Naval Environmental Prediction Research Facility
Monterey, CA 93943-5006
Technical Report TR 88-11 November 1988

ICING CONSIDERATIONS FOR HALE (HIGH ALTITUDE, LONG ENDURANCE) AIRCRAFT

Gerard N. Vogel
Naval Environmental Prediction Research Facility

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S) TR 88-11	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Environmental Prediction Research Facility 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Monterey, CA 93943-5006	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Naval Air Development Center 8b. OFFICE SYMBOL (If applicable) Code 3021	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Warminster, PA 18974-5000	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: 62122N PROJECT NO.: RR22-M51 TASK NO.: WORK UNIT ACCESSION NO.: DN658755

11. TITLE (Include Security Classification)

Icing Considerations for HALE (High Altitude, Long Endurance) Aircraft (U)

12. PERSONAL AUTHOR(S)

Vogel, Gerard N.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 5/1/88 TO FY89	1988, November	55

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Aircraft icing, Icing forecasting, Icing instrumentation, Supercooled clouds, Icing characteristics
04	02		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Although a low probability event, ice accretion does present a major obstacle to safe aircraft operations. In this report, the character of the aircraft icing environment is explored in terms of key meteorological and aerodynamic factors as related to the HALE (High Altitude, Long Endurance) aircraft. The distribution of icing in the atmosphere, mainly a function of temperature and cloud structure, is presented. Ice forecasting techniques and icing instrumentation are discussed as viable approaches for minimizing potential aircraft icing hazards. It is concluded that an onboard ice accumulation detector in combination with ground-based remote sensing instrumentation would provide the best capability for the detection and monitoring of icing conditions. The use of an automated icing forecasting program, which is both effort- and time-efficient, is recommended. Keywords:

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Gerard N. Vogel	22b. TELEPHONE (Include Area Code) (408) 647-4766 22c. OFFICE SYMBOL NEPRF WU 6.2-36

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

TABLE OF CONTENTS

1. INTRODUCTION

The accumulation of ice on airframe and engine components has a detrimental effect on aircraft by altering aerodynamic contours and affecting the nature of the boundary layer. Ice accretion reduces lift and increases weight, drag and stalling speed. Fuel efficiency drops and power requirements increase. Either de-icing procedures must be followed, or corrective action must be initiated to depart the icing environment expeditiously.

Potential icing hazards for HALE aircraft will be greatest during slow ascent or descent through supercooled clouds, or liquid precipitation at temperatures below freezing, within the lower troposphere. At operational altitudes (within the stratosphere), the icing hazard for HALE aircraft will be virtually nonexistent due to extremely low temperatures and insignificant moisture.

In this report, the character and distribution of the aircraft icing environment will be explored to define operational limits. Forecasting techniques and icing instrumentation will be discussed as viable approaches for minimizing icing hazards. Finally, recommendations are given which may serve to improve HALE aircraft performance during inflight icing encounters.

2. CHARACTERIZATION

In the atmosphere, cloud droplets generally remain in the liquid state even at temperatures well below freezing. The impact of such supercooled droplets upon a passing airplane will result in ice accretion on exposed surfaces. The nature of the ice accretion, and the nature of the potential hazard, is complex and depends on various meteorological and aerodynamic factors. Key meteorological factors include the liquid water content (LWC), the size of the droplets, and the temperature. Aerodynamic factors include the collection efficiency of, and the compressive heating over, all parts of the aircraft as a function of design and speed. These factors, along with the horizontal extent of the supercooled clouds along the flight path, determine the amount of icing.

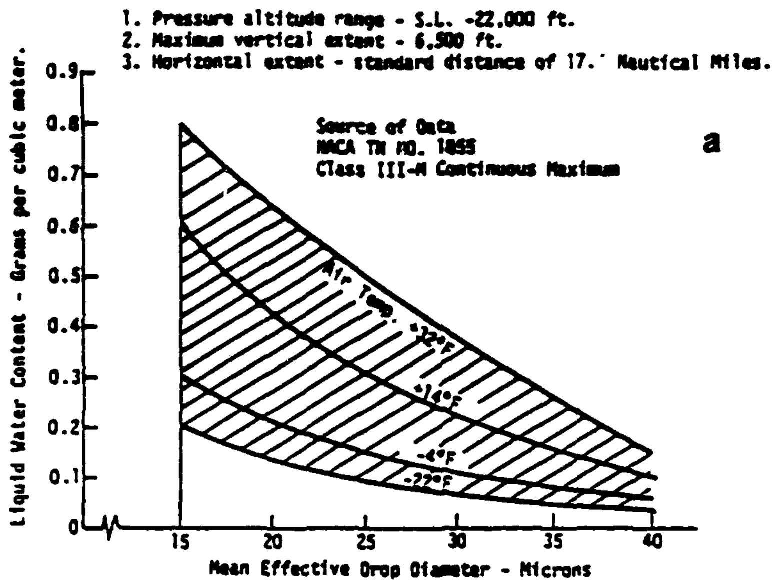
Aircraft icing occurs in three basic forms: clear ice, rime ice, and frost. In addition, the simultaneous occurrence of both clear and rime ice- called mixed icing- is common. A study by Perkins et al. (1957), based on reconnaissance flights at 700 mb (3 km) and 500 mb (5.5 km), reported the relative frequency of icing by types as follows: clear, 10%; rime, 72%; mixed, 17%, and frost, only 1%. Descriptions of the three basic icing types, taken from the Air Weather Service (AWS) Forecaster's Guide on Aircraft Icing (1980), are now presented.

Frost, a light, feathery deposit of ice crystals, forms by the deposition of ice on a cold surface directly from the vapor phase. It usually forms on the upper surfaces of parked aircraft due to radiative cooling. Frost is unlikely on an aircraft in level flight, but may occur if an aircraft descends quickly from subfreezing air into a warmer, moist layer below. This type of icing is unlikely to have any serious effects on the aerodynamic qualities of inflight aircraft.

Clear ice is a glossy, clear or translucent ice formed by the relatively slow freezing of large supercooled droplets, which spread out over the airfoil before completely freezing, forming a sheet of clear ice. This type of icing is most difficult to remove, as it bonds firmly to a surface. The rapid and heavy accumulation of clear ice, characteristic of freezing rain, is particularly hazardous. Clear icing usually forms at temperatures just below freezing and is generally associated with cumuliform (convective) clouds.

Rime ice, the most prevalent form, is a rough, milky, opaque ice formed by the instantaneous freezing of small supercooled droplets as they strike the aircraft. The opaque appearance is due to the fact that the droplets maintain their spherical shape upon freezing, between which air is trapped. Due to its porous and brittle nature, rime icing is easily broken away. Rime icing is generally acknowledged to form at lower temperatures than clear ice, and is prevalent in supercooled stratiform (layered) clouds.

For many years, the characterization of the icing environment has been recognized as being of prime importance in the setting of safety standards for flight operations. Worldwide aircraft observations during the late 1940's, collected by the National Advisory Committee on Aeronautics (NACA), were used by Jones and Lewis (1949) in the development of two icing envelopes defined by the liquid water content, droplet size distribution and temperature. One envelope, Figure 1a, represents maximum



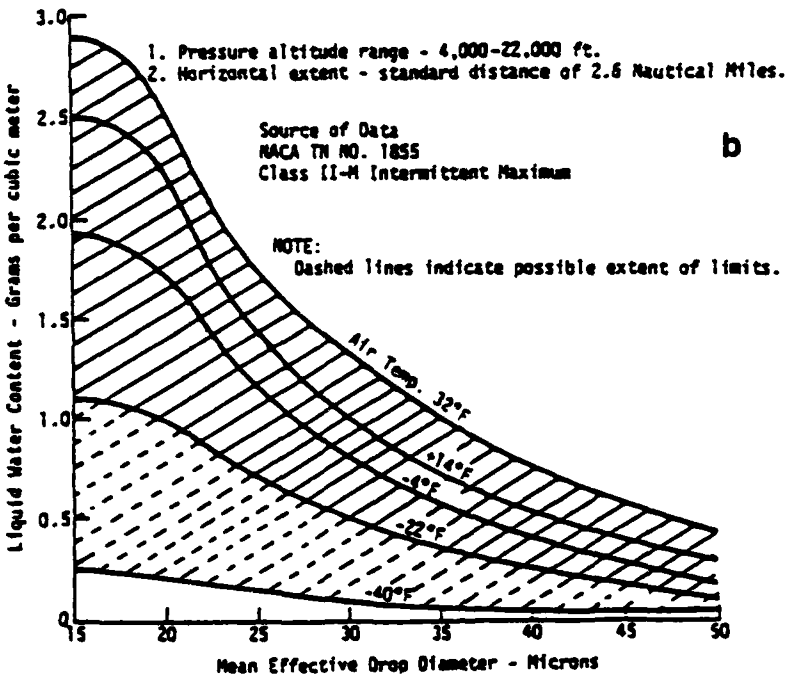


Figure 1. (a) Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions. (b) Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions (after FAA, 1974).

rime icing conditions occurring in stratiform clouds, and the other, Figure 1b, defines maximum clear icing that would be encountered in cumuliform clouds. Currently, the Federal Aviation Administration (FAA) uses these envelopes for flight certification into icing conditions for large transport category aircraft (Federal Air Regulations (FAR) Part 25, App. C), and these same data are included in the Department of Defense standard DOD-MIL-E-38453.

In response to a need to update the current FAA regulations for low altitude, low performance aircraft, Jeck (1985) combined historic NACA icing data with modern data from various sources to define a new characterization of the icing environment for altitudes below 10000 ft AGL (Above Ground Level), based on LWC, temperature and median volume diameter (MVD) of cloud droplets. In this analysis, the maximum observed LWC was determined to be 1.1 g/m^3 for layer clouds below 3 km and 1.7 g/m^3 for convective clouds over the continental United States. The MVDs of cloud droplets ranged from 3 to 35 μm, with a large fraction of the MVD measurements between 3 and 15 μm, especially for layer clouds.

The study revealed a temperature dependence of the MVD, with the upper limit to MVD in layer clouds decreasing from 35 μm at $0^{o}C$ to 15 μm at $\leq -20^{o}C$ but, for convective clouds, increasing from 15 μm at $0^{o}C$ to 30 μm at $-17^{o}C$. At $-20^{o}C$, the approximate temperature below which no convective clouds will be found at altitudes below 3 km AGL, the maximum MVD drops abruptly to 15 μm.

Supercooled cloud droplets were found to have a low temperature limit of -25°C in wintertime stratiform clouds at 4000 to 6000 ft AGL. Figure 2 presents a unified description of the overall icing environment for altitudes up to 10000 ft AGL. Here, no distinction is made between layer and convective clouds, as the author's purpose is to provide specific extreme LWC, MVD, and temperatures criteria for both design and flight testing.

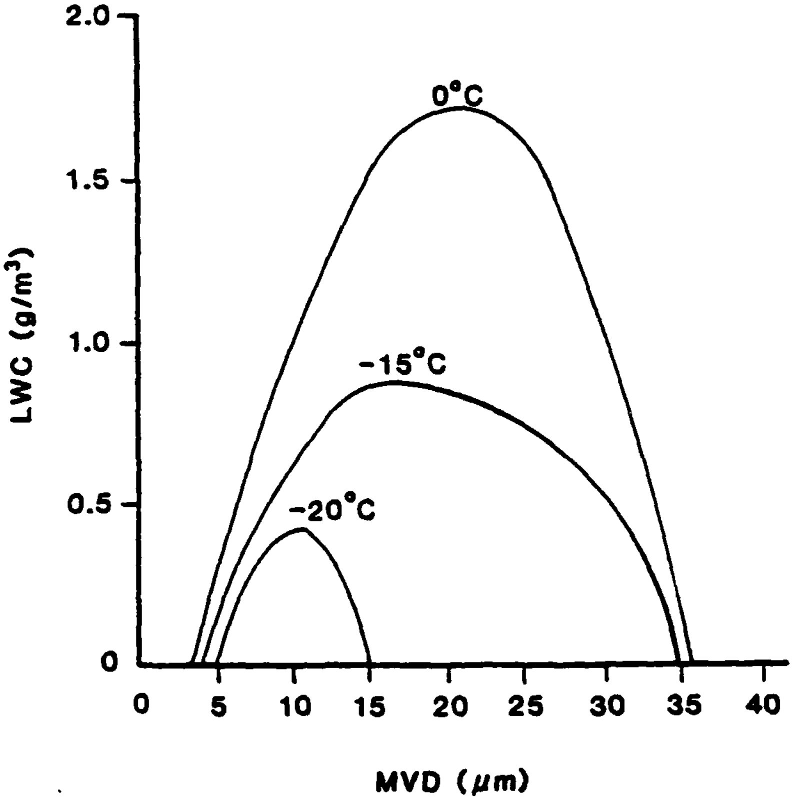


Figure 2. Approximate Extreme Values of LWC and MVD Combinations Observed in Supercooled Clouds at Altitudes up to 10000 ft AGL (after Jeck, 1985).

Statistics on the horizontal extent of icing events were also compiled by Jeck. To do this, the horizontal extent was arbitrarily defined as the cumulative distance of uniform cloud intervals (icing events) not broken by a gap greater than 1 nm. The analysis indicated that the maximum horizontal extent decreases with increasing LWC and that shorter extents are more common. Specifically, 50% of all cases had horizontal extents <5 nm, and 90% had extents <15 nm. The horizontal extent was greatest (up to 50 nm), in upslope supercooled stratiform clouds.

A comparison of the FAR Part 25, App. C requirements (Figure 1) and the new low altitude characterization (Figure 2) reveals several noteworthy differences. First, the new characterization encompasses MVDs between 3 and 15 μm which were omitted from FAR Part 25, App. C. Second, the new characterization gives a maximum LWC of ~1.7 g/m^3 at 22 μm, while the FAA requirement is for 2.9 g/m^3 at 15 μm. This difference is plausible since icing clouds developed within 10000 ft of the surface under convective conditions will be less severe, and thus with a lower LWC, than clouds with development extending to higher altitudes. Third, the new characterization has no temperature lower than -25°C, whereas FAR Part 25, App. C requirements indicate temperatures as low as -30°C, perhaps to -40°C. Finally, the occurrence of icing with MVDs > 36 μm is not shown in the new characterization. Indeed, the validity of the FAR Part 25, App. C icing envelopes beyond 36 μm is questioned by

Jeck (1985), who claims that large MVDs are likely to contain large positive errors due to limitations of the multicylinder technique upon which these data were gathered.

Another characterization of aircraft icing, based on some 42000 km of measurements over a 5 year period, is presented by Sand et al. (1984). The icing encounters occurred at altitudes from 0 to 8 km MSL (Mean Sea Level), in summer and winter over different geographic regions, in stratiform and cumuliform clouds, and at temperatures from 0 to -30°C. In general, the measurements in this extensive data set fall within the FAA icing envelopes of FAR Part 25, App. C. Most icing measurements were concentrated in the interval 0 to -20°C; the median temperature of the data set was -9°C. Maximum values of LWC, measured by different probes, were 2.5 g/m^3 and slightly less than 3 g/m^3. The high values of LWC did not extend over long distances; indeed, average LWCs > 1 g/m^3 (characteristic of severe icing), were rarely encountered over distances greater than 20 km. The median MVD of the cloud droplets was ~15 μm, but the observations included values from 5 to 40 μm. The droplet concentrations were < 400 cm^{-3} in 90%, and < 110 cm^{-3} in 50%, of the icing regions. The mean ice crystal concentration, in regions where the LWC was > .025 g/m^3, was observed to be 4 L^{-1}, but ice crystal concentrations ranged up to nearly 1000 L^{-1}; moreover, ~15% were greater (less) than 100 L^{-1} (.25 L^{-1}).

An additional icing characteristic determined by Sand et al. was the potential accumulation, defined as the mass of supercooled water that would accrete during an icing encounter, per unit surface area, if the collection efficiency was unity. The potential accumulation is a maximum limit since actual accumulation of ice, even without de-icing or anti-icing protection, would generally be less because collection efficiencies are usually less than unity and because some sublimation of ice is likely. Sand et al. report that for single icing events with the LWC continuously above .01 g/m^3, potential icing accumulations < .67 g/cm^{-1} (.84 cm) occurred in 99% of the cases. For the over 500 individual icing encounters which start with the first exposure to LWC > .025 g/m^3 and end when the temperature at flight level exceeds 0^oC, the potential accumulation exceeded 4 g/cm^{-2} (~5 cm) in only about 10% of the cases, and exceeded 8 g/cm^{-2} in only about 1%. The extreme value of 19 g/cm^{-2} (~24 cm) was determined for a several hour flight pattern through active summertime cumulus clouds.

In their report, Sand et al. also reported on the effects of these cloud characteristics on aircraft performance. Although their conclusions are specific to the Super King Air aircraft, the observed effects of icing on performance exemplify what could be expected on other aircraft, including HALE, under similar conditions. The findings include:

1) A reduction in the rate of climb, with a corresponding increase in drag and decrease in lift, was found to increase linearly with the potential accumulation for most icing events.

2) Flights through mixed-phase regions (ice aggregates in co-existence with supercooled cloud droplets) indicate that ice particles do not have any major influence on ice accretion, and their presence did not appear to have any significant influence on the performance of the aircraft.

3) Ice accretion in the form of clear ice had substantially greater effects on performance than cases of rime ice with similar total accretion.

4) Although seldom encountered, the most hazardous icing, and the greatest effect on airplane performance, occurred in cases where supercooled droplets of 40-300 μm diameter were present. The only two recorded instances of icing on the undersides of the wings, which resulted in necessary flight diversions, were associated with these sized droplets. Accretion of still larger supercooled droplets, and especially raindrops with diameters > 1 mm, seemed to have a less pronounced effect, as these very large drops have a tendency to splash rather than accrete on a surface.

In the presence of supercooled clouds, the actual rate of ice accretion on a HALE aircraft will depend to a great degree on the collection efficiency and aerodynamic heating of the aircraft component involved. The collection efficiency, the fraction of liquid water collected by the aircraft, varies directly with the droplet size and aircraft speed, and depends upon the curvature of the collecting surface. Ice will form more readily on parts of the aircraft having a small radius of curvature (i.e., thin wings and tail leading edges) as these edges disturb the airflow very little, allowing the capture of most droplets in the volume of air swept out by the edge.

On the other hand, bluff surfaces (i.e., thick wings, canopies) so disturb the airflow that only a small percentage of the cloud droplets, especially the smaller ones, are caught. Once ice accretion has begun, the shape of the collecting surface undergoes modification; almost always, the radius of curvature becomes smaller and the collection efficiency increases. The faster the aircraft speed, the greater the collection efficiency, since the trajectory of cloud droplets are deviated less and more drops in the swept volume are caught. Of course, the faster the aircraft the greater the rate of catch, since a greater volume of air is swept out per time by a unit area of the projected surface. For a given radius of curvature of a leading edge, and for a given speed, collection efficiency has been shown to increase in relation to droplet diameter (Jones, 1956). A summary of the mathematical analysis involved in the calculation of collection efficiency for various types of airfoil is given by Brun (1957).

Aerodynamic, or kinetic, heating is the temperature rise due to adiabatic compression and friction as an aircraft penetrates the air. This temperature rise is greatest on the leading edge of the wing (a stagnation point), and least for the portion of the upper wing surface to the rear of the midchord. The amount of heating varies directly with the speed of the aircraft and the air density. The kinetic heating effect is reduced in flight through supercooled cloud droplets, due to various heat transfers involving water droplets. A detailed discussion of aerodynamic heating in clear air, in supercooled clouds, and in mixed-phase clouds, is presented by Jones (1961).

Threshold, or critical temperatures, for the occurrence of aircraft icing on the leading edge of a wing and to the rear of the airfoil midchord, as a function of altitude and speed, are given in Figure 3. Comparison of Figures 3a and 3b indicates the differences in aerodynamic heating as a function of airfoil location. As one can observe in Figure 3a, the amount of aerodynamic heating, at a fixed level, is much less at low air speeds; for example, at 10000 ft, the kinetic heating at 150 kt is 1.2°C but, at 450 kt, it is greater than 12°C. Thus, for slow flying planes, such as HALE, the amount of ice protection from aerodynamic heating effects appears to be small. Moreover, according to Coles and Ruggeri (1954), the effectiveness of aerodynamic heating for the removal of accumulated ice at high altitudes is poor due to the slowness of the process.

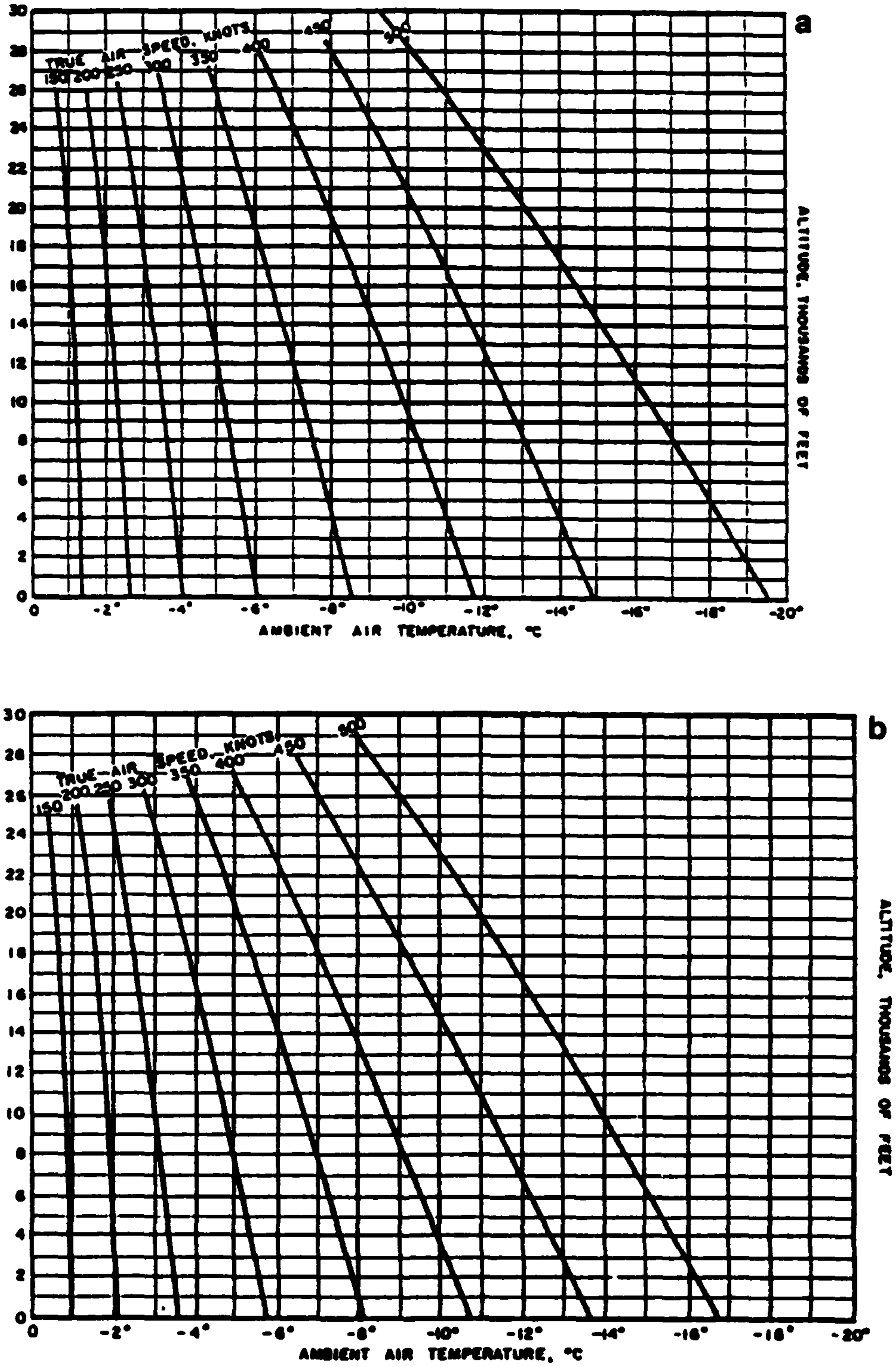


Figure 3. Critical Temperature for Occurrence of Aircraft Icing as a Function of Altitude and True Airspeed. (a) On the Leading Edge of Wing, (b) Due to Runback (from AWS, 1980).

3. DISTRIBUTION

The distribution of icing in the atmosphere is dependent upon the temperature and the cloud (liquid water) structure which, in turn, vary with altitude, synoptic conditions, orography, location and season. In this section, the importance of these secondary factors will be examined and, several icing probability climatologies will be presented.

In general, the frequency of icing decreases rapidly with decreasing temperature. Statistics compiled from reconnaissance flights by Perkins et al. (1957) indicate that, without any a priori knowledge of the existence of clouds, the probable frequency of icing for the 10000-18000 ft level drops appreciably with decreasing temperature, from about 6% at $-5^{o}C$ to approximately 1% at $-30^{o}C$ (Figure 4a). The probable frequency of icing increases dramatically if clouds are known to exist, ranging from slightly below 40% at $-5^{o}C$ to near 10% at $-30^{o}C$ near the 15000 ft level (Figure 4b). This graph is useful in that it could provide an estimate of how many flight miles through clouds at a certain temperature and altitude would be subject to icing conditions.

Various studies have been undertaken to determine the relationship among temperature, the dewpoint spread (the difference between the temperature and the dew point), and aircraft icing occurrence. In a study reported by AWS(1980), all-weather flight data, summarized irrespective of altitude and temperature, statistically showed a 84% probability that there would be no

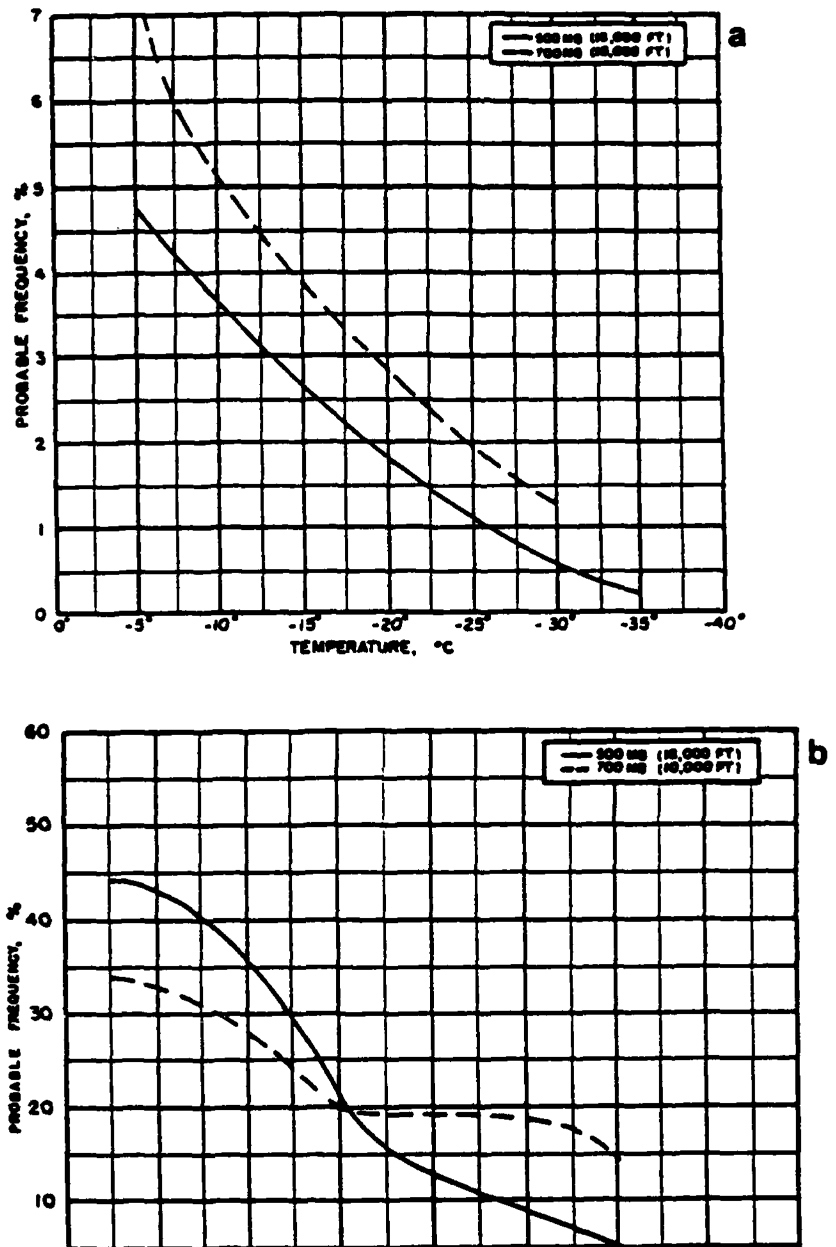


Figure 4. (a) Probable Frequency of Icing as a Function of Altitude and Temperature Without Consideration of Clouds. (b) Probable Frequency of Icing in Clouds as a Function of Altitude and Temperature (from AWS, 1980).

icing if the dewpoint spread was > $3^{o}C$, and a 80% probability that there would be icing if the spread was < $3^{o}C$. Statistics based on over 5000 AWS reconnaissance reports in stratiform clouds at free-air temperatures between 0 and $-32^{o}C$ (AWS,1980), show a predominant temperature range for icing from $-3^{o}C$ to $-7^{o}C$, a dewpoint spread of 0 to $-1^{o}C$ for the majority (55%) of the 1550 icing cases and, a minimum percentage of icing at dewpoint spreads of $7^{o}C$ or more. These results agree well with the empirical conclusions of Appleman (1954) which show that icing in stratiform clouds should occur only when the dewpoint spread is less than or equal to -0.2 times the dew point temperature.

The icing environment for aircraft is restricted to below 30000-35000 ft (~10 km) altitude. At this altitude, the U.S. (NACA) standard atmosphere temperature is close to $-50^{o}C$, which is considerably lower than the lowest temperature at which super-cooled droplets can exist ($\sim -40^{o}C$). Within the stratosphere, temperatures are generally even colder (a notable exception is the summer polar stratosphere, with temperatures near $-40^{o}C$ possible), and aircraft icing does not occur.

Aircraft icing can occur in stratiform and cumuliform clouds, but rarely is associated with cirrus clouds which, by description, are composed of ice crystals. The few occasions icing (of light intensity) has been reported with cirriform clouds are within the dense cirrus anvil tops of cumulonimbus thunderclouds), where strong updrafts allow the transport of liquid water to high levels at rather low temperatures.

For temperate latitudes, low-level and mid-level stratiform clouds occur at altitudes below 20000 ft. Icing within these clouds normally is confined to layers several thousand feet thick. Rime and mixed icing, usually of a light intensity, are observed in stratiform clouds, with maximum values of accretion most likely to occur in the upper portion of the cloud. Although icing intensity is usually of a light nature, it could create a problem if flight is prolonged in this environment, since stratiform cloud decks commonly extend over a considerable horizontal distance.

The icing environment associated with cumuliform clouds is more variable than that with stratiform clouds, being highly dependent on the stage of development of a particular cloudy. Fair weather cumulus clouds, found at 1 to 2 km altitudes, do not present a serious icing hazard. On the other hand, cumulus congestus and cumulonimbus, which can extend to 10 km and even beyond, present serious icing hazards. In a building cumulus, icing occurs at all levels above the $0^{o}C$ isotherm and is most intense in the upper half of the cloud. The most severe icing often occurs in the developmental stage from cumulus congestus to cumulonimbus. In a mature cumulonimbus, icing is most likely in updraft regions of small horizontal, but considerable vertical, extent. Icing associated with a decaying cumulonimbus generally concentrates into a shallow band above the freezing level.

Middle and high latitude weather fronts, boundary surfaces separating airmasses of different characteristics, are preferred locations for potential aircraft icing. Clouds associated with warm fronts, where warm air is replacing cold air (ie. warm-air advection), are usually stratiform. Warm frontal icing may occur both above and below the frontal surface. Hazardous icing conditions, with moderate to severe clear icing, are possible where freezing rain or drizzle falls through the cold air beneath the front. Icing above the frontal surface is usually confined to cloud bands several thousand feet thick and may extend over considerable horizontal extent. Icing may extend well in advance of the warm front surface position. Jones (1956) found a definite likelihood for light to moderate icing 100 to 300 miles ahead of the surface front, especially for fast moving, active warm fronts.

Icing associated with cold fronts, where cold air is occupying territory covered by warm air, is generally less widespread than warm frontal icing. Moderate clear icing usually occurs within 100 miles to the rear of the surface cold frontal position in unstable supercooled cumuliform clouds, and is often most intense immediately above the frontal zone. Often times, light icing may be encountered in extensive layers of supercooled low-level (<7000 ft) stratocumulus clouds which frequently exist behind cold fronts for several hundreds of miles. Icing conditions in stationary fronts and occluded (combined cold and warm) fronts are similar to those of a warm or cold front, depending on the type the stationary or occluded front most resembles.

Moderate icing conditions can occur in zones of vorticity maxima associated with upper air disturbances, cut-off lows, and deep, cold occluded cyclones.

In the tropics, icing is probable only in energetic convective clouds (cumulus congestus and cumulonimbus), at middle tropospheric levels (~5-10 km). Trade-wind cumulus clouds, which characteristically cover about one-third to one-half of the oceanic tropics, do not present an icing hazard as their tops (1500-2500 m) are well below the freezing level.

A major influence in the distribution of icing is orography. Icing is more intense in high or steep-sloping terrain than under identical conditions over low, flat terrain. Mechanical lifting of air by mountainous terrain often results in convective clouds and accompaning clear icing. Extensive aircraft icing zones are common on the windward slopes of coastal mountain ranges in winter as lifted moisture-laden maritime polar air results in the formation of widespread supercooled clouds. Additionally, the persistence of orographically-induced updrafts permit the air to support larger cloud droplets and higher LWC, which are favorable to more severe icing conditions. The combination of terrain-induced lifting and frontal situations produces especially hazardous icing conditions.

Wide variations exist in the geographic and seasonal distribution of aircraft icing frequency, due to large variations in temperature and available moisture. Although icing may occur during any season, it is more prevalent from late fall to early spring in mid-latitudes, when the temperature of the lower atmosphere is below freezing and cyclonic storms and fronts, with their associated cloudiness, are more frequent. During the winter season, icing is very frequent over the warm ocean current areas east of continents (ex. Gulf Stream, Kuroshio), and to the lee of large bodies of water (ex. Great Lakes), as a result of the rapid saturation of cold, dry air. High icing frequencies are also noted during the winter half of the year over those western portions of continents where strong westerly flow transport ample moisture inland from the oceans. Icing probabilities are enhanced during winter, due to intense orographic lifting, for those continents with high mountains covering the western portions (ex. North, South America). In polar regions, icing frequencies are minimal in winter due to intense cold and low moisture, and maximum in summer. Within the tropics, where the temperature below 10 km varies little from season to season, icing frequency is dependent upon available moisture and the state of atmospheric stability. As a result, the highest frequency of icing will occur in organized convergence (convective) systems during the rainy season(s), and the lowest frequency, during the dry season(s).

In their study based on weather reconnaissance data at 700 and 500 mb over ocean areas in the Northern Hemisphere (> 20 N), Perkins et al. (1957) found the greatest winter-icing frequency over the northern and western parts of the North Pacific and North Atlantic, and the least over the Arctic Ocean. At 700 mb

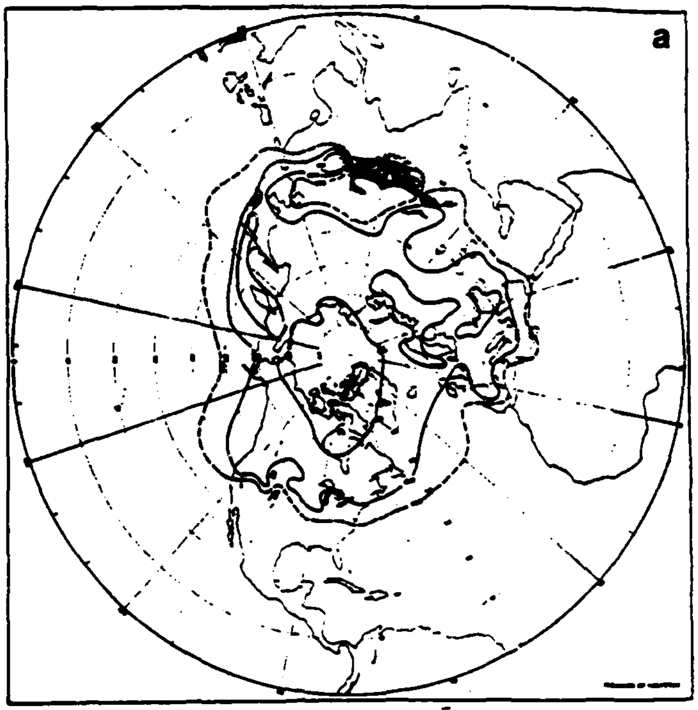
(~3 km), little seasonal variability is observed over the northern portions of the Atlantic and Pacific Oceans. However, comparatively large seasonal variations are found over other ocean areas, with winter the season of maximum icing (due to more suitable temperatures), except over the Arctic, which has a maximum in summer. At 500 mb (~5.5 km), because temperatures are almost always below $0^{o}C$, the seasonal variation of icing is more dependent on moisture than temperature. Summer seasonal maxima, due to higher moisture content, are found over the Arctic Ocean and western portions of the Atlantic and Pacific Oceans. For the eastern ocean areas, maximum icing near 500 mb is found in the fall, the season of greatest cyclonic and convective activity.

In addition to statistics of aircraft icing probabilities based on actual observations, several studies on the probability of encountering icing in the Northern Hemisphere have been conducted by Katz (1967) and Heath and Cantrell (1972). For both studies, icing probability charts are calculated for each month for several lower tropospheric levels; the type and severity of the icing are not considered. The earlier study utilizes observed temperature and cloud amount data to construct the probabilities. The updated study by Heath and Cantrell does not consider actual cloud observations but rather assumes the presence of clouds based on particular limits of temperature/ dew-point spread as determined from AWS reconnaissance flights into icing conditions. In general, both of these climatological probabilities of aircraft icing present similar geographic and seasonal distributions. Sample charts from Heath and Cantrell are presented for 700 mb in January, and for 500 mb in July, in Figures 5a and 5b, respectively.

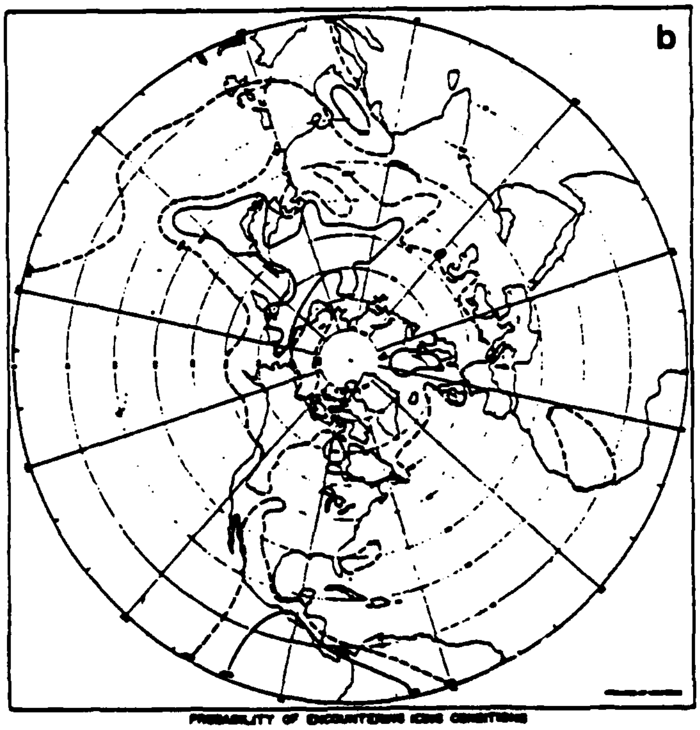
A climatic atlas that shows percent frequency of occurrence of potential icing conditions over North America has recently been published by USAFETAC (1986). Data from various sources are used to determine the percent frequency of occurrence of a liquid water content threshold concentration in a defined layer and temperature range. Output was generated for three concentrations (.1 g/m^3 (trace to light icing), .5 g/m^3 (moderate icing), and 1.0 g/m^3 (severe icing)), three layers (surface to 1524 m, 1525-3048 m, and 3049-4572 m), and for temperatures below freezing. This data was converted into monthly and annual maps showing percent frequency of occurrence of potential icing conditions. An example of one such chart is shown in Figure 6. To interpret this chart, consider the location New York City: the January cloud cover (surface to 1524 m) at New York City will have a liquid water content of .1 g/m^3 or more about 60% of the time at a temperature below freezing, conditions favorable for the formation of icing.

4. FORECASTING

It should be clear from the foregoing section on icing characterization that the detail of the icing experience likely to be encountered on a route is governed by so many complex factors as to make the forecasting problem most difficult.



PROBABILITY OF ENCOUNTERING ICING CONDITIONS
700 MB JANUARY



PROBABILITY OF ENCOUNTERING ICING CONDITIONS
500 MB JULY

Figure 5. Probability of Encountering Icing Conditions. (a) 700 mb January (b) 500 mb July (from Heath and Cantrell, 1972)

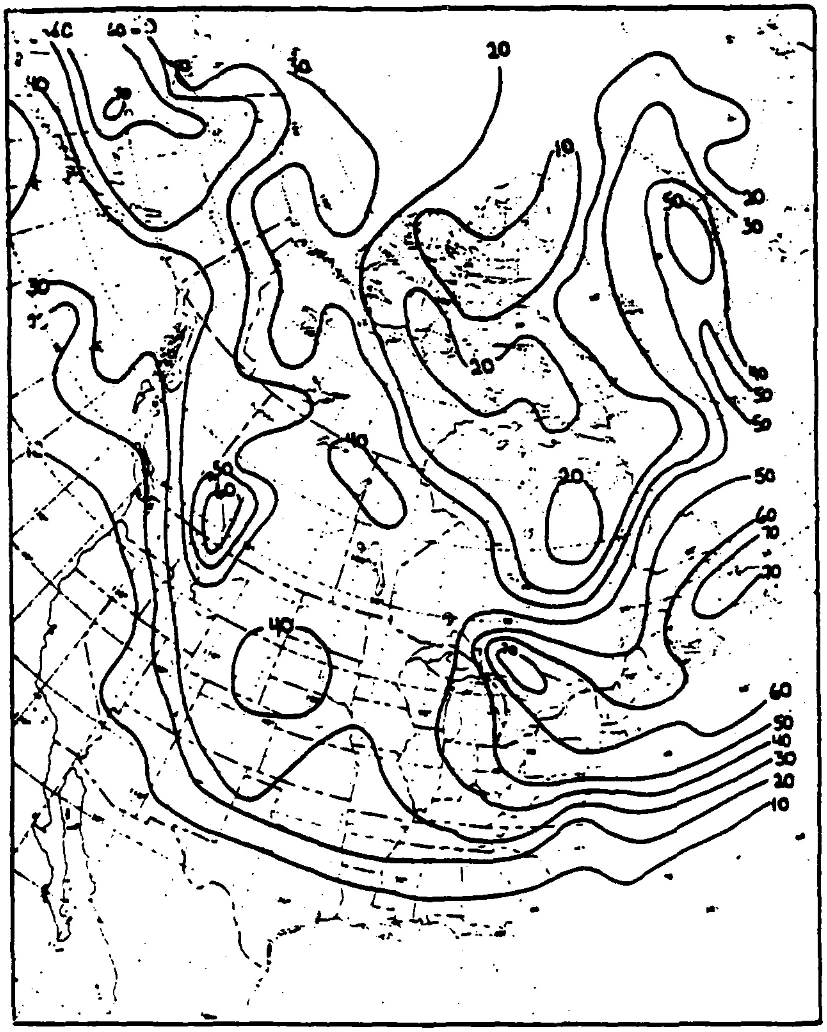


Figure 6. January, Surface to 1524 m, Concentration .10 g/m^3. (from USAFETAC, 1986)

Additionally, the coarseness of the radiosonde network coupled with the relative infrequency and randomness of data measurements does not lend to accurate and well-defined assessments of icing potential. Both liquid water content and droplet size distribution, very important parameters influencing accumulation rate and ice type, are not measured on a routine basis, but rather are inferred from radiosonde parameters for insertion into icing prediction models. Improvements in ice forecasting methods are hampered by inadequate verification. In general, reports which could be used in forecast verification lack statistical purity (especially in regards to icing intensity), and are dependent on airframe and de-ice capabilities. Nonetheless, in spite of the aforementioned problems associated with aircraft icing forecasting, it is certain that current forecasting techniques can contribute notably to the safety of a HALE mission by minimizing the risk of inflight icing.

In the United States, the National Weather Service (NWS) is responsible for preparing aircraft icing forecasts for the civilian sector, and the USAF Air Weather Service (AWS) and the USN Naval Oceanography Command for the military sector. While the NWS issues routine regional forecasts, military forecast tend to be oriented toward a particular flight mission. Irrespective of the issuing agency, icing forecasts usually cover large volumes, as meteorologists working with coarse-resolution data tend to forecast conservatively by predicting icing over unduly large areas or expanded times. Current procedures for forecasting aviation icing, based on the study of Tucker III (1983), are now reviewed.

NWS forecasts of potential icing conditions are issued via teletype for six regional aviation zones for the conterminous U.S. land and adjacent coastal waters three times daily, with updates whenever warranted. Although these forecasts are valid for 12 hours, more precise times and locations of anticipated icing are usually included. The accuracy of any particular forecast is dependent upon the skill and experience of the forecaster, the receipt of adequate data (pilot reports, satellite imagery, radar observations, upper air soundings, local analyses), and the accuracy and interpretation of computer and manually-derived NWS forecast guidance and aids. As a starting point, the forecaster has to locate those areas of sufficient moisture at altitudes above the freezing level; this is usually accomplished by use of any of several prognostic and analysis products. After such potential icing areas are defined, a more detailed analysis is undertaken, applying empirically-derived rules to establish the likely intensity and type of icing. This process is quite subjective and is a matter of the forecaster's ability and experience in realizing the importance of local icing effects (ex. terrain) that would not be evident in any standard NWS product.

The USAF is the lead activity for icing forecasts within the Department of Defense, being responsible for forecasts for both the Air Force AWS detachments and the Army; in addition, the Navy generally applies techniques used by the AWS in forecasting icing. The Air Force Global Weather Central (AFGWC) issues time-phased icing forecasts, depicting areas of potential icing for 12 hour periods, for the Northern Hemisphere for the layer from 10 to 55 thousand feet. Additionally, icing forecasts for the layer from the surface to 10000 ft are produced for the contiguous United States and Europe. These products, which are transmitted via facsimile or teletype, are the end product of an elaborate production cycle which makes use of both numerical and analysis products relevant to the icing environment.

Once available at AWS detachments, the AFGWC charts serve as primary guidance for preparing a specific mission icing forecast. Since they are valid for long periods (12 hr), the forecaster must use other aids to determine if the icing potential still exists for the local area of interest. Satellite imagery, weather depiction charts (nephanalyses), and upper air charts are used to determine current cloud locations (or areas of likely cloud formation) and, if needed, primary forecast guidance is corrected for advective effects. Oftentimes, a AWS detachment forecaster examines a rawinsonde sounding or soundings upwind of the operational forecast area for potential icing to ascertain what conditions in the near future may be advected into the location of interest. A popular technique that is applied to a sounding to accomplish this is the Minus 8D method, which is based on the dewpoint depression D and upon considerations of cloud saturation with respect to ice and water. By and large, the final detail and accuracy of an AWS detachment icing forecast is a function of the amount of available time, and the experience and ability of the forecaster.

Today, the procedural techniques set forth in AWS/TR-80/001, Forecaster's Guide on Aircraft Icing, are the most widely applied in the military operational setting; indeed, most of the rules and techniques listed in this guide are also found in the Navy Aerographer's Mate 1 & C (NAVETRA 1974). As the first phase of the procedure in the preparation of an aircraft icing forecast, preliminary investigations are made for the determination and prognosis of clouds, temperatures and areas of precipitation along the proposed flight path. A potential for icing is established by this preliminary analysis provided supercooled liquid water drops - clouds or precipitation - at below freezing temperatures are indicated along the flight path. For a definition of the type and/or severity of the icing conditions, the forecaster chooses one of three methods, based on available time and data.

Method 1, which requires rather detailed data, entails the examination of upwind or prognostic soundings which are expected to be representative of conditions along the route at flight time. The type of icing is determined by the temperature lapse rate (change of temperature with height) on the sounding in the supercooled cloud layers. Stable layers, within which air parcels are subject to restoring forces, are assumed to represent stratiform clouds (with rime icing), while unstable layers represent cumuliform clouds and clear icing. Once the type of icing hasbeen determined for the flight level, an overlay, designed for use on the USAF Skew T- Log P sounding plotting chart, is used to depict its severity. With icing intensity quantitatively defined in terms of droplet diameter and LWC, the assumption of mean droplet diameters of 14 μm for stratiform clouds (rime icing) and 17 μm for cumuliform clouds (clear icing) results in liquid water contents for various intensities (Table 1). Thus, the curves depicted on the forecasting overlay, based on considerations of liquid water content for various cloud base temperatures and heights for stratiform and cumuliform clouds, provide a quantitative method of predicting icing intensity.

Table 1. Relationship of Icing Intensity to Liquid Water Content (from AWS, 1980).

Cumuliform clouds Liquid-water content* g/m^3	Icing intensity	Stratriform clouds Liquid-water content** g/m^3
≤ 0.07	Trace	≤ 0.11
0.08 - 0.49	Light	0.12 - 0.68
0.50 - 1.00	Moderate	0.69 - 1.33
> 1.00	Severe	> 1.33

* Assumed droplet diameter 17 micrometers
** Assumed droplet diameter 14 micrometers

Method 2 is limited to stratiform clouds and is intended for use if a forecaster lacks sufficient data or time. This procedure determines the phase condition of the particles in stratiform clouds along the flight path using frost-point considerations. A nomogram, devised from studies by Appleman (1954) and updated with additional weather reconnaissance data, is provided in AWS/TR-80/001 for application of this procedure (Figure 7). To apply this method, the forecaster needs to establish the presence

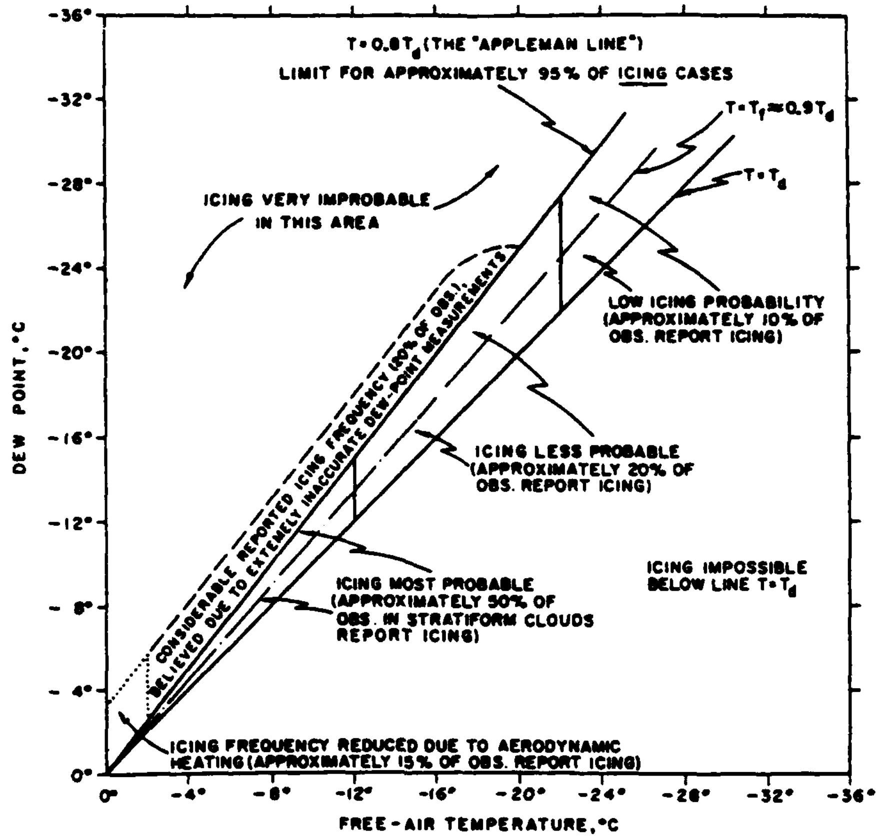


Figure 7. Nomogram for Application of Frost Point Technique for Rime Icing in Stratiform Clouds (from AWS, 1980).

of stratiform clouds (from stability or other considerations), then to plot flight level temperatures and dew points on the chart. The likelihood of icing is then read directly from the chart. In Figure 7, the line $T=T_d$ (temperature equals dew point temperature) represents saturation with respect to water and the line $T=T_f=0.9T_d$ is an approximation of saturation with respect to ice. Ideally, icing should occur between these two lines; however, the 95% limit of icing encounters from empirical studies is above $T=0.9T_d$, reflecting the fact that reported humidity values are often inaccurate (most often too low). This method by itself does not specify icing intensity.

Method 3 recommended by AWS/TR-80/001 consists of using established empirical rules to forecast icing intensity and type. These rules are based on temperature, dew point, temperature advection, cloud and precipitation information that can be obtained from surface reports, radiosondes, and upper air charts. A decision tree based on these empirical rules is shown in Figure 8.

Several AFGWC numerical icing products (used internally as production aids) automatically apply rules for the prediction of icing conditions as outlined in AWS/TR-80/001. The DWE (Diagnostic Weather Element) processes AFGWC temperature, cloud, dewpoint depression, and gridded winds using the TR-80 rules shown in Figure 8 to produce an icing chart. As an alternative to the DWE icing forecast model, which operationally has shown a bias toward analyzing and forecasting too much moisture and cloud, the AUTICE (Automated Ice) model was developed by Mansur (1984). AUTICE is essentially the same as DWE but with several additional physical restraints (ex. vertical velocity, vorticity advection) added to filter out what was felt to be excessive areal coverage by DWE; unfortunately, as reported by Mansur, test results for AUTICE were mediocre. Another icing model uses the output from the AFGWC Smith-Feddes LWC model coupled with the automatic application of the rules given in AWS/TR-80/001 to forecast the type and severity of aircraft icing. The Smith-Feddes LWC model extracts moisture data from a multilayer vertical cloud distribution data base and temperature from an

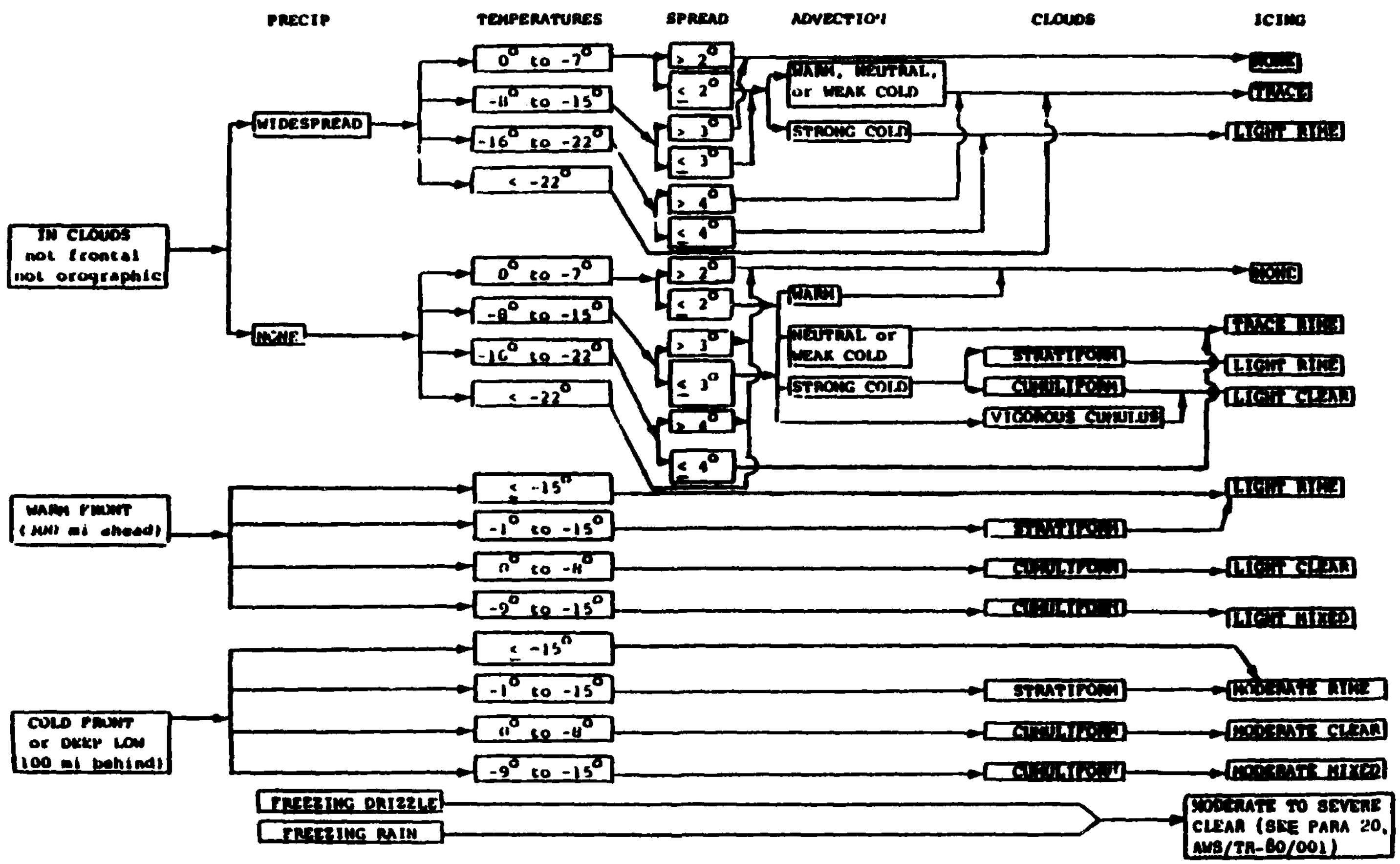


Figure 8. Decision Tree Based on Empirical Forecasting Rules Given in AWS/TR-80/001. (From AWS, 1979)

analysis data set, creating a gridded multilayer liquid water content field. The previously discussed icing potential climatology by USAFETAC (1986) was compiled using Smith-Feddes LWC model statistics covering a 4 year period.

Within the Navy, a remote site automatic icing analysis routine for radiosondes, based on AWS/TR-80/001 forecast rules (Figure 8) and updated cloud characterizations, is currently operational. This program, developed in Fortran 77 to run on the the HP9020A computer of the Navy's Tactical Environmental Support System (TESS), is now deployed at some land sites and aboard selected vessels within the fleet. Details of the TESS aircraft icing probability model, developed by Richard Jeck, can be found in NOO (1988).

The skill and accuracy of present day forecast techniques for aviation icing lag behind those for general weather phenomena (ex. precipitation, temperature, winds) due to the many complex aspects of the problem. Only 10 years ago, ice forecasting was judged to be accurate approximately 50 percent of the time by a group of experts in attendence at several workshops on meteorological and environmental inputs to aviation systems. Since then, progress has steadily been made in aviation icing forecasting. Improvements in numerical forecasting and data assimilation techniques now permit more timely icing forecasts utilizing more detailed data. The ingress of satellite derived temperature and dewpoint temperature profiles into numerical icing models alleviates the problem of inadequate observational data bases, especially for data sparse regions (ex. oceans).

Research toward understanding the structure of storms, and the atmospheric conditions within such storms that lead to icing, permits better characterization of icing for models. The development of new sensors, able to observe meteorological phenomena related to aircraft icing and yield new information on finer scales and with better continuity, support the efforts within the aviation icing research community directed toward verification and improvement of forecast techniques.

At the present time, the problem of aviation ice forecasting is being addressed by a multi-departmental (DOT, NASA, DOD, DOC, and NSF) and three-phase program entitled "National Plan to Improve Aircraft Icing Forecasts" (FCMSSR, 1986b). As stated in the executive summary, the goals of the program are to gather a reliable data base to better understand the characterization of aircraft icing, to evaluate icing forecasting techniques, to develop improved methods for detecting and forecasting icing, and to provide relevant technology transfer to the aviation community. Additional information relating to this program can be found in the "National Aircraft Icing Technology Plan," also published by the Federal Coordinator for Meteorological Services and Supporting Research in 1986.

5. INSTRUMENTATION

A required tool in the detecting, monitoring and forecasting of the aircraft icing environment is instrumentation. In order to adequately deal with the problem of aircraft icing, a wide variety of icing environment instrumentation may be employed, including balloon-borne radiosonde and rawinsonde, airborne sensors to measure LWC, drop size, temperature and ice accretion rate, and remote sensing devices, such as profilers, satellite sounders and radar. In an operational setting, what can be discerned from icing instrumentation, controls and regulates the operation of onboard ice protection systems.

Until such time that accurate satellite data are available on a routine and timely basis, telemetry in the form of radiosonde and rawinsonde will continue to be the primary source for upper atmosphere data required for "real-time" forecast purposes. Radiosondes and rawinsondes are usually launched at 12-hour intervals from station locations rather sparsely and irregularily distributed throughout the world. Rawinsondes provide accurate pressure (altitude), temperature, humidity and wind information, but do not provide direct measurements of cloud LWC or drop-size distribution. As a consequence, rawinsonde parameters and models are used to infer (rather inexactly) the essential ice forecasting parameters- LWC and drop-size distribution. Depending upon the level of sophistication at a forecasting office, available radiosonde and rawinsonde soundings could be utilized manually in the preparation of an icing forecast or could be processed for entry into automated icing forecasting routines, such as the Navy's TESS aircraft icing probability program. Additionally, radiosonde and rawinsonde data are transmitted in near real-time to weather centrals, which assimilate the data into three-dimensional analysis fields for entry into numerical icing models.

Airborne sensors permit in-situ real-time detecting and monitoring of the icing environment. Information from such sensors can be automatically relayed to onboard computers to activate de-icing systems or commence flight pattern corrections to avoid icing conditions. Additionally, data from airborne icing sensors can be telemetered to weather stations on a continuing basis to supplement the data base required for "real-time" analysis and forecasting of the icing environment along the flight route.

The "usual" icing parameters measured by airborne instrumentation are generally thought of as outside air temperature (OAT), liquid water content, and droplet size and distribution. For maximum operational effectiveness, each of these icing parameters needs to be measured to a high degree of accuracy and repeatability. Unfortunately, many instruments in use today for obtaining airborne icing environment information are not sufficiently accurate, reliable or consistent, or, are unsuitable for a particular airframe because of weight, power, size and vibration restrictions. Instrumentation to measure OAT, LWC and drop-size distribution are next reviewed.

Sensors for OAT are designed to provide an indication of the free air temperature surrounding the airplane in flight. Most commonly, the measurement of OAT is with a platinum sensing element located in a cylindical probe housing affixed to the underside of a wing or the fuselage. The design of the probe housing is such as to minimize the effects of radiation and conduction, and the impaction of water onto the probe element. Current accuracy for platinum sensing element temperature probes is +- 0.5°C.

LWC data commonly come from icing rate meters, hot wire probes, and by calculation from the drop-size distribution obtained with laser spectrometer probes. Although there are probes with both manual and remote electrical readout, the focus here will be on the latter, since these are the appropriate ones for a pilotless HALE aircraft. Much of the following description of LWC sensors is from Olsen (1980) and FCMSSR (1986a).

Electrical ice accretion rate meters measure the time it takes to accumulate ice to some preset thickness. All automatically turn on electric heaters to de-ice the sensing probe after some ice thickness is obtained, and then begin the detectionin terrupted by the growing ice layer on a small rod. The popular Rosemount detects changes in the resonant frequency of the vibrating sensor element as ice accumulates on it. The United Controls probe employs beta radiation, which is attenuated as the ice accumulates. Ice accretion rate meters do not measure LWC directly; rather, time averaged or instantaneous values of LWC are deduced from calibrations which contain uncertainties. In addition to calibration uncertainties, there is also an inherent error at temperatures greater than -5°C where run-off can cause under-estimations of LWC. According to Olsen, a practical problem which besets many of the electrical ice accretion rate instruments is that they do not have enough de-icing heat for a cloud of high LWC.

Hot wire probes, such as the J-W (Johnson and Williams), Normalaire-Garrett or CSIRO, use the greatly increased heat transfer coefficient that results from droplets impinging upon the sensor surface. In general, the surface temperature (i.e., the electrical resistance is measured) is held constant and the heat flux, i.e., electrical power to the surface heater, is measured. These probes use an "always-dry" sensor as a reference. Hot wire probes are calibrated directly in LWC which can operate at all ambient temperatures but are subject to drift and need frequent attention to rezero in cloud-free air during flight. The error limits of hot wire probes are within +- 20%, with accuracies of .1 to .2 g/m^3 and precisions from .05 to .1 g/m^3.

Laser spectrometers, such as the Forward Scattering Spectrometer Probe (FSSP) manufactured by Particle Measuring Systems (PMS), Inc. of Boulder, CO., calculate the LWC from the same drop-size histogram data that it uses to calculate the volume median drop size. The principal source of error known to apply to PMS probes is the 10% uncertainty in particle size determination as specified by the manufacturer. Since LWC is proportional to the cube of droplet diameter, a +- 10% error in droplet diameter results in a possible 30% error in LWC computed from the droplet size distribution.

The cloud droplet size spectrum, which mainly affects the extent of the surface where ice will accumulate, is most commonly measured by laser spectrometers. The FSSP is a single particle, optical counter which obtains, as a function of time and aircraft position, the total droplet number density and the droplet size spectrum between the limits of 1 to 45 μm, with an accuracy and precision of 2 μm. Data from this type probe are automatically recorded and processed by onboard computers. Drawbacks in the use of an FSSP probe include its relatively heavy weight and susceptability to icing within the sampling aperture, which results in a loss of data.

PMS, Inc. also manufactures other optical array probes to measure hydrometeors larger than those sampled by the FSSP (ex. ice crystals and water drops). In particular, two-dimensional PMS probes can generally distinguish ice particles from water drops for sizes larger than 200-250 μm. Although ice crystal content is generally believed not to have any serious effects on potential ice accumulation, large water drops that could be sensed by these 2-D probes can present serious icing hazards (i.e., freezing rain or drizzle).

By and large, the use of remote sensing to detect and monitor atmospheric icing conditions is still in the experimental research and development stage. Remote sensing instruments not only offer measurements useful for estimating the icing potential, but also provide better temporal and spatial resolution than is presently available.

Ground-based radar has proven useful in snow recognition, but is not very sensitive to supercooled cloud droplets of 5-50 μm diameters. Although very detailed information on the vertical structure of icing conditions is not obtainable from radar, it is able to detect bright bands which are generally recognized as lines of demarcation between snow and ice crystals and liquid water, near the $0^{o}C$ isotherm. When used with supporting data on temperature, moisture, and cloud type and motion, the detection of bright bands allows the radar operator to make a reasonable inference of the icing potential. Experimental radars, utilizing dual polarization, have demonstrated the capability of providing hydrometeor type and drop-size information.

Profiler radiometer data (LWC and temperature) appear to have good potential as an indication of aircraft icing conditions, especially if used in combination with other remote detection devices. The radiometer detects the total amount of liquid in a column above the radiometer without distinguishing different liquid water contents or whether the water is supercooled. A method to infer and predict icing conditions from these profilers would have to incorporate other remote-sounding parameters, e.g., radar cloud altitudes and satellite-sensed cloud tops, and incorporate other meteorological data. Further details on remote detection of aircraft icing conditions using microwave radiometers can be found in Decker et al. (1986). Information from satellite sounders, such as the VAS (Visible Infared Spin-scan Radiometer Atmospheric Sounder), although not studied as yet in relation to the icing problem, will be very useful in the development of good icing detection and monitoring algorithms, due to its wide coverage and type of data (moisture).

Generally speaking, ice protection systems could be classified under the heading of icing instrumentation. However, since the development of such protection systems is in the realm of aerospace engineering, and is essentially optimized for each aircraft type and design, it will not be treated here.

6. SUMMARY AND RECOMMENDATIONS

This report has dealt with four main topics: 1) the characterization of the icing environment; 2) its distribution; 3) icing forecasting; and 4) icing instrumentation. The first topic is of prime importance to HALE designers and engineers, who require knowledge of the atmospheric icing environment during design and testing of the HALE prototype. The latter three topics are operationally of great importance; both icing forecasting and instrumentation present viable approaches for minimizing inflight icing hazards during HALE missions.

Ice accretion occurs when supercooled cloud droplets impact upon a passing aircraft whose surface temperature is below freezing. The nature of ice accretion is complex and depends on various physical factors. Key meteorological factors include the LWC, the drop-size distribution, the temperature and the horizontal extent of the supercooled clouds along the flight path. Aerodynamic factors are the collection efficiency of, and the compressive heating over, all parts of the aircraft as a function of design and speed.

Aircraft icing occurs in three basic forms - clear ice, rime ice and frost, the latter of little importance for inflight operations. Clear ice is normally associated with cumuliform clouds, and rime icing, with stratiform clouds. Ice accretion in the form of clear ice has substantially greater effects on aircraft performance than cases of rime ice with similar total accretion. The existence of ice crystals does not have any major influence on aircraft ice accretion.

The distribution of icing in the atmosphere is dependent upon the temperature and moisture structure which, in turn, varies with altitude, synoptic conditions, orography, location and season. Aircraft icing is rare below $-30^{o}C$, and is mostly confined to altitudes below 20000 ft AGL. Statistics indicate that icing is very probable if the dewpoint spread is less than $3^{o}C$. Frontal systems are preferred locations for aircraft icing; indeed, the most hazardous icing condition, freezing rain or drizzle, are usually associated with warm fronts. Orographic uplift and air mass modification processes often lead to enhanced icing conditions. Although icing may occur during any season, it is most prevalent in the winter half of the year in middle latitudes, and during summer in polar regions. Within the tropics, the highest frequency of icing will occur in organized convective systems during the rainy season(s).

Aircraft icing forecasts are generally imprecise and widely considered in need of improvement. A major barrier to improved icing forecasts is the inadequate operational data base. Within the military sector, forecasting techniques are primarily based on methods detailed in AWS/TR-80/001. The AFGWC issues icing forecast products which serve as primary guidance for military detachments. Although automated icing forecast programs are now becoming available to field offices, the final detail and accuracy of the operational icing forecast for any specific flight mission ultimately depends on the experience and ability of the local forecaster.

Icing instrumentation is required in the detection, monitoring and forecasting of the aircraft icing environment. Ground-based rawinsonde and radar provide essential data needed for entry into manual or automated forecasting aids. Airborne sensors, capable of monitoring ice accretion, provide vital information for automatic control and regulation of onboard ice protection systems, or for flight pattern corrections. Advanced remote sensing instrumentation, such as profilers and satellite sounders, appear to have good potential for monitoring aircraft icing conditions, but are still largely in the experimental research and development stage.

Although aircraft icing is a low probability event, the icing environment does present a major barrier to full utilization of the HALE aircraft with safety. To overcome this barrier, the HALE prototype must be adequately designed and extensively tested for potential operation in icing conditions. A full assessment of the sensitivity of the HALE prototype design to ice accretion must be made. With inflight testing of the HALE aircraft's response to icing conditions neither practical nor advisable, analytical simulation modelling and laboratory testing should be utilized to determine HALE aircraft aerodynamic performance and handling qualities in an icing environment, as well as to evaluate anti-icing or de-icing equipment.

In addition to ice protection systems factored into the design of the HALE aircraft from the outset, the installation of an onboard ice accumulation detector should be considered. The usefulness of such an icing instrument should more than offset the slight added weight and power requirements. Operationally, signals from an ice detector could be processed by the onboard computer in terms of integrated rate units, a pure number which can be correlated to the thickness of ice which will have accreted on aircraft primary systems (ex. engine inlets, induction systems, etc.). Aircraft de-icing systems would be automatically activated if a preset number of integrated rate units is reached, and correction flight procedures initiated if a critical number is exceeded. Laboratory testing and calibration of any such ice measuring instrument would be required.

Icing forecasting should be utilized during all stages of a HALE mission susceptible to possible icing conditions, i.e., take off, landing, and ascent and descent through the lower troposphere. The forecast office should be staffed by personnel experienced and capable in aircraft icing forecasting, and knowledgeable of local meteorological conditions within the HALE operating area which could significantly impact icing forecasts.

The forecast office will require detailed observational data and guidance information, as available via teletype and facsimile circuits, for preparation of forecasts. If the forecast office is located at the site where the HALE plane will take off and land, that station should be equipped with either radiosonde or rawinsonde capability and, if possible, also with remote sensing capabilities, such as a weather radar and a microwave scanning radiometer. Finally, the use of an automated, in-situ icing forecasting program, which will reduce manpower requirements and provide more timely forecasts, is highly recommended.

Obviously, the only sure way to eliminate the icing threat is to fly the HALE aircraft in a cloudless environment; unfortunately, though, this is not always possible. To reduce the threat of inflight icing hazards, certain "actions and options" may be of some assistance to flight controllers. First, in recognition of the distinct possibility of premature stalling due to the undesirable effects of ice, no effort should be spared to keep the HALE aircraft as free as possible from any accumulation of frost or ice during takeoff or landing. Second, the HALE aircraft should avoid icing conditions if uncertainty exists about the magnitude or scope of the icing environment. Third, if flight through icing conditions is unavoidable, the flight path should be controlled in such a way as to avoid sustained flight in the upper half of cumulus and stratus clouds where large water droplets and LWC are found. Additionally, in flight over rugged terrain, the HALE aircraft should be flown perpendicular to the mountain range so as to minimize its exposure to intensive icing in regions where strong upward currents are capable of supporting larger than average water droplets. Finally, the HALE aircraft should be continuously monitored while within the lower troposphere for indications of ice accumulation, either by onboard icing instrumentation or by assessment of critical performance factors. Ice protection systems aboard the HALE aircraft should be activated when icing conditions become prevalent. Onboard indications of ice accumulation beyond the anti-icing capabilities of the plane should be met with immediate action to depart the icing environment expeditiously. Excessive ice accumulation could be best shed at low-level flight at temperatures above freezing.

REFERENCES

Air Weather Service, 1979: Meteorological Techniques, AWS Pamphlet 105-56, U.S. Air Force (MAC), Scott AFB, Illinois.

Air Weather Service, 1980: Forecaster's Guide on Aircraft Icing, AWS/TR-80/001, U.S. Air Force, Scott AFB, Illinois.

Appleman, H.S., 1954: Design of a Cloud-Phase Chart, Bull. Amer. Met. Soc., Vol. 35, No. 5, pp 223-225.

Brun, E.A., 1957: Icing Problems and Recommended Solutions-General Survey, NATO, AGARDograph 16.

Coles, W.D., and R.S. Ruggeri, 1954: "Experimental Investigation of Sublimation of Ice at Subsonic and Supersonic Speeds and Its Relation to Heat Transfer," NACA Tech. Note 3104, NACA, March.

Decker, M.T., I.A. Popa Fotino and J.A. Schroeder, 1986: Remote Detection of Aircraft Icing Conditions Using Microwave Radiometers. NOAA Tech. Memorandum ERL WPL-137, 40pp.

Federal Aviation Administration, 1974: Federal Aviation Regulations, Part 25: Airworthiness Standards, Transport Category Airplanes. U.S. Govn. Printing Office, Wash., D.C., 158pp.

Federal Coordinator for Meteorological Services and Supporting Research, 1986a: National Aircraft Icing Technology Plan, FCM-P20-1986, U.S. Dept. of Commerce, NOAA, Washington, D.C., April.

Federal Coordinator for Meteorological Services and Supporting Research, 1986b: National Plan to Improve Aircraft Icing Forecasts, FCM-P21-1986, U.S. Dept. of Commerce, NOAA, Washington, D.C., July.

Heath, E.D., and L.M. Cantrell, 1972: Aircraft Icing Climatology for the Northern Hemisphere. Tech. Report 220, Air Weather Service (MAC), USAF, 72pp.

Jeck, R.K., 1985: "A New Characterization of the Icing Environment below 10000 ft AGL from 7000 miles of Measurements in Supercooled Clouds," NASA Conference Publication 2388, Sept.

Jones, A.R., and W. Lewis, 1949: "Recommended Values of Meteorological Factors to be Considered in the Design of Aircraft Ice-prevention Equipment," NACA Tech. Note 1855, 14pp.

Jones, R.F., 1956: "Analysis of Reports of Ice Accretion on Aircraft," MRP 1017, London, 23 November.

Jones, R.F., 1961: Ice Formation On Aircraft, WMO Tech. Note No. 39, WMO No. 109.TP.47, 35pp.

Katz, L.G., 1967: Climatological Probability of Aircraft Icing. Tech. Report 194, Air Weather Service (MAC), USAF, 24 p.

Mansur, M.V., 1984: Automated Aircraft Icing Forecast Techniques Project Report. AFGWC-PR-84-001, Air Weather Service, USAF, Offutt AFB, Nebraska.

Naval Oceanographic Office, 1988: Tactical Environmental Support System Baseline (TESS 2.0) Program Performance Specification Volume 1. TESS 88-04 V-1, Environmental Systems Office, Bay St. Louis, NSTL, MS.

Olsen, W., 1980: "Icing Instrumentation," Proceedings: Fourth Annual Workshop on Meteorological and Environmental Inputs to Aviation Systems. NASA CP-2139, March.

Perkins, P.J., Lewis W., and D.R. Mulholland, 1957: "Statistical Study of Aircraft Icing Probabilities at the 700- and 500-Millibar Levels Over Ocean Areas in the Northern Hemisphere," NACA Tech. Note 3984, May.

Sand, W.R., Cooper W.A., Politovich M.K., and D.L. Veal, 1984: Icing Conditions Encountered by a Research Aircraft, Journal Climat. Appl. Met., Vol. 23, No. 10, pp 1427-1440.

Tucker III, W.B., 1983: Current Procedures for Forecasting Aviation Icing. Special Report 83-24, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

USAFETAC, 1986: Climatic Atlas of Icing Potential over North America. USAFETAC/DS-86/001, USAF Envir. Tech. Appl. Center, Scott Air Force Base, Illinois, January.

EXPERT LIST - AIRCRAFT ICING

NAME	ADDRESS	PHONE NUMBER
Richard I. Adams	AWS-104, FAA 800 Independence Ave. SW Washington, DC 20591	(202)267-9586
Donald C. Caldwell	NAVAIRSYSCOM, AIR-53634F Washington, DC 20361	(202)692-6021
Ingrid A. Popa Fotino	ERL/WPL, NOAA 325 Broadway Boulder, CO 80303	(303)497-6557
John W. Hinkelman	ERL, NOAA 325 Broadway Boulder, CO 80303	(303)497-6819
Richard J. Jeck	NRL, Code 4113 Washington, D.C. 20375	(202)767-2437 AV 297-2437
Warren Johnson	NCAR, Rsch. Aviation Group P.O. Box 3000 Boulder, CO 80307	(303)497-1040
Charles O. Masters	FAA Technical Center ACT-340, Bldg. 201 Atlantic City Airport NJ, 08405	(609)641-8200 x1147
Jack Reinmann	NASA Lewis Research Center 21000 Brookpark Road Cleveland, OH 44136	(216)433-4000
Wayne R. Sand	NCAR, Atm. Tech. Div. P.O. Box 3000 Boulder, CO 80307	(303)497-8654
Ed R. Westwater	ERL/WPL, NOAA 325 Broadway Boulder, CO 80303	(303)497-6527

(This page intentionally left blank)

DISTRIBUTION

CHIEF OF NAVAL RESEARCH (2)
LIBRARY SERVICES, CODE 784
BALLSTON TOWER #1
800 QUINCY ST.
ARLINGTON, VA 22217-5000

OFFICE OF NAVAL TECHNOLOGY
ONR, CODE 22
800 N. QUINCY ST.
ARLINGTON, VA 22217-5000

COMNAVOCEANCOM
ATTN: CODE N5
JCSSC, MS 39529-5000

COMMANDER
NAVAIRSYSCOM
ATTN: LIBRARY (AIR-723D)
WASHINGTON, DC 20361-0001

COMMANDER
NAVAIRSYSCOM, CODE 526W
WASHINGTON, DC 20361-0001

DIRECTOR (12)
DEFENSE TECH. INFORMATION
CENTER, CAMERON STATION
ALEXANDRIA, VA 22314

DIRECTOR, ENV. & LIFE SCI.
OFFICE OF UNDERSECRETARY OF
DEFENSE FOR RSCH & ENG E&LS
RM. 3D129, THE PENTAGON
WASHINGTON, DC 20505

RICHARD I. ADAMS
AWS-104, FAA
800 INDEPENDENCE AVE. SW
WASHINGTON, DC 20591

DONALD C. CALDWELL
NAVAIRSYSCOM, AIR-53634F
WASHINGTON, DC 20361

INGRID A. POPA FOTINO
ERL/WPL, NOAA
325 BROADWAY
BOULDER, CO 80303

JOHN W. HINKELMAN
ERL, NOAA
325 BROADWAY
BOULDER, CO 80303

RICHARD J. JECK
NRL, CODE 4113
WASHINGTON, DC 20375

WARREN JOHNSON
NCAR, RSCH. AVIATION GROUP
P.O. BOX 3000
BOULDER, CO 80307

CHARLES O. MASTERS
FAA TECHNICAL CENTER
ACT-340, BLDG. 201
ATLANTIC CITY AIRPORT, NJ
08405

JACK REINMANN
NASA LEWIS RESEARCH CENTER
21000 BROOKPARK ROAD
CLEVELAND, OH 44136

WAYNE R. SAND
NCAR, ATM. TECH. DIV.
P.O. BOX 3000
BOULDER, CO 80307

ED R. WESTWATER
ERL/WPL, NOAA
325 BROADWAY
BOULDER, CO 80303

NAVAL AIR DEVELOPMENT CENTER
ATTN: JOE LINDINGER, CODE 3031
WARMINSTER, PA 18974-5000

COMMANDING OFFICER
NAVAL AIR PROPULSION CENTER
P.O. BOX 7176
TRENTON, NJ 08628-0176

COMMANDER
NAVAL AIR TEST CENTER
PATUXENT RIVER, MD 20670-5304

COMMANDING OFFICER
NAVAL AIR ENGINEERING CENTER
LAKEHURST, NJ 08733-5000