NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1855

RECOMMENDED VALUES OF METEOROLOGICAL FACTORS TO BE CONSIDERED IN THE DESIGN OF AIRCRAFT ICE-PREVENTION EQUIPMENT

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SUMMARY

Meteorological conditions conducive to aircraft icing are arranged in four classifications: three are associated with cloud structure and the fourth with freezing rain. The range of possible meteorological factors for each classification is discussed and specific values recommended for consideration in the design of ice-prevention equipment for aircraft are selected and tabulated. The values selected are based upon a study of the available observational data and theoretical considerations where observations are lacking. Recommendations for future research in the field are presented.

INTRODUCTION

Design procedures have recently been established for the computation of the heat requirements for the protection of wings and windshields of aircraft operating in icing conditions (references 1 and 2); however, their use is dependent upon a knowledge of such factors as the amount of liquid water in the icing cloud and the average diameter of the cloud drops. Progress in the application of these procedures has been handicapped by the lack of sufficient data on the meteorological factors. To overcome this difficulty, considerable research in the laboratory and in flight has

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been undertaken independently by various civil Government agencies, the armed services, universities, and private concerns. This research has progressed to a point where a tentative listing of icing conditions[2] for design purposes can be attempted.

The preparation of such a list was undertaken with the view in mind of providing as complete a coverage as possible, within the probable flight range. It is not intended that each icing condition tabulated should be specified as a design requirement for all components of the airplane, but rather that each condition be considered as a possible meteorological situation to be encountered and, therefore, worthy of some attention. For example, the designer, having a certain component of the airplane in mind, should review the listing to determine which icing conditions would probably affect that component and, therefore, should be included in the design calculation. For his part, the operator should consider the listing as indicative of the wide variation of conditions through which his aircraft might be called upon to operate.

This report is based upon a paper which was originally prepared for the NACA Subcommittee on Icing Problems, Committee on Operating Problems, for discussion at a meeting held at the Lewis Flight Propulsion Laboratory, Cleveland, Ohio, on October 18, 1948. The purpose of the paper was to propose values of design icing conditions based on currently available data, and to indicate required further research. This report incorporates suggestions advanced by members of the Subcommittee during the meeting. The authors are also indebted to Mr. J. K. Hardy of the Royal Aircraft Establishment, Farnborough, England, for helpful comments which aided materially in the preparation of the report.

GENERAL CLASSES OF FLIGHT ICING CONDITIONS

Experience in icing research has shown that the selection of meteorological conditions for the design of aircraft ice-prevention

[2]The term "icing condition" as used herein denotes a state of the atmosphere defined by a set of values of temperature, liquid-water content, drop diameter, and pressure altitude in which the temperature is below freezing and the liquid-water content is greater than zero.

equipment is influenced somewhat by the particular component to be protected. For example, air-induction systems, in general, and turbine engine intakes, in particular, are most critically affected by an encounter with an icing condition of high liquid-water content, even though the duration of the encounter is very short. In contrast, propellers, wings, empennages, and windshields, if provided with adequate protection for continuous icing conditions, can usually tolerate brief and intermittent encounters with conditions of greater severity. In fact, the assumption of continuous flight at icing conditions known to be associated only with discontinuous clouds for these latter components would be unduly conservative and unjustified.

Flight icing conditions have been divided into four general classes for the purposes of this study. The first three classes are confined to cloud forms and are associated with the duration of an encounter with the condition. Since the duration of flight in an icing condition is dependent upon the flight speed, the more basic concept of horizontal extent of the condition will be utilized herein. This is readily convertible to duration at any selected flight speed. The fourth class of icing condition is the special case of freezing rain. A brief description of the characteristics of each class is given below, together with an example of the airplane component or feature to which the class applies in design considerations. The selection of values of the meteorological variables to be assigned to each class will be discussed in a later section.

Class I

Designation: Instantaneous.

Horizontal extent: 1/2 mile.[3]

Duration at 180 miles per hour: 10 seconds.

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[3]This should not be taken to imply that these conditions are necessarily limited to areas 1/2 mile in extent. This value was chosen because it is believed that the most severe conditions likely to be encountered are approximately uniform over a distance of about 1/2 mile. The distance across the upper portion of a single cumulus tower is ordinarily from 1 to 3 miles and rarely exceeds 5 miles. Average values of liquid-water content up to 80 percent of the 1/2-mile maximum may occasionally be expected for distances up to 3 miles.

Characteristic: Very high liquid-water content.

Applicable to: Any part of the airplane, such as guide vanes in interior ducting, where the sudden collection of a large mass of supercooled water would be critical.

Example: Induction systems, particularly turbine-engine inlets.

Class II

Designation: Intermittent.

Horizontal extent: 3 miles.

Duration at 180 miles per hour: 1 minute.

Characteristic: High liquid-water content.

Applicable to: Any critical component of the airplane where ice accretions, even though slight and of short duration, could not be tolerated.

Examples: Induction systems, windshields in any case where practically continuous visibility was required.

Class III

Designation: Continuous.

Horizontal extent and duration: Continuous.

Characteristic: Moderate to low liquid-water content.

Applicable to: All components of the airplane, that is, every part of the airplane should be examined with the question in mind, "Will this part be affected seriously by accretions during continuous flight in icing conditions?"

Example: Wings and tail surfaces.

Class IV

Designation: Freezing rain.

Horizontal extent: 100 miles.

Duration at 180 miles per hour: About 1/2 hour.

Characteristic: Very large drops at near-freezing temperatures and low values of liquid-water content.

Applicable to: Components of the airplane for which no protection would be supplied after considering Classes I, II, and III.

Example: Fuselage static-pressure airspeed vents probably would not require protection for Classes I, II, and III, but might be subject to icing in freezing rain.

SELECTION OF METEOROLOGICAL CONDITIONS FOR THE FOUR GENERAL CLASSES

One of the factors of major importance in the selection of design icing conditions, and the operation of aircraft in these conditions, is the probability of encountering any specified meteorological situation. At the time of the preparation of this report the statistical analysis of available meteorological data had not proceeded to a point where estimates of the likelihood of meeting a specified icing condition could be stated. Omission of the probability factor from this report was a necessity, therefore, and is not an indication that the subject is of secondary importance.

In addition to the four general icing classes already defined, the icing conditions were further classified into two groups; namely, most probable maximum, and normal or typical. The most probable maximum does not represent the maximum that nature could produce, but rather the maximum that would probably be encountered in all-weather aircraft operations. The normal or typical designation refers to the average or normal conditions to be anticipated in all-weather operations in the United States. To represent the most probable maximum conditions of a class, the letter M was used, for example, class I-M, II-M, etc. Similarly, the letter N was used for normal conditions.

Specific values proposed for all classes of icing conditions are presented in table I. The quantities presented for class I include maximum values of liquid-water content to be expected at various temperatures and the most probable corresponding values of drop diameter. For classes II and III, values of maximum liquid-water content are given for a range of values of both temperature and drop diameter. The approximate altitude ranges in which the specified conditions are most likely to occur are also given. The factors considered in estimating the altitude ranges were season, temperature, cloud type, and liquid-water content. Due to the absence of reliable data on drop-size distribution, uniform drop sizes only are considered in the proposed specification. Values of liquid-water content and drop diameter for temperatures of -22° and -40° F are included in the table for completeness but should be regarded as uncertain due to the lack of observations at very low temperatures.

In the selection of specific values to be included in table I, consideration has been given to (1) four recent NACA Technical Notes (references 3, 4, 5, and 6); (2) data which were obtained during the winter of 1947-48 by the Ames Laboratory and have not yet been published; (3) the monthly reports of the Air Materiel Command Aeronautical Ice Research Laboratory at Minneapolis; (4) the various reports published by the Mount Washington Observatory, New Hampshire; (5) data obtained by the Douglas Aircraft Company, United Air Lines, and American Airlines during flight tests with the DC-6 airplane in icing conditions; and (6) other publications or papers, such as references 7 and 8.

Class I-M.- Instantaneous, Maximum

In the listing of conditions for this class, an attempt was made to estimate the greatest values of liquid-water content that might be encountered, at freezing temperature and below, anywhere in the atmosphere, regardless of the season. The largest values of liquid-water content would be expected to occur in the tops of tall cumulus clouds, with the maximum water concentration being expected during the summer or in the tropics. Although the probability of flying through the top of a summer or tropical cumulus at temperatures below freezing is somewhat less than for a winter cumulus, the seriousness associated with the possible loss of function of the aircraft power plant suggests that design considerations be based upon the higher liquid-water contents of summer cumulus clouds.

Since no measurements of subcooled liquid-water content have been made in such clouds, the values proposed were calculated. As a basis for the calculation, the highest possible moisture charge was estimated from a consideration of the maximum sea surface temperature, given as 88° F in reference 9. Since values of dew point observed over the tropical seas are generally slightly lower than the water temperatures, a dew point of 85° F at 1000 millibars was chosen as representing the greatest moisture content for cumulus cloud formation. A condensation pressure of 950 millibars (948 ft pressure altitude) was chosen to represent the lowest cloud base likely to occur with tropical cumulus clouds. The following values of liquid-water content were calculated by the method given in reference 5, for the temperatures and the pressure altitudes indicated, using initial conditions listed previously and assuming adiabatic lifting with no mixing or precipitation:

Temperature (°F)	Pressure altitude, (ft)	Liquid-water content, (g/m^3)
32	23,000	8.9
14	29,000	8.7
−4	34,000	8.2
−22	38,000	7.5

Calculation of the instantaneous maximum water content was also made using the same initial conditions and considering the effect of entrainment and mixing of environmental air. It was assumed in this case that the entrainment rate was sufficient to double the cloud mass for each 400 millibars of ascent and that the relative humidity of the environment was 70 percent. These assumptions are based on a consideration of references 10 and 11. The results of the calculations are as follows:

Temperature (°F)	Pressure altitude, (ft)	Liquid-water content, (g/m^3)
32	20,000	5.5
14	25,000	5.2
−4	30,000	4.8
−22	34,000	4.2

At present, there is no basis for a satisfactory evaluation of the importance of the formation of liquid precipitation in depleting the liquid-water content of cumulus clouds. The formation of ice crystals, on the other hand, is known to produce an immediate and marked reduction in the liquid-water content. (See reference 5.) Cumulus clouds without ice crystals have been observed frequently at a temperature of 0° F and occasionally at temperatures as low as −10° F. Limited data are available for cumulus clouds below −10° F, but it is believed that the frequency of occurrence of ice crystals increases rapidly at temperatures below this value. A considerable reduction in maximum liquid-water content would therefore be expected at temperatures below −10° F. Consideration of these factors, and the fact that the values of dew point and condensation pressure chosen for the calculations represent extreme conditions, led to the conclusion that the values of liquid-water content chosen for design considerations should be somewhat lower than those calculated above. In the case of the lowest air temperature considered (−40° F) the probability of the occurrence of snow is so great that the liquid-water content cannot even be approximated by calculation and, therefore, a value has been estimated.

No measurements of drop size are available for summer or tropical cumulus clouds. Measurements in winter and spring (references 5 and 6, and data on file from Ames Aeronautical Laboratory icing tests in the winter of 1947–48) show that, of a total of 29 observations with liquid-water content more than 1.0 gram per cubic meter, the corresponding value of mean effective diameter was between 8 and 25 microns in all cases, with 24 cases between 15 and 25 microns. In the absence of more complete information, a drop diameter of 25 microns from 32° to −4° F, decreasing linearly with temperature to 15 microns at −40° F, is proposed.

Based on the foregoing discussion, suggested values for class I-M of liquid-water content, mean effective drop diameter, and most probable altitude of encounter are presented for the temperature range from 32° to −40° F as items 1 to 5, inclusive, in table I.

Class I-N.– Instantaneous, Normal

Since operations in the subfreezing portions of summer cumulus clouds are not regarded as normal, the values suggested for the instantaneous normal class are based on frequency distributions of data from observations in winter cumulus clouds. These conditions are listed as items 6 to 10 of table I.

Class II-M.- Intermittent, Maximum

The intermittent class of icing conditions is considered to be representative of clouds in which water concentrations about one-half as severe as those assigned to the instantaneous class would be encountered for durations of about five or six times the instantaneous class durations. Such conditions can be expected near the tops of cumulus clouds in both summer and winter; however, they are much more likely to be encountered at temperatures below freezing during winter. Because of this fact, and because escape from cumulus icing in summer can often be made by a descent to warmer altitudes, the winter cumulus conditions have been selected as the basis for the suggested values of the intermittent class icing conditions.

The selection of values for class II is based partly on the discussion in reference 5. The values proposed therein are the result of an estimate of the maximum liquid-water content likely to be encountered during winter and the lowest temperature and largest drop size likely to occur with the chosen value of water content. In the selection of the values presented in table I, it was considered desirable to include several combinations of temperature and drop diameter and to specify for each the probable maximum liquid-water content. The values selected were determined from an examination of scatter diagrams similar to figures 5 and 8 of reference 5, but incorporating all available data, including the 1947-48 Ames Laboratory observations. These conditions are listed as items 11 to 25, inclusive, in table I.

Class II-N.- Intermittent, Normal

Items 26 to 30 of table I are suggested to represent intermittent normal icing conditions, based on flight experience as discussed in references 5 and 6.

Class III-M.- Continuous, Maximum

Conditions in this class, which occur in layer-type clouds, have been discussed in references 5 and 6. Sufficient data are now available to estimate with reasonable accuracy the variation of maximum liquid-water content in layer clouds with both temperature and drop size. Suggested values are presented as items 31 to 45, inclusive, table I.

Class III–N.– Continuous, Normal

Items 46 to 49, inclusive, table I, which are based on frequency distributions of data from layer clouds (references 5 and 6), give the conditions likely to be experienced in a typical encounter with icing conditions of the continuous type.

Class IV–M.– Freezing Rain

Observational data are not available for this class, since, in the only case in which data have been taken, the water content of the rain was too low to measure in the presence of the clouds through which it was falling. For this reason, the values for the proposed condition (item 50, table I) were calculated. They were based on an assumed rate of rainfall of 0.10 inch per hour with drops 1 millimeter in diameter. The use of 0.10 inch per hour is considered appropriate because large-scale continuous precipitation in winter is usually of light intensity.

SUGGESTIONS FOR FUTURE RESEARCH

The preparation of table I required a fairly comprehensive review of available information on the subject of meteorological conditions conducive to aircraft icing and, consequently, revealed which factors require further investigation. In general, the required additional research falls into two categories which can be termed "formative" and "statistical."

The formative category defines the type of icing research which has contributed most of the available data. It consists of the establishment of a framework which will define the problem and provide initial answers. Such research requires the selection of the various factors to be measured or observed, the development of measurement methods, the establishment of ranges to be investigated, and a review of the results to define which factors are important and which are secondary, and to present initial maximum and average values for each factor. Obviously, the conduct of this type of research requires personnel trained in meteorology, or at least well acquainted with the subject, and familiar with meteorological instruments, techniques, and data analysis.

The statistical type of research is characterized by the procurement of a large volume of data, and may be performed by relatively untrained personnel, or even by automatic instruments. Obviously, it cannot be undertaken until the formative research has pointed the way as regards quantities to be investigated, their relative importance, the range to be anticipated, and the degree of accuracy desired.

In the following lists of suggested future formative and statistical research, an attempt has been made to arrange the items in order of importance, the most important items being listed first.

Suggested Continuation of Formative Research on Conditions Conducive to Icing

1. Extend flight research as required to establish whether the values of table I, which are based on winter flights and confined, for the most part, to northern United States, are representative of conditions everywhere. Conditions for which it would be of immediate interest to know the meteorological quantities are the low-temperature continuous icing associated with operations in Alaska and the Arctic, the conditions existing in the top of large summer cumulus clouds, and the conditions during summer in all types of clouds at altitudes above the freezing level. It is also desirable to eventually extend the scope of observations to include the entire world, since there may be important regional differences in cloud characteristics such as the difference in prevailing drop size between central and eastern United States and the Pacific coast area which is indicated in the data taken by the Ames Laboratory.

2. Obtain flight data on instantaneous values of maximum liquid-water content, drop size, temperature, and altitude.

3. Obtain flight data to establish drop-size distribution in clouds.

4. Obtain necessary data in flight through icing clouds for confirmation or modification of the method of assuming adiabatic lifting and no mixing for the calculation of liquid-water content at any level in a cloud.

Suggested Statistical Research on Conditions Conducive to Icing

1. Analyze all available meteorological icing data obtained in flight by statistical procedures to establish, at least

tentatively, the probability of encountering a specified icing condition.

2. Obtain measurements of liquid-water content, drop diameter (mean effective, at least, and maximum, if possible), temperatures, and altitude during regular military and commercial operations whenever icing conditions are encountered. Time and geographical location should also be recorded in order that the data may be analyzed with reference to the synoptic weather situation.

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TABLE I.– RECOMMENDED VALUES OF METEOROLOGICAL FACTORS FOR CONSIDERATION IN THE DESIGN OF AIRCRAFT ICE-PREVENTION EQUIPMENT

Class	Item	Air temp. (°F)	Liquid water content (g/m³)	Drop diameter (microns)	Pressure altitude (ft)	Remarks
I – M Instantaneous, Maximum	1	32	5.0	25	18,000 to 20,000	Horizontal extent: 1/2 mile. Duration at 180 mph: 10 seconds. Characteristic: Very high liquid water content. Applicable to: Any part of the airplane, such as guide vanes in inlet ducts, where a sudden large mass of supercooled water would be critical, even though of short duration. Example: Induction systems, particularly turbine-engine inlets.
	2	14	4.0	25	22,000 to 25,000	
	3	-4	3.0	25	25,000 to 30,000	
	4	-22	2.0	20	20,000 to 30,000	
	5	-40	.5	15	20,000 to 30,000	
I – N Instantaneous, Normal	6	32	1.0	20	10,000 to 20,000	
	7	14	1.0	20	10,000 to 25,000	
	8	-4	.6	18	12,000 to 30,000	
	9	-22	.2	15	15,000 to 30,000	
	10	-40	<.1	13	15,000 to 30,000	
II – M Intermittent, Maximum	11	32	2.5	20	10,000 to 15,000	Horizontal extent: 3 miles. Duration at 180 mph: 1 minute. Characteristic: High liquid water content. Applicable to: Any critical component of the airplane where ice accretions, even though slight and of short duration could not be tolerated. Example: Induction systems, windshields when continuous visibility is required.
	12	14	2.2		10,000 to 20,000	
	13	-4	1.7		12,000 to 30,000	
	14	-22	1.0		15,000 to 30,000	
	15	-40	.2		15,000 to 30,000	
	16	32	1.3	30	8,000 to 15,000	
	17	14	1.0		8,000 to 20,000	
	18	-4	.8		10,000 to 30,000	
	19	-22	.5		15,000 to 30,000	
	20	-40	.1		15,000 to 30,000	
	21	32	.4	50	8,000 to 15,000	
	22	14	.3		8,000 to 20,000	
	23	-4	.2		10,000 to 30,000	
	24	-22	.1		15,000 to 30,000	
	25	-40	<.1		15,000 to 30,000	
II – N Intermittent, Normal	26	32	.8	20	8,000 to 12,000	
	27	14	.6	20	8,000 to 15,000	
	28	-4	.4	18	12,000 to 20,000	
	29	-22	.1	15	15,000 to 25,000	
	30	-40	<.1	13	15,000 to 25,000	
III – M Continuous, Maximum	31	32	.8	15	3,000 to 20,000	Horizontal extent and duration: Continuous. Characteristic: Moderate to low liquid water content for an indefinite period of time. Applicable to: All components of the airplane; that is, every part of the airplane should be examined with the question in mind, "Will this part be affected seriously by accretions during continuous flight in icing conditions?" Example: Wings and tail surfaces.
	32	14	.6			
	33	-4	.3			
	34	-22	.2			
	35	-40	.05			
	36	32	.5	25		
	37	14	.3			
	38	-4	.15			
	39	-22	.10			
	40	-40	.03			
	41	32	.15	40		
	42	14	.10			
	43	-4	.06			
	44	-22	.04			
	45	-40	.01			
III – N Continuous, Normal	46	32	.3	15		
	47	14	.2			
	48	-4	.1			
	49	-22	<.1			
IV – M Freezing Rain	50	25 to 32	.15	1000	0 to 5,000	Horizontal extent: 100 miles. Duration at 180 mph: 30 minutes. Characteristic: Very large drops at near-freezing temperatures and low values of liquid water content. Applicable to: Components of the airplane for which no protection would be supplied after considering classes I, II, and III. Example: Fuselage static pressure airspeed vents.

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