An Integrated Approach to the Problem of Aircraft Icing

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This paper is directed toward the need for a definition of the intensity of icing conditions in terms of meteorological parameters which the forecaster can predict, the manufacturer can design to, and the pilot can identify. Contradictions in present regulatory and meteorological definitions of icing conditions are discussed and a method of resolving them is suggested. A discussion of the FAR 25 icing envelopes as engineering rather than meteorological standards is presented. The question of whether a mean effective drop diameter is representative of the drop size spectrum within an icing cloud is considered. Definitions of icing intensity are suggested and a method of flight test data acquisition, allowing determination of the intensity of icing conditions encountered, is described.

I. Introduction

THE definitions of the intensity of icing conditions currently in use by the National Weather Service, Federal Aviation Administration, and United States military services are presented in Table 1. These definitions were adopted by the Subcommittee for Aviation Meteorological Services in 1968.

It should be noted that these definitions make no reference whatsoever to the meteorological conditions which cause icing to exist. Further, it should be noted that these definitions relate the intensity of icing conditions only to the ability of the aircraft equipment to cope with the problem and not to the rate at which ice builds on the aircraft. The following two points must be kept firmly in mind if any meaningful use is to be made of Table 1:

1) It is just what it claims to be, a *reporting* table. A given combination of meteorological parameters could cause icing conditions which would be reported in accordance with this table as anywhere from light to severe, primarily depending upon the type of aircraft which is encountering the conditions. To make a forecast based on the definitions of this table is to make a forecast for only one type of aircraft, or, at most, for a few similar types, and it presumes familiarity of the forecaster with the type of aircraft involved. A forecast of this sort would be, at best, useless to pilots of aircraft other than the type which the forecaster had in mind and, at worst, dangerous.

2) As a reporting table, it is useful only if the pilot reviewing the report is familiar with the ice-handling capabilities of the type of aircraft which made the report. This also leaves aside the implicit presumption that the pilot making the report is familiar with the definitions in the table.

Thus, the present situation can only be described as one of utter chaos. Pilot reports of icing conditions, even supposing that they conform to the definitions of Table 1, are generally meaningless to forecasters who are not pilots, and are unambiguous only to pilots familiar with the type of aircraft making the report and able to relate the reported intensity to their own type of aircraft. It is impossible to make a forecast based on these definitions that would be generally meaningful. It is also impossible for an aircraft manufacturer to state the severity of icing conditions with which one of his products is equipped to cope, since the definition changes from airplane to airplane. Thus, the need for a definition of intensity of icing conditions in terms of parameters which the forecaster can forecast, the manufacturer can design to, and the pilot can understand and identify, is apparent.

II. Analysis of the Current Icing Situation

As the development of gyroscopic flight instruments opened up the possibility of sustained flight in clouds, it became obvious to all concerned that some approach to the problem of aircraft icing had to be developed. Flight investigations of the meteorological parameters involved in aircraft icing were begun in 1944 by the U.S. Army and the National Advisory Committee for Aeronautics (NACA). The results of these investigations were developed by Jones and Lewis into a number of icing envelopes.[1] The two envelopes derived from these data that are relevant to this paper are those defining continuous maximum and intermittent maximum atmospheric icing conditions. These are presented in Figs. 1 and 2. These envelopes were adopted as standards for certification of transport category aircraft, i.e., all aircraft weighing more than 12,500 lb and most jet aircraft, regardless of weight. They are part of the Federal Aviation Regulations (FAR) governing design and construction of such aircraft.[2]

It must be understood that these envelopes do not represent physical relationships between the variables. Rather, they

Table 1 Airframe icing reporting table

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

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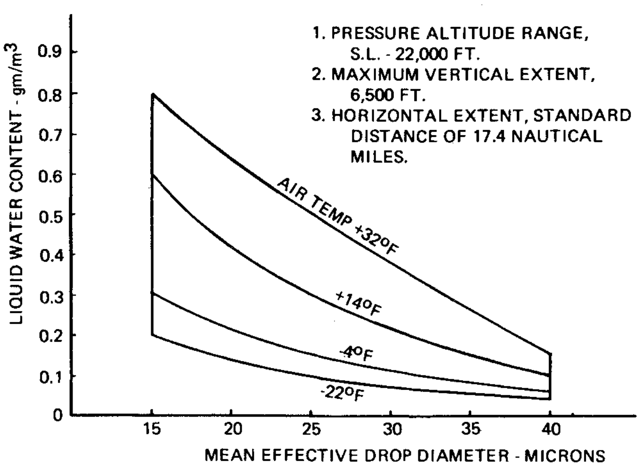


Fig. 1 Transport category continuous maximum icing envelope.

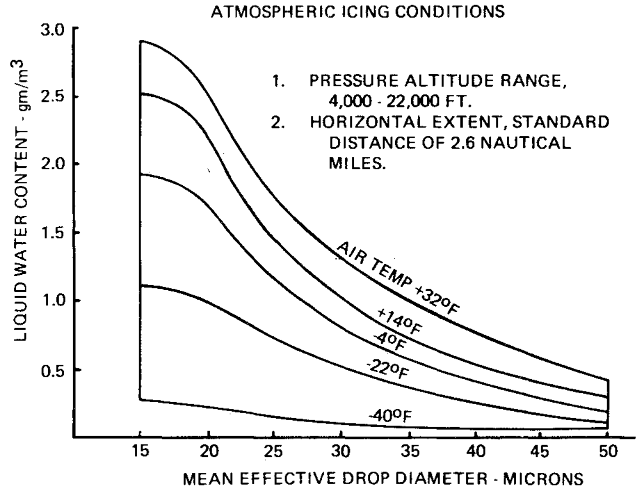


Fig. 2 Transport category intermittent maximum icing envelope.

represent combinations of parameters considered to have a sufficient probability of occurrence to make it appropriate that transport category aircraft be designed to cope with them. The manufacturer must consider every combination of liquid water content, drop diameter, and temperature represented by these envelopes, determine which points are critical to his particular aircraft, and thus provide ice protection systems capable of coping with any condition within the envelopes.

A detailed discussion of how well these envelopes have fulfilled their purpose was presented by Lewis in 1969.[3] It is sufficient here to note that they have withstood the test of time and use, and that aircraft designed to these standards have achieved a safety record which has resulted in their continuance as part of the transport category airworthiness standards.

At this point, however, a paradox of definition must be faced. Certification of aircraft to the standards of these envelopes is equivalent to a statement that such aircraft are equipped to cope with any icing conditions which they may encounter in service. The severity of the icing will be within the definition of the envelopes most of the time, and any conditions in excess of these definitions will be little enough in excess and of sufficiently short duration to be tolerable. These aircraft, then, effectively ignore forecasts of the intensity of icing conditions. The operating rules contained in FAR Parts 91 and 135, in fact, permit aircraft having ice protection provisions which meet these transport category standards to fly into known or forecast severe icing conditions. This contradicts the definition in the reporting table, since severe icing conditions are, by definition, impenetrable. The equipment fails to reduce or control the hazard, according to the table, and immediate diversion is necessary.

Furthermore, transport category standards are held by Gollings and Newton to be often inappropriate to non-transport aircraft for the following reasons:[4]

1) Such aircraft are frequently flown by nonprofessional pilots of limited experience, and it is not considered either necessary or desirable that they be so equipped that the operating rules to which they are subject permit them to be flown into severe icing conditions, leaving aside for the moment the previously discussed problem of definition.

2) While many transport aircraft have abundent power and weight-carrying capacity for support of the "brute force" ice protection systems which are required to cope with intermittent maximum conditions, such systems can significantly impair the electrical and useful load-carrying capability of smaller aircraft.

3) Noting from the figures that intermittent maximum and continuous maximum conditions are defined to exist up to altitudes of 22,000 ft, it is seen that many light aircraft cannot even reach some of the conditions for which the manufacturer would have to design the ice protection system.

4) The manufacturer who is faced with transport category ice protection standards must choose between a costly development program resulting in an airplane licensed to fly into conditions in which he may not wish to have it flown, or a regulatory restriction prohibiting flight into icing conditions altogether.

Prior to the adoption of the definitions of Table 1, there existed definitions of the intensity of icing conditions for reporting purposes in terms of rates of accretion on a small probe. These definitions were abandoned because airplanes did not necessarily carry small probes for the purpose of ice collection, and the term "small probe" was, in any case, undefined. Redefinition in terms of rate of accretion on airframe components was rejected because of the wide variation of accretion on objects of different sizes and shapes moving at different speeds through the same icing conditions. It was felt, nonetheless, that definitions useful to pilots should be developed and the definitions of Table 1 were arrived at. Given the situation as it now exists, it is the feeling of the author that a better solution probably would have been to define a small probe and require that aircraft flown into icing conditions carry one. However, the situation must be accepted as it stands and used as a starting point.

III. Suggested New Approach to Icing

There exists a definition of icing conditions which can be readily expanded into rates of accretion on an object of known geometric properites. This definition is not new, being first set forth in a Weather Bureau document in 1945. The original document is no longer available; therefore, it is only mentioned here and not listed as a reference. It is, in any event, not necessary as the definitions and their expansion into accretion rates are given by Lewis in a later NACA document.[5] The definitions relate the intensity of icing to the rate of collection of ice, at 200 mph, on a circular cylinder 3 in. in diameter, as follows:

Trace – 0.0-1.0 g/cm^2-h
Light – 1.0-6.0 g/cm^2-h
Moderate – 6.0-12.0 g/cm^2-h
Severe† – 12.0 or more g/cm^2-h

†The word "severe" replaces the word "heavy" which was used in the original reference. This substitution was made by the Subcommittee for Aviation Meteorological Services in 1968. "Severe" will be substituted wherever "heavy" appears in older documents used as references throughout this paper.

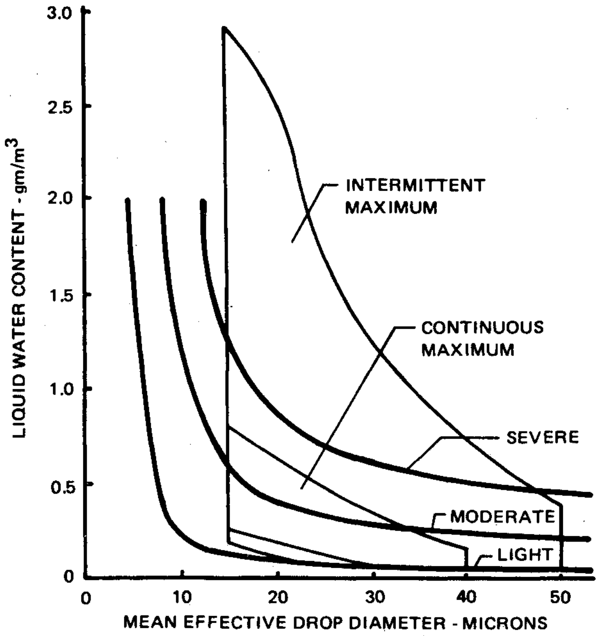


Fig. 3 Lewis definitions of icing intensity.

Lewis expanded these definitions to yield a plot of icing intensity in terms of liquid water content and uniform drop size at 10,000 ft pressure altitude and 15°F air temperature. This plot is shown in Fig. 3, in which the previously presented transport category envelopes are also shown for comparison. It is seen that the onset of light icing, as defined by the heavy curves of Fig. 3, is nearly conicident with the bottom of the transport category envelopes, that moderate icing begins near the top of the continuous maximum envelope, and that the onset of severe icing conditions is well into the intermittent maximum envelope. There is, thus, a reasonable correspondence between the Lewis definitions and the transport category envelopes. However, these definitions have two important characteristics which are entirely lacking in the transport category envelopes:

1) The Lewis envelopes are defined, such that the rate of accretion on a cylinder for the given altitude, airspeed, and temperature is independent of the drop size. Thus, the rate of accretion on a cylinder 3 in. in diameter which is exposed, under the given flight conditions, to meteorological conditions defining the boundary between moderate and severe icing is 12 g/cm^2h, whether the drop diameter is 15 μ, 50 μ, or any other value on the curve. As is shown in Sec. IV, this property lends itself to a method of flight test data acquisition much simpler and far less expensive than the methods required for transport category testing, aand which is also useful as a backup for the more conventional methods.

2) There exists a method of forecasting intensity of icing conditions based on the Lewis envelopes. There exists no such method for forecasting transport category conditions which, as previously stated, are statements of probability intended solely for engineering purposes and which ignore weather forecasts.

The forecasting method was developed by the U.S. Air Force.[6] The reference should, of course, be consulted for detailed instructions as to its use. However, a brief description of the method follows:

1) The mean effective drop diameter‡ is assumed to be 14 μ in layer clouds and 17μ in cumulus clouds. These values were recommended by Lewis[5] based on NACA flight investigations.

2) Using these drop diameters, liquid water contents corresponding to the onset of light, moderate, and severe icing conditions are obtained from the Lewis envelopes (Fig. 3), for layer and cumulus clouds.

3) The occurrence of these liquid water contents is forecast using a cloud model developed by Best.[7] This model considers adiabatic lifting with a rate of entrainment of air from an environment having 70% relative humidity, such that the mass of air in the cloud is doubled in 400 mbars of ascent. The full value of liquid water content produced with this model is used with convective clouds, and one-half of this value is used with layer clouds. The reduction of liquid water content in layer clouds is adopted by Best in accordance with the data and recommendations published as a result of the NACA flight investigations.

4) An overlay is used with the sounding to be evaluated plotted on a Skew T-Log P or other suitable thermodynamic diagram to perform the preceding steps. The cumulus or layer cloud liquid water content values are used depending upon whether the sounding is unstable or stable, respectively, in the level being considered.

The Air Force method instructs the forecaster to forecast rime icing in layer clouds and clear icing in cumulus. While it may be true that rime icing is encountered more frequently than clear icing in layer clouds, and vice versa in cumulus, engineering data complied by Bowden et al., and published for the design of ice protection systems shows that, under the same conditions of liquid water content and drop size, icing may be rime, clear, or mixed, depending upon air temperature and airplane speed.[8] Users of the Air Force method should recognize that the division into rime and clear types is arrived at based only upon consideration of cloud type. Different aircraft at different levels and, consequently, at different temperatures in the same cloud mass, as well as aircraft of different speeds at the same level, may encounter different types of icing.

The question of whether it is valid to assume that the mean effective drop diameter is representative of the drop size spectrum within an icing cloud is crucial. If this were found to be invalid, it would be necessary to consider the spectrum in order to arrive at a meaningful method of forecasting intensity of icing conditions. A forecast of liquid water content would not, by itself, be sufficient. This was evaluated by considering accretion on the spherical probe described in Sec. IV. Various hypothetical spectra of liquid water content versus drop size were used for calculations of rate of accretion on the probe using the method of computation given in Sec. IV. The results are summarized in Table 2. It is seen that the rate of accretion on the probe is not sensitive to the shape of the spectrum, as the error exceeds 10% only in the case of combined slow aircraft speed and an unrealistically bimodal liquid water content distribution. Hence, the concept of selecting representative mean effective diameters and forecasting the corresponding liquid water contents as read from the Lewis envelopes is considered valid.

No suggestions for change of the cloud model used in the Air Force method for forecasting liquid water content seem appropriate at present. As stated by Best, the model generates liquid water contents in good agreement with the maximum liquid water contents reported in the NACA data. In addition, the cloud base temperatures below which the model does not forecast severe icing seem reasonable. Severe icing is not forecast in convective clouds when the base temperature is less than $-12°C$, or in layer clouds when the temperature at cloud base is less than $-3°C$.

However, consideration should be given to changing the mean effective diameter assumed in cumulus-type clouds. Best shows that, of 159 NACA observations in layer clouds, 74.3% had mean effective diameters of less than 15μ and 93.1% less than 21μ. The value of 14μ chosen to represent

‡The definition of mean effective drop diameter used here is that which is generally used in icing literature, i.e., the diameter chosen such that one-half of the liquid water in a given drop spectrum is contained in drops of a size greater than, and one-half in drops of a size less than, the mean effective diameter.

layer clouds therefore seems appropriate. However, in 208 observations in convective clouds, only 40.4% had mean effective diameters of less than 18μ, whereas 76.4% had mean effective diameters less than 24μ and 89.9% less than 27μ. Since the Air Force method will underforecast if the actual mean effective diameter in an icing cloud is greater than the assumed value, it is suggested that changing the assumed diameter from 17 μ to 24μ for convective clouds, and reconstructing the forecast overlay on that basis, would probably be desirable.

IV. Practical Applications

The definitions and methods set forth in this paper are intended to permit a uniform approach to the problem of aircraft icing from the standpoints of forecasting, aircraft certification, and operational flying. Each of these areas is discussed in this section.

In the area of forecasting, it would be necessary to consistently forecast intensity of icing conditions using either the Air Force method or some similar method based on the same principles which might be found to be more realistic. The need for data to assist in the evaluation of such a forecasting method is discussed in Sec. V. The author has been involved in five icing flights during which data were obtained using drop size and liquid water content instrumentation for the purpose of aircraft certification. While no positive conclusions as to the validity of a forecasting method can be drawn from such a limited sample of data, the Air Force method verified in each of these cases.

Gollings and Newton have provided a method of flight test data acquisition for use in substantiating that a test aircraft has been flown in icing conditions as defined by the Lewis envelopes.[4] The method is essentially as follows. Calculations are made of the theoretical rate of accretion of ice upon a sphere exposed to icing conditions as defined by the Lewis envelopes. Photographs are then taken of the ice that actually builds up on the sphere during flight testing. The observed rate of accretion is then compared with the theoretical rate to determine the intensity of the icing conditions encountered.

The following method of calculation, originally developed by Dorsch et al.,[9] is used.

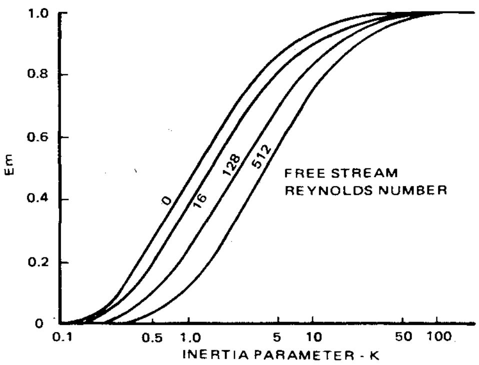


Fig. 4 Collection efficiency of sphere.

The total water catch of a sphere can be calculated using the relationship

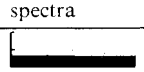
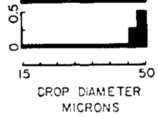
$$W_m = 1.196wR^2UE_m \qquad (1)$$

where W_m is the total rate of impingement of water (lb/h), w is the cloud liquid water content (g/m^3), R is the radius of the sphere (ft), U is the flight speed, i.e., the true airspeed (knots), and E_m is the dimensionless collection efficiency of the sphere. The values of w for these calculations are taken from the Lewis envelopes. All of the parameters except the collection efficiency may then be specified immediately for any desired case. The units, although admittedly inconvenient, are those in which the graphs used to calculate the water catch were originally prepared. It was felt to be neither necessary nor wise to enmesh a reader who might wish to consult the original references in a potentially error introducing units conversion exercise. For the purposes of this paper, it is the results of the method and not the calculations themselves which are of primary importance. These results can easily be converted into metric units or other convenient units if desired.

The collection efficiency E_m is related to a dimensionless inertia parameter K and the droplet Reynolds number Re. The parameter K is computed from the relationship

$$K = 1.96 \times 10^{-12}(Ud^2/hR) \qquad (2)$$

Table 2 Accretion computation using hypothetical drop spectra

Normalized liquid water content spectra	Mean effective diameter, μ	Impingement rates, lb/h, 200 knots, Actual spectral value	200 knots, Mean effective value	100 knots, Actual spectral value	100 knots, Mean effective value	Percentage error, 200 knots	Percentage error, 100 knots
	32.5	4.69	4.84	...	...	+3	...
	42.5	5.62	5.28	...	...	−6	...
	22.5	3.70	3.70	...	...	0	...
	25.0	4.30	4.03	1.77	1.68	−6	−5
	27.5	4.37	4.33	1.82	1.82	−1	0
	32.5	4.75	4.84	1.99	2.05	+2	+3
	32.5	4.52	4.84	1.83	2.05	+7	+12
	32.5	4.64	4.84	1.92	2.05	+4	+6
	40.0	5.02	5.46	2.10	2.31	+9	+10
	40.2	5.09	5.48	2.13	2.32	+8	+9
	47.5	5.61	5.96	2.37	2.53	+7	+7

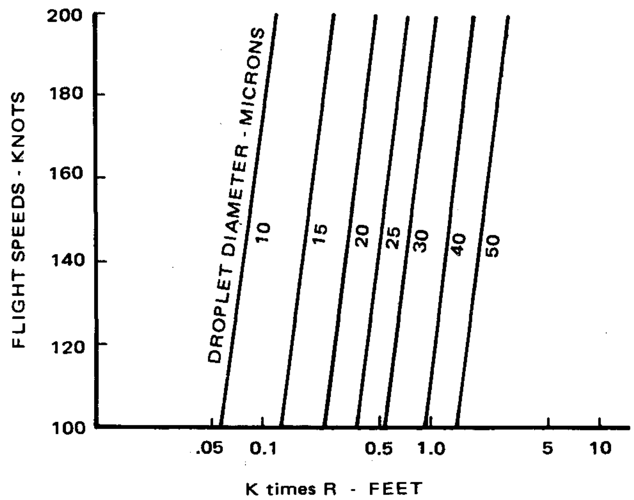


Fig. 5 Inertia parameter × sphere radius.

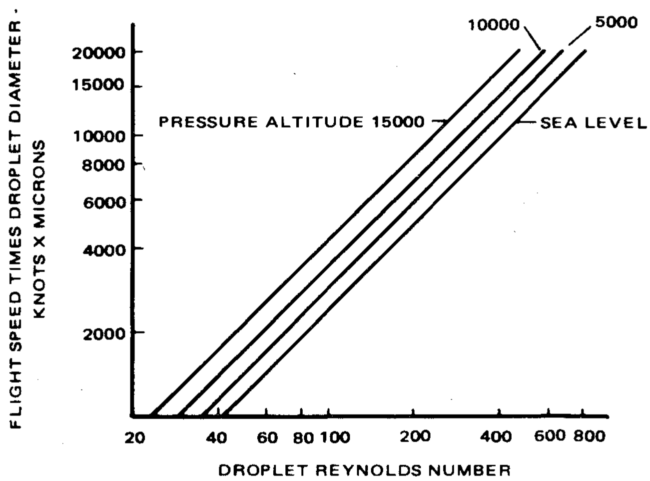


Fig. 6 Droplet Reynolds number.

where U and R are as previously defined, d is the droplet diameter to be used in conjunction with the Lewis envelopes (μ) and h is the absolute viscosity of air (slugs/ft-s). In computing the inertia parameter, h is assumed to be constant at an average value of 3.5×10^{-7}. The error in this assumption is less than 6% throughout a range from 0°C to −28°C. The relationship between E_m and K is graphically portrayed in Fig. 4, in which it may be seen that the small error caused by assuming the absolute viscosity to be constant is insignificant. The small effect of temperature on the total rate of accretion is therefore ignored. With this assumption

$$K = 5.6 \times 10^{-6} (Ud^2/R) \tag{3}$$

The effect of change in pressure altitude, as well as the effect of change in temperature, was ignored by Lewis.[5] However, the former effect, though small, is considered here.

A plot of $K \times R$ is given in Fig. 5. This quantity may be read from the figure for any flight speed and droplet size within the range considered. The value of K is then obtained by dividing the result by the appropriate sphere radius.

The droplet Reynolds number is read from Fig. 6. Variation of absolute viscosity with temperature is again ignored in using this number in the computation. The method of computation is then as follows:

1) Obtain the droplet Reynolds number for the case under study from Fig. 6.

2) Obtain $K \times R$ from Fig. 5 for the case under study and compute K.

3) Obtain the collection efficiency E_m from Fig. 4.

4) Compute the water catch limits, using the maximum and minimum liquid water contents appropriate to the droplet size as given by the Lewis envelopes (Fig. 3).

This calculation is then repeated for various droplet sizes along each curve of the Lewis envelopes for each speed and altitude condition. The accretion rate is found to be a constant within the limits of the computation at each condition, i.e., not a function of the droplet size. The Lewis envelopes are defined such that the rate of accretion on a cylinder is not a function of droplet size, and the calculations verified that this is also true for a sphere. A sample calculation may be found in Ref. 4. The results for a 4-in.-diam sphere are given in Table 3. Thus, a test aircraft may be considered to be encountering moderate icing if the initial rate of ice accretion on a spherical probe 4 in. in diameter falls within the limits shown. If the observed rate of accretion exceeds the tabulated upper value for the given flight conditions, the aircraft has encountered severe icing. If the observed rate of accretion is less than the appropriate lower value, light or trace icing has been encountered.

The rate of accretion varies from the initial rate as ice builds up on the sphere. Equation (1) shows dependence on E_m and R^2, and E_m decreases as R increases. If the buildup ice is treated as a spherical shell concentric to the probe, account may be taken of this. While the shape of the ice buildup is often not spherical, data taken in flight testing have produced results which make this method of accounting for the growth of ice appear reasonable.

The curves of E_m (Fig. 4) can be approximated to good accuracy for each Reynolds number using least-squares regressions, for values of E_m between 0.2 and 0.8 and Re not exceeding 16, and for E_m between 0.2 and 0.9 for larger Reynolds numbers. Upon making the substitution $E_m = a(Re) + b(Re) \log K$ in Eq. (1), the impingement rate becomes

$$W_m = 1.196wR^2 U[a(Re) + b(Re) \log(5.6 \times 10^{-6} Ud^2/R)] \tag{4}$$

The constants $a(Re)$ and $b(Re)$ were computed for each curve shown in Fig. 4, resulting in log/linear approximation to the curves having correlations of 98.9% or better within the stated limits. Linear interpolation was used for the values of $a(Re)$ and $b(Re)$ between the curves. Equation (4) was programmed in FORTRAN and run on the IBM 370 computer using various values of liquid water content and droplet size taken from the Lewis envelopes together with various aircraft speeds and altitudes. The values of Table 3 were

Table 3 Range of mass accretion on a spherical probe under moderate icing conditions (lb/h)

	Aircraft speed, knots				
Altitude, ft	100	125	150	175	200
Sea level	0.56-1.16	0.69-1.38	0.95-1.95	1.16-2.32	1.39-2.72
5,000	0.56-1.19	0.69-1.42	0.95-1.95	1.16-2.38	1.46-2.92
10,000	0.60-1.22	0.70-1.46	1.00-2.00	1.22-2.49	1.53-3.05
15,000	0.63-1.29	0.76-1.53	1.05-2.05	1.28-2.55	1.66-3.19

reproduced, generally to within 5%, and in all cases to within 10%.

This program was used to account for the effect of the increasing radius of the sphere in the following manner. For any given set of flight conditions, Eq. (4) can be expressed as

$$W_m = (C_1 - C_2 \log R) R^2 \tag{5}$$

where

$$C_1 = 1.196wU[a(Re) + b(Re)\log(5.6\times 10^{-6}Ud^2)] \tag{6}$$

and

$$C_2 = 1.196wUb(Re) \tag{7}$$

Remembering the accretion rate is independent of the droplet size, due to the manner in which the Lewis envelopes are defined, any value of liquid water content lying on one of the curves and its corresponding droplet size may be selected for use in the preceding relationships. If the aircraft speed and altitude are then specified, W_m is a function only of R. A program was run which:

1) Computed W_m using Eq. (5).

2) Computed the total mass accretion over a time step by multiplying W_m by the time interval.

3) Solved for the thickness of ice deposited on the sphere using a density of 0.8g/cm^3, the generally accepted value used in icing computations.

4) Incremented the radius of the sphere each time the thickness had grown 0.2 in. since the last incrementation, then looped back to step 1 and recomputed W_m.

Each time the thickness growth equalled or exceeded 0.2 in, the program branched to a segment where a new average rate of accretion, $\bar{W}_m$, was computed by taking the total mass collected on the sphere and dividing by the total time of collection up to that point. This method was used because it corresponds to the observables in flight testing, i.e., the thickness of ice, the total mass, and the length of time required for collection of the total mass. The quantity $\bar{W}_m / W_m$ was plotted against the thickness of ice, and the relationship was seen to be closely linear. A least-squares regression produced the relationship

$$\bar{W}_m / W_m = 0.88 + 0.473T \tag{8}$$

where T is the thickness of ice in inches. This equation is considered to be valid for thicknesses of ice between 0.5 and 1.25 in. measured from the stagnation point on the surface of the probe. For thicknesses less than 0.5 in., the difference between $\bar{W}_m$ and W_m is less than 10%, and can be ignored.

For purposes of data reduction the following rules apply:

1) If the thickness of ice collected on the probe during flight testing is less than 0.5 in., use Table 3 directly to determine the intensity of the icing conditions encountered.

2) For thickness of 0.5 in. or greater, multiply the values of Table 3 by a factor computed by substituting the thickness of ice collected into Eq. (8) to obtain the limits appropriate to that test.

Although the total rate of accretion on the sphere is not a function of the droplet size in these calculations due to the properties of the Lewis envelopes, the area of the sphere upon which the ice impinges increases as the droplet size increases. Dorsch, et al., have published a method of calculating the area of impingement.[9] The results of calculation by this method are that the limits of impingement are 48 deg for droplets 15 μ in diameter and 83 deg for droplets 50μ in diameter, where the angle is measured between radii drawn to the stagnation point and to the edge of the area of impingement. The relationship between $\bar{W}_m$ and W_m was computed for areas of impingement within these limits. It was found that, under the assumption that the collected ice shape was spherical, Eq. (8) continued to be valid, although the time to attain any given thickness varied.

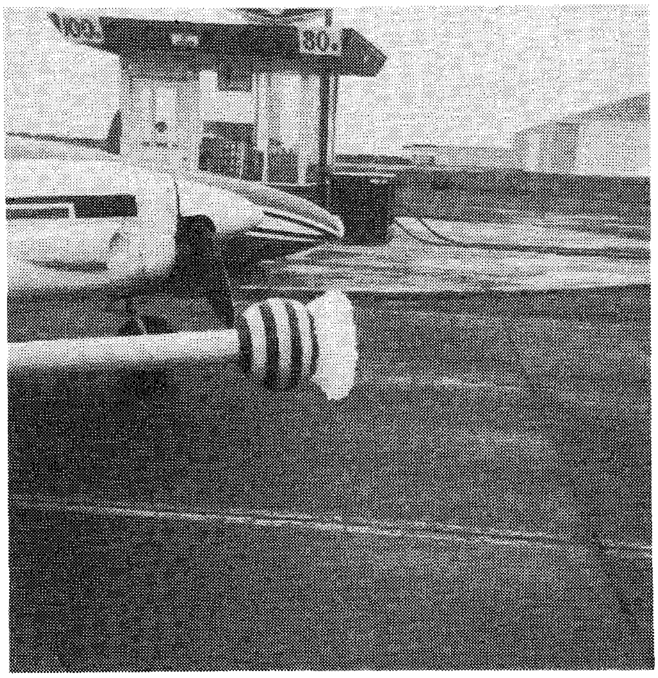


Fig. 7 Ice accretion on spherical probe.

A direct verification of this method is possible from data taken during a test flight made on May 7, 1973. Four encounters were made on this flight, as listed in Table 4, at an altitude of 6000 ft. The aircraft speed was 150 knots, and the outside air temperature was +24°F to +25°F.

Liquid water contents were measured using a Johnson-Williams hot-wire instrument and the droplet size was obtained by the gelatin replication technique, serving the dual purposes of obtaining meteorological information and substantiating the flight conditions for certification of the ice protection equipment aboard the aircraft. The Federal Aviation Administration subsequently accepted these data as part of the flight test requirements for certification of the equipment. The spherical probe was exposed during the entire series of encounters and the accretion of ice is shown in Fig. 7. The depth of ice, measured from the stagnation point on the surface of the sphere, is 1.16 in., the measured density of the ice is 0.84 g/cm^3, and the average rate of accretion is computed by dividing the mass of ice collected by the total time of exposure to icing.

The actual rate of accretion $\bar{W}_m$ was found to be 2.62 lb/h. The theoretical rate of accretion $\bar{W}_m$ was then obtained by substituting the measured parameters given in Table 4 into the program described earlier in this section, and was found to be 3.02 lb/h. This is within 15%, and is considered to be reasonable agreement in view of the fact that the leading edge of the ice is more flat than spherical. In addition, the computed thickness was 1.19 in., which is excellent agreement. New data, which will permit further direct verification of the accretion computations, was obtained during icing test flights

Table 4 Icing flight test data

Encounter number	Distance of encounter, n.mi.	Liquid water content, g/m^3	Mean effective drop diameter, μ
1	3.4	1.2	23.75
2	21.5	0.4	30.00
3	3.2	1.1	31.25
4	3.7	1.3	30.00

conducted in February and March of 1977, but the results are unfortunately not yet available.

If desired, an alternative approach is also possible, provided that frequent photographs are made of the ice buildup, and that is simply to periodically deice the probe by heating. This will minimize the change in shape of the sphere and requires only the assumption that the density of ice collected during the test is constant. This method has the additional advantage of allowing an ice accretion to be removed for a fresh start if a considerable period of flight in clear air between icing encounters is required, or if a data system failure occurs which makes a restart of data-taking desirable.

The Air Force method yielded a forecast of severe icing at the altitude flown for this flight. Encounters 1, 2, and 4 of this flight, as shown in Table 4, constitute individual severe encounters. Further, application of Eq. (8) to the values of Table 3 leads to a lower limit of severe icing of 2.79 lb/h, so that the encounter as a whole is only 6% under the limit of severe icing.

The philosophy of operation of aircraft designed and tested in according with the definitions of the Lewis envelopes would be as follows:

1) The manufacturer would select the intensity of icing for which the aircraft is to be equipped, and design to the appropriate envelope. Temperature and altitude limits appropriate to the individual aircraft type would be used. A suitable margin of safety would, of course, be designed into the systems. The intensity of icing conditions with which the aircraft was equipped to cope would be plainly set forth in the flight manual.

2) Forecasts would be made by the methods suggested, or by some other method hereafter found more suitable, but in any case, correlated with the same envelopes of icing intensity used by the manufacturer for certification.

3) The pilot would base the decision as to whether or not to conduct a planned flight on weather forecasts and on the airplane flight manual information, between which there would be a correlation which does not exist at present. Then, knowing the intensity of icing conditions for which the aircraft ice protection equipment was designed, the pilot could make meaningful reports of the intensity of icing conditions encountered on the basis of the effectiveness of the equipment in dealing with the ice.

V. Suggestions for Further Work

It is suggested that the following work be undertaken to prove and further develop the integration approach to forecasting, operating in, and designing protection to cope with icing conditions which has been discussed in this paper.

1) Make forecasts using the Air Force method, or some other method based on the Lewis envelopes which might be found more appropriate and which is agreeable to the forecasting agencies, and conduct deliberate quantitative verification flights using the data acquisition method described herein. At present, reliable and consistent reports of icing encounters suitable for judgment of any system of forecasting simply do not exist.

2) Investigate the cloud physics involved in creating an icing cloud. Data for such an investigation could be acquired during the verification program suggested above with additional instrumentation to measure state, cloud, and aerosol parameters.

3) Using the data acquired, develop a model of an icing cloud which could at least give physical justification to current, largely empirical, definitions and methods and probably improve them. For example, no account has been taken in any of the methods described herein of depletion of liquid water due to glaciation in a cloud, a factor well known to be important, but which cannot be assessed without data.

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