for rotorcraft.

A natural follow-on to any action such as that proposed above, which would require that all categories of airplanes and rotorcraft meet the same icing certification criterion, is to provide aircraft manufacturers with a single set of procedures with which icing certification may be accomplished. The icing certification requirements as outlined in FAR 25.1419 and in the NPRM provide an excellent basis for a consistent certification procedure. The intentionally vague wording of the regulations with regard to methodology, however, leaves the certification criterion open to some interpretation by the manufacturers. This is due, to a large extent, to the realization on the part of the FAA that knowledge of the natural atmospheric icing environment is less than perfect. Until such time as industry and government come to grips with this problem and can state with great confidence what constitutes all the conditions which contribute to the formation of natural ice, no improvement can be made in the current regulations as they pertain to a specific icing certification procedure.

Since the NPRM is derived from the existing FAR 25.1419, it should be expected that some of its shortcomings would also be present in the NPRM. Specifically, the NPRM makes no reference to hazardous icing conditions other than the super-cooled cloud (FAR 25, APP C). Again, this shortcoming may be rectified upon completion of the ongoing FAA and NASA investigations.

In summary, the review of rotorcraft FARs applicable to the ice protection certification problem has shown that:

1) Proposed rules for icing tests in all helicopter categories are identical.
2) Following the logic of the proposed FAR 29.1419 "Explanation", the icing certification requirements of transport category rotorcraft should be identical to those of transport category airplanes (as proposed in the NPRM).
3) The issue has been raised that if the logic of proposed FAR 29.1419 applies to normal category rotorcraft, then it should likewise apply to normal category fixed wing aircraft.
4) Regardless of the answer to the item 3) issue, all rotorcraft must satisfy the meteorological icing envelopes of FAR Part 29 Appendix B if the proposed rules are adopted. These criteria are currently identical to the fixed wing criteria of FAR Part 25 Appendix C for super-cooled icing clouds only.

The impacts of these four findings on icing test facility requirements are the following. First, rotorcraft must have the capability of obtaining certification in artificial or simulated test environments in addition to the natural environment. Second, as stated in the reference NPRM, the state-of-the-art in helicoper ice protection as shown by military and foreign helicopter test data has shown that certification of helicopters in icing to the level of safety of fixed wing aircraft is feasible. Third, the need for icing certification facilities for rotorcraft has been generated by the demand for increased IFR certification and the capabilities of the third generation civil U.S. helicopters. Finally, basing the rotorcraft icing test criteria and test facility design/improvement requirements on the Appendix C envelope is sound for several reasons:

1) These criteria are based on a significant amount of satisfactory and safe fixed wing ice protection certification.
2) Basing icing facility requirements on the stringent requirements of this envelope will allow for the worst case or broadest facility criteria. Since new icing envelope data analysis will undoubtedly be complete prior to any new facility availability or facility refurbishment, the requirement (envelope) can be redefined and facility requirements relaxed without negatively impacting icing facility development costs or schedules.

These conclusions bring the discussion of the relationship of regulations vs facility requirements down to the most basic technical requirements from a certification viewpoint. That is, what atmospheric icing conditions must be simulated to obtain ice protection data applicable to the certification process? This question is addressed in the following section.

3.1.4 Atmospheric Icing Conditions Required for Certification

The major topic of concern in the discussion of facilities requirements for icing certification is the definition of the icing envelope. Presently, that envelope is defined in FAR 25, Appendix C and represents the basis for design criterion for any ice protection systems to be certificated under FAR 23.1419, FAR 25.1419, FAR 27.1093 and FAR 29.1093 (as well as the NPRM). Figure 3.1 and 3.2 are graphical representations of that envelope. This discussion addresses the origins, validity and applicability of those icing envelope critieria.

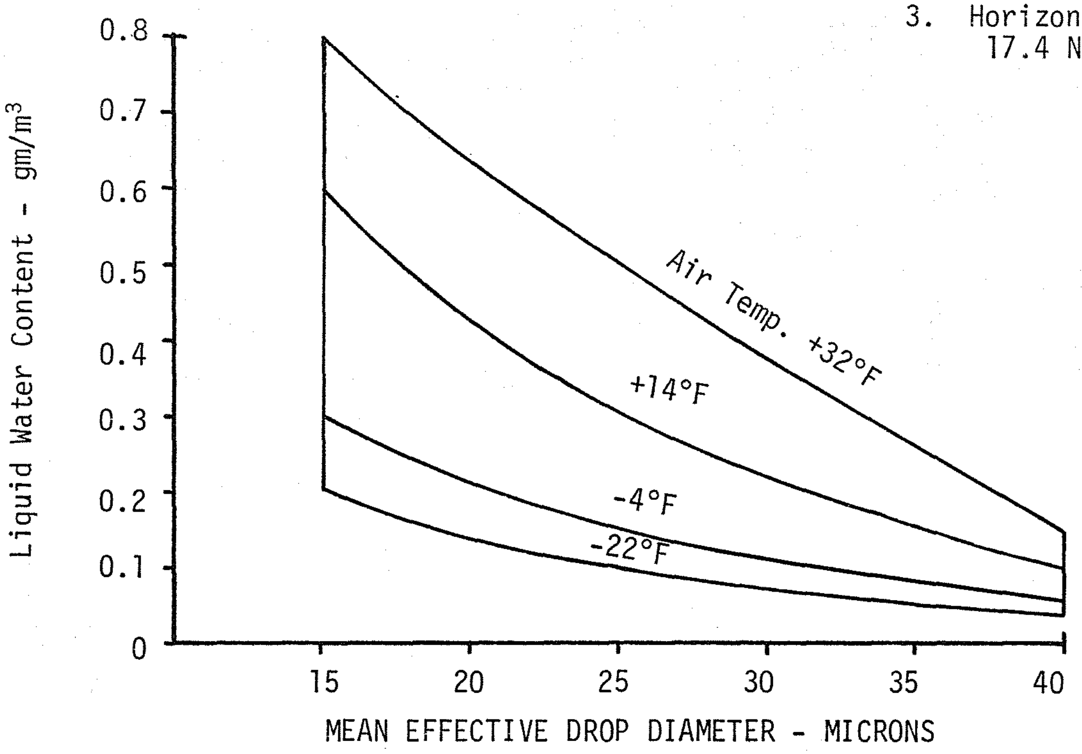
There are two basic icing envelope criteria shown in Figures 3.1 and 3.2. These are:

1) The continuous maximum envelope
2) The intermittent maximum envelope

Icing conditions can exist in most cloud types (Reference 2) with the proper temperature distribution (i.e., temperatures below 32°F). Rime ice is more common with little turbulence (stratiform type cloud formation), while clear ice predominates when turbulence and vertical velocities are present (cumuliform cloud formation). Another important factor in the formation of airframe or airfoil ice is the composition of the icing cloud with respect to Mean Effective Droplet Diameter (MDD) Liquid Water Content (LWC) and Outside Air Temperature (OAT). These factors, combined with the impact velocity of droplets on the airfoil, determine the type and severity of airframe icing on the airfoil.

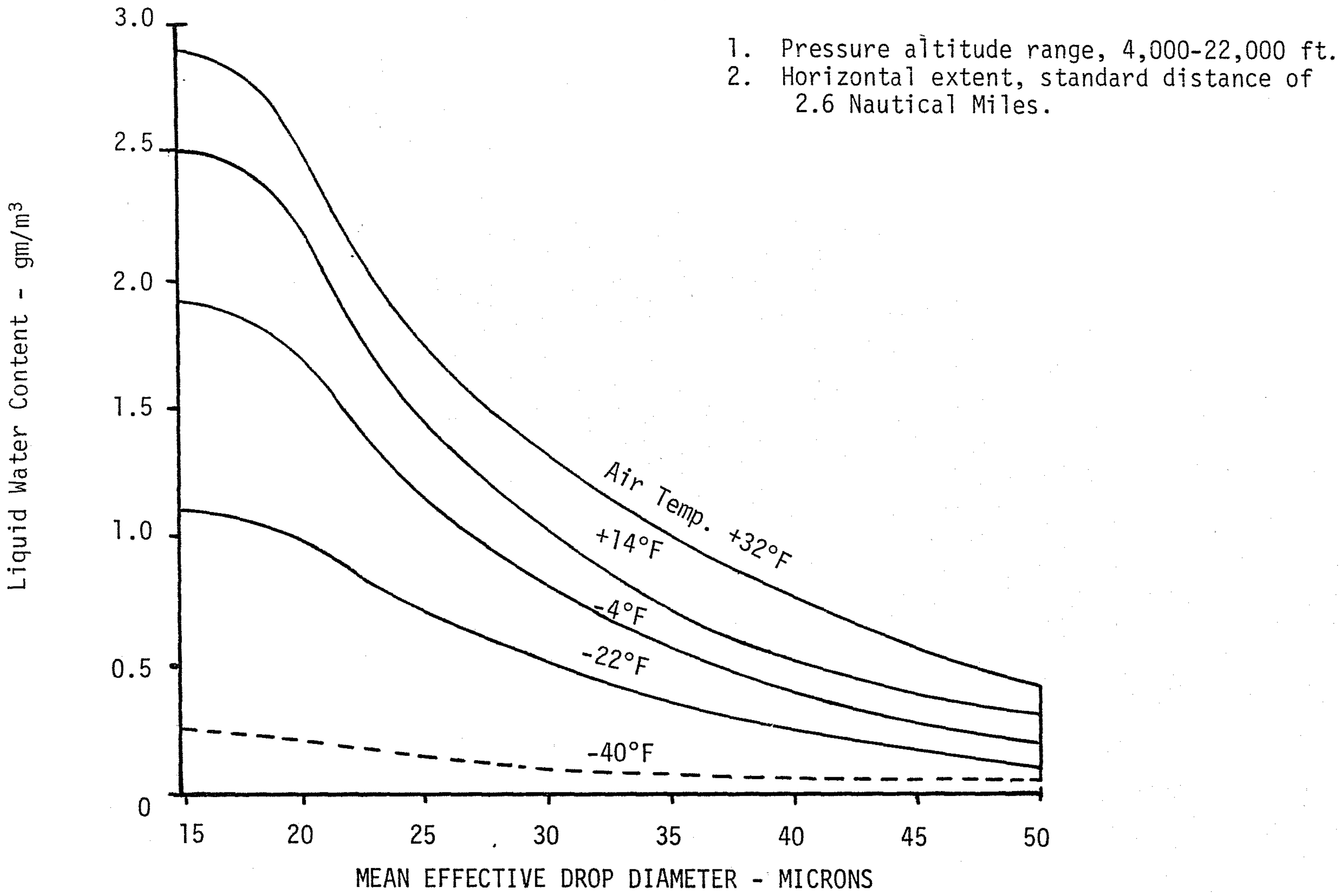
The continuous maximum envelope, Figure 3.1, defines the characteristics of a stratiform cloud with the potential for producing various types of ice, most predominately rime ice. Stratiform clouds existing at temperatures below 32° F may contain liquid water contents of .04 to .8 gm/m^3, maximum probable cloud depth of 6500 feet above the cloud base, mass (volume) median droplet diameters of 15 to 40 microns, temperatures of 32°F to -22°F, cloud base altitudes of 3,000 feet (Ref.3) to 22,000 feet, and horizontal extents of 20 miles to 270 miles. The LWC in stratiform clouds tends to increase somewhat with increasing cloud height, however, the overall trend is a reduction in LWC as air temperature decreases. It is observed that stratiform icing encounters in flight are most likely to occur at altitudes from 3,000 to 6,000 feet. Icing encounters above 22,000 feet are rare, and the minimum icing temperature appears to be about -22°F.

The intermittent maximum envelope, Figure 3.2, defines the characteristics of a cumuliform cloud with the potential for more severe icing conditions. Typical cumuliform clouds may vary from two to six miles in horizontal extent at altitudes from 4,000 to 24,000 feet, with



1. Pressure altitude range, S.L.-20,000 ft.
2. Maximum vertical extent, 6,500 ft.
3. Horizontal extent, standard distance of 17.4 Nautical Miles

Figure 3.1 Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions Liquid Water Content vs Mean Effective Drop Diameter



1. Pressure altitude range, 4,000-22,000 ft.
2. Horizontal extent, standard distance of 2.6 Nautical Miles.

Figure 3.2 Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions Liquid Water Content vs Mean Effective Drop Diameter

LWC of 0.2 to 2.8 gm/m^3, and mass (volume) median droplet diameters of 15 to 50 microns or larger with the higher LWC generally occurring at the smaller drop sizes. Because of the increased turbulence associated with the cumuliform clouds the LWC distribution is generally not as uniform as the stratiform cloud. Cumuliform icing encounters tend to be of relatively short time duration because the cloud horizontal extent is short (2.6 nautical miles), but can be about two or three times as severe as stratiform icing because of high liquid water content. Cumuliform icing encounters are most likely to occur at altitudes from 8,000 to 12,000 feet (Reference 3). Icing encounters above 22,000 feet are rare but possible up to 29,250 feet, and the minimum icing temperature appears to be about -22°F, although it has been exhibited at temperatures as low as -40°F.

The development of the meteorological data contained in FAR Part 25 Appendix C was generated to encompass all of these known characteristics of both stratiform and cumuliform clouds. In order to provide the aircraft systems designer with meteorological criterion for the development of anti-icing equipment, surveys were initiated to determine what constituted the natural icing environment. The data collected for that purpose during the late 1940s and early 1950s has since been recompiled and modified to the present format as shown in Appendix C.

The equipment used to collect the data for Appendix C represented the state-of-the art at that time. No one today, however, would suggest that that equipment could measure the weather phenomenon of liquid water content, droplet size, or even altitude with the accuracy with which it can be measured today. It should also be noted, as stated in Reference 3, that the values resulting from the survey were based on ".... study of the available observational data and theoretical considerations where observations were lacking". Additionally, it should be noted that "the majority of data utilized in the probability analysis was taken at comparatively low altitude (13,000 feet) whereas the temperature range between -4°F and -40°F represents considerably higher altitudes (Reference 3). The probability analysis which is referred to is the one which provides the basis for the FAA support of the Appendix C criteria. That analysis indicated that the probability of exceeding the intermittant maximum and continuous maximum icing envelopes was on the order of .001. The range of experience in both icing certification and actual icing encounters of fixed wing aircraft also lends credibility to the argument that the Appendix C envelopes should remain as they are currently defined. However, in recognition that the current criteria may be conservative, the FAA is reexamining the criteria.

Applicability of the Appendix C Envelope Through the 1990s

The ensuing years since the definition of the Appendix C envelope have produced a wide range of avionics and aircraft design developments which have resulted in icing certification under their applicable FARs. Additionally, the remaining years in this century will produce designs and applications which will increase the number of icing certification requests. Whether certification should be performed using the current icing envelope is a matter of great importance. Two primary factors should be addressed before reaching a conclusion. They are accuracy of the existing envelope and safety of the existing envelope.

Accuracy of the Existing Appendix C Envelope

As inferred previously, the accuracy of the envelope is questionable inasmuch as it was derived from data and extrapolation of data collected by relatively imprecise instruments. This is itself should not disqualify the envelope's use, but it indicates the possiblility at least, that the actual envelope is less than is specified. Conversely, the envelope may be larger than indicated. However, the inability, through years of icing certification trials and flight experience, to find ice in those portions of the curves where icing is expected seems to indicate that the converse is not true. That experience indicates that the envelope is smaller than currently defined.

If the envelope is smaller, it further substantiates the low exceedence probability.

Operation Within the Appendix C, FAR 25 Envelope

Based on the existing data accumulated for the formation of FAR 25 APP C envelope, the probability of exceeding values of Appendix C is .001. Thus, any aircraft which is certificated to fly in this envelope can be assured that icing conditions other than those for which it was designed are not likely to be encountered. Whether those additional conditions would influence the operation of the certificated ice protection systems is problematical. It can therefore be argued that reduction in the size of the envelope would result in a higher probability and the increased likelihood that the ice protection systems designed to lower standards could be overburdened by unexpected ice. Either of the preceding cases would result in a safety level less than is required today and thus unacceptable.

However, it has already been shown that the data collected may be suspect, in which case the actual probability may be even less than is currently expressed. It may, therefore, be possible to reduce the limits of the envelope and still retain (assuming a .001 probability as the standard) the same, low probability.

Finally, it should be determined whether or not the .001 probability of the icing envelope provides too wide a safety margin. Assuming that ice protection technology will not produce more effective and reliable systems, is the economic penalty of certification within the present envelope excessive for the additional margin of safety? This paper will not address that particular issue, due to its magnitude. However, it is one which the FAA must be aware of and consider in these times of rapidly rising costs for production and certification.

The FAR 25 APP C icing envelope must also be addressed with respect to the duration of required icing encounters. Assuming a simulated encounter with a cumuliform cloud of maximum liquid water content at an airspeed of 100 knots, the FAR would only require an encounter of approximately 2 minutes. This is insufficient time to determine the aerodynamic or performance effects of the icing encounter. Likewise a 2 hour encounter in a low LWC stratiform cloud is too stringent a requirement for testing in that condition. There exists a body of opinion that the horizontal extent requirement be eliminated in favor of a specific encounter duration for the various types of cloud formations. It is generally agreed that encounters of 15-20 minutes for cumuliform clouds (max LWC) and 1 hour for stratiform clouds (min LWC, are sufficient to satisfy the testing criteria. (References 1 and 3).

The issues that will be addressed in the remainder of this document are two fold. First, how does the current envelope relate to existing and projected aircraft performance capabilities? That is, is FAR Part 25 Appendix C sufficient and comprehensive enough to address certification through the year 2000? Second, how does the specified meteorological criteria impact national icing facilities improvements or design requirements?

3.1.5 Review of Icing Related Advisory Circulars

This section presents a brief synopsis of FAA advisory material related to icing certification. The specific elements of this review are included in the following Advisory Circulars (A.C.):

A.C. No.	Date	Subject
20-73	4/21/71	Aircraft Ice Protection
20-92	1/12/76	Anti-Icing Additives to Reduce Icing Problems in Aviation Gasoline
20-93	1/29/76	Flutter Due to Ice or Foreign Substance on or in Aircraft Control Surfaces
20-107	7/10/78	Composite Aircraft Structure
60-9	2/28/73	Induction Icing - Pilot Precautions and Procedures

This advisory material covers a wide range of technical and operational subjects as indicated by the subjects listed. In general, guidelines for methods considered acceptable by the FAA to obtain icing certification for each area are presented. The extent of testing and/or analysis and the degree of environmental accountability required differs for each subject area. However, each Advisory Circular has been developed to provide both the manufacturer and the pilot with an understanding of how icing and icing related phenomenon can impact either airworthiness, flight safety, or both.

As an example of the type of "advice" provided, AC 20-73 will be reviewed in detail since it is the most comprehensive, albeit the oldest, of the circulars reviewed. This Advisory Circular addresses "Aircraft

Ice Protection" in a tutorial sense. That is, it begins by defining the types of ice protection systems which are being used. These include:

1) Hot Air Systems
2) Electrical Resistance Systems
3) Liquid Systems
4) Expandable Boot Systems

From the explanation of how these systems are used, the Advisory Circular goes on to establish meteorological criteria for liquid water content, droplet diameter, temperature, etc. and how these data should be used for design/evaluation of aircraft ice protection systems. This basic atmospheric description is followed by a statement of pertinent factors which relate to the severity of the icing problem and the ice protection tasks for various components (airplane, rotorcraft, engine, engine inlet, windshield, propeller, etc.). The remainder of AC 20-73 specifically addresses icing tests including test methods, test procedures, finding natural ice, and the recommended procedures for type certification. However, these procedures and methods are general and advisory in nature such as: "Tanker tests have been useful as a development tool but can be dangerous or produce misleading results because of sharp variations in the water cloud and catch that come with changes in distance behind the tanker".

The "bottom line" of the review of the Advisory Circulars is that they contain no new material which would impact National Facilities Requirements. That is, they refer to FAR Part 25 Appendix C as the specific compliance criteria and offer guidelines as to how to achieve satisfactory compliance. The fact that no guidelines are offered as a means to acheive satisfactory compliance is indicitive of a major shortcoming of the existing icing certification criterion. Until such time as it is determined what is acceptable for icing certification, standardization of regulations alone will not solve the problem of inadequate icing certification. A single set of approved icing certification procedures, as well as the standards with which the procedures must be met, is a requirement to insure timely and cost effective certification of those aircraft desiring certification.

3.2 REVIEW OF CURRENT AND PROJECTED AIRCRAFT DEVELOPMENTS THROUGH THE YEAR 2000

The need for icing test facilities for the purpose of testing and certifying aircraft for flight into known icing conditions is not one which has arisen overnight. The economic prosperity and technical boom from the mid-sixties through the early 1970s has resulted in the rapid growth of the aircraft industry. Air travel and aircraft ownership is becoming more and more an essential element of the U.S. transportation needs. Military application of helicopters during that period also provided the stimulus for new growth and demand for the products of that industry. The result has been a vast increase in both the number of new aircraft types and the operational demands placed on them by their owners. Of particular importance to the subject of icing, is the demand that new, onboard navigation equipment be used to the limits of the aircraft, with the result that encounters with natural icing are becoming more and more frequent to both protected and unprotected aircraft. As the certification process for flights into icing conditions becomes both more expensive and time consuming, the need for test facilities which will allow an expedient, cost effective and safe means of icing certification becomes imperative.

In assessing the requirements for such facilities several factors must be addressed. These factors include the characteristics of the aircraft to be certified as well as their operational capabilities. Once these factors have been identified it is possible to begin planning the facilities needed to certify the aircraft.

In this section those factors will be addressed. Section 3.2.1 will address those characteristics and capabilities of current aircraft which will have an impact on the requirements for National Icing Facilities. Particular attention has been paid to the needs of rotorcraft. Likewise, Section 3.2.2 explores the impact on facilities of future aircraft developments, including their anticipated capabilities and characteristics, as well as trends in aircraft utilization and production through the year 2000. Section 3.3.3 provides a summary of research and development programs which are currently underway and outlines the overall, general impact of those programs on facility design and utilization. Section 3.2.4 summarizes the requirements imposed on the test facilities by the aircraft and research programs and provides recommendations for the incorporation of various capabilities in an array of National Icing Facilities.

3.2.1 Survey of Current Aircraft Capabilities and Characteristics

In determining the specifications for National Icing Facilities, a logical first step is an assessment of the capabilities and characteristics of aircraft presently in operation. This presents sizeable problems since several thousand different aircraft types are in operation today. It is therefore necessary to limit the number of aircraft considered in this investigation. A determination was made to limit the scope of the investigation to U.S. designs, since they will have the most immediate impact on icing facilities requirements. Inasmuch as U.S. designs are fairly representative of all aircraft currently in use, this should not skew the results of the research to a significant degree. The scope of this survey will be further narrowed by including only those aircraft with, or having the potential for, an Instrument Flight Rules (IFR) certification. Thus, certain special purpose aircraft, such as acrobatic airplanes, crop dusting aircraft and gliders, with no requirement for IFR or icing certification, will not be addressed. This survey will address the capabilities of the aircraft by first categorizing them in terms of civil transport, commuter transport, general aviation, business aircraft, military aircraft and helicopters. Aircraft in each category will be assessed with respect to the following characteristics:

1) Cruise Airspeed (or IFR airspeed if applicable)

2) Altitude/Ceiling
3) Cruise Radius
4) Length
5) Width (wingspan or rotor diameter)
6) Height

The mean value for each of these parameters have been computed, as well as the standard deviation of the parameter's distribution. From these values a rough description of the characteristics of each of the six aircraft categories has been obtained. This description constitutes a composite aircraft specification representative of that category. By analyzing the composite aircraft as well as the operational needs of each category, it was possible to provide an estimate of the specifications, in terms of size, airspeed and altitude capabilities of the National Icing Facilities.

Table 3.2 provides a summary of the mean values for each of the aircraft categories and it indicates that half of all the aircraft in each category exhibit characteristics and capabilities which are less than the values shown. Conversely, the other half of the aircraft in each category are capable of higher airspeeds and altitudes, as well as being larger in their overall dimensions than the mean length, width and height shown. For the purposes of defining the specifications for the National Icing Facilities, the mean values are only of general interest. They are helpful in providing a broad description of the aircraft categories which will derive the most use from the test facilities. Current and proposed FAR Icing Certification Requirements demand that for airplanes over 12,500 pounds and carrying 9 or more passengers and for all rotorcraft, icing certification will be contingent upon successful completion of icing trials in the natural icing environment. A short reference to Table 3.2 shows that rotorcraft, with their extremely limited cruise radius and altitude capability, will be very restricted in their ability to find the natural icing conditions required by the FARs. The same restrictions apply, although to a lesser degree, for general aviation and commuter transport aircraft, with only 50% of their number capable of exceeding the 22,000 foot altitude below which most icing conditions are likely to occur. Conversely, a civil transport, business aviation and military fighter and strategic aircraft should have less trouble in finding those natural conditions owing to their large cruise radius and altitude capability. Although the larger aircraft are better able to find natural icing conditions in which to accomplish certification testing, this procedure remains extremely expensive. However, the judicious use of component and scale model icing testing in facilities designed for smaller aircraft may reduce the time required for large aircraft to complete their icing trials in the natural enviornment.

Table 3.3 provides a comparison of the maximum limits of characteristics and capabilities within which 95% of the aircraft in each category can fit. While Table 3.2 was useful in determining which

Table 3.2 Mean Aircraft Characteristics by Aircraft Categories

CATEGORY	AIRSPEED (knots)	ALTITUDE (ft)	CRUISE RADIUS (nm)***	HEIGHT (ft)	WINGSPAN (ft)	LENGTH (ft)	NO. OF AIRCRAFT TYPES SURVEYED
Civil Transport	454		1494	41.1	133.5	146	65
Commuter Transport	158	23,500	487	15.1	52.7	44.8	17
Business Aviation	321	44,637	922	16.4	47.3	52	28
General Aviation	139	22,558	405	10.5	38.4	31	79
Helicopters	123	14,321	52	14.0	46.2	57	39
MILITARY TRANSPORT**							
Bombers/Strategic Transport	445	41,200	1160	36	125	129	24
Fighters/Tactical Bombers	530	56,000	600	16	40	54	27
Utility	254	*	*	13	50	40	32

*Information not available

**Values for military aircraft are based on best available estimates and may not reflect the actual aircraft capabilities

***Radius within which aircraft can seek natural icing conditions.
Assumptions are: - T/O with full fuel load
- IFR Cruise A/S to and from test conditions
- 1 hr on station in test conditions
- 45 min IFR reserve

Table 3.3 Aircraft Characteristics by Aircraft Categories (95% fit)

CATEGORY	AIRSPEED (knots)	ALTITUDE (ft)	CRUISE RADIUS (nm)***	HEIGHT (ft)	WINGSPAN (ft)	LENGTH (ft)	NO. OF AIRCRAFT TYPES SURVEYED
Civil Transport	676	42,000	3400	67.5	204	238	65
Commuter Transport	210	31,500	911	20.1	73.7	61	17
Business Aviation	385	58.300	1688	25.0	64.9	70	28
General Aviation	183	32,800	633	15.1	47.8	41	79
Helicopters	168	19,000	124	23.6	75.2	98	39
MILITARY AIRPLANES**							
Bombers/Stratigic Transport	650	65,000	2560	65	213	230	24
Fighters/Tactical Bombers	700	70,600	1100	26	80	82	27
Utility	338	*	*	22.9	67.5	63	32

*Information not available at time of draft submittal

**Values for military aircraft are based on best available estimates and may not reflect the limits of aircraft capabilities

***Radius within which aircraft can seek natural icing conditions.
Assumptions are: - T/O with full fuel load
- IFR cruise A/S to and from test conditions
- 1 hour on station in the test conditions
- 45 min IFR reserve

aircraft types should be accommodated by the National Icing Facilities, Table 3.3 provides information which will allow the derivation of the facilities' specifications in terms of size, altitude and airspeed criterion. As stated previously, those aircraft with the least ability to seek natural icing conditions are those in the general aviation commuter transport and helicopter categories. Therefore, as a minimum, the facilities must be capable of accommodating the range of parameters exhibited by those aircraft. Table 3.4 shows the preliminary minimum operational and dimensional requirements based on the operational and dimensional characteristics of the current aircraft which demonstrate the greatest need for icing test facilities. These minimum requirements will be further defined in additional analysis later in the report and will encompass additional requirements for advanced aircraft designs and atmospheric criteria.

The National Icing Facilities, despite goals of providing efficient and cost effective means of icing certification to those types of aircraft which encounter the greatest difficulty in finding natural test conditions, should not neglect other aircraft needs if they can be met cost effectively. The facilities capabilities would be enhanced by the incorporation of capabilities which would allow certification testing of other aircraft categories. In particular, capabilities for the certification of some military and business aviation aircraft could be incorporated by extending the facilities airspeed requirements to approximately 380 knots and its dimensions to 25x75x98 feet (height, width, and length, respectively).

Due to the immense size of several civil transport and military strategic aircraft, it may never be possible to build a facility which could perform full scale icing tests on those aircraft. However, with the verification of scaling laws now in progress, scale models of such large airplanes and their components could be adequately tested in wind tunnels sufficient in size to fit a full scale helicopter rotor. Sufficient aerodynamic data could be obtained in such a facility which would allow a minimum of inflight icing testing of those aircraft.

3.2.1.2 Special Icing Certification Problems of Helicopters

At the time of this writing, no U.S. built civil rotorcraft has been certified by the FAA for flight into known or forecast icing conditions. Although this is partly due to delays in their certification for IFR flight, the main problems are due to ice protection of rotor systems. Rotor systems do not lend themselves easily to the same varieties of ice protection systems which have been in use for many years in fixed wing aircraft. Nor do they lend themselves well to static wind tunnel tests such as can be performed on fixed airfoils with relative ease.

Since IFR capability is now being incorporated in most new helicopters and many older models, the possibility of the helicopter encountering icing conditions is increasing rapidly. The sensitivity

Table 3.4 Preliminary Minimum National Icing Facility Operational Requirements and Characteristics

PARAMETER	RANGE	UNITS
Airspeed	0 - 210	Knots
Altitude	0 - 22,000	Feet (pressure altitude)
Height	25*	Feet
Width	75*	Feet
Length	98*	Feet
Temperature	+32° to -40°	° Fahrenheit

*Dimensions apply to uniform cloud size

Note: Facilities displaying these characteristics can accomodate 95% of all helicopters, general aviation and commuter aviation aircraft.

of the helicopter's airfoils, which are responsible for the helicopter's unique performance characteristics, coupled with their high catch efficiencies, makes such an encounter by an unprotected airfoil extremely dangerous.

At the present time, certification for flights into icing conditions by helicopters must be accomplished by trials in various natural icing conditions. Here again, the helicopter's unique operating envelope works against it. As previously shown in Table 3.2, the helicopter, of all the categories shown, has the least ability to seek and fly in natural conditions. It must, therefore, wait on the ground until such conditions appear within its limited range, then fly to it to conduct the test. This is an extrememly time consuming and costly procedure which the helicopter industry estimates will require 3-5 years and could cost as much as 5 million dollars (Reference 1).

The following list provides a brief summary of problems encountered by helicopters in attaining certification for flight into icing conditions by means of icing simulators:

1) Available icing wind tunnels are not large enough to provide for the operation of the full scale rotor in a simulated icing cloud.
2) Static wind tunnel tests provide no means of determining the effects of G forces on ice accretion and shedding.
3) Full scale rotor tests in large cold rooms have been of marginal value due to the interference effects of the facilities' interior walls.
4) Helicopter flight tests in simulated icing conditions cannot presently be accomplished in the transitory phase of flight from hover and takeoff to cruise flight.

In specifying the requirements for a National Icing Facility, these aspects of helicopter operational and certification problems must be taken into account. The existing icing facilities all demonstrate deficiencies in their capability of producing a test environment in which the helicopter rotor system's aerodynamic and ice protection characteristics may be evaluated. These deficiencies will be addressed specifically in Section 3.3 and recommendations will be made to provide a more complete test environment for helicopters.

3.2.2 Impact of Future Aircraft Development Trends on National Icing Facilities Requirements

The National Icing Facilities must be adequate for testing and certification of not only the aircraft currently in operation, but must also be adequate, both quantitatively and qualitatively, for testing and certification of new aircraft designs. The projected new designs will impose additional requirements on existing facilities because of improved operational capabilities and design characteristics. In addition to these effects, it is also important to be able to predict trends in aircraft utilization which may place additional, quantitative requirements on individual facilities. The following sections will outline these potential impacts.

Impact of Projected Aircraft Developments

The next generation of aircraft will display many characteristics which will clearly separate them from the aircraft actively in use today. Among these characteristics are fuel efficiency and the relatively low noise levels with which they will be able to operate. Aircraft development in three particular areas, however, hold the potential for imposing the greatest impact on the requirements for National Icing Facilities. Those developments which are of greatest importance to facility specifications are in the areas of size, speed and navigational capabilities.

In addressing the subject of the impact of both size and speed capabilities of future aircraft developments on the requirements for National Icing Facilities, it is necessary that some standard, which will define what the maximum capabilities of the facility will be, be applied to the new developments in order to preclude unnecessary and costly improvements to existing facilities. As discussed previously, the ability of a particular aircraft to find, and be tested under natural icing conditions should have a significant influence on the national facility requirements. Thus, it is not necessary to design a facility around the unusual size of an aircraft, such as a C-5A Galaxy, since it is capable of finding natural conditions in which to be tested. It should be noted that the facilities requirements developed for smaller aircraft, while not driven by certification testing needs of aircraft such as the C-5A, could still provide a suitable, cost effective, testing environment for many of their testing needs.

The enormity of the potential problems associated with providing a simulated icing environment is graphically illustrated in Figure 3.3 (and Table 3.5). These indicate that if previous trends in the development of large aircraft continue the possibility exists that aircraft as large as 4,000,000 lbs gross weight may be introduced by the end of the century. The development of a large aircraft such as the one described, however, is largely dependent on its military and commercial applications. Although very large aircraft have been conceptualized, at present they offer no new capabilities (which are in high demand) that are not offered in current designs, and thus are not expected in the near term.

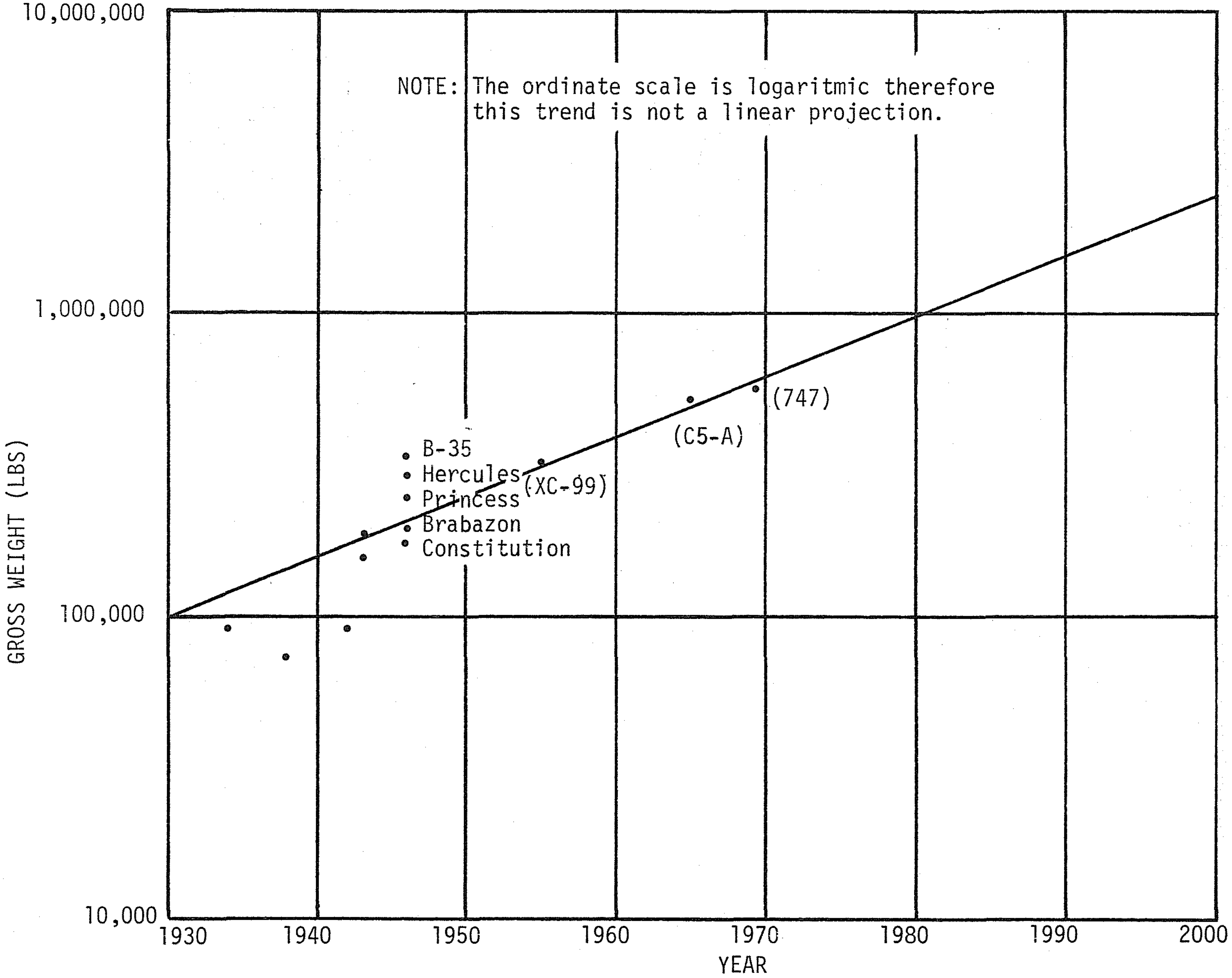


Figure 3.3 Projected Trend In Aircraft Weight By Year

Table 3.5 Large Aircraft Trends**

YEAR	MANUFACTURER	MODEL	GROSS WEIGHT (lbs)
1929	Junkers	G-38	66,000
1929	Dornier	DO-X	123,200
1933	Goodyear	Macon	403,000
1934	ANT	20	95,495
1938	Boeing	314	84,000
1942	Messerschmitt	323E-2	99,225
1943	Junkers	JU 390	160,930
1943	Blohm & Voss	BV238V-1	208,000
1946	Lockheed	Constitution	184,000
1946	Bristol	Brabazon	290,000
1946	Saunders-Roe	Princess	330,000
1946	Hughes	Hercules	400,000
1946	Northrop	B-35	209,000
1955	Convair	XC-99	400,000
1965	Lockheed	C-5A	769,000
1969	Boeing	747-200B	775,000

**Supplement to Figure 3.3 "Trends in Aircraft Weight by Year"

Although large transport airplanes are capable of testing in natural conditions, the certification process remains extremely expensive and time consuming. However, to provide simulated icing environment to test large aircraft would require drastic modification of existing facilities or the construction of dedicated new facilities which would offer a minimal (if any) advantage to large transport users. Thus, large transport aircraft should not affect size specifications of the icing simulation facilities.

If very large airplanes are developed in the near term, large propulsion systems would necessarily have to be developed to drive them. Most of the conceptual large aircraft utilize a series of relatively small engines for propulsion. However, in some cases large engines two to three times the size of the largest engines now in service are envisioned (Reference 27). These engines could not be adequately tested in existing engine icing facilities. However, the addition of a large facility such as the Altitude Wind Tunnel should be sufficient for the purpose of ground vertification of the engine. Here again, final verification of the engine would be possible by flights into actual conditions or by flights behind the various existing icing tankers.

It is anticipated that helicopters will also be developed which will be much larger than those presently in service in the United States. Designs for large transport rotorcraft have been seriously proposed to meet the expected requirements of the late 1980's and 1990's. Large scale tilt rotor, tandem rotor and quad rotor concepts have been proposed as a means to provide transportation to large numbers of passengers over distances up to 500 miles. As with large airplanes, large helicopters will have a greater ability to seek and find natural icing conditions for certification purposes than their smaller counterparts. An icing facility designed to provide full scale laboratory icing tests on rotating airfoils of approximately 50 feet in diameter, would be capable of testing 1:2 or 1:3 scale models (providing that scale modeling techniques are verified) of the rotors of large helicopters and would allow full scale testing of its engines, wind shields and other critical components.

Of more importance to facility requirements will be the relatively modest increases in speed which will be derived from improved rotorcraft and V/STOL technology. For pure helicopters, the increases in airspeed will be limited due to the problems of retreating blade aerodynamics and as such should not impose any new requirements on National Icing Facilities. One design presently being tested is intended to eliminate the problems of the retreating blade. The Advancing Blade Concept (ABC) rotorcraft incorporates two counter-rotating blades on a single mast. Although not yet proven, a design similar to this may be capable of airspeeds up to 300 knots.

Hybrid aircraft which incorporate flight characteristics of both helicopters and airplanes, such as the tilt rotor XV-15, will dramatically increase the airspeed capabilities of rotorcraft. The advantages of this type of aircraft lies in its ability to operate from confined or unimproved areas in its vertical takeoff and landing configuration and then transitioning to a high speed configuration (up to 350 knots) for the enroute segment of its flight. The XV-15 is expected to evolve into a civil transport or military transport aircraft capable of carrying up to 30 passengers to distances in excess of that permissible by pure helicopters. (Reference 16.)

The success of these designs in attracting a commercial market for their capabilities as well as interest for military applications, could result in many derivative models being produced, each with the requirement for flights into icing conditions. Although these aircraft may be capable of larger cruise radii than pure helicopters, their ability to find natural icing conditions will not be so improved that they could easily adapt to that task. Modification of the airspeed requirements of the facility are therefore in order to permit the certification of such rotorcraft in simulated conditions, should the need arise.

Of all the aircraft developments anticipated during the next 20 years, the one most likely to have a significant impact on National Icing Facilities is the improvement of onboard aircraft navigational equipment. Improvements in navigational equipment will allow a more effective use of the National Airspace System. Research is being conducted by NASA, DOD, FAA and industry which will allow instrument operations, including takeoff and landings, in near zero-zero conditions. Specifically, the research is directed towards allowing decision heights down to 50 feet AGL for instrument landings at remote sites, independent of external navigation aids. Several concepts are being independently analyzed as means to provide this all weather capability. One navigation concept is based on the combination into a single system of the capabilities provided by the Global Positioning System and an advanced Inertial Navigation System. Other concepts involve the use of active and passive sensing techniques, such as weather radar, infra-red video and radiometric. Development of this tremendous capability would have a very great impact on helicopters, giving them the same flexibility for operations in instrument conditions which they already possess in visual conditions. This enchanced capability will drive more and more aircraft towards certification in icing conditions in order to take full advantage of the opportunities which will result from the improved onboard navigational capabilities.

The impact, in this case, on National Icing Facilities, will not be in terms of size or airspeed capabilities but rather in the capacity of the facilities to absorb the increased workload. It is necessary, therefore, to plan for increased utilization of the facilities as these developments are incorporated in the helicopter fleet. This may require augmenting existing icing facilities with duplicate facilities so that timely development and certification efforts may be performed utilizing the test facilities.

The necessity for National Icing Facilities could be mitigated by the introduction of completely reliable ice and snow protection systems for all aircraft types. Table 3.6 provides a list of conceptual ice protection systems as well as those which are in use today. Although each has several distinct advantages, none are presently capable of filling the requirement of being totally reliable and totally effective. The fact that ice protection systems are not wholly effective at this time indicates that, in addition to the role of National Icing Facilities in the certification process of aircraft, test facilities must be capable of assisting in the development and testing of ice protection systems. This particular task is inherent in its primary mission of affording an effective means for the icing certification and testing of aircraft, but is mentioned to insure that adequate facilities are available to perform the task.

3.2.3 Impact of Aviation Growth Trends on Icing Facilities Requirements

In Section 3.2.1, preliminary operational limits and size characteristics for proposed National Icing Facilities were presented. These specifications were based on providing the greatest coverage to those aircraft types which had the greatest need for certification in simulated icing conditions as opposed to certification in natural icing. That need evolved from the inherent inability of the particular aircraft types to climb to or range to areas where test conditions were occurring, thus delaying the certification process until those conditions were readily available. In this section, those facility specifications developed previously in Section 3.2.1, are further supported by trends in aviation growth.

As stated previously, encounters with super-cooled clouds, freezing rain and mixed icing conditions are a function of the aircraft's altitude, outside air temperature, liquid water content and mean effective drop diameter of the atmosphere through which the aircraft is traveling. Of these parameters, the pilot can exercise influence on but one, his altitude (and thus, temperature). Ideally, the pilot would have the capability of climbing out of or descending under icing conditions. Unfortunately, the operating limits of his aircraft often prohibits climb, and terrain and airspace separation often inhibits his ability to descend. Figure 3.4 shows the percent of altitudes to which various types of aircraft are assigned during IFR departure. Bearing in mind that the maximum altitude in which ice is formed is approximately 22,000 feet MSL, the figure illustrates that by specify-

Table 3.6 Current and Conceptual Ice/Snow Protection Systems

SYSTEM NAME	DEICE OR ANTI-ICE	ICE/SNOW PROTECTION MECHANISIM	APPLICATIONS	SHORTCOMINGS
Electrothermal	Deice and Anti-Ice	Heater blanket incorporated in the protected surface provides heat to cyclically deice system or prevent ice accretion.	Wing, rotor, windshield pitot, engine inlets, empennage	High power demand unless used cyclically. Very expensive Excessive weight for helicopters.
Hot Air	Anti-Ice	Protected surface acts as double skinned heat exchanger through which engine bleed air transmits heat to prevent ice build-up.	Engine, engine inlets, wings, empennage, windsheilds	Limited applications to rotating airfoils. Engine performance penalties.
Hot Oil	Anti-Ice	Similar to hot air system, except engine oil or transmission oil is the heat exchange medium.	Engine front frames, nose gearbox fairings	Insufficient heat for immediate deice/anti-ice. Fluid leakage could cause engine malfunction.
Chemical	Anti-Ice	Freezing point depressant flows chordwise across airfoil preventing ice accumulation	Rotor blades radomes, wings windsheild	Fluid flow distributions are uneven. Fluid capacity limited to flights of short duration.
Ice Phobic	Deice	Ice adheres to coating at airfoil leading edge. As ice mass increases, shear stresses develop causing tearing of the coating and ice shedding	Rotor Blades	System seriously degraded after several icing encounters in a single flight. R&D phase only.

*TABLE CONTINUED NEXT PAGE

Table 3.6 Current and Conceptual Ice/Snow Protection Systems (Continued)

SYSTEM NAME	DEICE OR ANTI-ICE	ICE/SNOW PROTECTION MECHANISIM	APPLICATIONS	SHORTCOMINGS
Electro-Impulse	Deice	Skin of air foil is deformed under ice causing stress cracks in the ice and subsequent ice shedding.	Rotor blades, wings, empennage	May cause permanent deformation of skin material Fatique Noise
Pneumatic Boot	Deice	Flexible boot jackets the airfoil leading edge. Inflation of the boot causes stress cracks and subsequent ice shedding.	Rotor blades, wings empennage	High G-load and tip speeds of helicopter rotors impose severe environment on the boot material. Effects of boot inflation on rotor aerodynamics are not known. R&D phase only.
Micro-wave	Deice and Anti-Ice	Microwave energy transmitted through airfoil leading edge causing local ice shedding. Remaining energy heats airfoil surface causing progressive ice shedding.	Wings, rotors, empennage	Still in conceptual/ model stage of development.
Vibratory	Deice and Anti-Ice	Vibrations along airfoil leading edge inhibits ice buildup and causes stress fractures in and subsequent shedding of accreted ice.	Wings, rotorblades	System may cause damage to rotor and aircraft components R&D phase only.

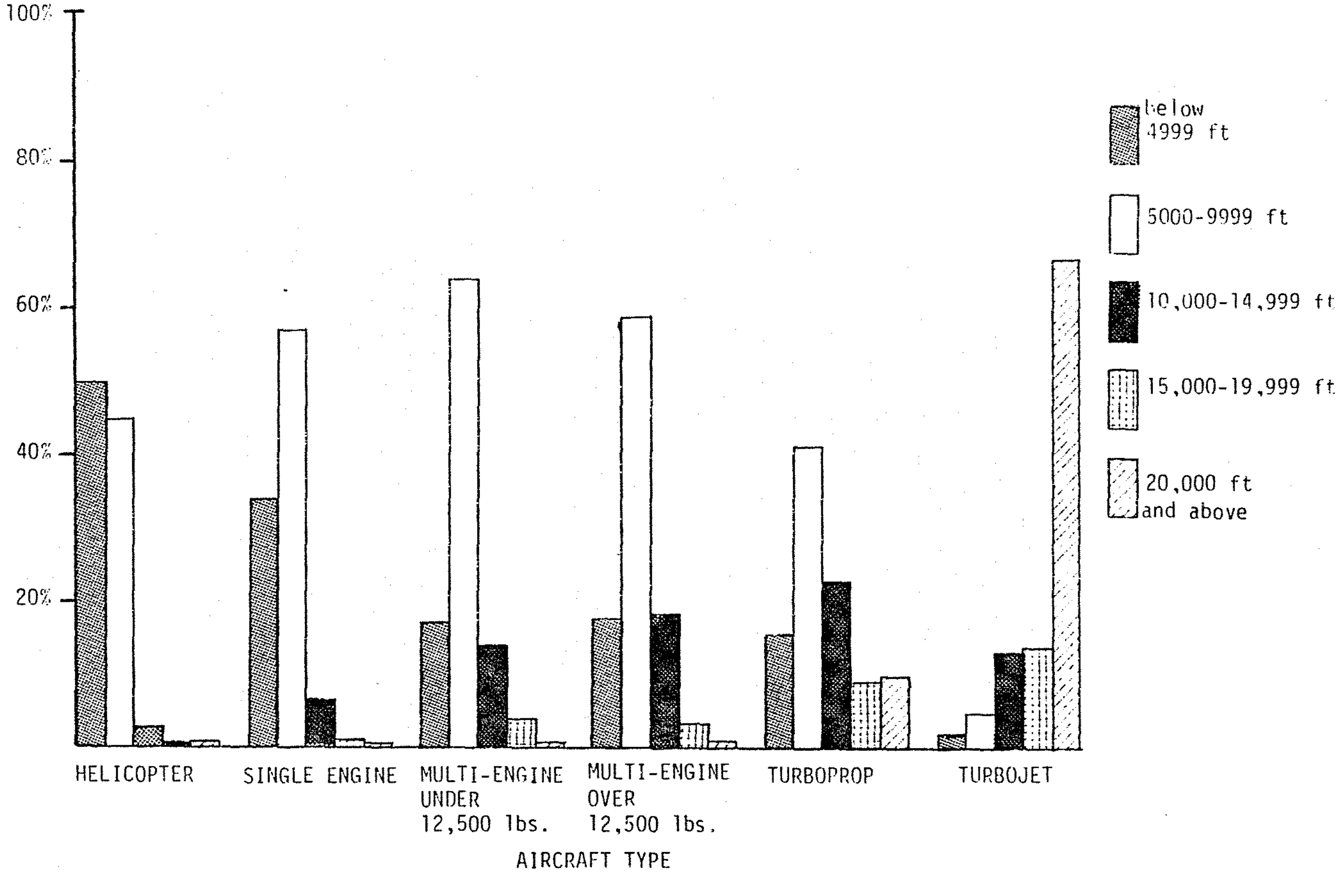


Figure 3.4 Percent of Assigned Altitudes from ARTCC and ATC for each Aircraft Type for Peak Day IFR Departures (Ref. 31)

ing facility capabilities to meet the requirements of helicopters, general aviation and commuter aviation (depicted in the figure as helicopters, single engine, multi-engine under 12,500 lbs and multi-engine over 12,500 lbs), the facility will be capable of accommodating those aircraft which frequent the icing environment the most, and which are the least capable of finding natural conditions for test purposes (e.g., 95% of helicopter IFR operations are below 10,000 feet; 90% of general aviation IFR operations are below 10,000 feet)(Ref.31).

The basis for the preliminary specifications of National Icing Facilities can be further substantiated by analysis of the projected growth rates of the various types of aircraft. Figures 3.5, 3.6, 3.7 and 3.8 provide growth summaries in terms of the expected growth in actual numbers, annual growth rates and the percent of each type (helicopters, general aviation, transport and military aircraft) of the total national aircraft population. These figures were derived from FAA annual aviation forecasts compiled in 1978 (Reference 29), and represent the most recent forecast available. They provide a tool for broad generalization. The forecasts used in this study were based on an average economic environment, and are subject to change with any long term change in the nation's economic climate. It should also be noted that the forecasts presented by the FAA were of 10 year duration. Some license has been taken in this investigation by extrapolation of the forecast through the end of the century, using a linear approximation.

As shown in the figures, the current forecast is for a general decline in aviation growth rates, although annual growth of the industry will continue. The figures (Reference 29) show that through the 1990's general aviation will grow at a faster annual rate than either helicopters, transport or military aircraft, with an average annual growth rate during that period of approximately 4%. Helicopters will grow at the next highest rate, approximately 2%*, followed by military and civil growth ranging between zero** and 1.6% annual growth. The significance of these figures does not reside in the numbers themsleves, but rather in the overall trends they portend. That is, that general aviation and helicopters will continue to grow at faster rates than other segments of the aviation community. Recent articles in helicopter journals bear this fact out. During the past year, for example, it has been estimated that the number of helicopters in service grew by 20%. In view of this growth, it is important to note a comment by Gerald Tobias (Reference 24), former President of Sikorsky Helicopter Division of United Technologies, "... that 80% of the growth in helicopters during the remainder of this century would be in helicopters under 6000 pounds".

Industry growth rates, by themselves, tell little about the future requirements for National Icing Facilities. However, inherent in growth rates lies the potential for new designs. It is expected, therefore, that higher growth rates in both general aviation and helicopters

NOTE: *Helicopter growth is somewhat offset by declining military helicopter growth

**Military data not available past 1986

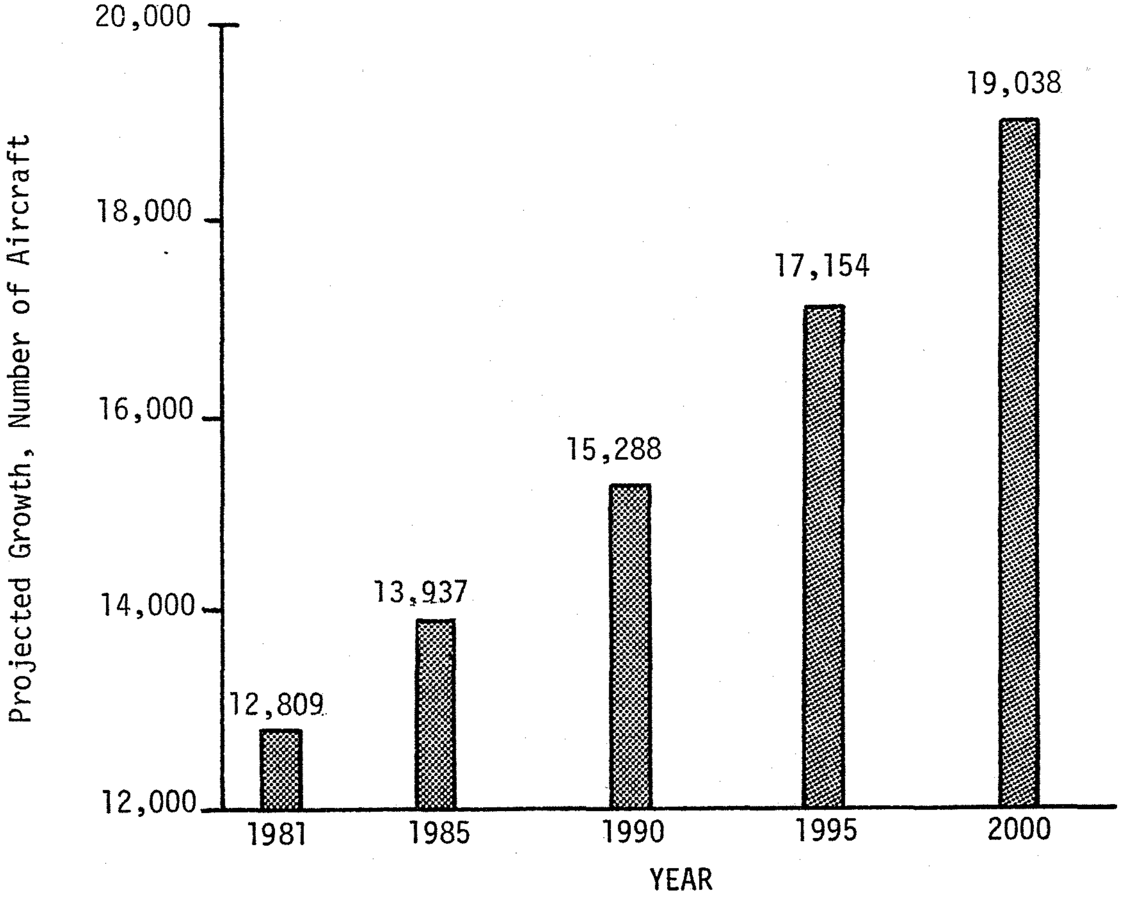


Figure 3.5 Helicopter Growth Summary, 1981-2000 (continued on next page)

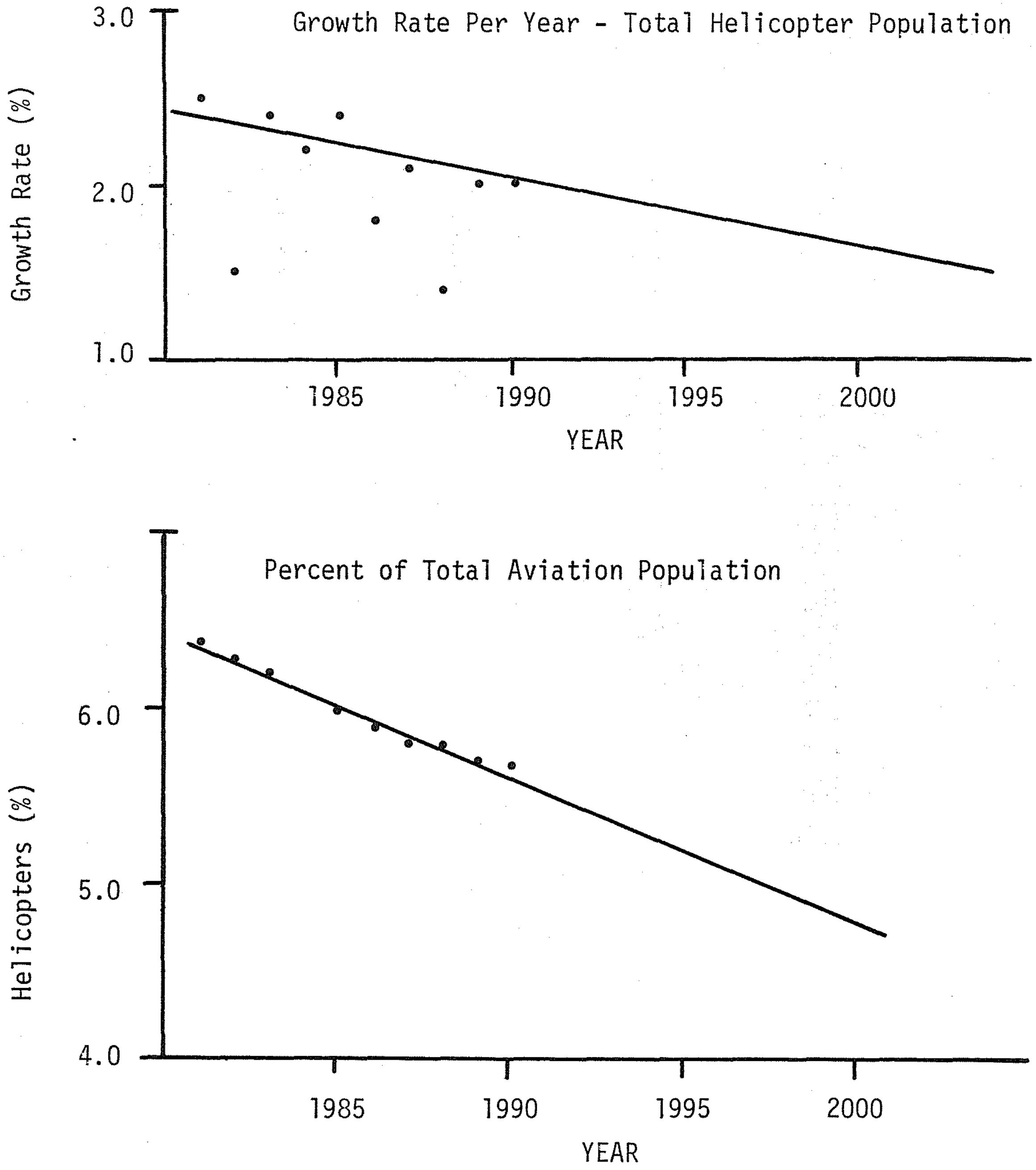


Figure 3.5 Helicopter Growth Summary, 1981 - 2000 (continued)

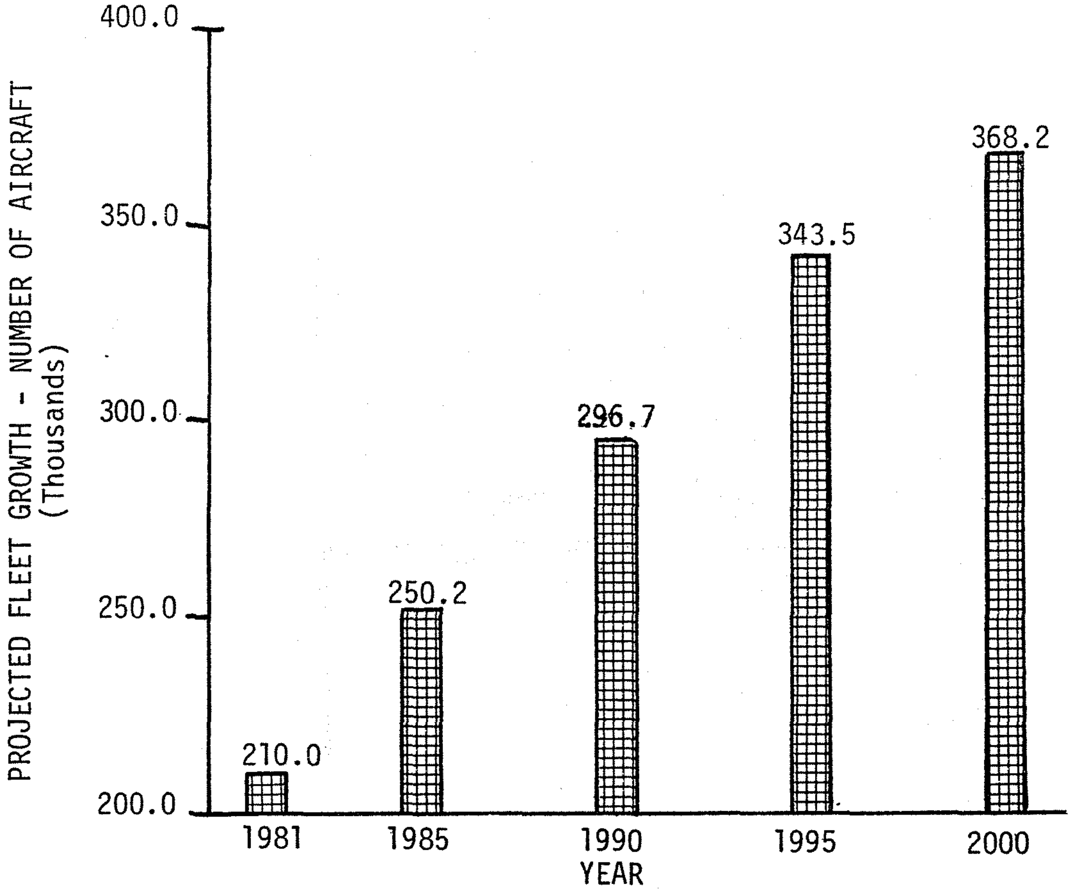


Figure 3.6 General Aviation Growth Summary 1981 - 2000

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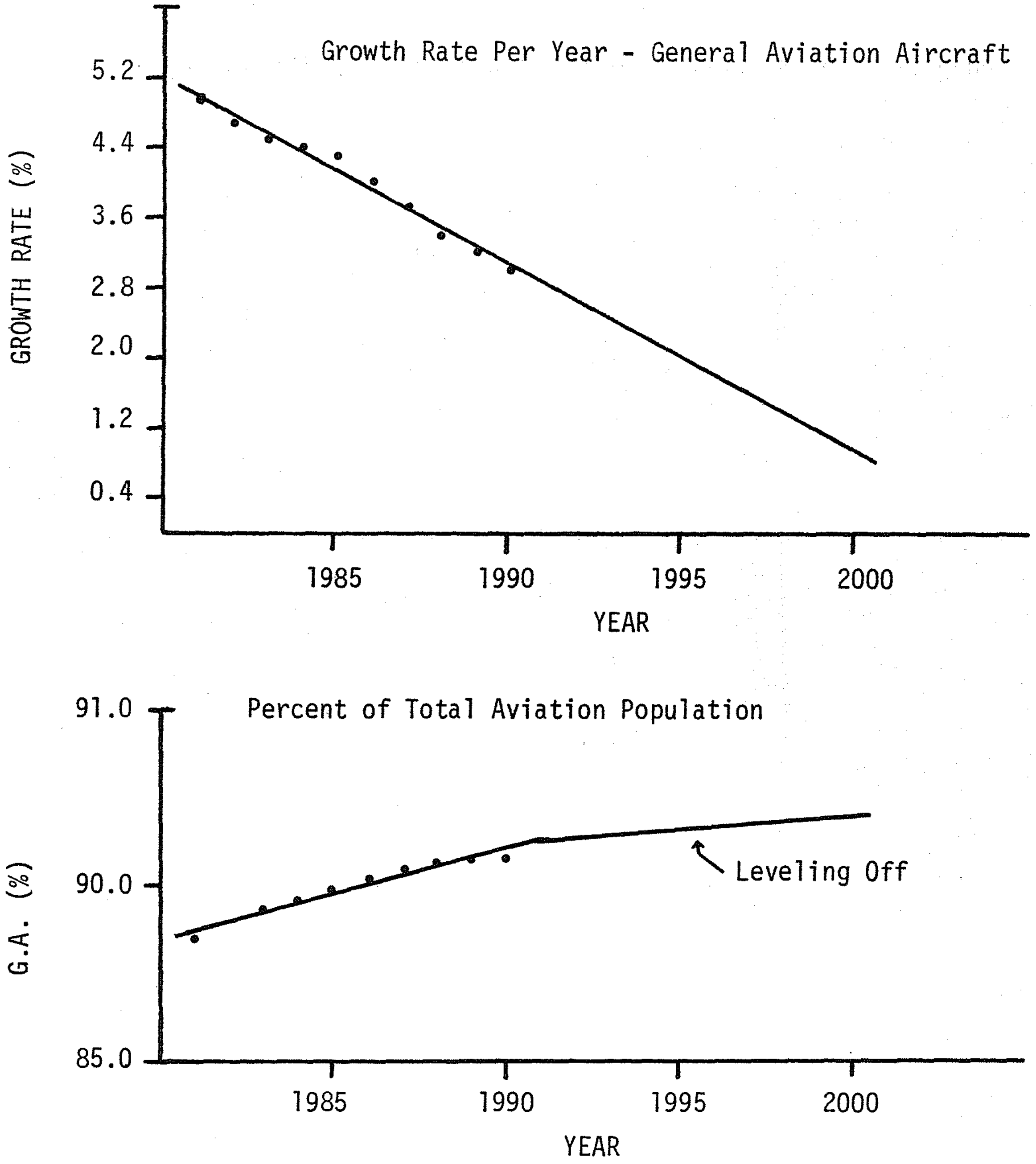


Figure 3.6 General Aviation Growth Summary 1981 - 2000 (continued)

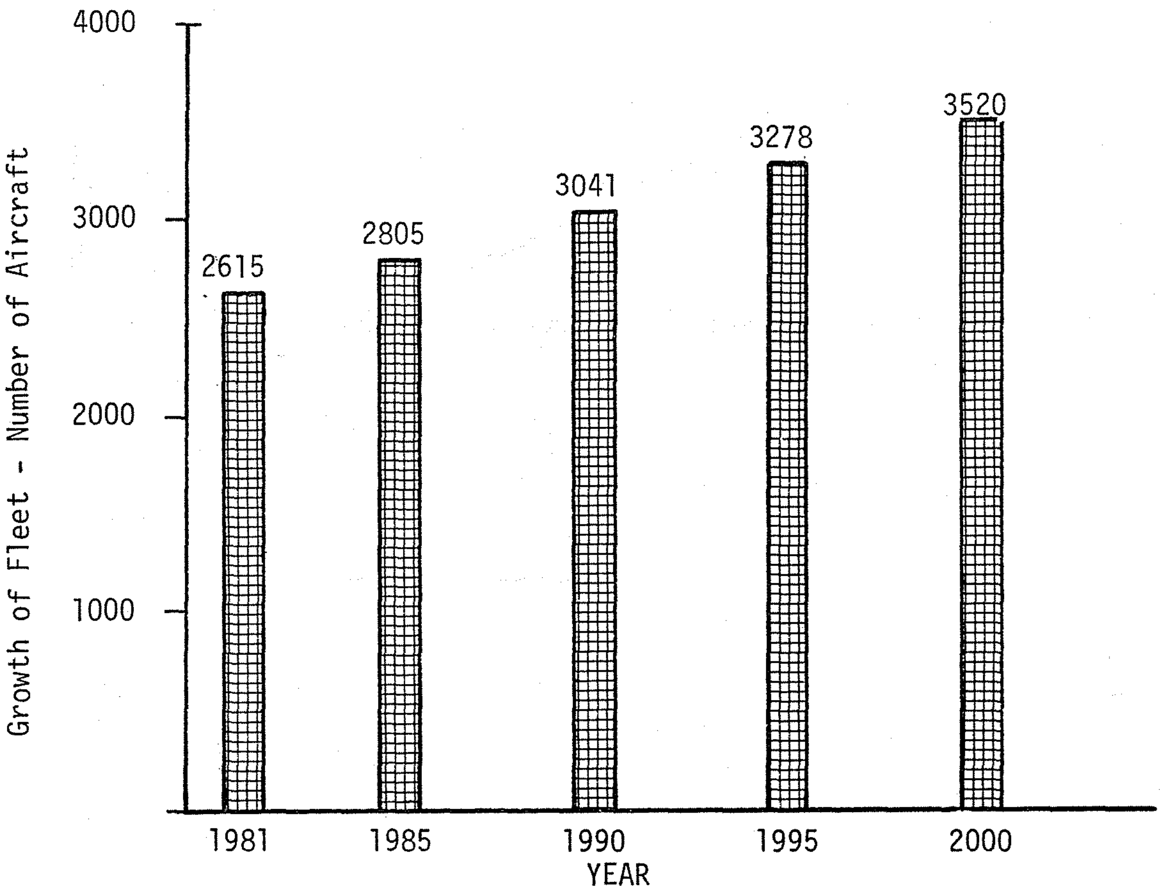


Figure 3.7 Civil Transport Growth Summary (figure continued on next page)

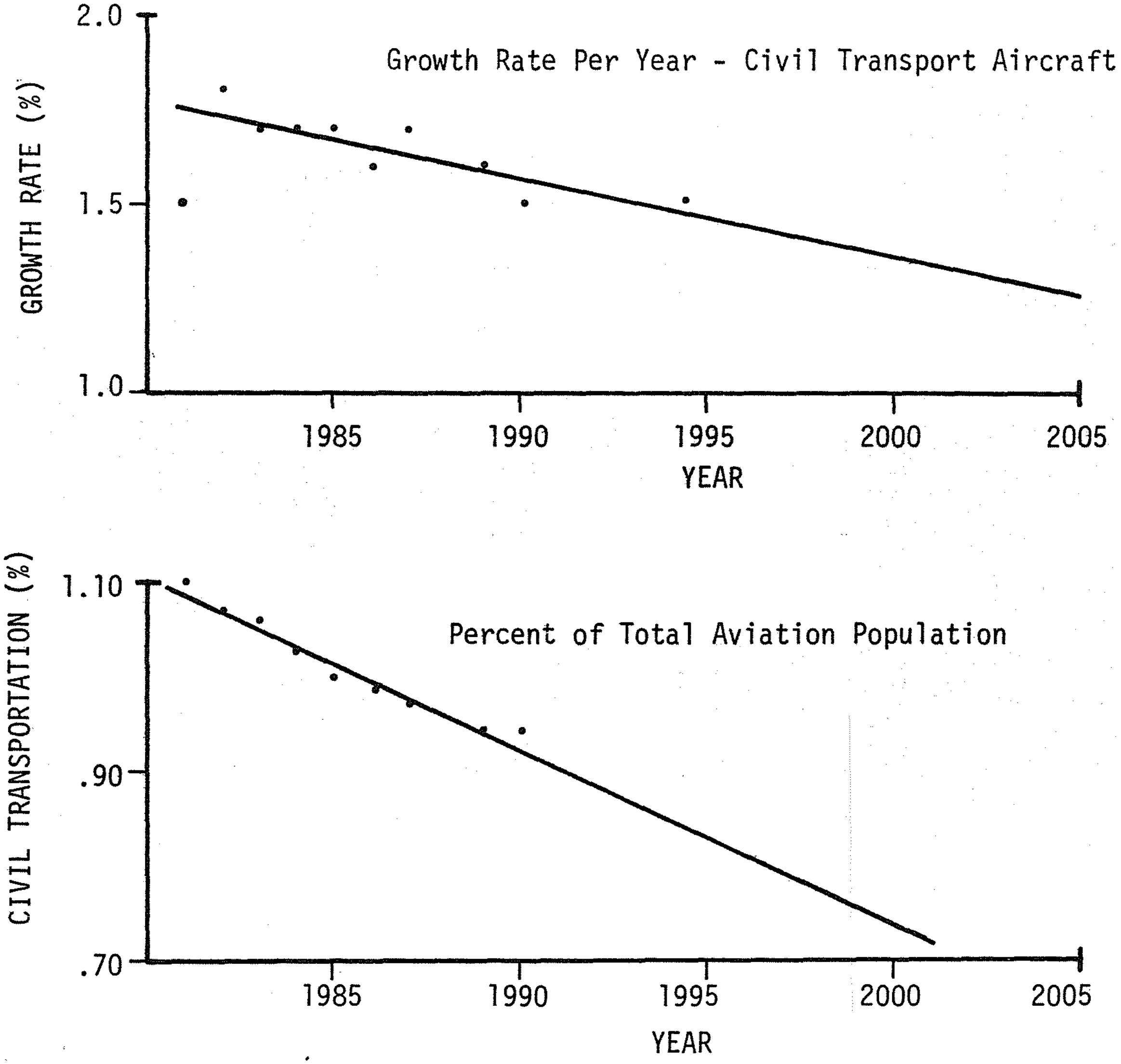
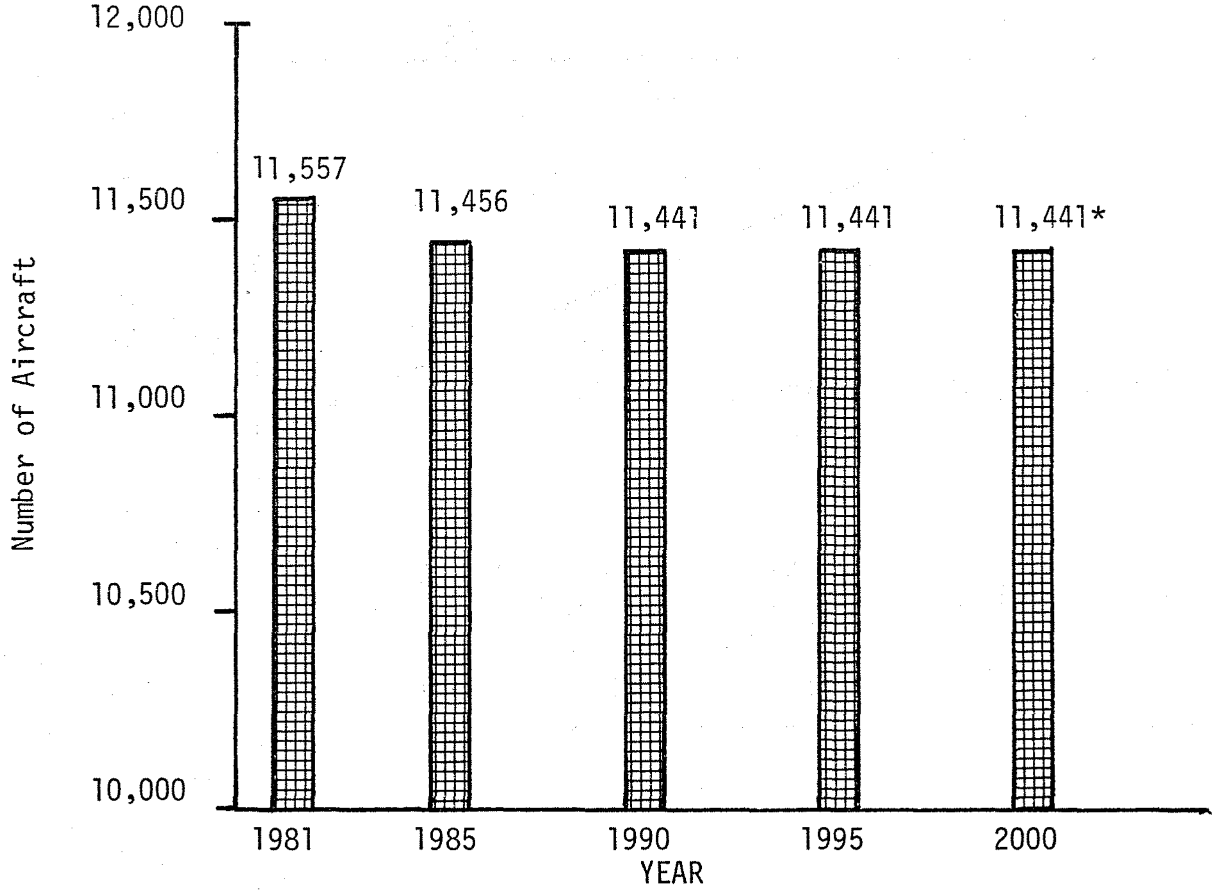


Figure 3.7 Civil Transport Growth Summary (continued)



*Detailed planning information not available beyond 1986
1987 - 2000 projected at 1986 level.

Figure 3.8 U. S. Military Aircraft Growth Summary 1981 - 2000
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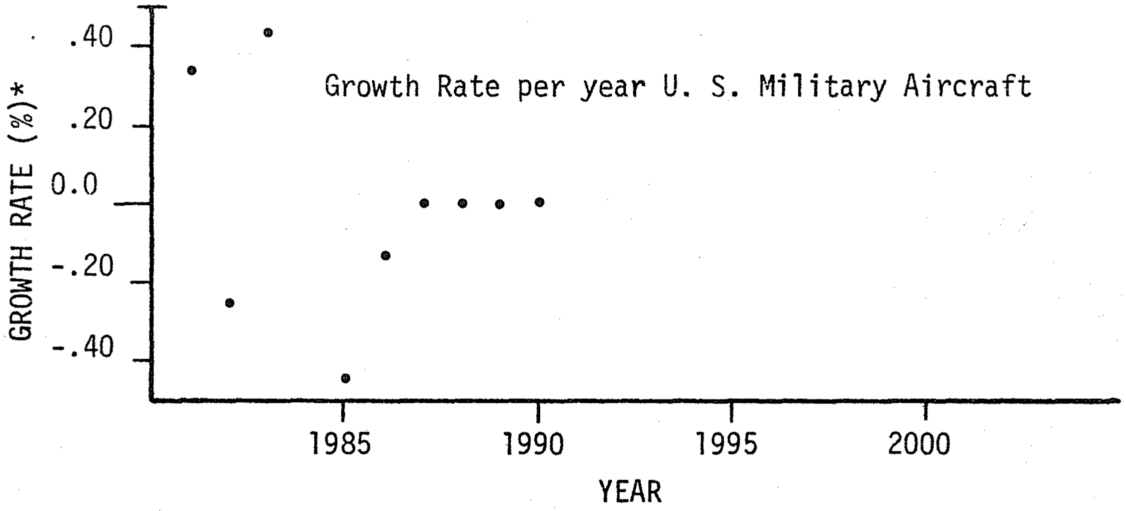
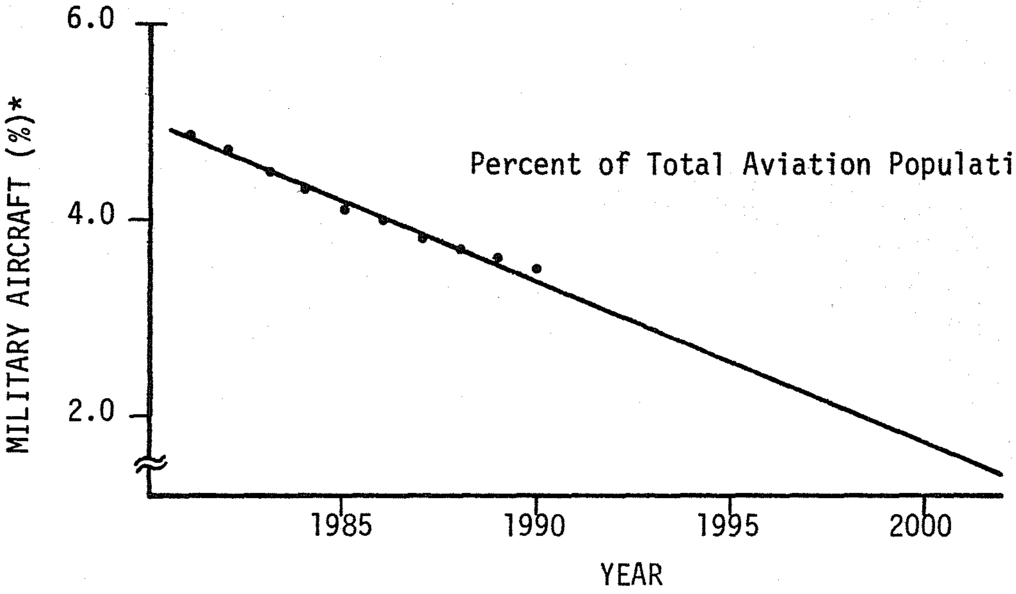


*Detailed planning information not available beyond 1986.
1987 - 2000 projected at 1986 level.



*Detailed planning information not available beyond 1986.
1987 - 2000 projected at 1986 level.

Figure 3.8 U.S. Military Aircraft Growth Summary 1981 - 2000 will result in more new designs than will be forthcoming from the military and civil transport secors.

In order to quantify this intuitive assumption, the following analysis was performed to establish at least a rough order of magnitude estimate of the number of new aircraft designs in these general categories which might be expected to appear in the industry throughout the remainder of the century. Since current projection techniques in use by the Federal Aviation Administration and the Aerospace Industries Association only forecast overall fleet size, general fleet mix, numbers of aircraft operations and passenger movements, a different technique was employed to establish these planning purpose numbers.

Each general category of aircraft types was subdivided according to specific known airframe design/manufacturing organizations, (see Appendix B), and the historical pattern of introduction of new models over the past twenty years by the manufacturers was investigated. These historical data were then projected into potential numbers of future designs to produce the numbers contained in Table 3.7. A detailed explanation of the methodology, ground rules and raw data used to make the projections can be found in Appendix B. The values shown in Table 3.7, while not definitive in the sense that they represent only known aircraft developments, do provide reasonable estimates of the overall magnitude of the demand for icing research, development and certification facilities in the forseable future.

Table 3.7 Projected New Aircraft Designs, 1981-2000

AIRCRAFT CATEGORY	NEW DESIGNS	NEW DESIGNS REQUIRING ICING CERTIFICATION
Transport	11	11
Business Aviation	25	25
Helicopter	32	26
General Aviation	42	34

NOTE: It is assumed that all transport and business aircraft, and 80% of GA and helicopter aircraft will require icing certification. Transport category includes all airplanes with a seating configuration of more than 10 seats.

In addition to indicating the magnitude of the demand for icing certification and research and development testing, the table also provides substantiation for the use of rotorcraft characteristics and capabilities as design criteria for the icing test facilities. Table 3.3 indicates that more than 95% of business and general aviation aircraft could be tested in facilities designed for rotorcraft. Nearly 90% of the aircraft designs projected in the remaining years in the century will fall in these categories and would benefit from facilities designed to accomodate rotorcraft.

3.2.4 Impact of Research and Development on Icing Facility Requirements

The difficulties encountered in finding and testing in natural icing conditions has had a negative impact on aircraft icing certification, but also on basic icing research and development. This difficulty has been recognized by governmental agencies and has provided the impetus for several parallel efforts to define the icing research and development needs for the near and long term. The agencies, NASA, FAA and DOD have developed detailed program plans for the purpose of conducting the research necessary for the better understanding of the icing phenomenon. It is hoped that these efforts will ultimately culminate in safer and more efficient means for aircraft icing certification.

The results of the following studies form the basis for the individual agency's program plan:

NASA CR-165344, "Rotorcraft Aviation Icing Research Requirements"

NASA CR-165290-165290, "Light Transport and General Aviation Icing Research Requirements"

NASA CR-165336, "Commercial Aviation Icing Research Requirements"

FAA-CT-80-210 "Helicopter Icing Reveiw"

NASA Conference Publication 2086 "Aircraft Icing"

These research efforts provide detailed analyses of the requirements for icing research and development for the various types of aircraft which may require icing certification. It is not the purpose of this investigation to provide the detailed conclusions of the previous studies or an outline of the agencies' icing research program plan. However, in order to highlight the impact of the research needs on icing facility requirements, it is necessary to summarize the major areas of required research. From these research needs it is possible to provide an assessment of their impact on facility requirements.

The major icing research efforts previously mentioned will focus on two primary areas. First will be research to expand the knowledge of ice and the icing environment. The second research category will be directed towards developing means to simulate the icing environment for the purpose of development testing and certification. The following is a summary of the primary research goals for these categories of research

3.2.4.1 Definition of the Icing Environment

The development of icing simulation technology requires a thorough understanding of the icing environment. At present sufficient doubt exists as to the validity of the FAR 25 APP C icing criteria for the supercooled cloud to warrant examination. Additionally, NASA, FAA, and DOD recognize serious shortcomings in the definition of the icing environment with regard to other icing phenomenon such as snow, freezing rain and drizzle, freezing fog, and mixed icing conditions. Research directed towards filling these informational gaps will require ancillary research efforts. These efforts include the following:

- Determine the mechanical properties of ice and the influence of these properties on ice protection system designs. The research will be directed toward better understanding of the physics of ice accretion, the characteristic bonding dynamics of various ice forms, as well as the dynamics of ice shedding. These specific research efforts will play an important role in research directed toward development of ice protection systems and aircraft component design.

- Development of standardized instrumenation for acquisition of meterological data, and for use in ice protection system development and certification. The instrumentation would have improved capabilities for measuring LWC in excess of 1 gm/m^3, and at temperatures near 32° F. Research is also directed toward development of low bulk, economical equipment for droplet size measurement, and the measurement of snow and mixed icing conditions. In addition to instrumenation for the purpose of acquisition of meterological data, instrumentation is required to provide the pilot knowledge of the rate and severity of ice accumulation. For helicopters, additional research efforts are directed toward providing a means of indicating immediate or instantaneous torque rise in icing conditions.

3.2.4.2 Development of Icing Simulation and Ice Protection Technology

A better definition of the icing environment should result in more reliable means for icing simulation and ice protection. Most icing certification is currently performed in natural icing conditions, which have the disadvantages of being imprecise, costly and time consuming. The introduction of highly reliable icing simulation technologies should greatly reduce the necessity for natural icing testing and result in a more cost effective development and certification process. Research projects which, as a group, hold a vary great potential for minimizing the necessity for natural icing testing are summarized below:

- Development and verification of computer codes for analytical prediction and assessment of icing characteristics, ice protection systems performance and aircraft penalties during icing encounters. This research will entail the development of numerical ice accretion modeling codes for both rime ice, hoar frost and glaze ice and will be used to analyze ice protection systems and to create artificial ice shapes. This research will be dependent upon development of sectional airfoil data for airfoils under various icing conditions. It is hoped that verification of these mathematical models will be sufficient to support an a priori assessment of the adequacy of ice protection systems, to provide a means to extrapolate data derived from models to full scale, and to provide the means to extrapolate full scale data from tested conditions to untested conditions.

- Develop and verify scaling laws and scale modeling test techniques for development and certification purposes.
- Develop and verify heat transfer laws and scale modeling techniques.

The employment of scale modeling techniques for fixed, rotary and oscillating airfoils will greatly enhance the capabilities of current icing simulation facilities. It will reduce many of the size limitations encountered in those facilities. However, at present, these capabilities remain unverified and unacceptable for use in icing certification. The shortcomings of heat transfer modeling are most evident in the conduct of testing of ice protection systems utilizing heat as the primary deice agent. The proposed research will include as part of the analysis, conduction heat transfer through multi-layered structures within the airfoil, and heat transfer through the ice layer. The computer codes developed will extend the conventional ice protection system analysis by modeling the ice melting process. The ID numerical model has been generated with work proceeding on 2D and 3D numerical models.

Once the computer models have been completed, verification of those models and analytical prediction techniques must be accomplished through correlation of the simulated test results and those results obtained through encounters with natural icing conditions. Correlation of results from the simulated and natural icing conditions will continue to be an ongoing research requirement. Results of this research will establish the degree to which the models and analytical techniques can be used to compliment or replace natural icing testing.

The ultimate goal of the current icing research will be the development and evaluation of advanced ice protection systems and concepts. Research on this subject area will result in several parallel and convergent analyses. Currently, research efforts are underway to determine the feasibility of various ice protection concepts. These efforts include, but are not limited to, electro-thermal rotor deice systems, icephobics, freezing point depressents, pneumatic, vibratory, microwave and hybrid ice protection concepts. In addition to studying design requirements for the systems, emphasis will be placed on assessment of aircraft performance effects during operation of the ice protection equipment, in all conditions including power-off (propulsion) flight.

3.2.4.3 Impact of Research Requirements on the National Icing Facilities

The previous sections (3.2.4.1 and 3.2.4.2) provide a general summary of the various icing research efforts currently proposed, or underway, under the auspices of the various agencies' icing research program plans. The list is not all inclusive, but it does cover the major categories of the research efforts, and indicates the potential scope of facility utilization and suggests the degree to which the existing facilities may require modification to accomodate the research needs.

The primary impact which the planned research efforts will have on the National Icing Facilities will be in their utilization. Conduct of basic icing research will necessarily constitute a major share of the facilities workload, particularly for icing wind tunnels, in the near term. The nature of the research will insure its high priority, since effective utilization of the simulation facilities is predicated upon the successful outcome of those efforts. Subsequent to the completion of the research, it is anticipated that the facilities will be used for aircraft development programs as well as icing certification, provided that the results of on-going and planned research indicate that natural icing certification can be supplemented or supplanted by certification in simulated conditions.

Whether icing research will cause an overall increase in facility utilization, or merely result in a cyclic shift in the type of utilization (research, development or certification) is an important, but unanswered question, since it will dictate the necessity for new construction. While rough order of magnitude estimates of facility utilization are attainable for the various research projects, those estimates are inappropriate for use in projecting new facility construction. Until detailed information concerning the projected utilization and workload capabities of the existing facilities is made available, new facility construction should remain a consideration only.

The requirements for icing research will have their most immediate impact on icing research test bed aircraft, and icing wind tunnels such as the AWT and IRT.

Icing test bed aircraft for research purposes are considered essential for several reasons. Such aircraft, capable of sustained flight in natural icing conditions are necessary to: better define and understand the icing environment, to determine ice effects on the aircraft and components, to correlate results of simulated and natural icing tests, to validate or verify analytical models, to assess advanced ice protection comcepts, etc. Currently, the U.S. Army is operating a JUH-1H in this capacity and NASA is scaling a fixed wing aircraft for this purpose. Icing research test bed aircraft (both rotary wing and fixed wing) are considered essential elements of a National Icing Facilities array.

Icing wind tunnels, such as the IRT and AWT, will necessarily be heavily utilized during the conduct of icing research. The IRT, currently the largest icing tunnel in North America in use today, is ideally suited for many of the research efforts thus far envisioned. Its size, and range of icing parameters, although limited, allow scaling of components to manageable dimensions, as well as allowing for small, full scale component testing. However, a specific deficiency exists in the IRT, if it is to be used extensively in the development and verification of scaled model test techniques, in its inability to produce an icing cloud with mean effective droplet diameters less than 10 microns. In order to be employed effectively, the facility must be capable of producing an icing cloud with all its parameters scaled to the test requirements.

The AWT, assuming its rehabilitation, is expected to provide complete coverage of the FAR 25, APP C super-cooled cloud icing environment, but is also limited to a minimum MDD of 10 microns. This limitation may not be as critical to AWT utilization, However, since its large size permits less radical scaling than is required in the IRT.

Must of the research planned in the near future will be directed towards the verification or redefinition of the FAR 25 APP C icing envelopes. Until that research has reached fruition, modification of other icing simulation facilities to conform with any standard other than the FAR 25, APP C envelope may be superfluous and result in needless expenditures.

3.2.5 Summary

In the preceding sections, several factors which will have an impact on the proposed National Icing Facilities were defined. These factors are aircraft size, airspeed and altitude capabilities, onboard navigational equipment, growth trends and research requirements. The conclusions reached, based on an analysis of these factors are listed as follows:

1) National Icing Facilities should not be designed to meet extraordinary aircraft operational and dimensional characteristics. Total numbers of these aircraft are projected to be few. Development and certification testing can be accomplished on a component basis and the total system airworthiness demonstrated in natural icing tests and analysis.

2) Those aircraft least capable of finding natural icing for testing and certification purposes are general aviation, helicopters and military utility aircraft.

3) By designing a test facility to be capable of meeting the current and future requirements of most helicopter and general aviation aircraft, the facility will be capable of meeting the certification requirements of a vast majority of commuter, business aviation and military aircraft as well.

4) Expected growth rates indicate that general aviation and helicopters hold the most potential for producing new designs requiring certification, with approximately 32 new helicopter and 32 new G.A. designs forthcoming in the next twenty years, and icing facilities should be designed to accomodate testing of those designs.

5) Improvement of onboard navigational capabilities for helicopters will increase the demand for icing certification for rotorcraft, which will result in increased demand for icing simulation/test facilities capable of accomodating rotorcraft.

6) The requirements for icing research and development in the ensuing years will affect both the quantity of facilities required for research or development and certification as well as the icing simulation capabilities required of those facilities.

Table 3.8 provides revised Facility capability specifications which will be used to determine the particular requirements for the various Facility types.

Table 3.8 Facility Requirements Based on Current and Projected Aircraft Characteristics and Operational Features

PARAMETER	OPERATIONAL RANGE	UNITS
Altitude	0 - 22,000	Feet (pressure altitude)
Airspeed	0 - 350	Knots
Temperature	+32° to -40°	°Fahrenheit
Length	98*	Feet
Width	75*	Feet
Height	25*	Feet

*Uniform icing cloud dimensions

3.3 ICING FACILITIES ASSESSMENT

The need for icing simulation facilities such as implied in the FARs pertaining to icing certification has not gone unnoticed by industry or government. At the present time, a wide array of such facilities exist at various locations of the United States and Canada. Although several of the major facilities are dedicated to a large extent to the needs of NASA and the military for the purpose of icing research and development, most are available to industry for their needs. The existing facilities may be used for a multitude of purposes, and should comprise the basis for an array of National Icing Facilities.

The current family of icing facilities can be catalogued as a member of one (or more) of four general facility types. These types include wind tunnels, engine test facilities, low velocity facilities, and inflight icing tankers. Each of the facilities is capable of simulating, to some degree, portions of the icing envelope defined by FAR 25 Appendix C, as well as various other icing phenomenon. However, due to size, altitude and airspeed limitations, many of the facilities may not be germane to National Icing Facilities, the purpose of which is the efficient conduct of research, development and certification testing of aircraft and engines for operation in known or forecast icing conditions.

In the following subsections, a cursory review of the four general icing facility categories (wind tunnels, low velocity facilities, engine test facilities, and inflight tankers) is presented. The review consists of a general discussion of the composite capabilities of the individual facilities in each category (Sections 3.3.1 through 3.3.4). (For a more detailed review of current icing facilities capabilities, consult the "Proceedings and Minutes of the National Icing Facilities Coordination Meeting", September, 1980.) Following the review, an assessment is made of potential that each facility holds for inclusion in an array of National Icing Facilities. Those facilities selected as having capabilities, which justify their inclusion in the array of National Icing Facilities, are further assessed to determine their potential in meeting future aircraft development testing requirements (through the year 2000), icing research needs, and in meeting the requirements of the applicable FAR icing certification requirements. Section 3.3.5 presents a summary of the overall strengths and weaknesses of the selected facilities, and recommendations for improving the capabilities of each facility. Section 3.3.6 presents rough order of magnitude cost estimates for modification of existing facilities, additional new facilities and user operating costs. Additionally, estimates of facility staffing requirements and modification schedules are provided.

3.3.1 Icing Wind Tunnels

A wind tunnel, as the name implies, is a chamber through which air is forced at controlled velocities in order to study the aerodynamic flow around, and effects on, airfoils, scale models, and other objects mounted within. The introduction of spray manifolds in the chamber, coupled with the ability to adjust air temperatures to desired levels, has produced a valuable means of determining the effects of ice on the tested object. The icing wind tunnel allows manufacturers and designers of aircraft and their components to study, in a closely controlled, low risk environment, the ice accretion and shedding tendencies of their designs, and the effectiveness of their ice protection system designs. The tunnel also provides an excellent means by which the model scaling laws may be verified for their use in small scale heat transfer modeling, ice modeling, accretion modeling, etc.

There are currently eleven such icing wind tunnels in operation in the United States and Canada. Table 3.9 categorizes them in terms of their applicability to National Icing Facilities.

The parameters addressed in assessing their roles as parts of an array of National Icing Facilities include their size, availability, airspeed capability and capability of simulating the Appendix C, FAR 25 icing environment. In addition to their ability to simulate the supercooled cloud, the ability of the subject facilities to simulate other icing conditions, such as freezing rain, snow, hail and mixed conditions, is also assessed. Facilities 7 through 11 are categorized as supplemental primarily because of their small chamber size (measured in inches), but also due to the fact that they are privately owned and operated, they may not be readily available for use by competitors or by the government. Although the Lockheed tunnel (Number 6) is somewhat larger than Facilities 7 through 11, its private ownership makes it similarly inappropriate for inclusion as a National Facility. Facility 5, Army Natick R&D Climatic Chamber, though government owned, is not capable of producing an icing envelope and as such will play a very limited role, if any. Facilities 3 and 4 are capable of producing a uniform icing cloud which closely approximates some portions of the icing envelope defined in Appendix C FAR 25. Because they are government run facilities, they should be responsive to the needs of government, and therefore available for their use. Their small chamber and uniform icing cloud will limit their contributions primarily to research and development, not certification, and are therefore listed as significant research facilities.

The remaining two facilities, both located at the NASA Lewis Research Center, currently have or are proposed to have, capabilities which warrant their consideration for utilization as integral components of National Icing Facilities. These facilities are selected as having potential for icing certification, due to their relatively large size, airspeed capabilities, and capabilities of simulating portions of the Appendix C icing envelopes. Additonally they hold the potential for utilization for icing research and development work. A detailed description of the capabilities and shortcomings of the NASA Lewis Icing Research Tunnel and Altitude Wind Tunnel (rehabilitation) is provided in the following sections.

Table 3.9 Applicability of Icing Wind Tunnels to the National Icing Facility

FACILITY NAME AND LOCATION	INTEGRAL TO NATIONAL FACILITY	SIGNIFICANT RESEARCH FACILITY	SUPPLEMENTAL FACILITY
1. Icing Research Tunnel, NASA/Lewis Research Center, Cleveland, OH	✓		
2. Altitude Wind Tunnel NASA/Lewis Research Center, Cleveland, OH	✓		
3. High Speed Wind Tunnel Ottawa, Canada		✓	
4. AEDC Research Cell Arnold AFS, Tenn.		✓	
5. Army Natick Research & Development Climatic Chamber, Natick, Mass.			✓
6. Lockheed Wind Tunnel Burbank, California			✓
7. Boeing Wind Tunnel Seattle, Wash.			✓
8. & 9 Rosemount Wind Tunnels (High and Low Speed) Minneapolis, Minn.			✓ ✓
10. Frost Tunnel University of Alberta Alberta, Canada			✓
11. UCLA Cloud Tunnel Los Angeles, Calif.			✓

3.3.1.1 Icing Research Tunnel (IRT) - NASA/Lewis Research Center

The Icing Research Tunnel at the NASA/Lewis Research Center, shown schematically in Figure 3.9, is currently the largest icing wind tunnel in the U.S. Figures 3.10 and 3.11 and Table 3.10 provide a comparison of intermittent and continuous maximum icing conditions with those simulated by the IRT at the present time. As shown in these figures, the IRT is capable of simulating an icing environment which comprises approximately 20% of the continuous maximum envelope, as well as over 40% of the intermittent maximum envelopes. Although this appears to be only a small portion of the FAR 25 APP C envelope, it represents the highest liquid water content regions in which icing encounters occur. Furthermore, proposals are under consideration which would also give the IRT the added capability of producting freezing rain.

The IRT is capable of performing various tests within the limits of its icing envelope. Despite the relatively small size of its uniform icing cloud (.9 meters x 1.5 meters), the test chamber is capable of handling full scale component testing of small components, such as horizontal and vertical stabilizers, elevators, windshields, pitot static systems, small engine inlets, ice detection instruments, etc. The tests may be for the purpose of evaluating icing effects on protected and unprotected components. The facility has the potential for performing scale model tests and ice adhesion tests. Due to the relatively large size of the actual test chamber, it has been proposed that the tunnel be used for full scale testing of rotating airfoils, such as small propellers and helicopter tail rotors.

The range of parameters which the IRT can simulate, although currently limited, makes it an excellent facility for use in research and development testing. It provides an efficient and cost effective means for verification of various scaling laws, including heat transfer, aerodynamic, ice shape/size, and aerodynamic performance scaling. Utilization of the tunnel in the research and development role could enhance the effectiveness of other existing icing facilities, by the development of scaling laws which would allow for accurate extrapolation of results to those portions of the icing envelopes which the individual facilities are unable to duplicate.

Despite the fact that it is essentially a sea level tunnel, the IRT is capable of producing atmospheric perssures up to 3000 feet at high velocity. The temperature range is sufficient to include regions in the FAR icing envelope down to the possible extent of limits (-22° to -40°F), and can achieve static temperatures as low as -32°F.

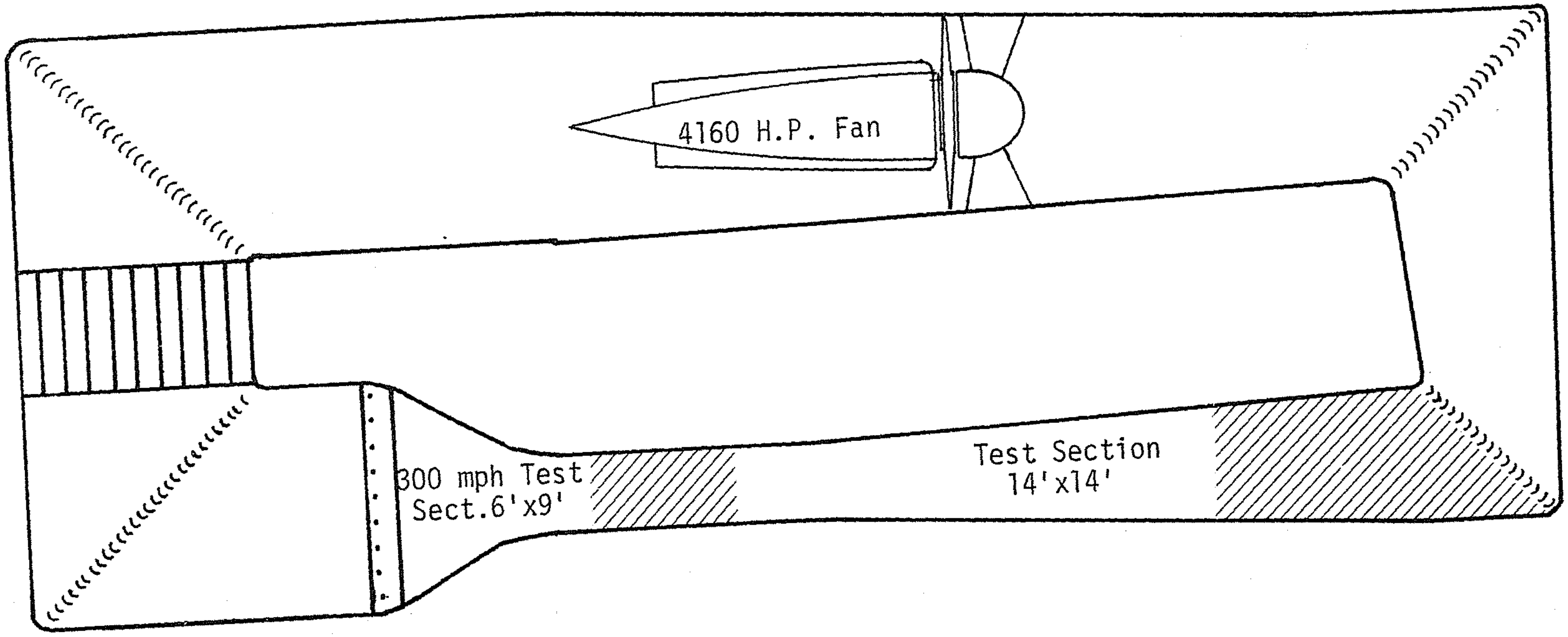
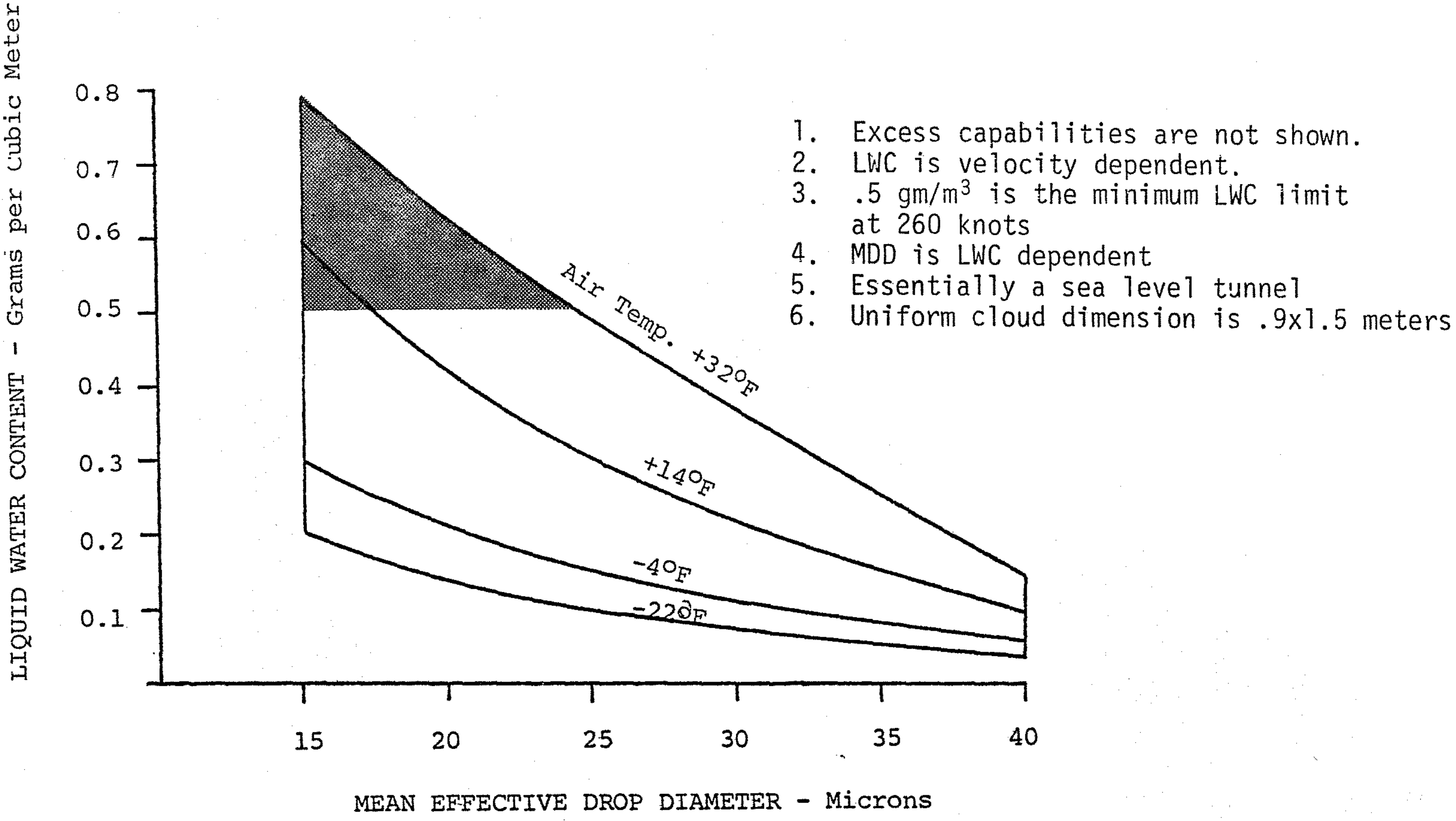
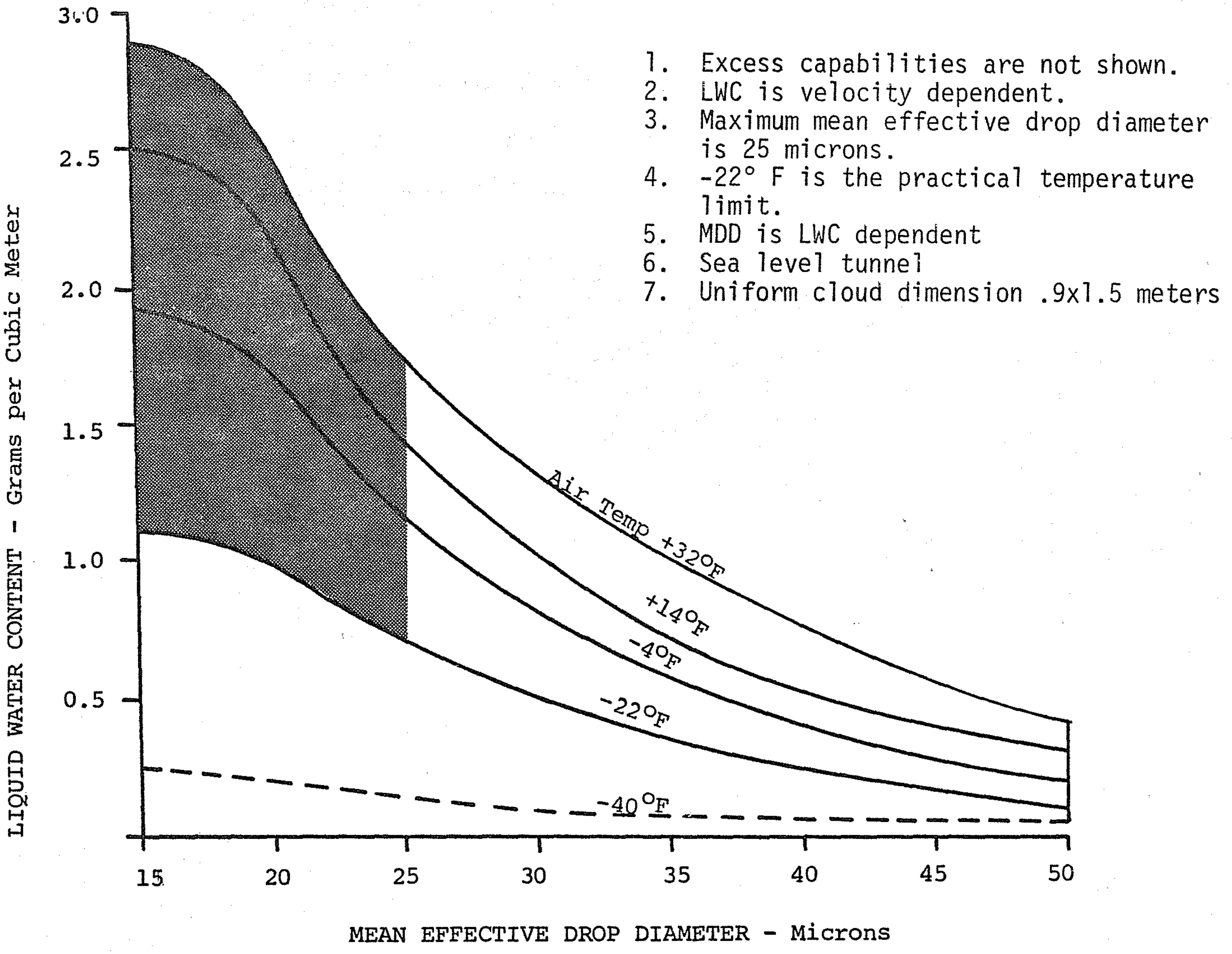


Figure 3.9 Icing Research Tunnel, Lewis Research Center



1. Excess capabilities are not shown.
2. LWC is velocity dependent.
3. .5 gm/m^3 is the minimum LWC limit at 260 knots
4. MDD is LWC dependent
5. Essentially a sea level tunnel
6. Uniform cloud dimension is .9x1.5 meters

Figure 3.10 Icing Research Tunnel Icing Cloud Vs. Continuous Maximum (Stratiform Cloud) Atmospheric Icing Conditions



1. Excess capabilities are not shown.
2. LWC is velocity dependent.
3. Maximum mean effective drop diameter is 25 microns.
4. -22° F is the practical temperature limit.
5. MDD is LWC dependent
6. Sea level tunnel
7. Uniform cloud dimension .9x1.5 meters

Figure 3.11 Icing Research Tunnel Icing Cloud Vs. Intermittent Maximum (Cumuliform Cloud) Atmospheric Icing Conditions

Table 3.10 Synopsis of IRT Capabilities

ICING TEST PARAMETER	RANGE OF OPERATION	FAR 25 APPENDIX C RANGE		UNITS
		CONTINUOUS	INTERMITTANT	
Liquid Water Content	.5 - 3.0**	.04 - .8	.25 - 2.8	gm/m^3
Mean Drop Diameter	11 - 25***	15 - 40	15 - 50	μm
Temperature	+32 to -22°	-22°	-40*	°Fahrenheit
Altitude	0 - 3000	0-22,000	0-29,250	Pressure Altitude, Ft
Airspeed	0 - 260	-	-	Knots
Chamber Size	1.8 x 2.7 x 6	-	-	H x W x L m
Uniform Cloud Size	.9 X 1.5	-	-	H x W m

*indicates possible extent of limits

**velocity dependent

***LWC dependent

The IRT is not without its shortcomings. Icing conditions cannot be produced which duplicate the FAR 25 APP C icing envelope in its entirety. The interdependency of air velocity, LWC, MDD and temperature limits further limits the extent to which the IRT can duplicate the icing envelope. The IRT is incapable of simulating other hazardous icing test conditions which may become test condition requirements in the forthcoming years. These conditions include snow, freezing rain, hail and mixed icing conditions.

Another deficiency is that of tunnel wall effects when large objects are introduced into the chamber. In some instances, varying angles of incidence of the icing cloud on the tested object are required to determine the effect that angle of attack has on ice accretion or shedding. This function cannot be readily performed on large objects in the facility. Another shortcoming is that its size prohibits the testing of other than small components or models of components. Full scale testing, the most accurate method employed today, is not possible for such components as helicopter main rotors, or large wing sections.

Although size is maintained as a shortcoming of the IRT, it should be noted that the need for small facilities is no less important than the need for larger ones. Given the economic realities involved in building large wind tunnels capable of testing full scale aircraft and components, there should be no doubt as to why very few are in existence. The smaller, more economical wind tunnel, if properly utilized can perform an important role in augmenting the capabilities of the larger ones, particularly for research and development. The IRT is such a facility.

In recognition of the shortcomings of the facility, the NASA Lewis Research Center submitted an FY 1983 C of F (Construction of Facilities) request, to improve the icing nozzle spray system, refrigeration system and exhaust flow system. It has been estimated that these improvements would cost appproximately $950,000, and would provide for testing within the full range of the FAR 25 APP C envelope, and partially eliminate some of the velocity dependency of the current configuration tunnel. Additionally, a C of F for FY 84 for 2.6 million dollars would have automated the spray system, airspeed and temperature control systems which would have upgraded the facility to a first rate, modern icing tunnel. These requests at the time of this writing were not approved.

The following recommendations are offered to realize the full potential of the facility:

1) Improve the liquid water content capability of the facility to provide a range from .04-2.8 gm/m^3 to more closely simulate conditions described in FAR 25 Appendix C and allow for greater flexibility in scaling.
2) Improve mean effective drop diameter range from the current range to a maximum of 50 μm to more closely simulate the FAR 25 Appendix C definition of the icing environment.
3) Reduce interdependency of the parameters to allow attainment of various conditions within FAR 25 APP C.
4) Improve refrigeration to provide temperature ranges which extend to the maximum possible extent of limits, (-40°F) if that improvement can be performed cost effectively.
5) Proceed with plans to incorporate a freezing rain and mixed condition capability.
6) Investigate the feasibility of increasing cloud size to its maximum, practical limits within the confines of the existing test sections.
7) Utilize the facility for research (e.g., verifying scaling laws), development and certification testing of small components.

3.3.1.2 Altitude Wind Tunnel (AWT) - NASA/Lewis Research Center

The Altitude Wind Tunnel is the largest wind tunnel with the potential for an icing capability in North America. A schematic of this facility is provided in Figure 3.12 for comparison with the IRT. It was built in the early 1940's as a propulsion test facility and was used extensively during the 1940's for that purpose. Since that time it has been used as a space chamber facility by NASA, although it has been inactive since the early 1970's. Major components have been removed from the tunnel such as the fan, turning vanes, engine exhaust scoop and test section cover. The refrigeration system and drive system have been disconnected. A resurgence of interest in icing research as well as in propeller propulsion systems has brought the facility back to NASA's attention. The AWT is now under consideration by the Aeronautics and Astronautics Coordinating Board as a national facility for icing research, as well as other research needs. The recommendations of the AACB that the AWT be rehabilitated and designated as a National Icing Facility. Implementation of these recommendations is necessary to insure its role as a National Icing Facility.

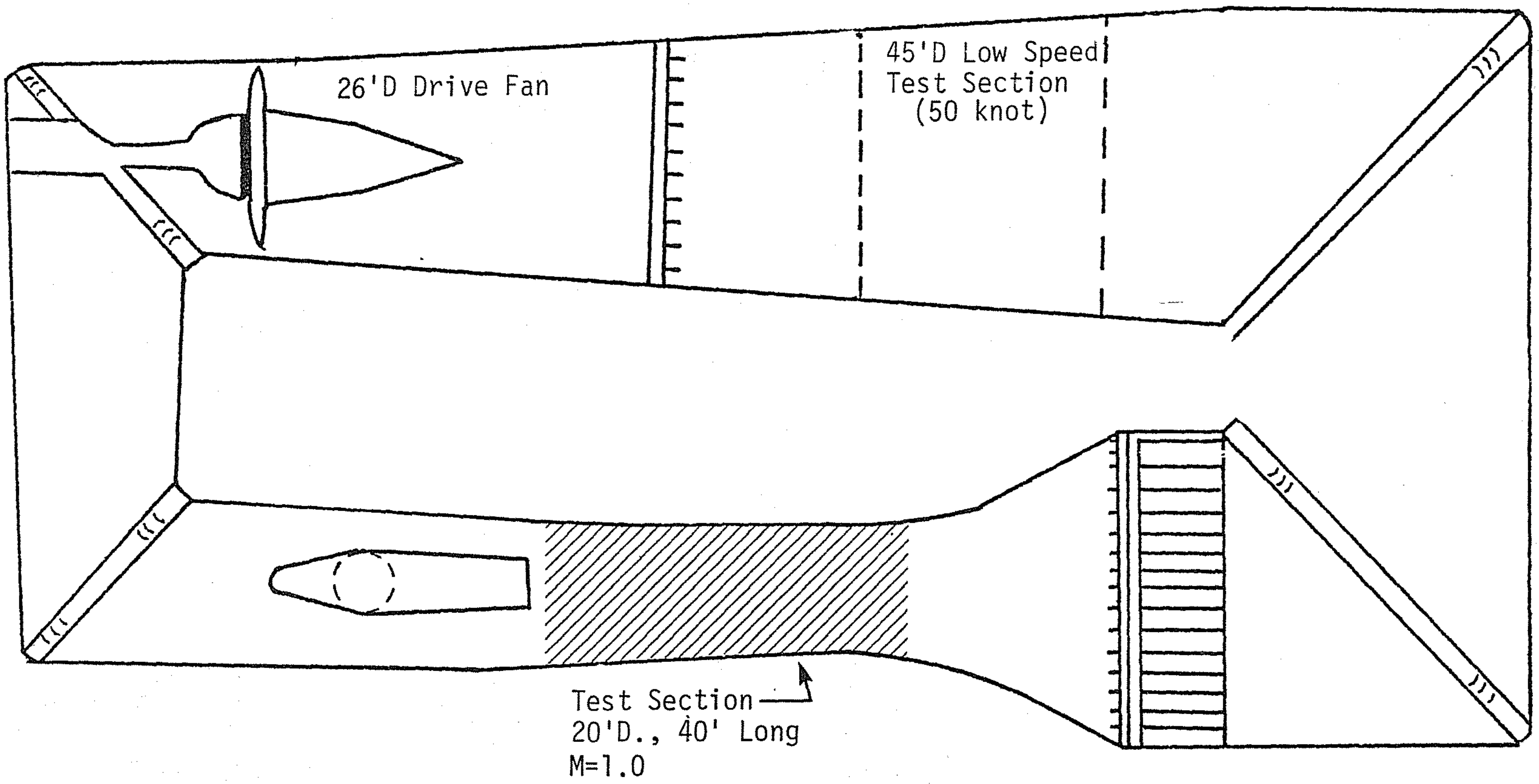


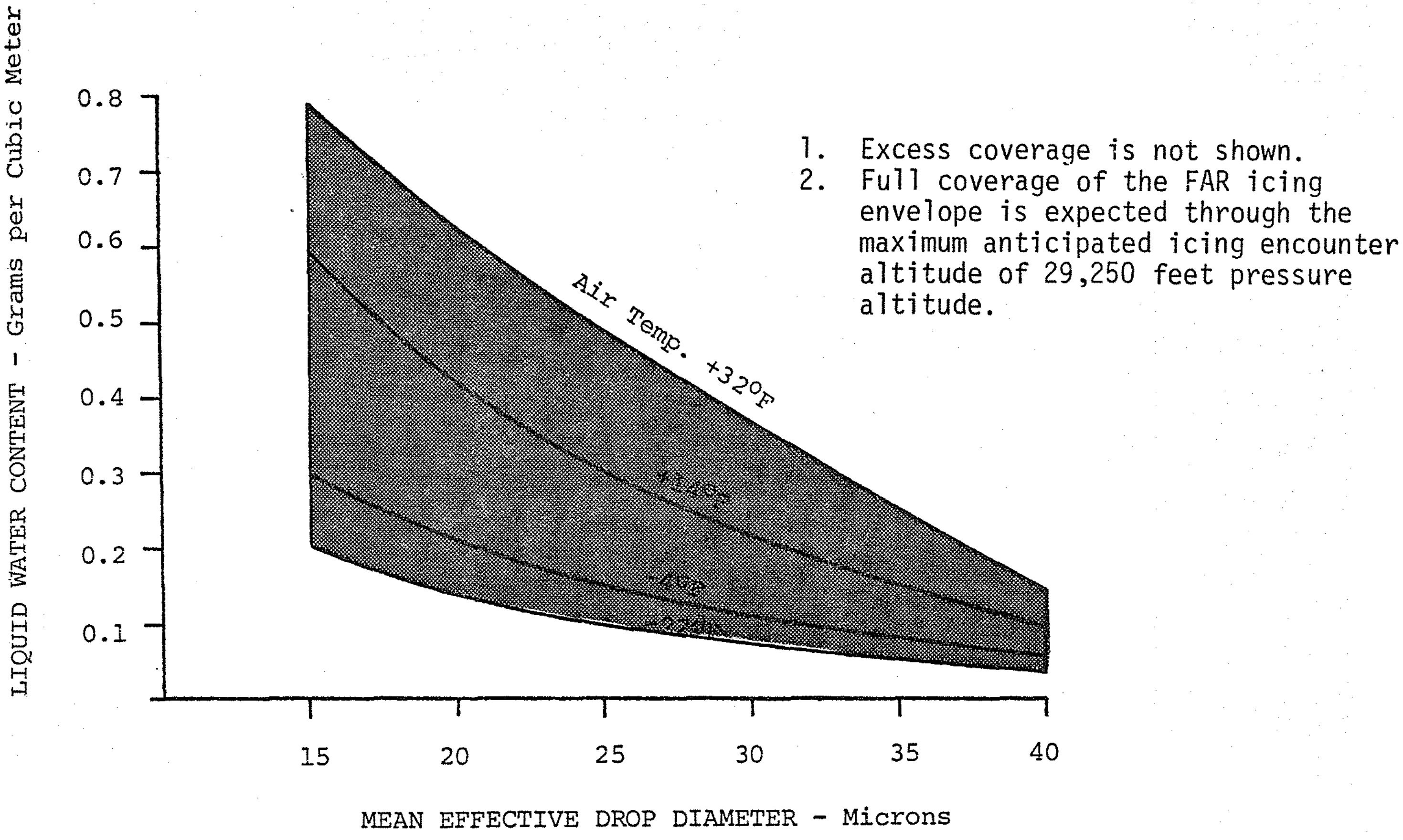
Figure 3.12 Altitude Wind Tunnel (Proposed, 1987)

Two funding options are available in that regard. Option one would entail reconnecting a new air drive and the old refrigeration system and placing the test section cover back in position. Conversion to an icing facility would be accomplished by placing an icing spray manifold in the settling chamber of the original test section and in the back leg for a large low speed test chamber. The second option would be to provide a new higher powered air drive system and increase the refrigeration capacity of the facility for the purpose of performing higher speed icing tests.

The altitude wind tunnel, assuming that the rehabilitation is accomplished, will provide better coverage of the FAR 25 Appendix C envelope than the IRT or any other existing wind tunnel. Figures 3.13 and 3.14 show a comparison between the FAR 25 Appendix C icing envelope and that which could be simulated by the rehabilitated AWT. In addition to nearly complete coverage of the intermittant and continuous maximum icing envelopes, the AWT will also have the capability of producing weather phenomenon heretofore not simulated in icing tunnels, such as solid ice particles and mixed icing conditions. It will also be able, as its name implies, to simulate atmospheric pressure altitudes up to 50,000 feet. The proposed AWT will be able to produce airspeeds up to Mach 1.0 using its smaller 18 foot diameter chamber as well as airspeeds up to 50 knots with the 45 foot diameter chamber. This will allow ground icing testing of airfoils, static and rotating, designed for both low and high airspeed flight regimes such as helicopter rotor systems, and high and low speed military and civil fixed wing aircraft. A synopsis of the AWT's capabilities with respect to the FAR 25 Appendix C icing envelope is shown in Table 3.11.

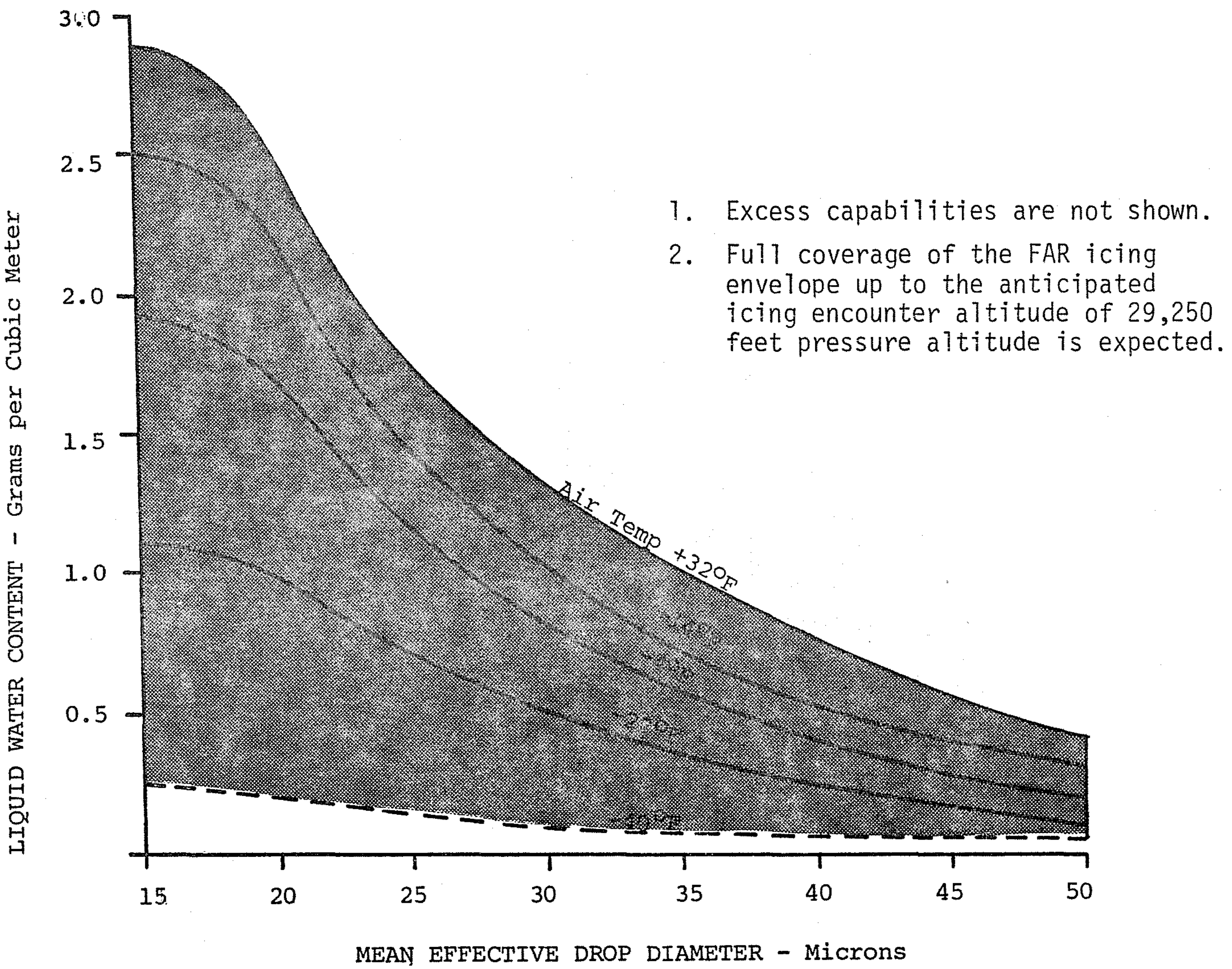
The facility, due to its large size will be less sensitive to the problems of scale model testing. It will be capable of performing tests on some full scale components and aircraft (general aviation) up to 14 feet in diameter as well as scale models up to the same size, with complete immersion in the uniform icng cloud. This attribute will become increasingly important as large aircraft of the mangitude described in Section 3.2 are designed and require testing; however, it is unlikely at this time that airfoils of that magnitude could ever be tested, full scale, in an indoor facility, future validation of scaling laws may allow for their testing in the AWT.

The Altitude Wind Tunnel will have the capability of testing large, complete propulsion units, including engines and engine inlets throughout most of the atmospheric icing envelopes, at varying altitudes and airspeeds. The AWT would be capable of performing icing tests on the largest aircraft engines in use today, and should provide sufficiently large to test any designs produced into the 21st century.



1. Excess coverage is not shown.
2. Full coverage of the FAR icing envelope is expected through the maximum anticipated icing encounter altitude of 29,250 feet pressure altitude.

Figure 3.13 Altitude Wind Tunnel Icing Cloud vs Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions



1. Excess capabilities are not shown.
2. Full coverage of the FAR icing envelope up to the anticipated icing encounter altitude of 29,250 feet pressure altitude is expected.

Figure 3.14 Altitude Wind Tunnel Icing Cloud Vs. Intermittent Maximum (Cumuliform Cloud) Atmospheric Icing Conditions

Table 3.11 Synopsis of AWT Capabilities

ICING TEST PARAMETER	RANGE OF OPERATION	FAR 25 APPENDIX C RANGE		UNITS
		CONTINUOUS	INTERMITTANT	
Liquid water content	.2 - 3.0	.04 - .8	.25 - 2.8	gm/m^3
Mean Drop Diameter	10 - 50+	15 - 40	15 - 50	μm
Temperature	-40°	-22°	-40*	°Fahrenheit
Altitude	0 - 50,000	0 - 22,000	0 - 29,250*	Pressure Altitude, Ft
Airspeed	0 - M = 1.0	-	-	Knots
Chamber size	variable to 14 m dia.	-	-	m
Uniform Cloud Size	up to 14 m dia.	-	-	m

*Indicates possibile extent of limits

The AWT will not be perfect in every respect. Although it will be capable of producing an icing cloud, freezing rain and solid ice particles as well as mixed conditions, no plans are being made for the inclusion of a snow or hail capability in the test facility. However, the most pressing shortcoming of the facility at this stage is its lack of availability. Estimates at this time are that the facility will not be available for use until the 1987 time frame (Reference 4).

The AWT, for the reasons previously mentioned, will provide a significant capability for future icing certification and R&D testing. The following recommendations are submitted which, if incorporated in the facility will make the AWT an even more valuable facility than is currently planned:

1) Assess the possibility of providing the capability of producing both snow and hail. If that capability is feasible, incorporate this capability in the facility.
2) Accelerate the development and construction schedule of the proposed facility.
3) Provide the additional funding required to design a facility with a new airdrive system and increased refrigeration capacity.

3.3.2 Low Velocity Facilities

Low velocity facilities are similar to wind tunnels in as much as they provide a means by which the aerodynamic effects of air or an icing cloud passing over an airfoil or other object may be measured and studied. Unlike wind tunnels, low velocity facilities are not as constrained in test chamber size. There are thirteen low velocity facilities which are currently in use. Table 3.12 shows the results of the assessment of the individual facilities' relative significance in the overall framework of an array of National Icing Facilities. Although all of the facilities listed have the capability of producing freezing rain, only seven of them are capable of simulating portions of the FAR 25 Appendix C icing envelope. Those facilities which are unable to simulate the icing envelope are generally used to study the effects of cold, wet weather on personnel and ground equipment, and thus are of only marginal importance to National Icing Facilities. Facility 2, the G.E. crosswind facility, is considered inappropriate for inclusion as a National Icing Facility due to its status as a privately owned and operated facility. The Mt. Washington Observatory is not considered to have capabilities which would be consistent with National Icing Facilities needs. Dependency on the weather, unpredictable and very severe winds for its icing testing environment, as well as inaccessability, extremely limit its usefulness to the national icing certification effort.

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) cold room is not expected to contribute to National Icing Facilities needs as it does not provide unique capabilities. The

Table 3.12 Applicability of Low Velocity Facilities to the National Icing Facility

FACILITY NAME/LOCATION	INTEGRAL TO NATIONAL FACILITY	SIGNIFICANT RESEARCH FACILITY	SUPPLEMENTAL FACILITY
1. NRC Helicopter Spray Rig, Ottawa, Canada	✓		
2. GE Cross Wind Facility, Peebles, OH			✓
3. McKinley Climatic Lab, Eglin AFB, FL (Main Chamber)	✓		
4. (Engine Test Cell)		✓	
5. (All Weather Room)		✓	
6. U. S. Army CRREL Cold Room, Hanover, NH			✓
7. Mt. Washington Observatory, Gorham, NH			✓
8. U. S. Navy PMTC Climatic Hangar, Pt. Mugu, CA			✓
9. Acton Environmental Test Corp., Acton, MA			✓
10. NRC Cold Chamber #1, Ottawa, Canada			✓
11. Cold Chamber #2			✓
12. Wyle Labs, Norco, CA			✓
13. Arctec Canada Limited, Ottawa, Canada			✓

remaining facilities, the Canadian National Research Council (NRC) Spray Rig and McKinley Climatic Lab, do provide unique icing research capabilities which justify their inclusion in the framework of National Icing Facilities. The unique characteristics which recommend their inclusion are, for the Ottawa Spray Rig, the capability to perform controlled helicopter icing tests in the hover and low speed flight regime. The McKinley Climatic Lab is large enough to test entire full scale aircraft if atmospheric icing conditions can be simulated.

3.3.2.1 NRC Spray Rig - Ottawa, Canada

The problems encountered in helicopter ice protection system development and certification are due, to a large extent, to the helicopter's unique rotor system. At the present time, and for the near term at least, no indoor facility is capable of fully immersing the helicopter's rotating rotor system in a uniform icing cloud. The NRC Spray Rig (also known as the Ottawa Spray Rig) provides the potential for performing this feat. The spray rig (shown in Figure 3.15) consists of a tower on top of which is a spray manifold. Wind passing through the manifold produces a large icing cloud. The helicopter then hovers into the cloud and immerses the rotor system. Figures 3.16 and 3.17 compare the FAR Part 25 Appendix C icing environment with that which can be simulated by the spray rig. The present array of spray nozzles is capable of simulating only a relatively small segment of the intermittent maximum atmospheric envelope defined by FAR 25 Appendix C (Figure 3.17). The spray rig also provides coverage of the continuous maximum icing envelope in which, owing to their inherent altitude limitations, helicopters are most likely to encounter icing conditions.

The spray rig provides a testing environment which allows for efficient recording of test results. Unlike inflight testing in natural conditions, ground based photographic recording equipment may be used to monitor the entire aircraft. This equipment would be in addition to rotor hub mounted equipment or other cameras mounted on the aircraft designed to record ice accretion and shedding characteristics of the rotor blades. Since the rotorcraft would be at a hover during the testing, manual recording of ice accretion rates on non-rotating surfaces could be measured immediately upon exit of the icing cloud. The test environment also affords rapid egress from dangerous situations, should such situations occur during the performance of a test.

The spray rig also allows inflight (at a hover and at low forward airspeed) testing of ice protection systems of the rotor blades, engine inlets, windshields and other protected surface. It also allows testing to determine the performance degradation of unprotected surfaces and engines due to ice buildup or ingestion in a relatively safe flight regime.

In addition to the capability of the facility to simulate a supercooled icing cloud, tests conducted in previous icing seasons have shown the feasibility of simulating freezing rain. Although the capability

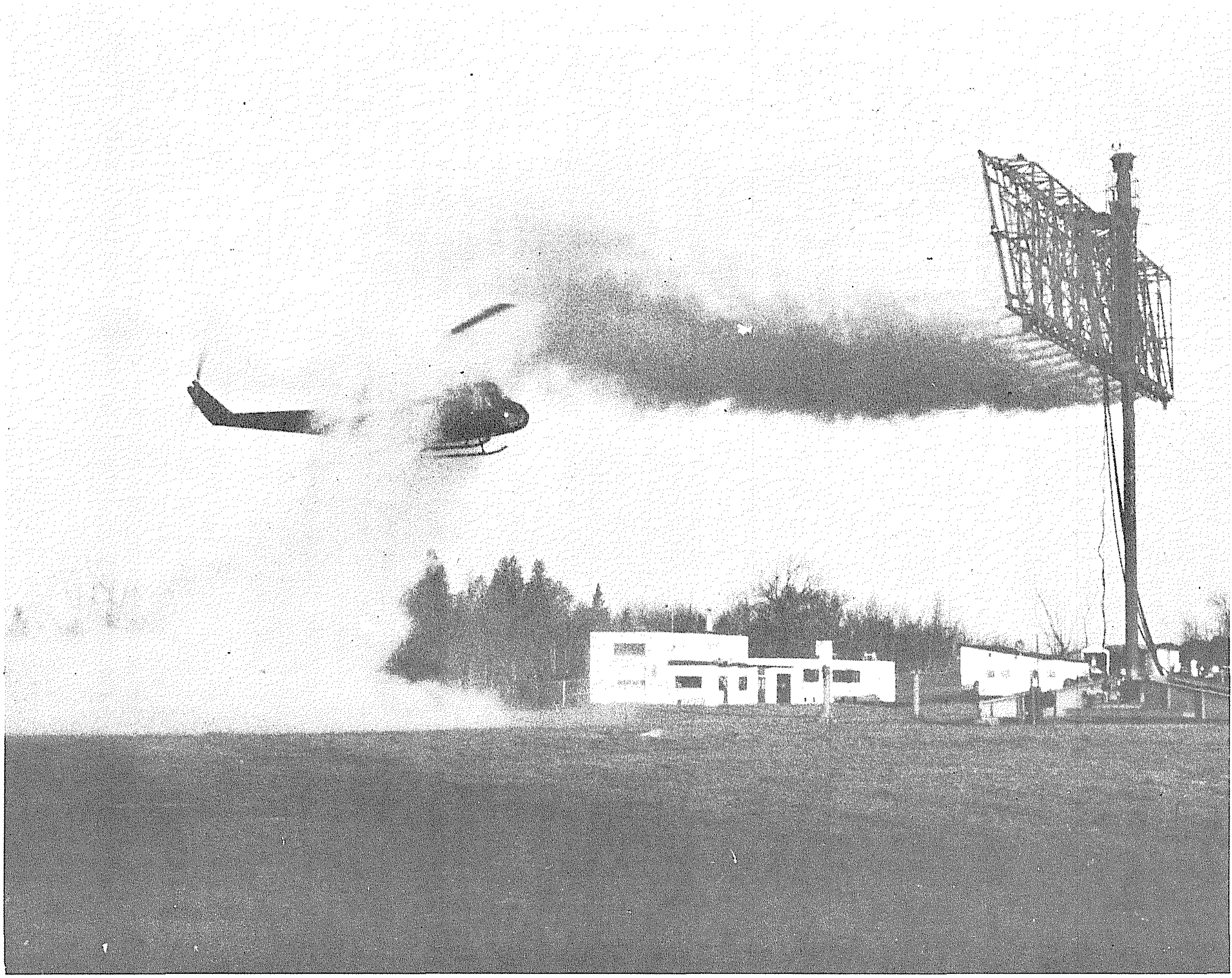
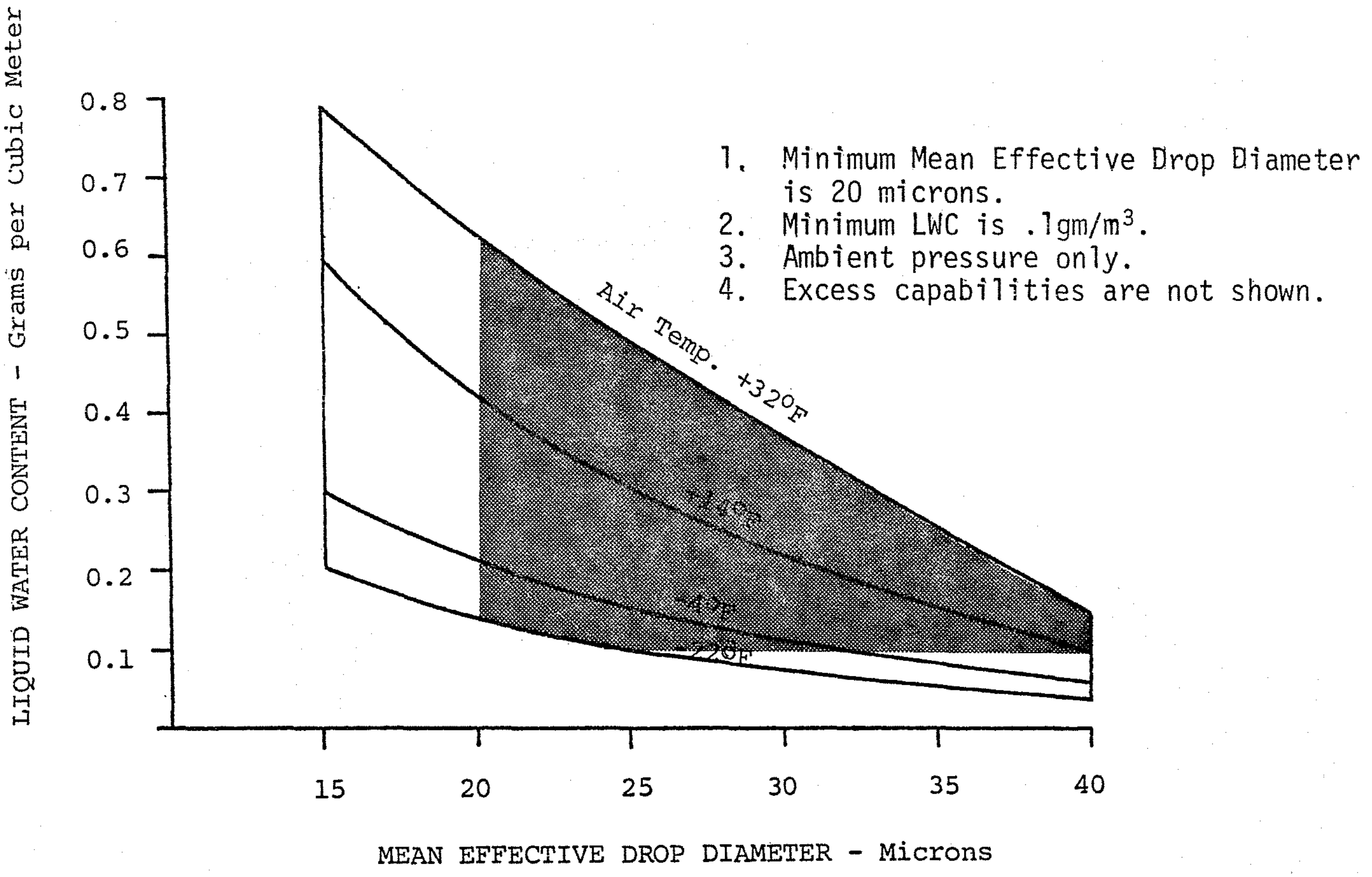
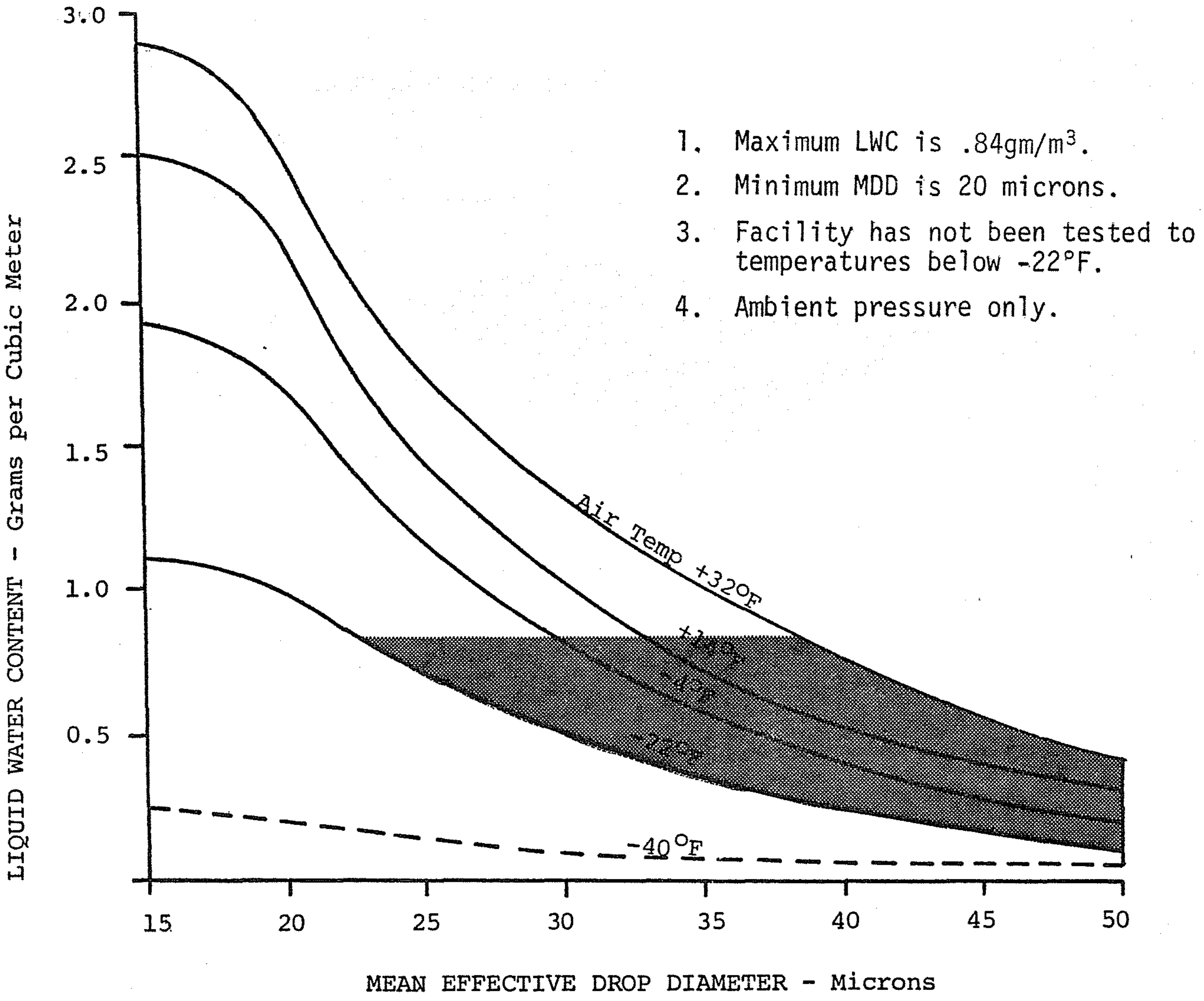


Figure 3.15 Immersion of UH-1 Helicopter in Ottawa Spray Rig Icing Cloud



1. Minimum Mean Effective Drop Diameter is 20 microns.
2. Minimum LWC is .1gm/m^3.
3. Ambient pressure only.
4. Excess capabilities are not shown.

Figure 3.16 Ottawa Spray Rig Icing Cloud vs Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions



1. Maximum LWC is .84gm/m^3.
2. Minimum MDD is 20 microns.
3. Facility has not been tested to temperatures below -22°F.
4. Ambient pressure only.

Figure 3.17 Ottawa Spray Rig Icing Cloud vs Intermittent Maximum (Cumuliform Cloud) Atmospheric Icing Conditions has not been verified to the extent that it can now be used for icing testing in those conditions, it remains an essential potential capability which must be further explored.

Table 3.13 presents a summary of the capabilities of the Ottawa spray rig in terms of the FAR icing parameters. Of particular note is its capability to produce a large, uniform icing cloud. Table 3.2 shows the median dimensions of all current U.S. helicopter designs, and indicates that well over 50% of the existing helicopters could immerse their rotor system in the icing cloud produced by the spray rig. The cloud is also large enough to contain the rotor systems of new designs such as the NASA/BELL XV-15 tilt rotor or to provide a test capability for V/STOL aircraft.

The Ottawa Spray Rig, despite its unique capabilities, is still deficient in several important areas. Among those are the inability to simulate altitude in its test environment. The composition of the uniform icing cloud is also deficient inasmuch as its liquid water content and mean drop diameter do not conform with large portions of the FAR icing environment. Another limitation of this test facility is its dependency on surface winds to provide movement of the cloud mass and ambient temperatures. Dependency on weather conditions prohibits its use except during winter months. Although little can be done in the way of improving the temperature ranges of the facility, studies have been made to determine the feasibility of incorporating velocity inducing equipment to augment the air velocity in no-wind conditions. This additional capability would cost an estimated 2.5 M dollars, and would necessitate the construction of an entirely new facility. It is suspected that such a device would induce cloud uniformity problems which would offset any improvements in airspeed control and consistency. Thus, it has been determined that an airspeed augmentation capability is not necessarily a desirable improvement, and plans for its incorporation have been cancelled.

Although this facility can produce a cloud size sufficient for immersion of most rotor systems, very large rotor systems of large transport rotorcraft cannot presently be completely immersed. Tandem rotor systems pose a particular problem in that the forward rotor displaces and dissipates the icing cloud before the aft rotor can be immersed. Additionally, there is no adequate verification of the validity of extrapolation of data obtained in hover for predicting performance in forward flight. A final and very pressing problem with the facility is not one of capabilities, but of economics. The Canadian Government has made the decision to decommission the facility in 1985, or sooner if demand for the facility diminishes. Unless plans are made in the interim for the relocation of the facility to this country, or for the construction of a similar facility, a valuable capability for development testing of helicopters for flight in icing conditions will be lost. It should be noted that the date 1985 represents a target closing date, based upon usage, equipment/material wearout, and retirement of trained operating personnel.

Table 3.13 Synopsis of NRC Spray Rig (Ottawa Spray Rig) Capabilities

ICING TEST PARAMETER	RANGE OF OPERATION	FAR 25 APPENDIX C RANGE		UNITS
		CONTINUOUS	INTERMITTENT	
Liquid Water Content	.1 - .8	.04 - .8	.25 - 2.8	gm/m^3
Median Volumetric Drop Diameter	20 - 50+	15 - 40	15 - 50	μm
Temperature	+32 to - 20°**(Ambient)	-22°	-40*	°Fahrenheit
Altitude	Ambient Pressure	0-22,000	0 - 29,250	Pressure Altitude, Ft.
Airspeed	20 to 45 (wind dependent)	-	-	Knots
Chamber Size	N/A	-	-	H x W x L m
Uniform Cloud Size	4.5 X 23 m	-	-	H x W m

*Indicates possible extent of limits

**Temperature ranges in below -20°F are possible depending upon ambient conditions

Relocation of the existing facility, therefore, may not be a cost effective means of insuring the continued use of the facility.

The following recommendations for the improvements to, and future disposition of, the facility are offered in order that the full potential of the Ottawa spray rig may be realized:

1) Until such time as a similar or improved version of the NRC Spray Rig can be produced in this country, support efforts to maintain the spray rig's operational status.
2) In the interim period, before deactivation of the rig, provide U.S. personnel, from both government and industry, for training in the operation of the facility.
3) Begin planning and implementing changes to the facility (or a similar U.S. Facility) which will increase the size of uniform icing cloud to approximately 75 x 24 feet (sufficient for immersion of 95% of projected U.S. helicopter models).
4) Improve the range of liquid water content and mean effective drop diameter to their maximum extent so that these parameters can more closely approximate the ranges defined in FAR 25 Appendix C.
5) Incorporate freezing rain and snow simulation capability in the facility.
6) Determine the validity of extrapolation of hover flight data to predict performance (helicopter and ice protection system) in forward flight.
7) Determine whether the effects of solar radiation and relative humidity have a significant impact on the validity of test results.

3.3.2.2 McKinley Climatic Laboratory - Eglin AFB, Florida

The McKinley Climatic Laboratory is a complex of three climatic simulation facilities consisting of engine test cells and all weather test chambers. This facility is used for a variety of climatic tests ranging from tropical to arctic environments. Details of the capabilities of the facility may be found in Reference 1.

The climatic laboratory has been used in the past to perform limited simulated icing tests. These limited experiments yielded results of minimal value but concepts or ideas were developed by McKinley Laboratory personnel that, if implemented, could allow the facility to produce very usefull test results. It is emphasized that these concepts have not yet been proven, but, if they were, the facility and especially the main test chamber could contribute significantly to an arrary of National Icing Facilities.

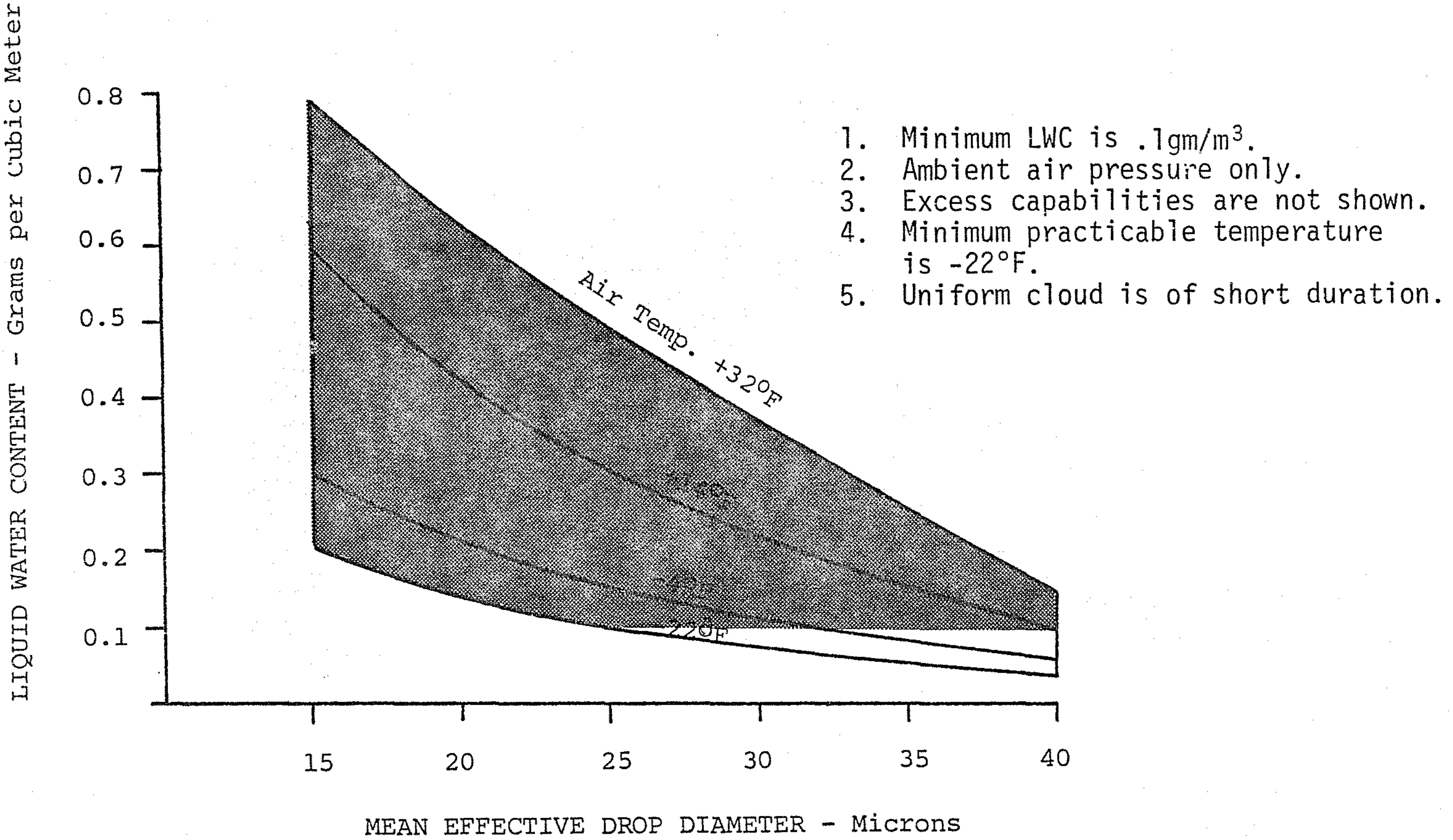
The McKinley Climatic Laboratory if modified and proven would be one of the few facilities which combines large size and the ability to duplicate portions of the Appendix C atmospheric icing conditions (no altitude capability and very low airspeed capability, however). Figures 3.18 and 3.19 provide a comparison between its producible cloud and the FAR target envelopes. The climatic lab if properly modified could meet or exceed the intermittent and continuous maximum icing environment parameters with the exception of temperature and altitude. It should be noted that -20°F is sufficient for full coverage of the stratiform cloud atmospheric icing conditions and marks the beginning of the "extent of possible limits" for cumuliform clouds.

The large test chamber (21 x 76 x 76 m) allows the introduction of large full scale components for icing testing. These components could range from complete pilot and copilot windshields, empennage, airfoils (both stationary and rotating) and other surfaces for which icing protection is desired. The chamber is capable of enclosing complete aircraft (up to and including the C-5A), large aircraft components and aircraft systems, and selectively icing various portions of the aircraft. The lab is capable of performing icing testing on aircraft with all power systems in operation. Although the facility is listed as a low velocity facility, it has the advantage of providing a capability for engine testing (as do the laboratory's auxillary facilities). Until such time as the AWT is operational, the Climatic Laboratory could be one of the most effective facilities for ground tie down testing of large propeller driven engines.

Table 3.14 provides a synopsis of the laboratory's capabilities in terms of FAR 25 Appendix C icing environment parameters, and other parameters affecting the facility's potential applications.

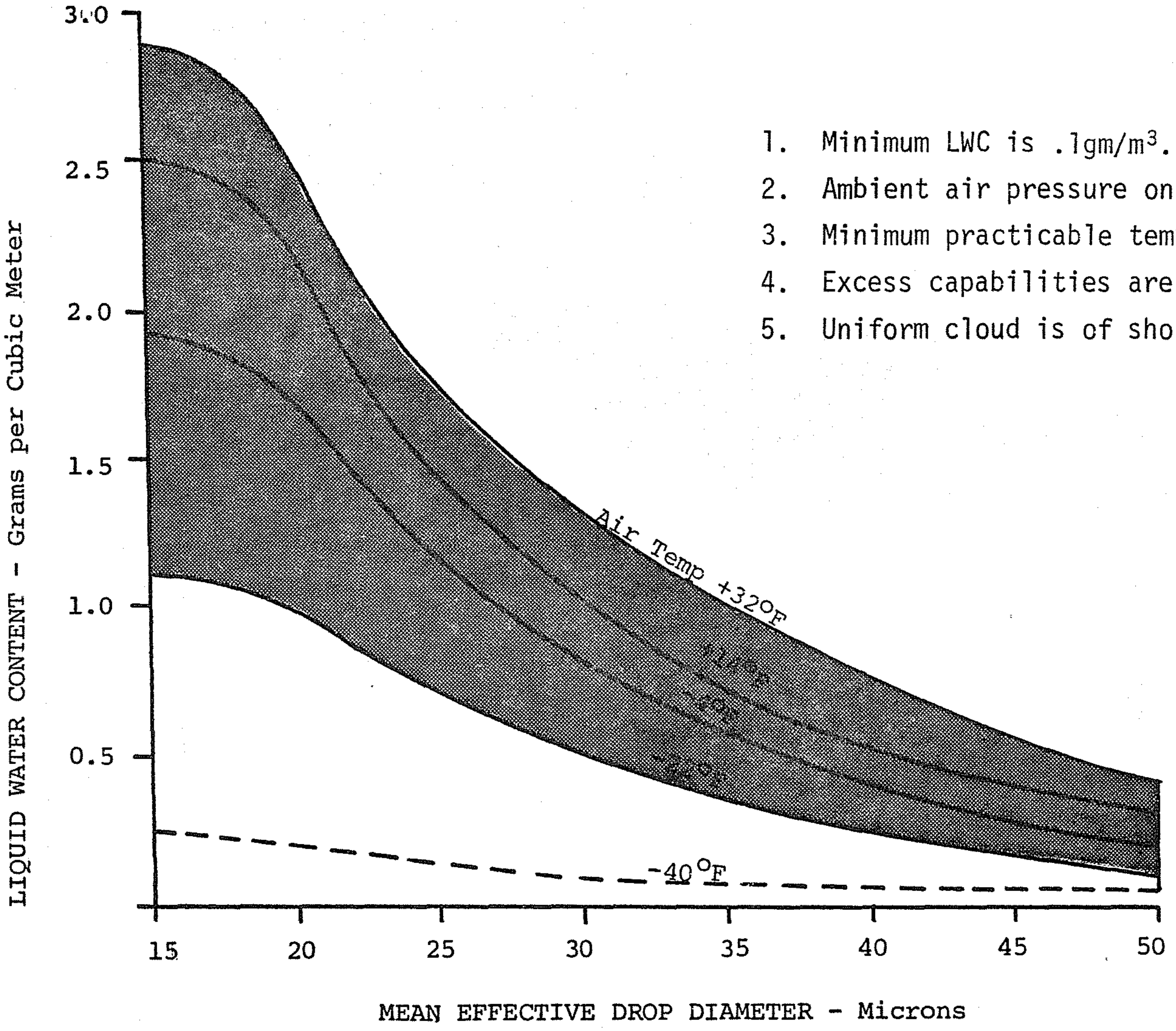
Unlike the Ottawa Spray Rig, whose climatic conditions are dependent on the weather, the Climatic Laboratory is capable of year round operation. Another related advantage is the ease with which the icing environment may be controlled and modified within the facility. This capability permits testing over a wide range of parameters during a short period of time. Additionally, as with all ground simulation facilities, its configuration facilitates ease of data collection and reduction.

As shown in Figures 3.18 and 3.19, the Climatic Lab does provide nearly complete coverage of the FAR 25 APP C icing envelope, in terms of LWC and mean effective drop diameter, over a wide range of temperatures. However, the inability to provide an altitude capability in the facility is a significant shortcoming. The most serious shortcoming of the facility lies in the problems of end wall effects and air recirculation which are manifested during full scale helicopter tie down tests. Airflow interference by the facility's interior walls and ceiling has caused serious disruption of the uniform icing cloud, rendering most previous testing, and thus the test results, inadequate for evaluating the ice accretion and shedding dynamics of the rotor system. The ability of the Climatic Lab to meet future requirements for icing certification and R&D will be dependent upon improving the facility to eliminate these air circulation problems. Still another deficiency exists in the range of airspeeds through which the facility can operate. The maximum airspeed of 40 knots, while encompassing an important portion of the helicopter's flight envelope, is well below the flying speed of most fixed wing aircraft.



1. Minimum LWC is .1gm/m^3.
2. Ambient air pressure only.
3. Excess capabilities are not shown.
4. Minimum practicable temperature is -22°F.
5. Uniform cloud is of short duration.

Figure 3.18 McKinley Climatic Lab Icing Cloud Vs. Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions



1. Minimum LWC is .1gm/m³.
2. Ambient air pressure only.
3. Minimum practicable temperature is -22°F.
4. Excess capabilities are not shown.
5. Uniform cloud is of short duration.

Figure 3.19 McKinley Climatic Lab Icing Cloud Vs. Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions

Table 3.14 Synopsis of McKinley Climatic Laboratory Capabilities

ICING TEST PARAMETER	RANGE OF OPERATION	FAR 25 APPENDIX C RANGE		UNITS
		CONTINUOUS	INTERMITTENT	
Liquid Water Content	.25 - 4.	.04 - .8	.25 - 2.8	gm/m^3
Mean Drop Diameter	12 - 60	15 - 40	15 - 50	µm
Temperature	below -22°	-22°	-40*	°Fahrenheit
Altitude	0	0 - 22,000	0 - 22,000	Pressure Altitude, Ft.
Airspeed	0 - 40	-	-	Knots
Chamber Size	21 x 76 x 76	-	-	H x W x L m
Uniform Cloud Size	3 x 9	-	-	H x W m

*Indicates possible extent of limits

The following recommendations are proposed:

1) Examine and analyse concepts identified by McKinley Laboratory personnel to determine their feasibility.
2) Examine the facility workload to assume that if modifications are incorporated the new capabilities can be adequately utilized in view of an existing, extremely high, workload.
3) Should these concepts prove feasible and the projected workload excessive, examine the need and possibilities for duplication of these facilities.
4) Should it be determined that modification to the existing facility or construction of a duplicate facility is warranted the following capabilities should be sought:
    a) Cloud size (24' high x 75' wide) sufficient for complete immersion of aircraft components such as rotor systems and fuselages.
    b) Airspeed capability from 20 to 70 knots to cover the airspeed gap of other full scale simulation facilities.
    c) Liquid water content, droplet size and temperature ranges of FAR 25 APP C.
    d) Capabilities for freezing rain, snow and mixed condition testing.

3.3.3 Inflight Icing Tankers

Inflight icing tankers offer a means by which aircraft anti-icing and deicing systems may be verified in forward flight, in a uniform calibrated icing cloud, short of flight into the natural icing environment. The U.S. Government and the aircraft industry are using inflight tankers as an aid in research and development as well as icing certification testing. There are six such tankers (Reference 4) in either the planning stages or in actual operation at this time. Table 3.15 categorizes the six tankers in accordance with their applicability to National Icing Facilities. Three of the tankers (Numbers 4, 5 and 6 in Table 3.15) are owned and operated by industry and are therefore inappropriate for inclusion in the array of a National Icing Facilities. However, experience gained during inflight icing testing by industry should supplement the work being performed by the government along the same lines. A further reason for industry tanker's exclusion in the discussion of inflight icing facilities is that the size of the icing clouds they produce is too small for use in development and certification testing of the variety of aircraft likely to be developed in the next 20 years. Also, the limited water payload of the current industry tankers is insufficient to produce a large cloud for adequate duration.

The remaining icing tankers are owned and operated by the Federal Government, specifically by the U.S. Army and Air Force. Their primary role, until now, has been in research and development and icing

Table 3.15 Applicability of Inflight Icing Tankers to National Icing Facility

FACILITY NAME AND LOCATION	INTEGRAL TO NATIONAL FACILITY	SIGNIFICANT RESEARCH FACILITY	SUPPLEMENTAL FACILITY
1. Air Force KC-135 Tanker Edwards AFB, California	✓		
2. Air Force C-130 Tanker Edwards AFB, California	✓		
3. Army HISS Helicopter Tanker Edwards AFB, California	✓		
4. Cessna 404 Tanker Wichita, Kansas		✓	
5. Piper Cheyenne Tanker Lock Haven, Penna.		✓	
6. Flight Systems T-33 Tanker Mojave, California		✓	

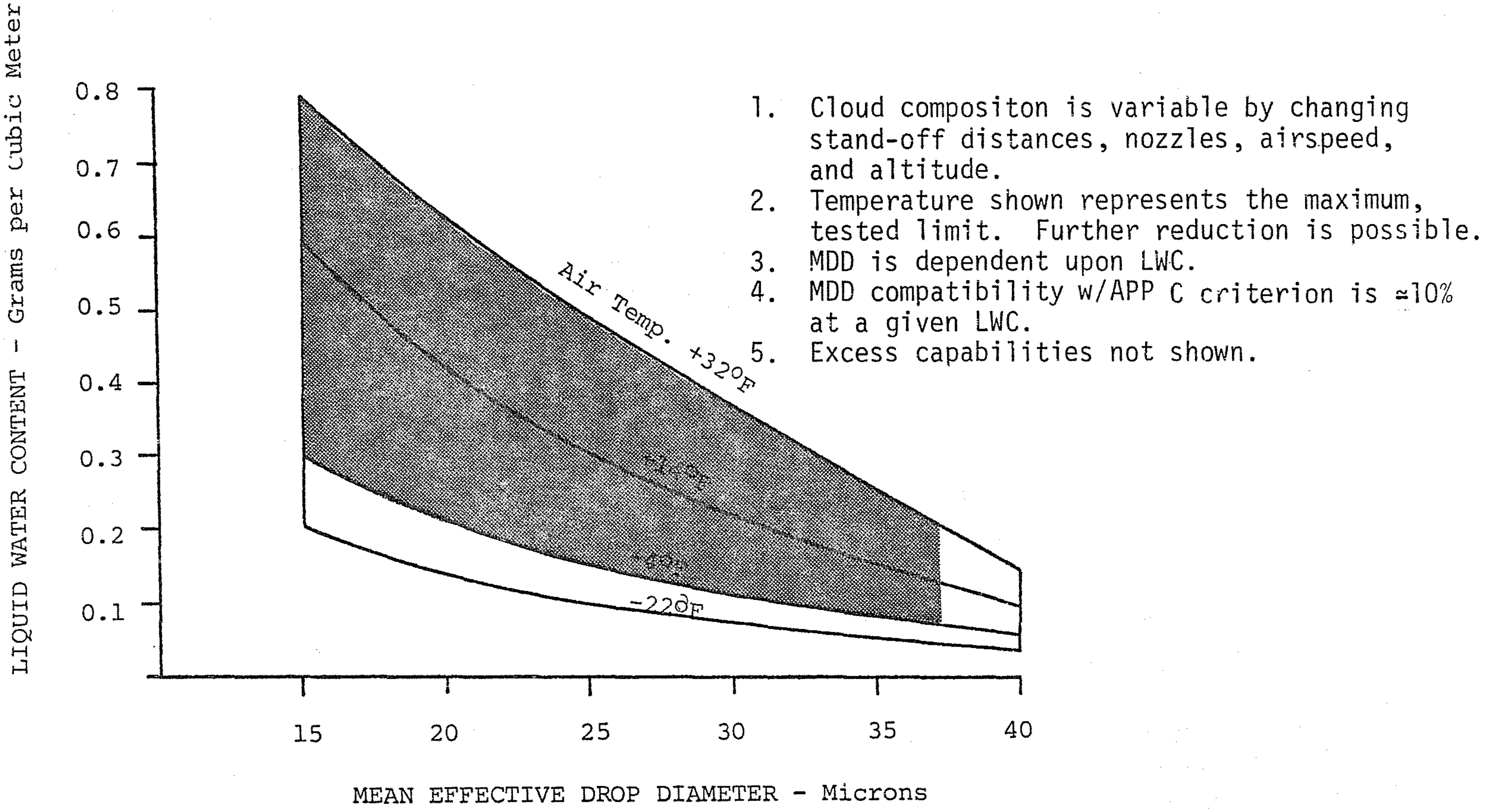
testing for military aircraft designs. Their usefulness in that regard has resulted in requests by other branches of government, as well as industry, for the use of the facilities. These facilities possess the unique ability to produce a moving, uniform icing cloud through which the test aircraft may fly. In such a facility it is possible to test not only the ice protection systems' ability to deice or prevent ice accumulation, but also to determine the effects of ice on aircraft performance, stability and control.

Due to the inherent operational limitations (airspeed, ceiling, payload) of the tanker aircraft themselves, no single inflight tanker can satisfy the airspeed and altitude requirements of all aircraft types expected to be developed and certificated over the next 20 years. The "family" of government operated tankers (the KC-135, C-130, and Army "HISS" Helicopter Tanker) does provide a wide range of icing parameters which should, with some modification and improvements, provide sufficient icing cloud coverage for most aircraft designs in use today or projected through the year 2000.

The C-130 and KC-135 tankers both exhibit similar capabilities in their ability to duplicate portions of the FAR 25 Appendix C icing envelope. Figures 3.20 and 3.21 provide an overlay of their capabilities vs the intermittant maximum and continuous maximum atmospheric icing envelopes. It should be noted that their minimum temperature capability is only the limit to which the tankers have been tested, and there is no reason that temperatures lower than -20°F cannot be achieved, provided means are developed to prevent freezing of the nozzle system.

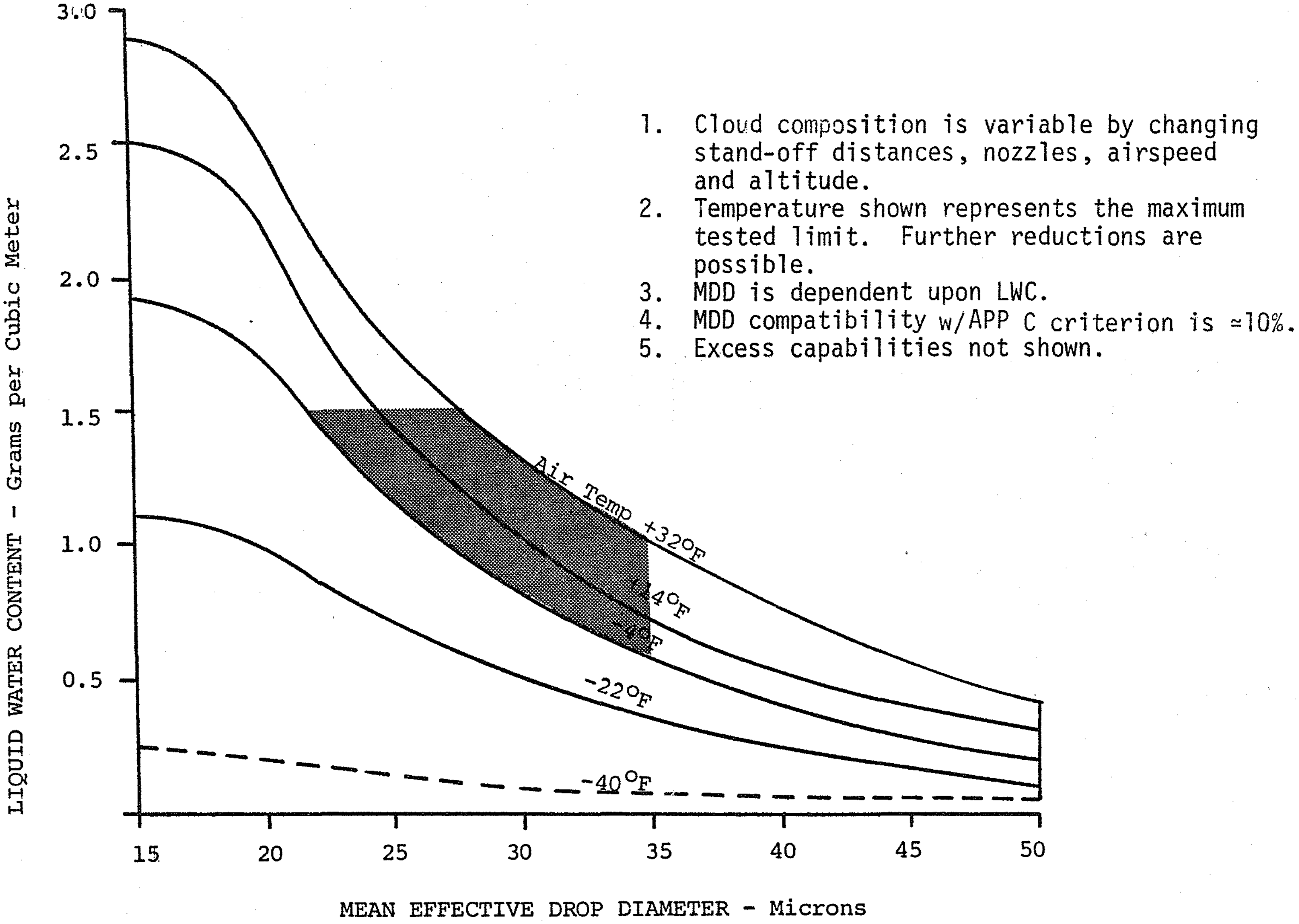
The HISS tanker, on the other hand, may be limited, due to its ceiling restraints, to temperatures in that realm. Figures 3.22 and 3.23 show the HISS's coverage of the accepted FAR Appendix C envelope. As shown, temperature is a limiting factor as is drop size and liquid water content. Although temperatures below -20°F may be difficult to achieve on a recurring basis, the drop size and liquid water content of the icing clouds will certainly be improved. With the introduction of a new spray nozzle and improvements in the available aspiration flow and pressure, liquid water content range from .25 to 5.0 gm/m^3 and drop diameters from 15 to 50 μm should be attainable. This improvement will greatly enhance the HISS's overall ability to simulate super-cooled clouds, particularly in the intermittant maximum envelope.

Another key factor in judging the potential advantages of this sort of airborne facility, is the size of the uniform icing cloud. In this regard, the HISS (Figure 3.24) is superior to both the KC-135 and C-130. Figure 3.25 shows a comparison of the relative cross sectional dimensions of the icing clouds produced by the three tankers, with respect to the dimensional characteristics of all U.S. built helicopters. The superiority of the HISS is not surprising in view of the purposes for which the different tankers were developed. The HISS was designed for the purpose of immersing entire rotor systems in an icing cloud. The KC-135 and C-130 tankers were designed to ice only specific components of the tested aircraft. In all cases, however, the size of the icing cloud can be increased or decreased by adjusting the



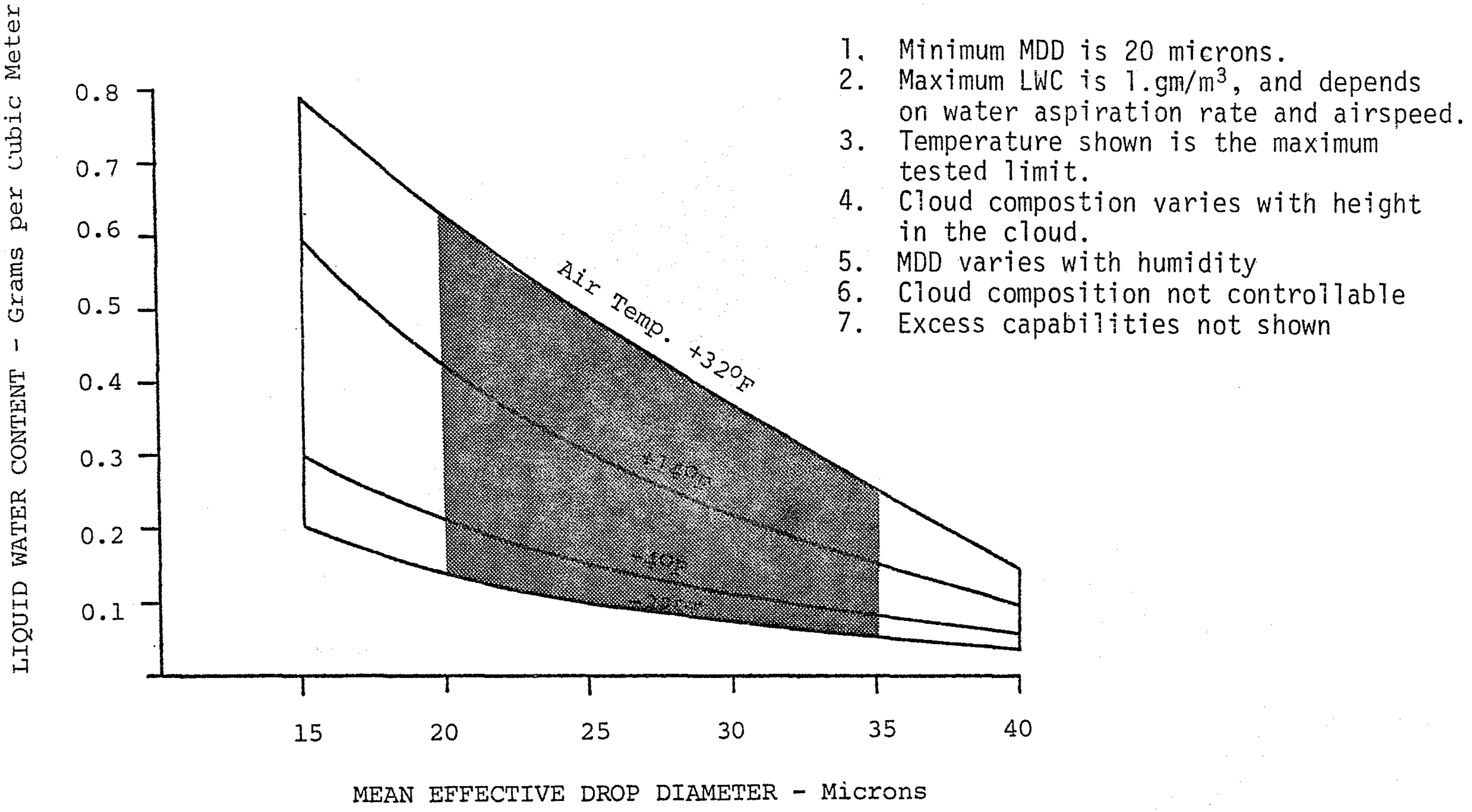
1. Cloud compositon is variable by changing stand-off distances, nozzles, airspeed, and altitude.
2. Temperature shown represents the maximum, tested limit. Further reduction is possible.
3. MDD is dependent upon LWC.
4. MDD compatibility w/APP C criterion is ≈10% at a given LWC.
5. Excess capabilities not shown.

Figure 3.20 C-130 and KC-135 Tanker Icing Cloud vs Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions



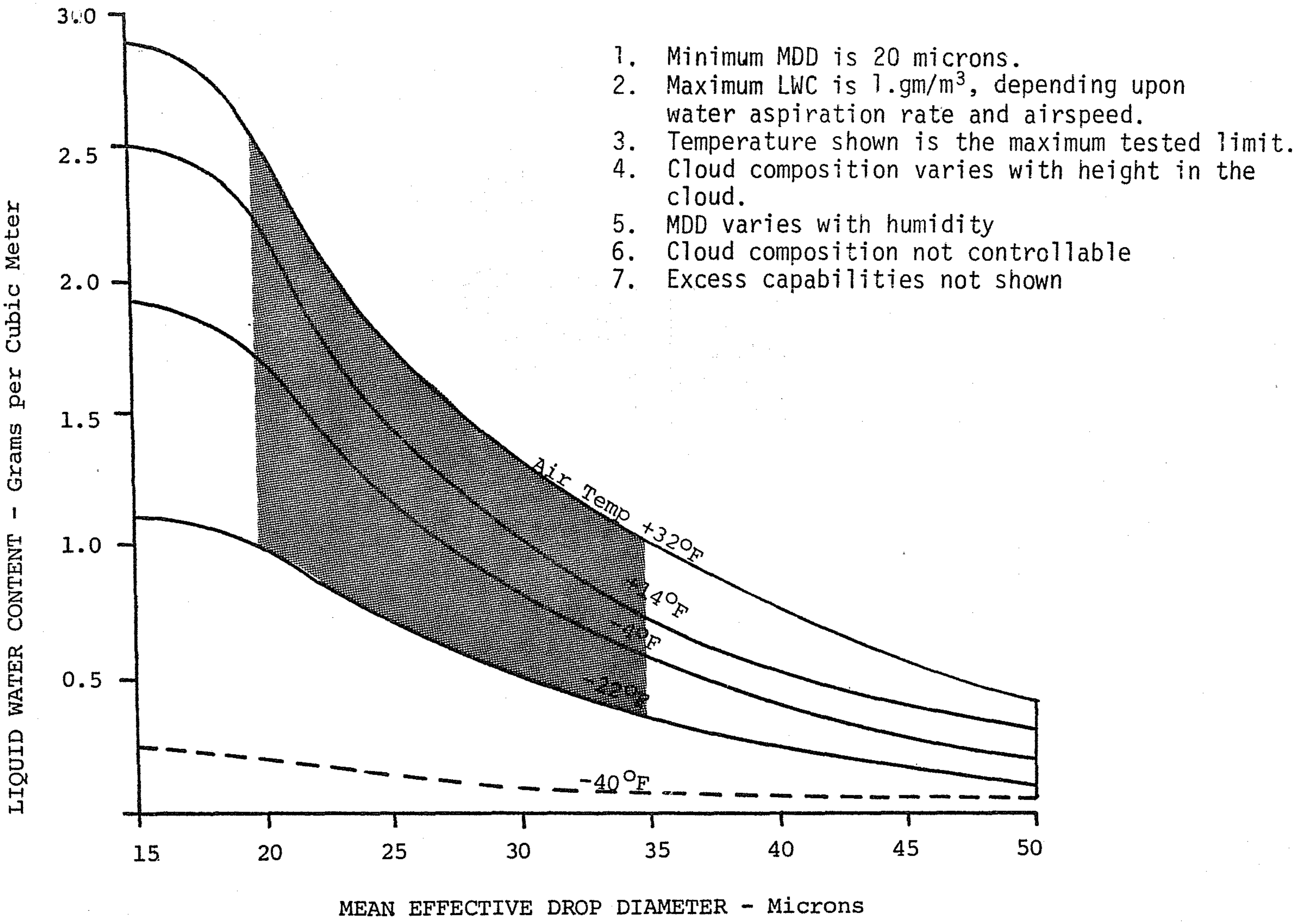
1. Cloud composition is variable by changing stand-off distances, nozzles, airspeed and altitude.
2. Temperature shown represents the maximum tested limit. Further reductions are possible.
3. MDD is dependent upon LWC.
4. MDD compatibility w/APP C criterion is ≈10%.
5. Excess capabilities not shown.

Figure 3.21 C-130 and KC-135 Tanker Icing Cloud vs Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions



1. Minimum MDD is 20 microns.
2. Maximum LWC is 1.gm/m^3, and depends on water aspiration rate and airspeed.
3. Temperature shown is the maximum tested limit.
4. Cloud compostion varies with height in the cloud.
5. MDD varies with humidity
6. Cloud composition not controllable
7. Excess capabilities not shown

Figure 3.22 HISS Tanker Icing Cloud Vs. Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions



1. Minimum MDD is 20 microns.
2. Maximum LWC is 1.gm/m^3, depending upon water aspiration rate and airspeed.
3. Temperature shown is the maximum tested limit.
4. Cloud composition varies with height in the cloud.
5. MDD varies with humidity
6. Cloud composition not controllable
7. Excess capabilities not shown

Figure 3.23 HISS Tanker Icing Cloud Vs. Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions

Figure 3.24 Double Boom Configuration of Helicopter Icing Spray System (HISS)

standoff distance of the trailing aircraft. Further, despite the relatively small clouds produced by the Air Force fixed wing tankers today, the technology is available with could enable the formation of an icing cloud similar to the HISS in both dimension and composition.

One factor determining the ultimate size of the icing cloud is water pay load capacity. In this regard, the HISS is more limited than either the C-130 or the KC-135. Expansion of cloud size to limits large enough for immersion of entire rotorcraft will limit the test endurance. It may be necessary, therefore, to consider

NOTE: The tanker cloud size varies with distance from the spray boom.

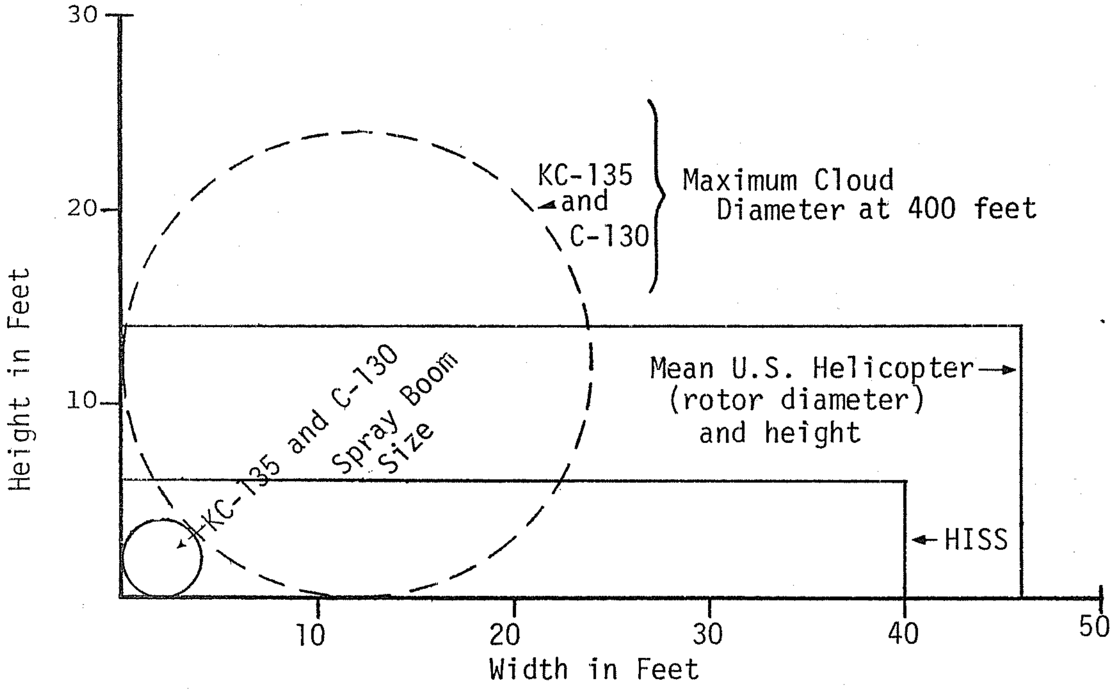


Figure 3.25 Cross Sectional Areas of Icing Tanker Produced Clouds Vs Mean Helicopter Dimensions

the use of larger helicopter tankers to provide cloud simulation of adequate duration in these lower airspeed, and altitude regimes. The KC-135 and C-130 tankers, on the other hand, with a larger payload capacity, do not have that same limitation.

These large transport aircraft have the ability to carry sufficient water payload to produce large enough cloud sizes. In this case, it is the question of providing a modified, dedicated icing aircraft that can only be used 3 - 4 months each year vs. a palletized water carrying capability. Neither the C-130 or the KC-135 can carry sufficient water in a palletized configuration. For this reason, the most cost effective solution may be to utilize a C-141 in the palletized water carrying mode rather than modifying either the C-130 or the KC-135.

The basic difference between the three tankers lies in their ceiling and airspeed restrictions. The airspeed and altitude capabilities are primarily a function of the operational envelopes of the tankers themselves. This fact provides an explanation for the necessity of several tankers as opposed to just one. If the ultimate goal of icing certification through simulation is to reduce the necessity for flights into natural icing conditions for as many different types and sizes of aircraft as possible, a family of tankers with different capabilities is a necessity. Figure 3.26 depicts the current specified airspeed and ceiling limits of the inflight tankers. The ceilings and airspeeds shown are based on test results through early 1980 and do not necessarily constitute current limits of the tankers. Although the airspeeds are fairly firm, altitude ranges will probably increase as further testing is completed.

With certain improvements in the capabilities of the current inflight tankers, complete immersion of many types of aircraft in a uniform icing cloud will be possible. The inflight tankers simulate a wide range of altitudes, airspeeds and cloud compositions in which to perform research and development testing or certification trials. These trials can be recorded photographically by chase aircraft or the tanker itself as well as by hub or aircraft mounted photographic equipment. The inflight tankers, because of their controllable environment also allow for rapid egress from the icing environment in the event of unsafe conditions or for photographic recording of ice formation and shedding characteristics. These capabilities give the tankers the potential for use an an alternative to natural icing testing for research and development and possibly for certification.

As mentioned previously, the tankers have several problems which inhibit their full potential. The current droplet sizes and liquid water content of the simulated cloud do not allow for full coverage of the natural icing envelope. Also, the effects of solar radiation and relative humidity on ice accretion and shedding are not known. This is important because much of the testing performed by the tankers is in clear and low humidity conditions. Beacause of altitude

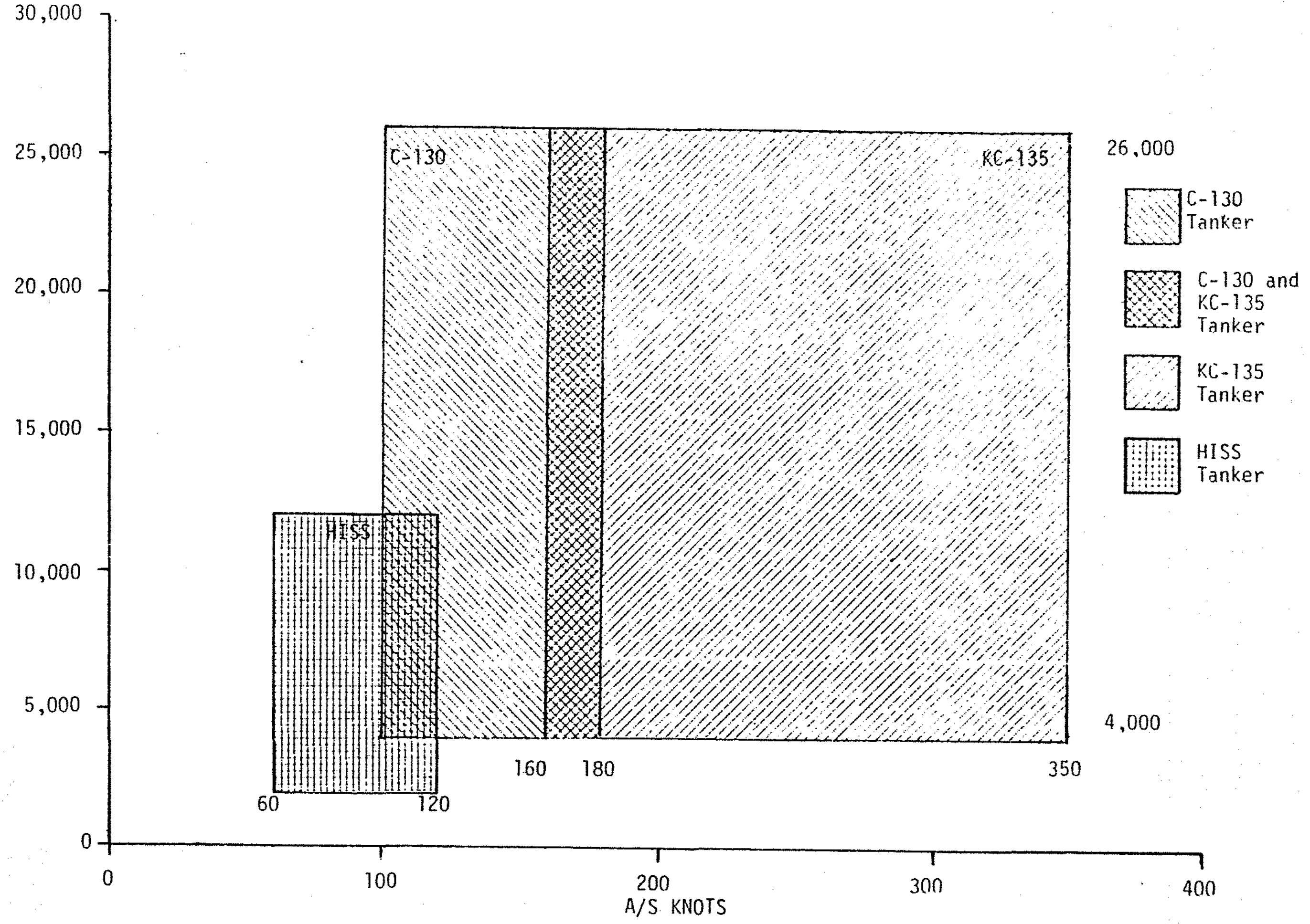


Figure 3.26 Altitude vs Airspeed Envelopes (HISS, KC-135, C-130)

restrictions, the HISS is only available for use in the winter months. Availability of the facilities for industry use is further restricted by the predisposition of those facilities to military use. Until these deficiencies are corrected, optimum utilization of the facilities for the purpose of icing development and certification testing cannot be accomplished.

The following recommendations are made to correct the deficiencies of the tanker facilities:

1) Improve the cloud composition produced by the tankers, to include liquid water content and mean effective drop diameters most likely to be encountered at low altitudes.
2) Increase the cloud dimensions of the current producible clouds to approximately 75 feet by 24 feet.
3) Investigate possiblity of increasing HISS airspeed range to include low speed regimes down to 40 knots and up to 120 knots.
4) Determine the effect of solar radiation and relative humidity on ice accretion and shedding.
5) Dedicate the icing tankers for the use of icing testing and certification for both government and industry.
6) Develop a new tanker to support projected workload.

3.3.4 Engine Test Facilities

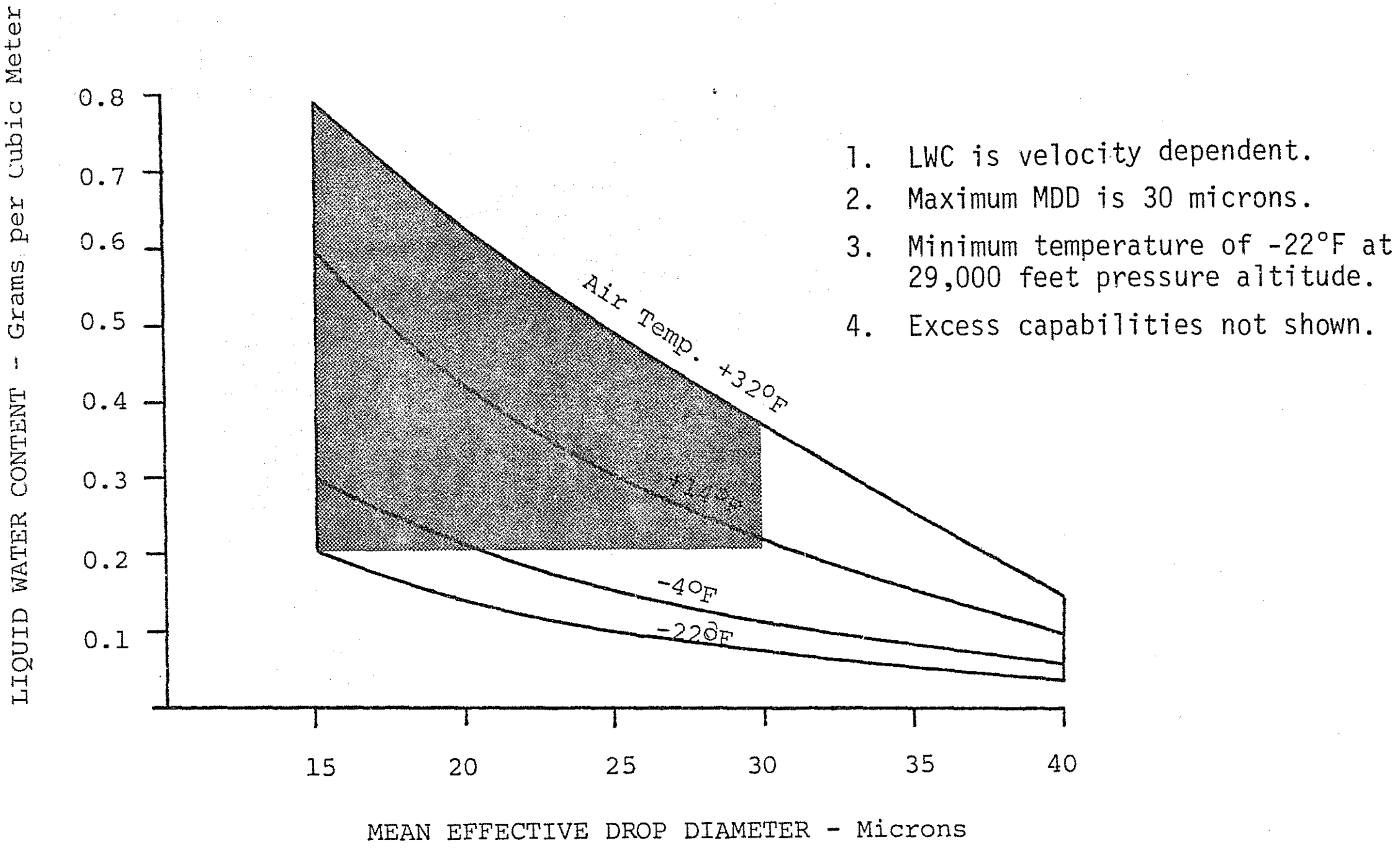
Appendix A indicates that there are 28 engine test facilities in the U.S. and Canada which are actively involved in engine icing development and certification testing. Most of these facilities are privately owned, and thus not appropriate for inclusion in an array of National Facilities. Table 3.16 categorizes the facilities by their potential for inclusion as part of National Icing Facilities. Those selected as significant research facilities will continue to perform the majority of engine icing testing and certification, as they have in the past. However, for those engines whose dimensions exceed the capabilities of the private facilities, use of the AWT, the McKinley Climatic Laboratory, the Arnold Test Facility or the Naval Air Propulsion Test Center will be required.

Figures 3.27 and 3.28 show the capability of the Aeropropulsion System Test Facility (ASTF) in simulating the icing envelope. Although limitations of the ASTF in terms of drop size diameter greatly reduce the portions of the natural icing envelope that the facility can cover, there is no reason that the drop diameter range cannot be increased.

The icing simulation capabilities of the U.S. Naval Air Propulsion Center's icing tunnels are shown in Figures 3.29 and 3.30. As shown, the facilities are capable of producing independent icing parameters

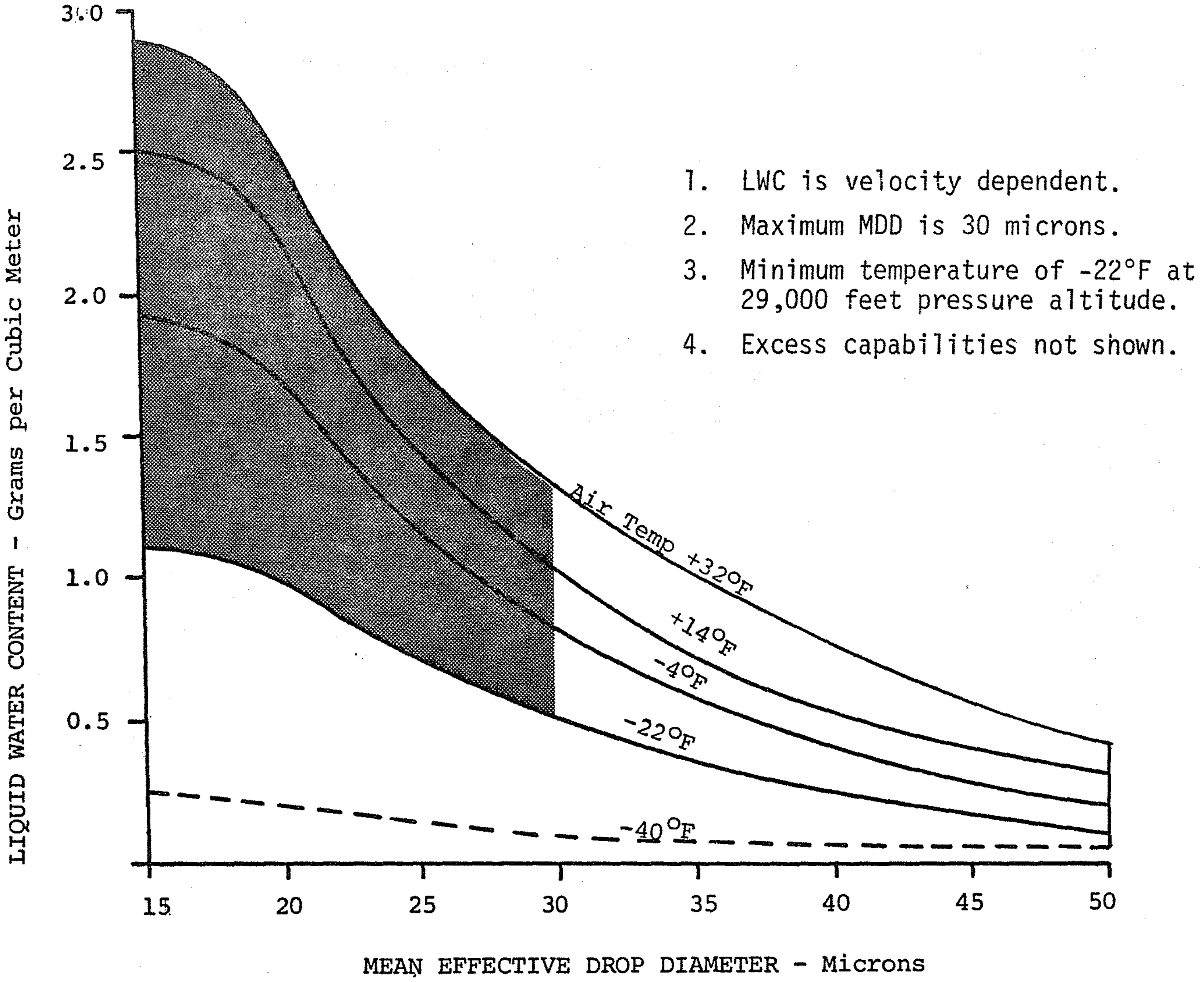
Table 3.16 Applicability of Engine Test Facilities to the National Icing Facility

FACILITY NAME AND LOCATION	INTEGRAL TO NATIONAL FACILITY	SIGNIFICANT RESEARCH FACILITY	SUPPLEMENTAL FACILITY
1. Arnold Engineering Development Center Tullahoma, Tenn.	✓		
2. Detroit Diesel Allison Indianapolis, Ind.		✓	
3. GE Cross Wind Facility Peebles, Ohio		✓	
4. P&W Altitude Facility East Hartford, Conn.		✓	
5. McKinley Climatic Laboratory Eglin AFB, Fla.	✓ (Sec. 3.3.2.3)		
6. Naval Air Propulsion Facility Trenton, N.J.	✓	✓	
7. Teledyne Altitude Cells Toledo, Ohio		✓	
8. Avco Lycoming Stratford, Conn.		✓	
9. NRC Ottawa, Canada		✓	
10. Garret Icing Facilities Phoenix, Arizona		✓	



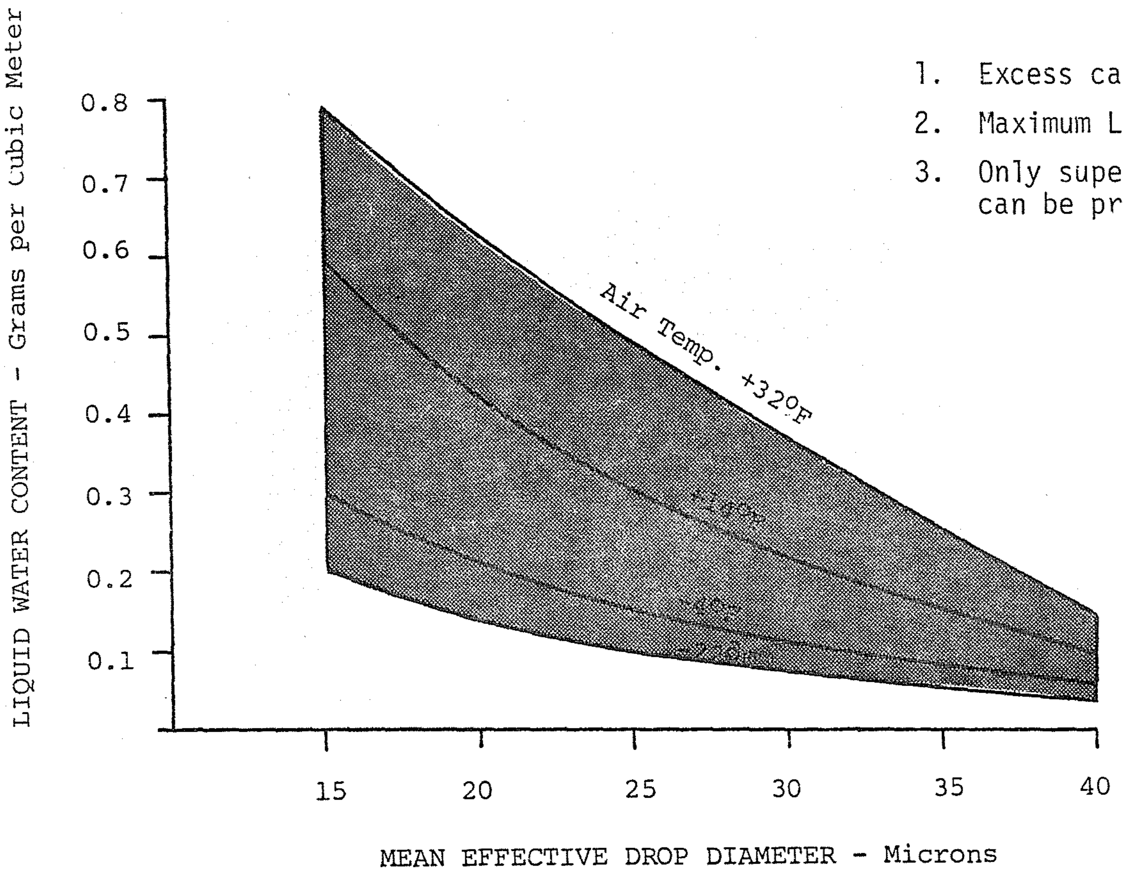
1. LWC is velocity dependent.
2. Maximum MDD is 30 microns.
3. Minimum temperature of -22°F at 29,000 feet pressure altitude.
4. Excess capabilities not shown.

Figure 3.27 Arnold Engineering and Development Center, ASTF, Icing Cloud Vs. Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions



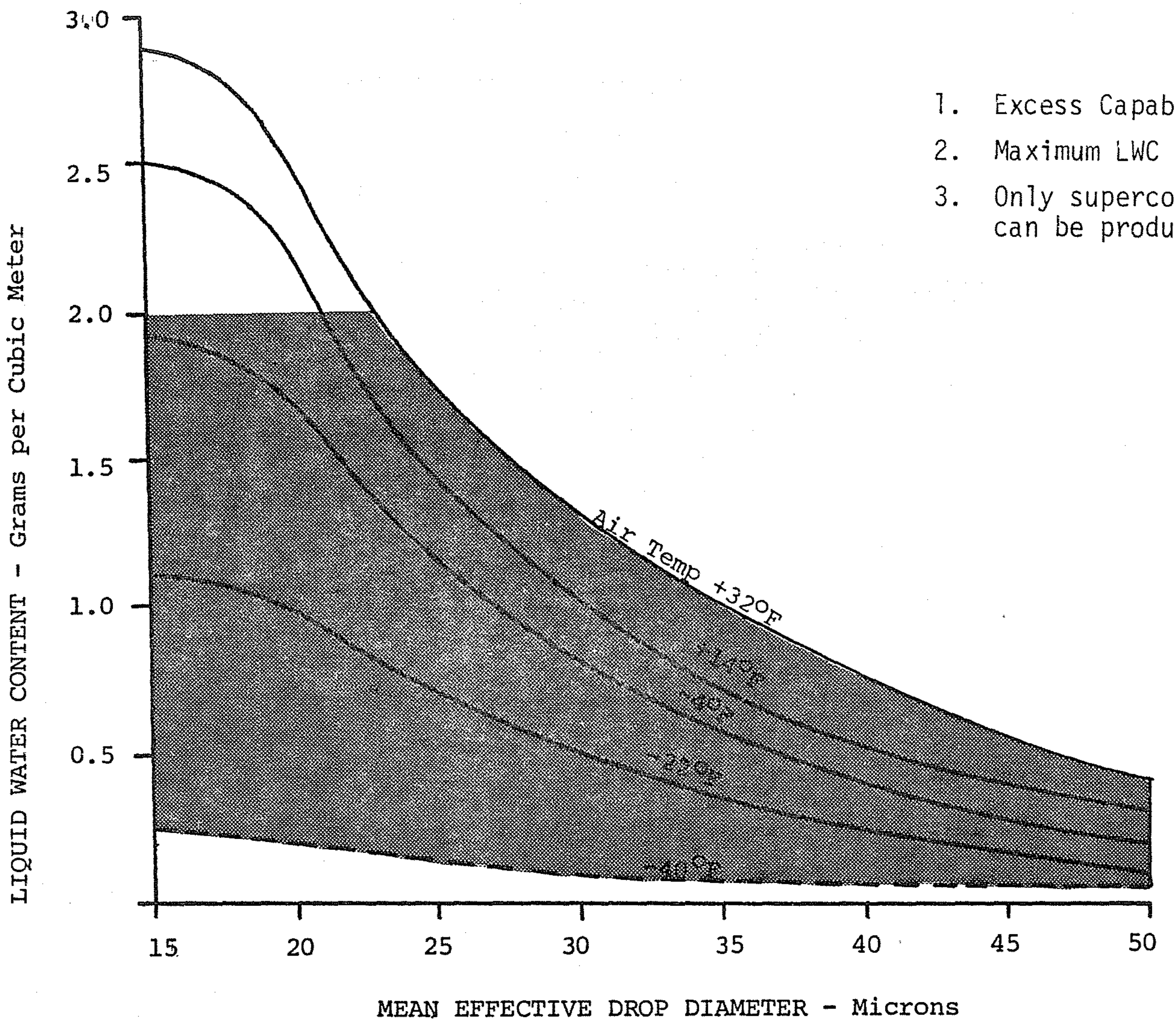
1. LWC is velocity dependent.
2. Maximum MDD is 30 microns.
3. Minimum temperature of -22°F at 29,000 feet pressure altitude.
4. Excess capabilities not shown.

Figure 3.28 Arnold Engineering and Development Center, ASTF, Icing Cloud vs Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions



1. Excess capabilities not shown
2. Maximum LWC .3 2 gm/m^3
3. Only supercooled icing cloud can be produced

Figure 3.29 USNAPC Icing Cloud vs Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions



1. Excess Capabilities not shown
2. Maximum LWC is 2 gm/m^3
3. Only supercooled icing cloud can be produced

Figure 3.30 USNAPC Icing Cloud vs Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions with LWC ranges up to 2.0 gm/m^3. While this range does not allow testing at the maximum liquid water content ranges specified by the intermittent maximum criterion, it is sufficient to test the entire continuous maximum range.

The NAPTC facilities undergo periodic facility improvements, and it is anticipated that future improvements will include expansion of liquid water content ranges.

The use of engine icing facilities need not be restricted to the testing and certification of engines. As many of the test facilities are of the free jet variety, they may be applied to many research and development tasks which are associated with wind tunnels. In fact, their size, altitude capabilities and airspeed capabilities make them as well suited for that task as some of the pure wind tunnels. They therefore compliment the wind tunnels and will be very useful in further research and development as well as certification testing of small auxillary equipment. None of the facilities are capable of, or are projected to have, the capability of producing snow and mixed icing conditions.

Past experience with engine test facilities indicates that the facilities are adequate for current needs (Reference 1). During the next 20 years, it is not anticipated that fundamentally new engine designs will appear which cannot be tested in the facilities in operation or in the planning stages. Although continued monitoring of testing techniques and test results derived from use of the private facilities by regulatory agencies is warranted, their inclusion as components of National Icing Facilities should not be necessary. Nor should certification testing in government operated facilities be made a requirement if the private facilities are adequate.

The ASTF at Tullahoma, TN, as an element of National Icing Facilities, should provide capabilities not available in private facilities. The following recommendations are made which should rectify the existing shortcomings:

- Provide a complete coverage of the FAR 25 Appendix C envelope by increasing mean effective drop diameter up to 50 microns and reducing the minimum liquid water content to .04gm/m^3.
- Incorporate capability of producing snow, freezing rain, and mixed icing conditions in the ASTF.

3.3.5 Summary of Selected Facilities Strengths and Weaknesses

Selection of a facility as integral to the needs of National Icing Facilities was primarily a function of those unique and useful characteristics which separated the facility from others in its class. Those characteristics and capabilities, define their role in National Icing Facilities. Table 3.17 provides a summary of the strengths of each

Table 3.17 Summary of Contributions and Applications of Selected Icing Facilities

FACILITY NAME	MAJOR CONTRIBUTION TO NATIONAL ICING FACILITY	APPLICATION TO FUTURE CERTIFICATION PROCEDURES	APPLICABLE TO CIVIL OR MILITARY
Icing Research Tunnel NASA/Lewis	Largest existing icing tunnel	Full scale component testing at moderate speeds	Civil & Military
Altitude Wind Tunnel NASA Lewis	Largest proposed icing tunnel with altitude capability high speed	Full scale component and aircraft testing at high speed	Civil & Military
Ottawa Spray Rig Canada - NRC	Sea level tests in near natural ice for rotorcraft at a hover.	Helicopter/VSTOL flight tests at hover or low forward airspeed	Civil & Military
McKinley Climatic Laboratory	Largest low velocity facility with ability to contain full scale airplanes and helicopters	Helicopter and airplane tie down tests at zero to low speeds. G.A. tiedown tests.	Civil & Military
Arnold Engineering & Development Center	Largest engine test facility	Engine testing and use as icing wind tunnel	Civil & Military
USNAPC Engine Test Facilities	Large Engine Test/Icing Wind Tunnel	Large Engine Testing and use as an icing wind tunnel	Civil & Military
Inflight Tankers (all)	Inflight icing conditions in controlled environment	Possible alternative to flights in natural icing	Civil & Military
HISS	Controlled inflight meteorological conditions	Low speed and low altitude testing of airplanes and helicopters	Civil & Military
C-130 and KC-135	Controlled inflight meteorological conditions	Moderate speed and moderate altitude testing of airplanes and helicopters	Civil & Military

of the facilities with a brief description of their role in the National Icing Facilities.

The icing facilities described in Table 3.17 provide a wide range of resources and capabilities for icing research, development and certification of aircraft and their components for flight into icing conditions. There remain several crucial weaknesses in addition to those described previously for the individual facilities, which may restrict the use of the facilities or the validity of the data obtained through their use. One important weakness is the lack of correlation of data from one facility to another. At the present time, there is no single standard by which parameters, such as liquid water content and mean effective drop diameters, are measured. A standard must be established, and facilities used for conduct of icing tests must conform to those standards, to assure uniformity and accuracy of test results.

Since much of the icing testing is performed in icing wind tunnels, aerodynamic scaling laws, heat transfer laws, model scaling laws, etc., must be modified and verified before the results of icing wind tunnel testing of ice protection systems can be used for other than design and development purposes.

A further shortcoming of existing facilities is that most of the facilities designated for inclusion as National Icing Facilities are currently operated by government agencies with vast interests which include icing as one element. Use of these facilities by manufacturers, although not impossible, is extremely difficult due to the existing research and development commitments. In order for these facilities to provide the most efficient service for all potential users, provisions must be made at an early date for timely scheduling of the facilities by all concerned.

The validity of any test result which is derived from the use of a simulated icing medium is dependent upon the accuracy of the simulation with respect to the natural conditions it is designed to simulate. In order to determine the validity of the simulation, it is therefore a necessity that the natural icing conditions be understood. In surveying the capabilities of simulation of the existing facilities, it has been presumed that the FAR Part 25 Appendix C envelope provides the best description of the super-cooled cloud. As there is concern regarding the accuracy of the icing envelope, further investigation of the natural icing environment is justified. Once this necessary step has been accomplished, greater credence can be lent to the test results derived from use of icing simulation facilities.

3.3.6 Projected Facilities Improvement Costs

In the preceeding sections, recommendations for the improvement of existing facilities were made in order that the facilities might provide a more complete test environment for icing research, development and certification. This section presents a summary of the estimated facilities' modification costs, as well as, construction schedules, staffing requirements and user fees.

In each case, cognizant facility operators or managers were queried to allow the FAA to determine rough order of magnitude estimates of the facility modification costs, staffing requirements and user fees. Table 3.18 represents a summary of the results. The information provided by facility operators/managers were used as the primary basis for the estimates. These estimates are intended only to provide a rough order of magnitude statement of potential costs and construction schedules for initial decision purposes, e.g.; establishment of the National Icing Facilities Task Force.

It is possible to ascertain the extent to which various factors will impact in the requirements for national icing facilities. It is equally possible to project construction costs, user costs, etc., for the individual icing simulation. However, these factors alone cannot dictate a decision to proceed with new construction or modification of the existing facilities. Mr. Milt Beheim of the NASA Lewis Research Center was well aware of this fact as evidenced by his comments at the National Icing Facilities Coordination Meeting in September 1980. He stated,

> *"....The unfortunate problem in selling any major facility is that the project that you know could use it, will probably be done by the time the facility is done, because each one has about the same time period to accomplishment. Therefore, really a major facility decision is a philosophical decision, on whether or not that capability is required in the future and you may not know in detail who is going to use it and how."*

It is these philosophical considerations which will occupy a large part of the National Icing Facilities Task Force's workload.

Table 3.18 Estimated Icing Facility Modification Costs, User Fees, Staffing Requirements and Construction Schedules

FACILITY NAME	MODIFICATION CONSTRUCTION COSTS	USER FEES	STAFFING REQUIREMENTS	CONSTRUCTION SCHEDULES
Icing Research Tunnel	$3.7 M	1) $18,000/week	2 professional 8 non-professional	24 mos
Altitude Wind Tunnel	$75 M	1) $41,000/week	To be determined	36 mos
NRC Helicopter Spray Rig	$300 K (new facility cost)	$2,500/week	1 professional 2 non-professional	none established, approx. 1½ years to complete
McKinley Climatic Laboratory	$100 K	2) $2,200/day 1) $5,000/day	12 professional 58 non-professional	8 mos (conceptual only)
Aeropropulsion System Test Facility (ASTF)	$500 M	$40,000/week	4 professional 16 non-professional	Dec. 1983 (65% Complete)
USNAPC Engine Test Facility	7) TBD	$20,000/week	2 professional 8 non-professional	7)
Army HISS Tanker	$1.5 M (additional tankers to cost $5.6 M)	1,3,4) $3,500/hr 2,3) $1,300/hr	5 professional 19 non-professional	Start 1979 Completion 1984
KC-135 Tanker	6) $600 K	1,4,5) $8,000/hr	5 professional 3 non-professional	6) modification not begun. 2 yrs to complete.
C-130 Tanker	$300 K	1,4,5) $7,500/hr	5 professional 3 non-professional	modification not begun. 1½ yrs to complete

1) Cost is for non-governmental user.
2) Cost is for use by other governmental agencies.
3) Operation, maintenance and TDY costs of $100,000/month divided among all facility users for each icing season.
4) 3rd party liability insurance and loss-of-use insurance costs are not included.
5) Does not include cost of photo-chase/safety aircraft.
6) Large cloud producing capability in non-dedicated KC-135 tanker is not recommeneded. Cost is for modification of a non-dedicated C-141 aircraft.
7) Estimates not available. Ongoing component improvement program

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

In Section 3.0, Icing Facilities Requirements Analysis, the three factors which will have the most significant impact on the capabilities, requirements and framework of the National Icing Facilities were addressed. Specifically, rationale was presented which dictates facility simulation capabilities and the overall scope of their operational needs. In arriving at the conclusions and recommendations concerning National Icing Facilities capabilities, emphasis has been placed on the findings of past investigations into the needs for icing simulation facilities, and the potential for icing simulation as opposed to, or in supplement to, natural icing conditions as the test medium for research, development and certification of aircraft for flight into known or forecast icing conditions. The conclusions reached in this study fall into several subject areas, and are listed below.

1) Impact of existing Federal Aviation Regulations on future icing certification requirements.
2) Impact of current and future aircraft developments and trends on the requirements for National Icing Facilities.
3) Impact of research and development needs on icing facility requirements.
4) Ability of current icing facilities to meet future icing research, development and certification requirements.

The major findings for each of the three subject areas are described herein.

4.1.1 Impact of FARs on National Icing Test Facility Requirements

1) The existing FARs applicable to aircraft icing certification requirements do not impose the same certification requirements on the various aircraft categories.
2) In accordance with the logic for upgrading of rotorcraft (all categories) certification requirements to make them equivalent to the standards applicable to transport category rotorcraft, the standards for icing certification of normal category airplanes should also be upgraded to the same level.
3) Appendix C, FAR Part 25, represents the best definition of the natural icing environment in super-cooled clouds and therefore its continued use as the standard for measuring the effectiveness of icing simulation is required.

4) Sufficient doubt concerning the adequacy of the FAR Part 25, Appendix C icing environment exists to warrant further investigations of the natural icing environment.

5) With the exception of FAR Part 33, no mention of other hazardous icing test conditions, such as snow, is made. Further research is required to determine the effects of freezing rain, snow and mixed conditions. National Icing Facilities must be modified to provide simulation of those conditions if the results of ongoing research dictates the necessity.

6) The proposed rulemakings regarding rotorcraft icing certification will create a significant increase in the need for more icing test facilities for research, development and certification.

4.1.2 Impact of Aircraft Development and Trends on Requirements for National Icing Facilities

The major findings of Section 3.2 are restated below to emphasize their significance to the requirements for National Icing Facilities.

1) In specifying the requirements for National Icing Facilities, it is impractical to attempt to provide simulated icing conditions for the certification and testing of all aircraft types due to size limitations.

2) The capabilities and characteristics of icing test facilities should be predicated on the characteristics and operational capabilities of those aircraft least able to find and test in natural icing conditions.

3) The aircraft with the least ability to find natural icing conditions are helicopters, general aviation and military utility aircraft.

4) By designing the National Icing Facilities around the requirements of those aircraft types, a great majority of commuter transport and business aviation aircraft can also be accommodated.

5) Improvements in flight control systems, avionics, and navigation aids for helicopters will greatly increase the demand for icing certification of helicopters.

6) Expected growth rates indicate that general aviation and helicopters will account for most new aircraft designs through the 1990s. It is estimated that as many as 104 new helicopter and G.A. designs will be forthcoming through the end of this century, further substantiating the validity of designing the icing test facilities to meet their specific needs.

4.1.3 Impact of Icing Research Needs on Icing Facility Requirements

Section 3.2.4 summarizes the icing research efforts which constitute the Icing Research Program Plans of NASA, DOD, and the FAA. Although quantification of the impact of the research efforts on facility design and utilization is difficult, the following impacts are expected:

1) Modernization of the IRT and rehabilitation of the AWT are necessary to support the projected facility utilization for development and verification of scale modeling and analytical prediction techniques.
2) Use of the icing wind tunnels will be predominately for the purpose of research work, with development and certification as a low priority.
3) Validation of the results of the research efforts will allow more dependence on simulated icing for certification. This should generate an increased certification workload as manufacturers supplement or supplant natural icing testing with simulated test conditions.
4) Several research programs will require increased usage and modernization of the U.S. Army Icing Research Test Bed Aircraft. The increased usage may warrant replacing this aircraft (JUH-1H) with a more modern rotorcraft and development of a fixed wing test bed aircraft as well.
5) Costly expenditures to modify existing facilities to comply with current FAR 25 Appendix C criteria, should be closely coordinated with on-going research to verify existing criteria.

4.1.4 Adequacy of Existing Icing Simulation Facilities to Support Future Icing Research, Development and Certification Test Requirements

Section 3.3 discusses the strengths, weaknesses and possible applications of the existing icing simulation facilities. The following conclusions concerning their ability to meet future icing research, development and certification requirements were reached.

1) The following facilities, owing to their unique capabilities and potential for providing a simulated icing test environment should form the framework for the National Icing Facilities:
    - ICING RESEARCH TUNNEL
    - ALTITUDE WIND TUNNEL (1987)
    - ARNOLD ENGINEERING AND DEVELOPMENT CENTER-ASTF (1983)
    - USNAPC Engine Test Facilities
    - McKINLEY CLIMATIC LABORATORY - MAIN CHAMBER
    - NATIONAL RESEARCH COUNCIL (Canada) OTTAWA SPRAY RIG
    - INFLIGHT ICING TANKERS -
        - U.S. Army HISS Tanker

  - U.S. Air Force C-130 Icing Tanker
  - U.S. Air Force KC-135 Icing Tanker
- ICING RESEARCH TEST BED AIRCRAFT

2) Modifications and improvements to those facilities as outlined in Section 3.3 will be required in order to optimize their usefulness in future icing research, development and certification programs.

3) Since a large icing wind tunnel capable of performing full scale icing tests on large aircraft components or complete aircraft systems may not be available even after 1987, scaling laws must be adequately defined and verified in order that all icing tunnels may be utilized to their maximum extent. The need will continue to exist for a large icing wind tunnel such as the AWT.

4) Engine icing facilities currently in use are adequate for the needs of engine icing certification through 2000. The addition of the ASTF will provide the capability to test very large turbine engines in a simulated icing environment.

5) At the present time, there are no means provided for the correlation of data derived from use of different icing test facilities. A technique for that purpose, and a single, standard means of correlation and calibration, must be established.

6) Existing facilities are generally inadequate for the purposes of meeting all the requirements for icing research, development and certification. However, incorporation of the recommended modifications will assure the availability of flexible and efficient icing simulation facilities for those purposes.

7) A National Icing Facilities Program Plan must be established for the purpose of recommending improvements to the existing facilities, prioritization of those improvements, securing funding for those improvements and assessing requirements for new or additional icing test facilities.

4.1.5 Estimates of Facility Modification costs

Rough order of magnitude estimates of modification costs to improve existing icing simulation facilities are as follows:

Facility	Estimated Improvement Cost
1. Inflight Tankers	
HISS	$1500 K
KC-135	$600 K
C-130	$300 K
2. Ottawa Spray Rig	$300 K

3. Icing Wind Tunnels	
IRT	$3,700 K
AWT	$75,000 K
4. McKinley Climatic Lab	$100 K
5. Aeropropulsive System Test Facility	$500,000 K

4.2 RECOMMENDATIONS

The recommendations presented herein address specifically the requirements for National Icing Facilities and the establishment of a National Icing Facilities Task Force.

4.2.1 Recommendations for Establishment of National Icing Facilities

As stated previously, no single icing simulation facility is presently capable of, or holds the potential for, meeting all the requirements for icing research development and certification of aircraft for flight in icing conditions. It is therefore necessary to utilize the existing facilities' capabilities and improve upon them, to provide an array of icing simulation facilities, which will allow a logical progression of icing research, development and certification in a timely and cost effective manner. To that end, the recommendations for modification and utilization of the existing and proposed facilities, as well as recommendations for the addition of new facilities, have been prepared in detail and are provided in Table 4.1.

4.2.2 Recommendations For The Establishment of a National Icing Facilities Task Force

The primary purpose of the recommended task force would be to establish a National Icing Facilities program plan, designed to insure the timely introduction of facilities required for icing research, development, and ultimately, certification testing. During the formative stages of such a plan, high level government decisions must be made and brought to bear on such key issues as funding, facilities improvement prioritizations, staffing and agency responsibilities. Such decisions can best be made by a group of key government officials, assembled as a task force for the specific purpose of rendering and executing those decisions relative to the National Icing Facilities effort.

Supporting rationale for the establishment of the National Icing Facilities Task Force are as follows:

1) The current stage of development of various segments of the aviation community will result in greatly increased demand for aircraft with all weather capabilities, including the capability for flight into icing conditions.

Table 4.1 Recommendations for the Improvement of Existing Icing Facilities

FACILITY NAME	RECOMMENDED IMPROVEMENTS	FUNCTION AS PART OF THE NATIONAL ICING FACILITY
Icing Research Tunnel	Expand LWC range to .04-2.8 g/m^3 and MDD range to 5-50 μm over a temperature range of -40°F to +32°F. Incorporate freezing rain and solid ice particle capability in the facility. Increase cloud size to its maximum extent within the confines of the chamber.	Utilize as facility to develop and verify scaling laws. Central calibration facility for all cloud composition measuring instruments. Testing and certification of small ice protection systems for application to small aircraft components (e.g., windshield pitot system, engine inlets, etc.)
Altitude Wind Tunnel (proposed)	Accelerate the development and construction schedule of the facility - target 1985. Expand LWC range to .04-2.8 g/m^3 over a temperature range of -40°F to +32°F. Increase uniform cloud dimensions to 10 m diameter. Provide capability of producing freezing rain, hail, snow and mixed conditions, in addition to the supercooled icing cloud.	Utilization for testing of large scale models of transport aircraft and large rotating and static airfoils. Testing full scale aircraft up to the business jet class. Certification of ice protection systems for large, full scale aircraft components. Engine test facility for large diameter engines. Certification facility for large diameter engines and their ice protection systems.

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Table 4.1 Recommendations for the Improvement of Existing Icing Facilities (Continued)

FACILITY NAME	RECOMMENDED IMPROVEMENT	FUNCTION AS PART OF THE NATIONAL ICING
Arnold Engineering and Development Center - ASTF (proposed 1983)	Increase mean effective drop diameter range to 50 microns and expand liquid water content range to include range of .04 to 2.8 g/m^3. Incorporate freezing rain, snow, hail and mixed condition capability.	Primary engine test, evaluation and certification facility.
McKinley Climatic Laboratory - Main Chamber	Explore the feasibility and, if possible, increase uniform cloud size of the facility to 5 x 15 meters for full immersion of small helicopter rotors. Explore the feasibility, and, if possible, increase airspeed range to a minimum of 70 knots to simulate effect of slow forward airspeed helicopter and airplane flights. Explore impact of increased icing testing on existing Facility usage demand.	Ground tie down verification tests for helicopters and small aircraft prior to release for simulated or natural icing flights. Ground tie down tests in freezing rain. Useful function of the climatic lab is dependent on eliminating end wall and circulation effects of the induced velocity icing cloud, as well as the enlargement of the uniform icing cloud for use in full scale rotor icing tests.
NRC Helicopter Spray Rig (Ottawa Spray Rig)	Immediately initiate plans for construction of a similar improved facility in the United States. Location should be in an environment of long winter season with windy conditions and dry air. Possible sites are at government facilities in North Dakota or Minnesota. Improve uniform icing cloud composition to range from: LWC - .04 to 2.8 g/m^3 Mean Effective Drop Diameter - 15-50 μm	Utilize for verification of ice protection systems on full scale helicopter and V/STOL aircraft in hover and low forward airspeed conditions. Ground tie down tests for small to moderate size fixed wing aircraft. Final verification of systems before approval for inflight icing testing certification. Incorporate freezing rain capability, if feasible.

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Table 4.1 Recommendations for the Improvement of Existing Icing Facilities (Continued)

FACILITY NAME	RECOMMENDED IMPROVEMENTS	FUNCTION AS PART OF THE NATIONAL ICING
Inflight Icing Tankers (HISS, C-130, KC-135)	Increase icing cloud dimensions to approximately 75 x 24 feet. Improve icing cloud composition to better simulate FAR Part 25, Appendix C icing envelope. Icing parameter ranges should ideally be increased as follows: Mean Effective Drop Diameter - 15-50 μm (variable) LWC - .04 - 2.8 g/m^3 Improve icing cloud duration to provide 20 minutes endurance at 3.0 g/m^3 and 1 hour at 1.0 g/m^3. This may require the use of larger capacity helicopter tankers than currently exist. As a minimum, drop diameter and liquid water content ranges should be increased to conform with the ranges likely to be encountered up to altitudes of 12,000 feet pressure altitude Increase airspeed capability of the HISS tanker to range from 40-120 knots, thereby providing overlapping airspeed coverage by all tankers from 40-350 knots. As a minimum, an additional helicopter tanker, such as the HISS, and C-130 icing tanker (with the previously mentioned modifications) will be required to absorb the projected icing certification workload through the year 2000. Relocate the icing tanker fleet to a site suitable for icing simulation over a long period, at a location in close proximity to areas where a prevalence of natural icing conditions exist.	Ultimately to be used for final testing and certification (if possible) of helicopters, general aviation aircraft, small commuters, business aircraft and many military utility designs. In the interim, prior to validation of inflight tankers for certification, confirmatory flights in natural icing conditions will be required. Partial verification of ice protection systems of large aircraft by selective inflight icing of various large aircraft components.

2) Icing test facilities currently available for research, development and certification are generally inadequate in terms of simulation capabilities and testing capacity for fulfulling the needs of projected icing research, development and certification. Major improvements and additions to the existing facilities are necessary to meet the future requirements.

3) No single governmental or civilian agency has the resources capable of accomplishing the work necessary to provide all required icing test facilities. There must, therefore, be a coordinated, national effort to improve the existing facilities, with government assuming the leadership role.

4) Budgetary requirements will necessitate high level visibility and backing at both departmental and congressional levels.

5) A group of key government personnel is required to plan and nurture the National Icing Facilities effort, at least to the point where the facilities can become economically self-reliant.

4.2.3 Recommended National Icing Facilities Task Force Charter and Function

The need for a unified National Icing Facilities Task Force is emphasized by the diverse factions which will use the National Icing Facilities. Obviously, the needs of civil and military users are not the same, nor will the needs of regulatory and research agencies always coincide with the needs of aircraft developers and manufacturers. It is, therefore, important that the efforts of all the agencies involved in planning a future national facility be directed towards a single goal: providing the most time efficient, cost effective means of icing research and development, and, ultimately, certification of aircraft for flights into icing conditions, when the need for that exists, now.

The charter of the Task Force is an essential element for insuring the unified effort of the Task Force members toward that goal. The charter must define the Task Force's purpose and specify the individual member's role in achieving that purpose. As stated previously, the purpose of the National Icing Facilities Task Force would be to develop a national plan for the establishment of an inventory of National Icing Test Facilities. Inherent in that mission is the requirement that the task force recommend and implement modifications and improvements to existing facilities to insure their usefulness in future icing research and development, and certification testing, through the year 2000. The task force must also make recommendations for the addition of new icing test facilities, if such a need is warranted, and secure funding for all facilities modifications and additional facilities.

The nature of the work to be performed by the Task Force, necessitates that it be comprised of high level government officials. Those officials should be policy making representatives of FAA, NASA and DOD, as those agencies and departments control the R&D facilities which will provide the framework for an array of National Icing Facilities. In addition to the governmental agencies, an industry advisory group should be established to provide a single point of contact for the Task Force for coordinating matters of mutual concern to industry and government. The industry advisory group would be comprised of representatives of both manufacturers and operators, such as GAMA, AIA, and HAI.

The responsibilities of the individual governmental departments and agencies should be established during the initial deliberations of the Task Force. The responsibility of the industry advisory group, as previously stated, would be to advise the Task Force regarding items of concern to both aircraft manufacturers and operators.

REFERENCES

1. Proceedings and Minutes of the "National Icing Facilities Coordination Meeting", Federal Aviation Administration Technical Center, September 23, 24, 1980.

2. Berry, F. A.; Bolley, E., et al, "Handbook of Meteorology", 1945

3. Peterson, A. A.; Dadone, L. V., "Helicopter Icing Review", Boeing Vertol Company - Division of the Boeing Company, September 1980.

4. Olsen, W., "Survey of Aircraft Icing Simulation Test Facilities in North America", NASA - Lewis Research Center.

5. Minutes, "National Icing Facilities Coordination Meeting", National Aviation Facilities Experimental Center - Federal Aviation Administration, January 16, 1980.

6. Werner, J. B., "The Development of an Advanced Anti-Icing/Deicing Capability for U. S. Army Helicopters", Volume I - Design Criteria and Technology Considerations, U. S. Army, November 1975.

7. Advisory Circular AC No. 20-73, "Aircraft Ice Protection", Federal Aviation Administration, April 21, 1971.

8. Federal Aviation Regulations, Parts 21, 23, 25, 27, 29, 31, 33, Department of Transportation - Federal Aviation Administration.

9. Task Force Report, "Advanced Rotocraft Technology", NASA - Office of Aeronautics and Space Technology, October 15, 1978.

10. Information Bulletin, "Tilt Rotor Research Aircraft", NASA - U.S. Army Research and Technology Laboratories, April 1978.

11. Federal Register, Rotorcraft Regulatory Review Program, "Notice No.1, Proposed Rulemaking", December 18, 1980.

12. Deckert, W.H., "Moving V/STOL from Technology to System", Ames Research Center - NASA, December 1977.

13. Few, D.D., Edenborough, H.K., "Tilt Proprotor Perspective", Ames Research Center - NASA, December 1977.

14. Quigley, H.C.; Franklin, J.A., "Lift/Cruise Fan VTOL Aircraft", Ames Research Center - NASA, December 1977.

15. Anderson, S.B.; Petersen, R.H., "How Good is Jet Lift VTOL Technology", Ames Research Center - NASA, December 1977.

16. O'Lone, R. G., "XV-15 Tilt Rotor Aircraft Applications Under Study", Aviation Week and Space Technology, December 15, 1980.

17. "Tip - Jet - Drive Helicopter Design Utilizes Trailing Edge Blowing", Aviation Week and Space Technology, December 15, 1980.

18. Mikolowsky, W. T.; Nogyle, L. W., et al, "The Military Utility of Very Large Airplanes and Alternative Fuels", September 1977.

19. Stuelpnagel, T. R., "Light Turbine Helicopters to the Year 2000", Hughes Helicopters, Corp., November 1979.

20. McCollough, "JB", "A Design Perspective on New Technologies for General Aviation", Aircraft Flight Safety Board - Federal Aviation Administration, September 1979.

21. Robinson, C. A., Jr., "Industry Proposes Supersonic V/STOL Development", Aviation Week and Space Technology, January 12, 1981.

22. Ropelewski, R. R., "NASA Shows Research Aircraft", Aviation Week and Space Technology, September 8, 1980.

23. Steiner, J. E., "The Timing of Technology for Commercial Transport Aircraft", The Boeing Company, October 1977.

24. Trammell, A.; Parrish, R., "The Commuter Airlines - The Growth Potential, Regulatory Outlook and Equipment Needs", Business and Commercial Aviation, February 1978.

25. "1978 Planning and Purchasing Handbook", Business and Commercial Aviation, April 1978.

26. "Specifications", Aviation Week and Space Technology, March 13, 1978.

27. Nogyle, L. W.; Jobe, C. E., "Large Vehicle Concepts", April, 1979.

28. Watts, F., "Janes' Book of All the World's Aircraft", Janes' Yearbook Publications, 1979.

29. "FAA Forecasts Fiscal Years 1979 - 1980", Department of Transportation - Federal Aviation Administration, September 1978.

30. Arata, Winfield H., "Very Large Vehicles - To Be Or ....?", Astronautics and Aeronautics, April 1979.

31. Anonymous, "FAA Statistical Handbook of Aviation", Department of Transportation - Federal Aviation Administration, 1972.

APPENDIX A

SURVEY OF AIRCRAFT ICING SIMULATION FACILITIES IN NORTH AMERICA*

WILLIAM OLSEN
ICING RESEARCH SECTION
NASA LEWIS RESEARCH CENTER

NASA was requested to survey the capabilities of the facilities in North America that can do aircraft icing simulation tests. The survey was requested by the Standing Committee on Icing, which is jointly sponsored by NASA, FAA and NOAA; the military services have also expressed a need for this survey. European icing facilities have already been surveyed and reported in AGARD Advisory Report 127.

The reasons for the survey are to: (1) inform the icing research community of the capabilities of existing icing facilities, (2) make it easier for a potential facility user to select and contact the icing facility that is appropriate for his test requirements, and (3) help facility managers evaluate and improve their facility.

The survey determined the location and size of each facility, its airspeed and temperature range, icing cloud parameter ranges, and the technical person to contact. The facilities surveyed and their capabilities are listed in tables A to D, one for each of the four types of simulation facilities that are described on figures A to D. The capabilities of each facility were estimated by the engineers working with that facility. The numbers in the tables are single point approximations by them of the complex operating curves of their facility. Many of the facilities have capabilities beyond that required for icing testing and these excess capabilities were not included in the tables.

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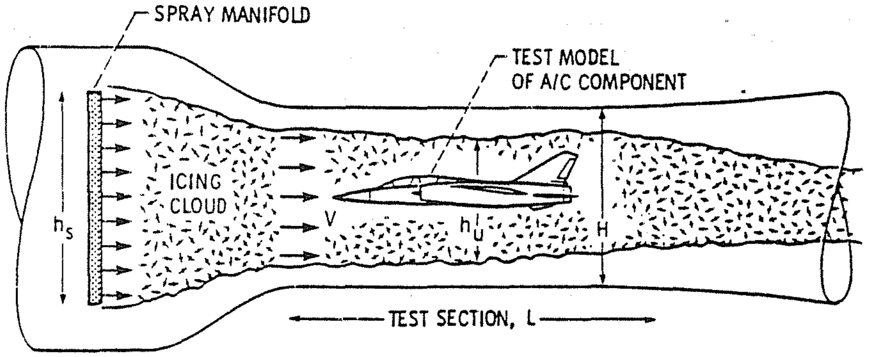
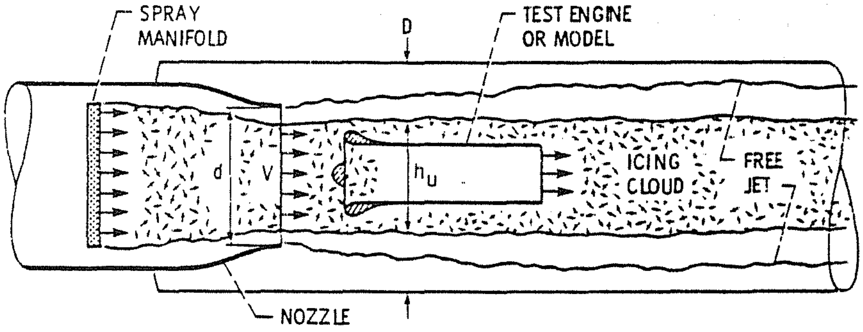
* For your convenience, 2 tables listing European icing facilities are also attached.

TYPES OF ICING SIMULATION FACILITIES.

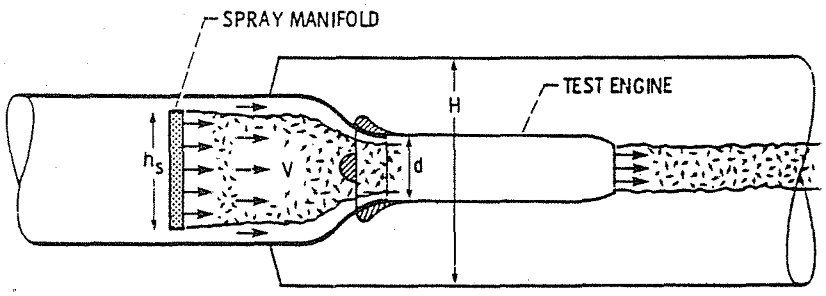
SCHEMATIC SKETCHES FROM SIDEVIEW



A. WIND TUNNELS

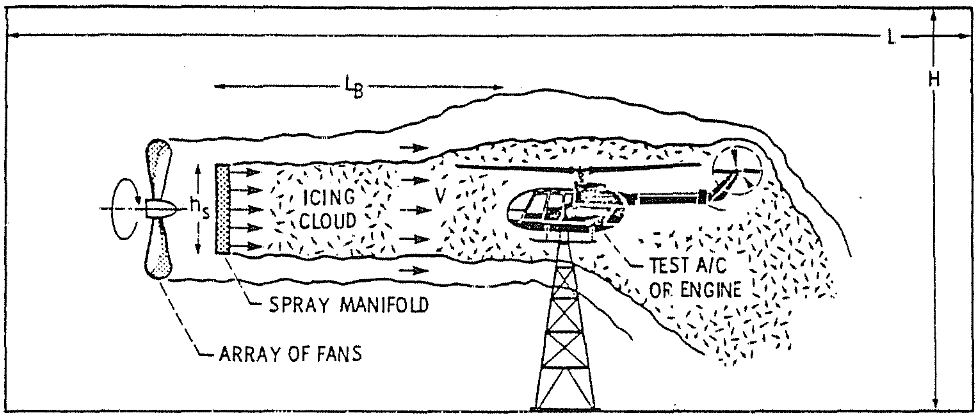


(a) FREE JET.

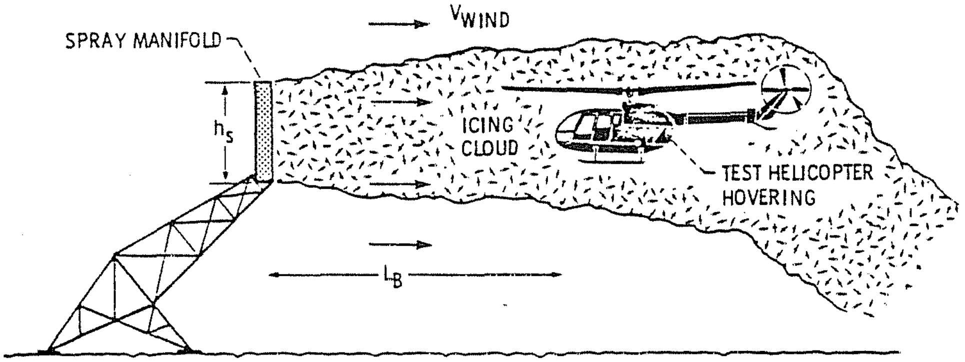


(b) DIRECT CONNECT.

B. ENGINE TEST FACILITIES

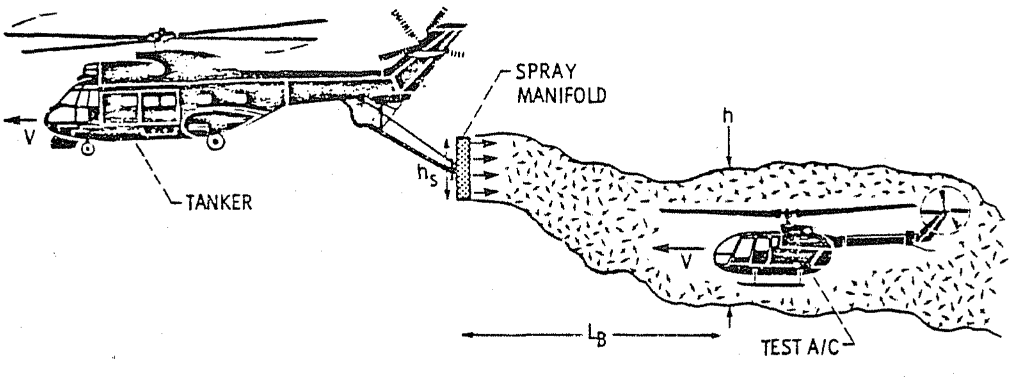


(a) FAN BLOWN SPRAY IN A LARGE ROOM OR OUTDOORS.



(b) WIND BLOWN SPRAY OUTDOORS.

C. LOW VELOCITY FACILITIES



D. FLIGHT TESTS WITH TANKER

CAPABILITIES OF ICING SIMULATION TEST FACILITIES IN NORTH AMERICA

[Capabilities estimated by technical contact person for each facility]

A WIND TUNNELS

Facility no.	Facility name (Location)	Types of icing tests run (a)	Weather simulated (b)	Type of facility	Size (see sketches), m		Range of parameters used in icing tests^c					Instruments used for local drop size and (LWC)	Technical person to contact	Test season	Comment
					Test chamber	Uniform icing cloud	Air speed, km/hr	Min. total air temperature, °C	Altitude, m	LWC, g/m^3	Vol med drop size, µm				
A-1	NASA - Lewis Research Center (Cleveland, OH) (a) IRT	FSC, I MS, R, IA, P^d	ICE, FR^d	Wind tunnel	H = 1.8 W = 2.7 L = 6	$h_u = 0.9$ $w_u = 1.5$	10 to 470	-25	0	^{e}0.5 to 3.0	^{e}11 to 25	Rot. cycls. and various modern instruments (rot. cyl.)	J. Reinmann (216)433-4000	All year	Modernization nearly complete
	(b) AWT - Rehabilitation	FSC, I, MS, R, CPU, G, P	ICE, FR, SI	Wind tunnel	D = 8 H = 3 to 14 W = 14 (Free jet)	$d_u = 4.5$ $d_u = 9$	10 to M = 1.0 Up to 370	-30	0 to 15 000	0.2 to 3.	10 to 50 (nozzles changed)	Various modern instruments	J. Reinmann (216)433-4000	All year	Proposed for 1985
A-2	Lockheed (Burbank, CA)	MS, FSC, I	ICE	Wind tunnel	H = 1.2 W = 0.8	$h_u = 0.5$ $w_u = 0.3$	90 to 340	-20	0	0.7 to 4.0	10 to 25	Rot. cyls. (rot. cyl.)	B. Robinson (213)847-6121	All year	---------------------
A-3	Boeing (Seattle, WA)	MS, FSC, I	ICE	Wind tunnel	H = 0.5 W = 0.4 L = 0.9	$h_u = 0.4$ $w_u = 0.3$	180 to 370	-30	0	0.3 to 5.0	10 to 50 (nozzles changed)	Rot. cycls., oil slide (sm. cyl.)	R. Wilder (206)342-4776	All year	---------------------
A-4	NRC (Ottawa, Canada) (a) Large Tunnel	FSC, MS, I G	ICE FR	Wind tunnel	H = W = 1.4	$h_u = w_u = 1$	110 to 460 30 to 110	-20	0	-----	15 to 30 (nozzles changed)	Rot. cycls., oil slide (rot. cyl.)	A. Price (613)993-2371	All year	Dismantled in 1979
	(b) High Speed	MS, FSC	ICE	Wind tunnel	H = W = 0.3	$h_u = w_u = 0.25$	90 to M = 0.8	-30	0 to 9 000	0.2 to 2.	15 to 25	Oil slide (rot. cyl.)	A. Price (613)993-2371	All year	---------------------
A-5	AEDC Research Cell (Arnold AFS, TN)	FSC, MS	ICE	Free jet d = 0.3	D = 0.9	$d_u = 0.3$	150 to $M_{jet} = 0.7$	-30	0 to 15 000	0.2 to 3.	15 to 30	Various modern instruments	J. Hunt (615)455-2611	All year	---------------------
A-6	Rosemount (Minneapolis, MN) (a) Low Speed	MS	ICE	Wind tunnel	H = 0.15 W = 0.1 L = 0.3	$h_u = 0.1$ $w_u = 0.07$	90 to 170	-30	0	0.2 to 1.5	20 to 40	Oil slide (rot. cyl.)	R. DeLeo (612)941-5560	All year	Rosemount use only
	(b) High Speed	MS	ICE	Wind tunnel	H = 0.15 W = 0.3 L = 0.8	$h_u = w_u = 0.1$	90 to 740	-25	0 to 3 000	0.1 to 3.0	10 to 40	Oil slide (rot cyl.)	R. DeLeo (612)941-5560	All year	Rosemount use only
A-7	Frost Tunnel (Univ. of Alberta, Canada)	MS, IA	ICE	Wind tunnel	D = 0.5 (Octagonal) L = 0.9	$d_u = 0.3$	10 to 240	-20	0	0.4 to 3.0	20 to 50 (nozzles changed)	Oil slide (rot. cyl.)	E. Gates (403)432-5180	All year	---------------------
A-8	UCLA Cloud Tunnel	MS, CP	ICE, R	Vertical wind tunnel	H = W = 0.15 L = 0.5	$h_u = w_u = 0.1$	0 to 55	-30	0	0.1 to 3.	2 to 50	Various modern instruments	H. Pruppacher (213)825-1038	All year	Free particle suspension
A-9	Army Natick R&D (Natick, Mass.) Climatic Chamber	G, FSC, H	FR, R, S	Wind tunnel	H = 3 W = 4.5 L = 18	---------	4 to 65	-30 and lower	0	10 cm rain/hr	Not measured (rain gauge)		M. Kellberg (617)653-1000	All year	Mainly physiological tests of humans

B. ENGINE TEST FACILITIES

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

Facility no.	Facility name (Location)	Types of icing tests run (a)	Weather simulated (b)	Type of facility	Size (see sketches), m		Range of parameters used in icing tests^c					Instruments used for local drop size and (LWC)	Technical person to contact	Test season	Comment
					Test chamber	Uniform icing cloud	Air speed, km/hr	Min. total air temperature, ^oC	Altitude, m	LWC, g/m^3	Vol. med. drop size, μm				
B-1	AEDC (Arnold AFS, TN) (a) ETF	EDC	ICE	Direct connect d = 1.5	D = 3.7 or 4.5 L = 11	Spray bars sized to engine	0 to M = 0.7+	-30	0 to 15 000	0.2 to 3.+	15 to 30	Various modern instruments	J. Hunt (615)455-2611)	All year	---------------------
	(b) Free Jet	CPU, FSC I, MS	ICE	Free jet d = 1.5	D = 3.7 or 4.5 L = 11	Spray bars sized to engine	0 to M = 0.7+	-30 and lower	0 to 15 000	0.2 to 3.+	15 to 30	Various modern instruments	J. Hunt (615)455-2611	All year	---------------------
	(c) ASTF	CPU, FSC, I	ICE	Free jet d = 2.7	D = 8 L = 18	Spray bars sized to engine	0 to M = 0.7+	-30 and lower	0 to 15 000	0.2 to 3.+	15 to 30	Various modern instruments	W. Bates (615)455-2611	All year	Planned for 1983
B-2	Detroit Diesel Allison (Indianapolis, IN) (a) Comp. Test Facility	Inlet and compressor stage	ICE	Free jet Direct connect d = 0.5	D = 2.3 L = 9	Spray bars sized to engine	0 to M = 0.7+	-30 and lower	0 0 to 6 000	0.2 to 3.5	15 to 40	Rotating cylinders	W. Stiefel (317)243-4066	All year	---------------------
	(b) Small Engine Facility	EDC	ICE	Direct connect	D = 0.45 L = 1.2	Spray bars sized to engine	0 to M = 0.7+	-30 and lower	0 to 6 000	0.2 to 3.5	15 to 40	Rotating cylinders	W. Stiefel (317)243-4066	All year	---------------------
B-3	GE Cross-wind Facility (Peebles, OH)	CPU, P^d, R^d	ICE	Free-jet outdoors d = 7.0	Outdoors	d_u = 4.5	90	Ambient air to -20	0	0.4 to 3.5	15 to 50	Knollenberg spectrometer (rot cyl.)	R. Keller (513)243-4483	Winter	---------------------
B-4	P&W Altitude Facilities (E. Hartford, CT) (a) Large	EDC, I	ICE	Direct connect	D = 5.5 L = 10	Spray bars sized to engine	0 to M = 0.5	-25	0 to 6 700	0.2 to 9.0	15 to 40	Oil slide	J. Barlock (203)565-2091	All year	---------------------
	(b) Smaller	EDC, I	ICE	Direct connect	D = 3.7	Spray bars sized to engine	0 to M = 0.5	-30 and lower	0 to 6 700	0.2 to 9.0	15 to 40	Oil slide	J. Barlock (203)565-2091	All year	---------------------
	(c) P&W Sea Level Facility	EDC	ICE	Direct connect	Varies with test cells	Spray bars sized to engine	0 to M = 0.5	-20 (ambient)	0	0.2 to 9.0	15 to 40	Oil slide	J. Barlock (203)565-2091	Winter	---------------------

B Concluded. ENGINE TEST FACILITIES

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

Facility no	Facility name (Location)	Types of icing tests run (a)	Weather simulated (b)	Type of facility	Size (see sketches), m		Range of parameters used in icing tests^c					Instruments used for local drop size and (LWC)	Technical person to contact	Test season	Comment
					Test chamber	Uniform icing cloud	Air speed, km/hr	Min total air temperature, ^oC	Altitude, m	LWC, g/m^3	Vol. med drop size, μm				
B-5	McKinley Climatic Lab Engine Test Cell (Eglin AFB, FL)	CPU, FSC	ICE, SI FR, R	Fan blown spray indoors	H = 7.5 W = 9 L = 40	h_u = 3 w_u = 6	0 to (30 to 75)	-30 and lower	0	0.1 to 3.	12 to 60 800 to 1500 (nozzles changed)	Particle interferometer (rot. cyl.)	R. Tollver (904)882-3626	All year	--------------------
B-6	Naval Air Propulsion Facility (Trenton, NJ)														
	(a) Five small engine cells	EDC, CPU, I, FSC, MS	ICE, SI, FR, R	Free jet d = 0.6	H = W = 3 L = 6	Spray bars sized to engine	0 to M = 0.7+	30 and lower	0 to 15 000	0.1 to 2.	15 to 50 (nozzles changed)	Knollenberg spectrometer and OAP (rot. cyl.)	Resource Mgr. (609)896-5655	All year	--------------------
	(b) Two large sea level cells	EDC, CPU, I, FSC, MS	ICE, SI, FR, R	Free jet d = 1.2	H = 4.5 W = 7 L = 17	Spray bars sized to engine	0 to M = 0.7+	-30 and lower	0	0.1 to 2.	15 to 50 (nozzles changed)	Knollenberg spectrometer and OAP (rot. cyl.)	Resource Mgr (609)896-5655	All year	--------------------
	(c) Three large altitude cells	EDC, CPU, I, FSC, MS	ICE, SI, FR, R	Free jet d = 1.2	D = 5 L = 9	Spray bars sized to engine	0 to M = 0.7+	-30 and lower	0 to 15 000	0.1 to 2.	15 to 50 (nozzles changed)	Knollenberg spectrometer and OAP (rot. cyl.)	Resource Mgr. (609)896-5655	All year	--------------------
B-7	Teledyne Altitude Cells (Toledo, OH)														
	(a) Chamber 1	CPU, EDC	ICE, SI, FR, R	Free jet or direct connect, d = 0.2	D = 2.7 L = 5	Spray bars sized to engine	0 to M = 0.7+	-30 and lower	0 to 15 000	Up to 3.	15 to 25	Oil slide	R. Trauth (419)470-3236	All year	--------------------
	(b) Chamber 2	CPU, EDC	ICE, SI, FR, R		H = 2.5 W = 2.5 L = 4	Spray bars sized to engine	0 to M = 0.7+	-30 and lower	0 to 15 000	Up to 3.	15 to 25	Rotating cylinders	R. Trauth (419)470-3236	All year	--------------------
B-8	Avco Lycoming (Stratford, CT)														
	(a) Component Facility	EDC	ICE, FR	Direct connect d = 0.4	-------	Spray bars sized to engine	0 to 370	-30 and lower	0	0.1 to 3.	15 to 40	Oil slide (rot. cyl.)	J. Sherman (203)378-8215	All year	--------------------
	(b) Engine Test Facility	EDC	ICE, FR	d = 0.4	W = 3.7 H = 2.7	Spray bars sized to engine	0 to 200	-30 and lower	0	0.1 to 3.	15 to 40	Oil slide (rot. cyl.)	J. Sherman (203)378-8215	All year	--------------------
				d = 1.2	Outdoors			-20						Winter	
B-9	NRC, Cell #4 (Ottawa, Canada)	EDC, CPU	ICE, SI	Free jet or direct connect d = 0.75	H = W = 7.5	Spray bars sized to engine	0 to 650	-20 and lower	0	0.2 to 2.	15 to 40	Oil slide (rot. cyl.)	W. Grabe (613)993-2214	Winter	--------------------
		CPU, P		d = 2.0			0 to 93	Ambient							

C. LOW VELOCITY FACILITIES

Facility no.	Facility name (Location)	Type of icing tests run (a)	Weather simulated (b)	Type of facility	Size (see sketches), m		Range of parameters used in icing tests^c					Instruments used for local drop size and (LWC)	Technical person to contact	Test season	Comment
					Test chamber	Uniform icing cloud	Air speed, km/hr	Min. total air temperature, °C	Altitude, m	LWC, g/m^3	Vol. med drop size, μm				
C-1	NRC Helicopter Spray Rig (Ottawa, Canada)	FLT(helicopters in hover)	ICE, FR	Wind blown spray outdoors	D = ∞	Spray manifold h_s 4.5 w_s 23	Ambient wind, 20 to 45 (gusty)	-20 (ambient)	0	0.1 to 0.8	30 to 60	Oil slide (rot. cyl.)	T. Ringer (613)993-2439	Winter	To be mothballed in 1985
C-2	G.E. Cross Wind Facility (Peebles, OH)	CPU, P^d, R^d	ICE, FR	Free jet outdoors	D = ∞	d_n 4.5	90	-20 (ambient)	0	0.4 to 3.6	15 to 50	Knollenberg spectrometer (rot. cyl.)	R. Keller (513)243-4483	Winter	------------------
C-3	McKinley Climatic Lab (Eglin AFB, FL) (a) Main Chamber	FS, R^d	ICE, SI FR, R	Fan blown spray indoors	H = 21 W = 76 L = 76	Spray manifold h_s = 3 w_s = 9	0 to (30 to 75^e) (depending on L_H)	-30 and lower	0	0.1 to 3	12 to 60 800 to 1500 (nozzles changed)	Particle interferometer (rot. cyl.)	R. Tollver (904)882-3626	All year	Largest cold room
	(b) Engine Test Cell	CPU, FSC	ICE, SI FR, R	Fan blown spray indoors	H = 7.5 W = 9 L = 40	Manifold h_s = 3 w_s 6	0 to (30 to 75) (depending on L_H)	-30 and lower	0	0.1 to 3	12 to 60 800 to 1500 (nozzles changed)	Particle interferometer (rot. cyl.)	R. Tollver (904)882-3626	All year	------------------
	(c) All Weather Room	FSC	ICE, SI FR, R	Fan blown spray indoors	H = 4.5 W = 6.5 L = 12	Manifold h_s = 3 w_s = 3	0 to (30 to 75) (depending on L_H)	-30 and lower	0	0.1 to 3	12 to 60 800 to 1500 (nozzles changed)	Particle interferometer (rot. cyl.)	R. Tollver (904)882-3626	All year	------------------
C-4	U.S. Army CRREL Cold Room (Hanover, NH)	FSC, MS R, IA	ICE, SI, FR, R	Fan blown spray indoors	H = 1.1 W = 0.7 L = 1.5	--------	0 to 20	-30 and lower	0	1 to 2.5	10 to 60	Cascade impactor	G. Ashton (603)643-3200	All year	------------------
C-5	Mt. Washington Observatory (Gorham, NH)	FS, CP, MS	Natural icing of tied down equipment on top of mountain				0 to 180 (gusty)	-20 and lower	1800	Generally severe natural conditions		Rotating cylinders	J. Howe (603)466-3388	Fall to spring	------------------
C-6	U.S. Navy PMTC (Pt. Mugu) Climatic Hanger	FSC, FS, G	R, FR	Fan blown spray indoors	H = 7.6 W = L = 18	h_s = w_s = 1.2	0 to 75	-30 and lower	0	30 cm rain/hr	500 to 4500	Oil slide (rain gauge)	D. Everett (805)982-8011	All year	------------------
			S							5 cm snow/hr	50 to 100				
C-7	Acton Environmental Test Corp. (Acton, Mass.)	G	R, FR, S^d	Fan blown spray indoors	H = 6 W = 4.5 L = 7.5	d_s = 2.5	0 to 45	-30 and lower	0	10 cm rain/hr	1000 to 1000	Not measured (rain gauge)	R. Gilfoy (617)263-2933	All year	------------------
C-8	NRC (Ottawa, Canada) Cold Chamber #1	G, FS	FR, S^d	Fan blown spray indoors	H = 4.3 W = 4.5 L = 15.2	d_s = 1.2 to 2.5	0 to 55	-30 and lower	0	0.3 cm rain/hr	500 to 1000	Screen method (accumulation rate)	T. Ringer (613)593-2439	All year	------------------
	NRC (Ottawa, Canada) Cold Chamber #2)	G, FS	FR	Fan blown spray indoors	H = 5 W = 5 L = 7	d_s = 1.8	0 to 55	-30 and lower	0	0.3^d cm rain/hr	500 to 1000	Screen method (accumulation rate)	T. Ringer (613)993-2439	All year	------------------
C-9	Wyle Labs (Norco, CA) Cold Room	G, FSC	FR	Fan blown spray indoors	H = 5 W = 4.5 L = 11	--------	0 to 35	-30 and lower	0	12 cm rain/hr	--------	-------------	M. Clark (714)737-0871	All year	------------------

D TANKERS FOR FLIGHT TESTS

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

Facility no.	Facility name (Location)	Types of icing tests run (a)	Weather simulated (b)	Time in icing at high LWC, min	Size of spray, m		Range of parameters used in icing tests[c]					Instruments used for local drop size and (LWC)	Technical person to contact	Test season (find temp. at altitude)	Comment
					At nominal distance L_B	Manifold	Air speed, km/hr IAS	Min total air temperature, °C	Altitude, m	LWC, g/m^3	Vol. med drop size, μm				
D-1	Air Force (Edwards AFB, CA) (a) KC 135 Tanker	Flt.	ICE, N R, FR	60	At L_B = 60 d = 3	d_s = 1.2	300 to 650 (370 nom.)	-20 (ambient)	1200 to 8000	0.05 to 1.5 0.5 to 32.	28 to 35 200 to 800	Knollenberg spectrometer (")	R. Morrison (805)277-3068	All year	Final calibration in 1981
	(b) C 130 Tanker	Flt.	ICE, N R, FR	60	At L_B = 60 d = 5	d_s = 1.2	190 to 390 (280 nom.)	-20 (ambient)	1200 to 8000	0.05 to 1.5 0.05 to 32.	28 to 35 desired 200 to 800	Knollenberg spectrometer (")	R. Morrison (805)277-3068	All year	Planned for 1981
D-2	Army HISS Helicopter Tanker (Edwards AFB, CA)	Flt.	ICE, N	30	At L_B = 50 h = 3 w = 12	h_s = 1.6 w_s = 12	110 to 140 (120 nom.)	-20 (ambient)	600 to 3500	0.1 to 1.0	25 to 30 desired	Knollenberg spectrometer (Leigh)	C. Frankenberger (805)277-2271	Normally winter	Testing to increase cloud size
D-3	Cessna 404 Tanker (Wichita, KA)	Flt.	ICE, R, FR, N	60	At L_B = 150 d = 6	d_s = 0.6 (V-bar)	165 to 330 (260 nom.)	-20 (ambient)	300 to 8000	0.05 to 4.0	20 to 49 (water nozzles)	Gelatin slide (J&W)	D. Hazelwood (316)946-6606	All year	-----------------
D-4	Piper Cheyenne Tanker (Lock Haven, PA)	Flt.	ICE, FR, R, N	14	At L_B = 30 h = 3 w = 5	h_s = 1.2 w_s = 1.8	200 to 300 (240 nom.)	-20 (ambient)	300 to 8000	0.1 to 1.7	30 to 50	Gelatin slide (J&W)	J. Bryerton (717)748-6711	Not summer	-----------------
D-5	Flight Systems T-33 Tanker (Mojave, CA)	Flt.	ICE, R, FR, N	45	At L_B = 60 d = 2.5	h_s = 0.3 w_s = 0.9	230 to 420 (370 nom.)	-20 (ambient)	300 to 8000	0.1 to 1.0	17 to 50	Knollenberg spectrometer (")	J. Ligon (805)824-4601	All year	-----------------

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

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

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

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

[e] Tests in progress to extend these limits.

CAPABILITIES OF ICING SIMULATION TEST FACILITIES IN EUROPE

TABLE A – WIND TUNNELS

No	Facility Name Location	Types of Icing Tests Run	Weather Simulated	Type of Facility	Size		Range of Parameters used in Icing Tests					Instruments Used for Local Drop Size and LWC	Technical Person to Contact	Test Season	Comment
					Test Chamber m	Uniform Icing Cloud m	Maximum Air Speed km/h	Min Total Air Temp °C	Altitude m	LWC gm/m³	Vol Med Drop Size μm				
	Federal Republic of Germany														
A1	Volkswagen climatic Wind Tunnel, Wolfsburg			Wind Tunnel	5 x 7		180	–25	0				Hr Schwab 05361–225130		To date, only tests on cars
A2	DFVLR			Wind Tunnel	2.4 x 2.4		290–320	–173	0				Dr Viehweger 02203–6012295		Under reconstruction. Icing tests possible 1981
	France														
A3	Etu Technique Bourges	FSC MS	Ice R	Wind Tunnel	H = 4.1 W = 5.5 L = 15		145	–40	0			a, b	IPETA Chastagnol (16–48) 70.52.75	All Year	
A4	CEPr Saclay	MS	Ice	Wind Tunnel	ϕ = 0.25 ϕ = 0.9	ϕ_u = 0.25 ϕ_u = 0.9	900 290	–40	4900	0.1–3	15–30		M Page-Galtier 941.81.50	All Year	
A5	ONERA Modane	FSC MS R	Ice	Wind Tunnel	ϕ = 8	H_u = 2 W_u = 2 or H_u = 1 W_u = 3	540	–15*	1100–2500	0.4–10	10–30	Various	C Armand (16–79) 0.5.00.35	Winter	*depends on ambient conditions
	Italy														
A6	Fiat Research Centre Turin	FSC MS	Ice	Wind Tunnel	H = 3 W = 4.2 L = 12		160	–50	0					All Year	
	United Kingdom														
A7	[illegible] Blower Tunnel Boscombe Down	FSC MS	Ice	Wind Tunnel	W = 18 L = 27	ϕ = 1.2 ϕ = 1.8	500 400	–30	0	0–3	20–1000	a, c	Supt of Engineering (0980) 23331	Winter	
A8	Lucas Aerospace Artington	MS	Ice SI R	Wind Tunnel	H = 0.2 W = 0.3 to H = 0.5 W = 0.5	80% of cross-section	660 215	–40	0	0.1–5 0.2–10 Ice	12–40 1mm ice	a, d	G Edgington (0483)66876	All Year	

CAPABILITIES OF ICING SIMULATION TEST FACILITIES IN EUROPE

TABLE B – ENGINE TEST FACILITIES

No	Facility Name Location	Types of Icing Tests Run	Weather Simulated	Type of Facility	Size		Range of Parameters used in Icing Tests					Instruments Used for Local Drop Size and LWC	Technical Person to Contact	Test Season	Comments
					Test Chamber m	Uniform Icing Cloud m	Maximum Air Speed km/h	Min Total Air Temp °C.	Altitude m	LWC gm/m^3	Vol Med Drop Size μm				
France															
B1	CEPr Saclay R2 cell	CPU FSC	Ice	Free Jet	$\varnothing = 4.4$	$\varnothing_u = 1.2$	540	-60		0-6	15-30	a	M Page-Galtier 941.81.50	All Year	
B2	CEPr Saclay	CPU FSC	Ice	Free Jet	$\varnothing = 5$	$\varnothing_u = 2$	540	-60		0-10	15-30	a	M Page-Galtier 941.81.50	All Year	
United Kingdom															
B3	NGTE Pyestock Cell 3	EDC CPU	Ice SI	Direct Connect or Free Jet	$\varnothing = 6.1$	Engine dia or $\varnothing_u = 1$	To suit engine or 820	-70	0-15000	0.2-10	15-30	d	Head, Engine Test Dept (0252) 44411	All Year	
B4	NGTE Pyestock Cell 3 West	EDC CPU FSC MS	Ice SI R	Direct Connect or Free Jet	$\varnothing = 7.6$	Engine dia or $\varnothing_u = 2.5$	To suit engine or 770	-40	0-15000	0.2-10	15-30	d	Head, Engine Test Dept (0252) 44411	All Year	Solid ice available 1981
B5	Lucas Aerospace Burnley	EDC MS	Ice SI	Direct Connect or Free Jet	$\varnothing = 4$		To suit engine or 250	-55	0-15200	0.2-10	15-30	a	Mr B A Coar (0282) 25051	All Year	

APPENDIX B

At the outset of the investigation, it had been expected that government and trade organizations would have access to estimates of the number of new aircraft designs through the year 2000. Further investigation, however, showed that such projections were not available. As this information was essential to assessing the impact of future aircraft developments on National Icing Facilities, it was determined that a logical approach to obtaining such projections was to base them upon past industry performance. The following paragraphs and table discuss the methodology, ground rules and the data used in formulating the projections.

Ground Rules

In order to make our projections, it was necessary to obtain a large sampling of past industry performance. Industry performance is measured in terms of introduction of a new aircraft design. A historical review of past performance was made covering a minimum of 25 years for manufacturers of each of four general categories (i.e., General Aviation, Business Aviation, Transport Airplanes and Helicopters).

It was desirable that the aircraft listed be new, non-derivative designs. This presented an obvious difficulty since many aircraft, (G.A. and Business, in particular) have a long history of derivation from previous models. However, by cross checking aircraft performance and physical characteristics, mode of utilization and certification dates, it was possible to eliminate many obvious derivative designs from consideration.

A seating convention was used to classify fixed wing airplanes into each of the three applicable categories, G.A., business and transport. The General Aviation category is comprised of all airplanes with from 1 - 5 seats, including pilot. Transport category includes all airplanes with in excess of 10 seat configuration. All helicopters, including military designs, are included in the helicopter category.

This investigation did not include special purpose aircraft, such as those designed exclusively for aerial application or acrobatics.

Methodology

As stated previously, projections shown in Table 3.7 are derived from historical data. As such, the possibility exists that the manufacturer's individual performance in a given year or period of years has been dependent on the economic climate, consumer demand or industry maturity. Is is hoped that by analyzing performance over a long time period, aberrations in company performance can be obviated and a broad generalization can be made for future performance. In an effort to further refine the projections and eliminate the effects of economics and individual maufacturer performance, the raw data was handled by two discrete methods, and the projections for each category, shown in Table 3.7, represent the mean of the sum of the various calculations:

METHOD I: Mean Manufacturer Performance (Aircraft/Year)

In this method, the individual manufacturer's performance is assessed based on its performance (Aircraft/Year) during the time covered by the investigation. Thus:

$$\overline{x_M} = (\Sigma_1^n \; p_1 + p_2 + p_3 \ldots p_n) \div n$$

where $\overline{x_M}$ is the manufacturer's mean performance (Aircraft/Year)

n is the number of years analyzed

p is annual performance (Aircraft)

By determining the mean performance for each aircraft manufacturer of the particular category of aircraft, a projection of the test performance of all manufacturers in a particular category can be made as follows:

$$S = \Sigma_1^m \; \overline{x}_{M_1} + \overline{x}_{M_2} + \ldots + \overline{x}_{M_m}$$

where: S is the sum of the manufacturer's mean performance

and m is the number of manufacturers per category

The projection for a given time period is therefore:

$$T = S \times Y$$

where T is the total number of new designs in a given category, and Y is the projection period (years).

METHOD II: Mean Aircraft Developments Per Year

By this method, the effects of an individual manufacturer's performance will be eliminated in assessing overall performance measurement. It also has the advantage of accounting for the introduction or elimination of a manufacturer which produces aircraft in a particular category. The method is described as follows:

$$\overline{x}_y = (\Sigma_1^z \; PT_1 + PT_2 + \ldots + PT_z) \div z$$

where: $\overline{x}_y$ = the mean annual performance (aircraft/year, all manufacturers)

PT = annual performance (aircraft, all manufacturers) in a given year

Z = the number of years analyzed

By applying the annual performance measurement $\overline{x}_y$, to the number of years to be projected, an estimate of the number of new designs can be established.

$$T = \overline{x}_y \times Y$$

where: T is the projection of new designs, the

Y is the number of years projected.

The values shown in Table 3.7 are the mean of these two projections.

$$T = (\Sigma\ T_I + T_{II}) \div 2$$

where: T_I is the projection derived by Method I

and T_{II} is the projection derived by Method II

The raw data used to establish these projections are shown in Table B.1.

Table B.1 Manufacturer Performance by Design Introduction/Certification Data

TYPE	MANUFACTURER	DESIGN		YEAR
GENERAL AVIATION				
	Beechcraft	Bonanza	F-33	1956
		Baron	B-55	1957
		Sierra	A-24	1962
		Duke	A-60	1968
		Sundowner	C-23	1971
		Sport	B-19	1971
		Baron	58-P	1974
		Baron	58-TC	1975
		Duchess	76	1974
		Skipper	77	1979
	Belanca	Citabria		1965
		Viking		1969
		Skyrocket		1973
		Aries	T-250	1976
	Cessna	310		1954
		150		1958
		182		1956
		210		1959
		172		1960
		185		1961
		206		1963
		337		1964
		177		1967
		207		1969
		340		1971
	Gulfstream/American	Cheetah		1970
		GA-7		1973
		American		1974
		Trainer		1972
	Mooney	Ranger		1955
		201		1974
	Piper	Aztec		1954
		Commanchee		1957
		Arrow		1960
		Cherokee		1961
		Lance		1965
		Cherokee Six		1965
		Adrostar 600		1968
		DaCota		1968

Table B.1 Manufacturer Performance by Design Introduction/Certification Data (continued)

TYPE	MANUFACTURER	DESIGN	YEAR
		Warrior	1970
		Twin Commanchee	1970
		Seneca	1971
		Tomahawk	1978
		Seminole	1978
	Rockwell	Shrike Commander	1952
		Alpine Commander	1970
		Commander 112	1972
BUSINESS			
	Beechcraft	Queenair B80	1959
		Kingair C90	1959
		Kingair 100	1968
		Kingair 200	1973
		Commuter	1981
	Cessna	402	1964
		Citation I, II	1971
		441 Conquest	1974
		404 Titan	1976
		Citation III	1977
	Foxjet International	ST/600S	1978
	Gates/Learjet	24	1963
		25	1970
		28	1977
	Gulfstream/American	Gulfstream	1958
		Gulfstream III	1978
		Hustler	1978
	Learavia	Learfan	1981
	Lockheed	Jetstar	1961
	Piper	Navajo	1966
		Cheyenne	1966
		Cheyenne III	1976
	Rockwell	Commander 690	1955
		Commander 500	1956
		Sabre 60, 65, 75	1962
		Commander 700	1974
	Swearingen	Merlin II, III	1966

Table B.1 Manufacturer Performance by Design Introduction/Certification Data (continued)

TYPE	MANUFACTURER	DESIGN	YEAR
TRANSPORT			
	Boeing	707	1953
		727	1960
		737	1965
		747	1968
		747 SP	1974
	Beechcraft	Airline B-99	1968
		Commuter Transport	1981
	Gulfstream/American	Gulfstream	1958
	Lockheed	Electra	1958
		L-1011	1970
		Hercules	1954
	McDonnell Douglas	DC-8	1955
		DC-9	1965
		DC-10	1970
	Swearingen	Metro	1969
HELICOPTER			
	Bell	205	1960
		206	1965
		209	1966
		212	1969
		214	1970
		301	1973
		222	1976
		412	1979
		AHIP	1981
	Boeing Vertol	107	1961
		114	1964
		105C	1972
		145	1976
		HLH	Prototype
	Brantley/Hynes	305	1964
		B-2	1975
	Enstrom	F-28A	1962
	Hughes	300	1966
		500C	1968

Table B.1 Manufacturer Performance by Design Introduction/Certification Data (continued)

TYPE	MANUFACTURER	DESIGN	YEAR
		500 D	1971
		YAH-64	Prototype
		Model 2000	Prototype
	Kaman	K-860 (series)	1968
	Robinson	R-22	1958
	Sikorsky	S-61	
		S-62	
		S-64	1967
		S-65	1966
		S-69	Prototype
		S-70	1975
		S-72	1973
		S-76	1976