technical note technical note

Cloud Sampling Instruments for Icing Flight Tests: (1) Icing Rate Indicators

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16. Abstract

This series of technical notes, "Cloud Sampling Instruments for Icing Test Flights," provides information and guidance for devices that are most commonly used for measuring cloud water and droplet sizes during aircraft certification test flights in natural icing conditions. Advice is given on the suitability, procedure, and precautions for using various instruments and on data analysis techniques. This technical note is devoted to a common icing rate (or icing severity) indicator—the Goodrich (formerly Rosemount) model 0871FA icing detector. The other technical notes in the series are:

- DOT/FAA/AR-TN06/30, Cloud Sampling Instruments for Icing Flight Tests: (2) Cloud Water Concentration Indicators
- DOT/FAA/AR-TN06/31, Cloud Sampling Instruments for Icing Flight Tests: (3) Cloud Droplet Sizers
- DOT/FAA/AR-TN06/32, Cloud Sampling Instruments for Icing Flight Tests: (4) Large Drop Sizers

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LIST OF ABBREVIATIONS AND ACRONYMS

ACO	Aircraft Certification Office
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
IPS	Ice protection system
LWC	Liquid water content
MVD	Median-volume diameter
nmi	Nautical mile
OAT	Outside air temperature
ROC	Rate of climb
TAS	True airspeed
TAT	Total air temperature
V	Volt

INTRODUCTION

Federal aviation regulations, such as Title 14 Code of Federal Regulations (CFR) 25.1419, "Ice Protection," require that, for aircraft being certificated for flight in icing conditions, flight tests be conducted in measured natural or simulated icing conditions. Different aircraft manufacturers have employed different types of instrumentation to measure the relevant icing cloud variables, primarily water content, droplet sizes, and temperature. The available instrumentation ranges from the simple to the complex, from the old to the new, and from the relatively inexpensive to the expensive. Most of the instrumentation comes from the cloud physics research community and requires a certain amount of knowledge and experience to ensure that the probes are properly installed, calibrated, and operated. In addition, all probe types can have subtle systematic errors that may be difficult to recognize by the inexperienced operator or data analyst.

The Federal Aviation Administration (FAA) Aircraft Certification Offices (ACO) have had little guidance on this type of instrumentation and, as a result of these complexities, have had to rely on the aircraft manufacturers to supply presumably adequate instrumentation and technicians or to hire experienced contractors to install and operate suitable instrumentation and analyze the icing cloud data.

To help standardize policy and procedures among ACOs for icing certification projects, there was a need for official guidance on instrumentation for measuring the properties of icing conditions during natural icing test flights. This need was solidified as part of Task A.13.4 of the revised FAA Aircraft Icing Plan [1] of 2000, which calls for the FAA to develop certification guidance for measuring natural icing conditions.

The result was the following series of stand-alone technical notes—one for each type of instrument.

- DOT/FAA/AR-TN06/29, Cloud Sampling Instruments for Icing Flight Tests: (1) Icing Rate Indicators

- DOT/FAA/AR-TN06/30, Cloud Sampling Instruments for Icing Flight Tests: (2) Cloud Water Concentration Indicators

- DOT/FAA/AR-TN06/31, Cloud Sampling Instruments for Icing Flight Tests: (3) Cloud Droplet Sizers

- DOT/FAA/AR-TN06/32, Cloud Sampling Instruments for Icing Flight Tests: (4) Large Drop Sizers

The technical notes are intended to be a ready reference for ACOs, designated engineering representatives, aircraft manufacturers, and any other interested parties. They include advice on the suitability, procedure, and precautions for the most commonly used instruments for in-flight measurement of icing cloud variables. They also include advice on data quality assurance, data processing, and presentation of results.

The information and guidance was based on the author's own extensive experience with using the various instruments and analyzing the data from them. It was also based on information in the scientific and technical literature [2-11] and on the lessons learned during a comprehensive instrument comparison exercise conducted in 1998 in the Icing Research Wind Tunnel at the National Aeronautics and Space Administration Glenn Research Center near Cleveland, Ohio.

THE GOODRICH MODEL 0871FA ICE DETECTOR

The following is a description of the Goodrich model 0871FA ice detector.

- Classification: Electro-mechanical (vibrating rod, probe-type) icing detector or icing rate indicator

- Manufacturer: Goodrich Aircraft Sensors (Rosemount Aerospace), Inc.
  14300 Judicial Road
  Burnsville, Minnesota 55306
  Telephone: 952-892-4300
  Website: http://www.sensors.goodrich.com/literature/

- Purpose: To detect and indicate ice accretion and icing rate or severity

- Specifications:

  - Icing rate range: 0 to about 7 mm/min (17 inches/hour)

  - Sampling rate: variable (interrupted by intermittent de-icing mode)

  - Physical size: 1-inch-long sensing rod mounted on 3- by 4-inch-diameter electronics container (see figure 1)

  - Probe weight: approximately 2 pounds (1 kg)

  - Accessories needed: rate indicating meter and/or digital or analog voltage recorder

  - Cost of new detector: $6200

- Intended Use. Primary or secondary icing detector and icing rate (intensity) indicator for aircraft.

BACKGROUND.

The Goodrich Series 0871 of patented ice detectors shown in figure 1 was developed in the mid-1960s in response to a widespread requirement for a reliable ice warning system for aircraft. Currently, these sensors are used on a variety of civil and military aircraft.

PRINCIPLE OF OPERATION [3, 4, and 5].

As ice builds up on the sensitive rod (figure 1), the device outputs an analog voltage that is proportional to the mass or thickness of the accumulating ice. When a certain ice mass is reached, usually equivalent to a thickness of about 0.5 mm, a heater is automatically energized to melt and remove the accumulated ice. The analog output voltage then drops to its baseline (uniced) value, the heating stops, and the ice accumulation can resume as soon as the surface temperature of the rod cools to below 0°C.

Examples of the output signal are shown in figures 2 and 3. Qualitatively, the sawtooth voltage in figure 3 clearly documents when icing was occurring, and the number of cycles per unit time is an indication of the icing intensity. Quantitatively, the ascending slope during the accumulation intervals, as shown in the figure 2 example, is directly proportional to the ice accumulation rate.

The following lists the advantages and disadvantages of the Goodrich model 0871FA ice detector:

- Advantages
  - Inexpensive, simple, small sensor normally used on aircraft anyway
  - Works at any airspeed (props or jets)
  - Usable on all airplanes
  - Insensitive to ice crystals or snow
  - Allows continuous record of presence and intensity of ice accretion
  - Requires no special operator or equipment (except data recorder)
  - Data easy to process, evaluate, and interpret
  - Automatically integrates all important factors—LWC, TAT, drop size, and TAS
  - Can be left on airplane indefinitely for icing encounters of opportunity
  - Subject to Ludlam Limit effects like the rest of the airframe (i.e., reflects actual icing conditions on the aircraft)
  - Computationally or experimentally relatable to actual icing rates on other components of the airplane
  - Measured icing rate is directly relatable to 14 CFR Part 25 Appendix C (converted from LWC to icing rate)

- Disadvantages

  - The duty cycle decreases with increasing icing rate. (Dead time exceeds ice accretion time for LWCs greater than about 0.3 g/m^3 at 200 kt.)

RECOMMENDED DATA PROCESSING PROCEDURE.

RECORDING THE SIGNAL. The Goodrich model 871FA outputs a saw tooth voltage like that shown in figures 2 and 3. Because the voltage can build up quickly in moderate or worse icing conditions, it is necessary to record the signal with a time resolution of one second or better. Digital sampling and recording is preferred so that the voltage readings can be more easily processed using a computerized spreadsheet (see table 1) or other computerized method. For digital recordings, the time of day (hh:mm:ss) or elapsed time (in seconds) for each reading should also be recorded so that the ascending slope of the signal can be accurately computed (see the next section Computing the Icing Rate). For analog (chart) recording, the time scale must be known and of sufficiently high resolution to permit an accurate measure of the slope from the trace on the chart. Figure 3 shows a chart record that clearly reveals when icing was occurring during a flight, but whose time scale is too compressed for useful determination of the slopes.

COMPUTING THE ICING RATE. Various schemes for converting the voltage signal to icing rate have been proposed. Two of these methods are explained next, although only the second one is recommended for the present purposes.

The Cycle-Counting Method. The most common one, because it is the simplest, is the cycle counting method [4]. It attempts to relate the time between the peaks (heater activation points, or trip points) to the icing rate, icing intensity (severity), or LWC. The shorter the time interval between peaks (the full cycle time), the greater the icing rate (and LWC). While adequate for some applications[1], this coarse method suffers from a serious deficiency for computing accurate icing rates. This is because, as the icing rate increases, the portion of the cycle time occupied by the dead time due to the heater and cool-down process also increases. At modest LWCs (0.3 g/m^3 or so), the dead time (typically 7 to 15 seconds or more) begins to exceed the ice accretion time. At faster icing rates, the accretion time becomes so short that the cycle time is determined mostly by the dead time and the cycle time is no longer easily relatable to the icing rate.

The Slope Method. The only reliable method for accurate computations is to make use of the fact that the icing rate is directly proportional to the upward slope of the sawtooth signal during the ice accretion portion of the cycle. This slope always represents the icing rate during the accretion interval, no matter how brief. The icing rate cannot be measured during the dead time (heater/recovery interval), which will always take 7 to 15 seconds or more. This means that the icing measurements are not really continuous, and for high icing rates, they are more like spot samples 3 or 4 times a minute. Nevertheless, the slope-derived icing rates during these samples are the most accurate, and their frequency is satisfactory for the purposes of icing test flights.

[1] The manufacturer uses the cycle-counting method for deciding when to activate various ice protection systems on the aircraft [4].

For Goodrich model 871FA icing detectors set for a sensitivity of 0.5 mm of ice over a 4-volt (V) output range[2] (1-5 V), the ice accretion rate in mm/min is given by

$$\text{Rate (mm/min)} = \frac{0.5\,\text{mm}}{4\,\text{volts}} \times \frac{\Delta V\ \text{(volts)}}{\Delta t\ \text{(sec)}} \times \frac{60\ \text{sec}}{\text{min}} = \frac{7.5\,\Delta V\ \text{(volts)}}{\Delta t\ \text{(sec)}} \tag{1}$$

where $\Delta V/\Delta t$ is the ascending slope of the output voltage signal. This can be easily computed from the record if the output voltage is recorded with sufficient time resolution (e.g., every second, as in figure 2) during the encounters. For example, the icing rates computed for the ascending slopes in cycles 1-3 in figure 2 are 3.1, 2.1, and 1.9 mm/min, respectively.

The icing rates from these individual cycles can be plotted vs time during the encounter, or they may be combined into a single average, as needed.

DISPLAYING THE DATA.

Second-By-Second Measurements. Table 1 illustrates a tabular (spreadsheet) presentation of the Goodrich model 871FA data in figure 2, along with other recorded and derived variables. This could serve as a uniform style for presenting icing rate data. The spreadsheet is automated such that after the user pastes the basic recorded data into five of the columns (shaded), the subsequent computations are all done automatically by the formulas in the spreadsheet cells.

The automated part translates the 871FA icing rates (column 4) into the corresponding nominal icing rates (columns 5-8) to be expected on the airframe component(s) of interest on the subject airplane. In this example, it is a mid-wing section on a Lockheed C-130 airplane. This gives the analyst a better idea of what any particular icing encounter means to the airplane itself.

The spreadsheet also translates icing rates in column 5 into icing intensity (severity) (column 6), according to new definitions recently proposed [7] and adopted by an FAA-sponsored, interagency working group formed under Task 1-B of the 1997 FAA In-Flight Icing Plan. The intensities in column 6 can help the analyst evaluate the significance of the icing encounters. For comparison purposes, an encounter resulting in moderate ice accretion rates would be more significant than an encounter producing only trace or light accretion. But the cumulative ice accretion is important too, and column 8 tallies that.

The last column tallies the overall distance (horizontal extent) flown in the tabulated icing conditions. Other variables can be added by the user, if desired.

Tabular Summaries. A summary exposure record can be constructed as shown in table 2. This example is based on figure 3 after the second-by-second details have been computed as in table 1. Columns A-D in the lower half of table 2 document the duration and distance traveled in the selected icing encounter. In this example, based on the icing exposures between 14:29 and

[2] The sensitivity (calibration) of each Goodrich model 871FA will likely be different [6]. Use the correct calibration for the probe at hand.

15:22 in figure 3, the airplane spent 34 minutes and 86 nautical miles (nmi) in actual icing conditions.

Column F gives the icing rate (on the Goodrich model 871FA) for intervals of interest during the icing encounter.

The Goodrich model 871FA icing rate can also be conveniently expressed in familiar intensity terms (trace, light, moderate, and heavy) in column G by making use of the new, quantified definitions of icing intensity (see the second page of table 1), as proposed by the Task 1-B Working Group under the 1997 FAA In-Flight Aircraft Icing Plan.

Furthermore, the icing rates measured by the Goodrich model 871FA can be used to estimate the icing rates occurring simultaneously on components of interest, such as the outer wing leading edge, on the test airplane. This is done by simply reducing the measured icing rate by the ratio of the droplet collection efficiencies of the Goodrich model 871FA sensor to the component of interest. The results for a hypothetical outer wing are shown in columns I-K in table 2. In this example, the outer wing of the test airplane was subject to mostly light icing.

Although the aircraft is designed and certificated to 14 CFR Part 25 Appendix C icing conditions, the operating regulations (14 CFR 91.527, 121.341, 125.221, and 135.227 for operating in icing conditions) require that the icing certificated aircraft be able to fly safely in light, moderate, and heavy icing conditions. Past certification programs have not verified that the subject aircraft meets these operational requirements. In fact, there has been no attempt to relate icing intensities to 14 CFR Part 25 Appendix C for any aircraft. (How do we know, for example, that moderate and heavy icing conditions fall within 14 CFR Part 25 Appendix C for a given airplane?)

Therefore, it may be meaningful to relate icing test flights to these measured icing intensities as well as trying to relate them to the 14 CFR Part 25 Appendix C envelopes. Operationally, this makes sense—a pilot has no way of knowing where a given icing encounter falls within (or outside of) 14 CFR Part 25 Appendix C, but the icing intensity can be routinely measured with an icing rate sensor. If the aircraft has been demonstrated safe in measured moderate and heavy icing conditions for a certain distance, then the pilot can easily understand that. These icing intensities are terms with which pilots are familiar—not with 14 CFR Part 25 Appendix C.

Therefore, icing test flights could also help demonstrate that the aircraft can fly safely in light, moderate, and heavy icing exposures.

Additionally, any effects of icing on the performance and handling of the airplane can be documented using the level-of-effects table (table 3) proposed by the Task 1-B Working Group under the 1997 FAA In-Flight Aircraft Icing Plan.

This table was actually devised as a pilot reporting (PIREP) table for icing conditions, but it is also suitable as a checklist and rating scheme for icing test flights. The table lists four increasingly worsening levels of effect of icing conditions on three performance factors (speed,

power, and climb capability) and two handling aspects (control and vibration). Hypothetical effects are listed in columns S-W of table 2 for the icing intervals tabulated there.

In this example, after the end of the 86-nmi encounter, only the power and climb capability showed any significant (level 2) degradation. This degradation occurred even though the boots were cycled several times (columns P-Q of table 2) during the encounter. If the boots had not been used, an estimated 9.4 mm (3/8 inch) of ice would have accumulated (column K) on the outer wing.

An alternate test procedure would be to avoid using the ice protection system (IPS) until a desired amount of ice has accumulated on the outer wing. Then, the handling and performance (level-of-effect) tests can be performed with a stated load of ice on the wing. Thus, less than 1/4-inch accumulation would be a trace load of ice, 1/4- to 1-inch is a light load of ice, 1 to 3 inches is a moderate load, and more than 3 inches can be reported as a heavy load of ice.

In any case, these ideas illustrate some possible ways to simplify the presentation of flight test data and to relate icing effects to quantifiable icing intensities.

Comparing to the 14 CFR 25 Appendix C Envelopes. In addition to using icing intensity as one way to rate icing exposures, further evaluation of the test flight conditions can be had by comparing them to 14 CFR Part 25 Appendix C envelopes or to natural probabilities of occurrence of the available icing rates.

Some practitioners attempt to convert the icing rate signal into an equivalent value of LWC to compare to the 14 CFR Part 25 Appendix C envelopes. While this is theoretically possible under certain conditions, experience has shown that, for various reasons, the LWC derived this way seldom produces satisfactory results when compared to regular LWC meters.

The measured icing rates can be compared directly to 14 CFR Part 25 Appendix C if the latter is converted [8] from LWC to an icing rate on the vertical axis. The rate of ice accretion on the sensitive element is given by

$$\text{Icing Rate (mm/min)} = (\text{A})(\text{LWC})(\beta)(\text{TAS})/\rho$$

Where A = 30.9×10^3 is a units conversion constant, β is the cloud droplet local collection efficiency, and $\rho = 0.917 \times 10^6$ g/m^3 is the density of ice. For cloud droplets impinging on a 1/4-inch-diameter cylinder, $\beta \cong 0.9$ for airspeeds of 150 to 250 kt. For a given airspeed, the above equation can be used to convert LWC to icing rate. This can also be used to convert figures 1 and 4 of 14 CFR Part 25 Appendix C into equivalent icing rate envelopes [8] tailored specifically for the Goodrich model 871FA probe.

To illustrate one way of comparing icing rates to 14 CFR Part 25 Appendix C, one can borrow from reference 9 which demonstrates the process using figure 3 as an example.

Figure 4 shows the -10°C curve of the continuous maximum envelopes in 14 CFR Part 25 Appendix C displayed in the equivalent, distance-based format [8] of icing rate versus horizontal

extent. The icing intensity scale for the outer wing at 150 kt is also shown. The two larger icing rates from the record in table 2 and an overall average icing rate are plotted on the graph as "demonstrated test zones." These boxed-in areas show how much of 14 CFR Part 25 Appendix C that the test flight was able to cover.

Note that the intensity scale in figure 4 shows that heavy icing (> 1.3 mm/min) is so close to the top of the envelope that it will hardly ever occur on this wing in stratiform (continuous maximum) icing conditions at -10°C. If these heavy icing conditions are found, however, the portion of the -10°C envelope above the heavy icing threshold shows that any heavy icing will probably not last longer than about 12 nmi (about 5 minutes at 150 kt), according to 14 CFR Part 25 Appendix C.

Comparing to Natural Probabilities for Icing Rates. Another useful comparison may be to superimpose actual icing rate probabilities on the data. Figure 5 is similar to figure 4 except that probability (percentile) curves (derived from 28,000 nmi of icing data at the FAA William J. Hughes Technical Center) are displayed instead of 14 CFR Part 25 Appendix C envelopes. The results show that the last 18 nmi of exposure at an icing rate (on the outer wing) of 0.5 mm/min was above average, but the first 28 nmi and the overall exposure in this hypothetical icing flight were about average. This puts the exposures into perspective and helps the test crew and data analysts evaluate their significance.

If it is conceded that the 90th percentile value of icing rate is about the most that can be realistically hoped for on most icing flights, then the 90% curve on figure 5 shows that 0.9 mm/min or less, depending on the averaging distance, is the greatest icing rate to be expected. This corresponds to a mid-moderate icing rate, according to the intensity scale. Therefore, the most that this wing can be tested for, in layer clouds, is mid-moderate icing conditions. This gives both the applicant and the ACO realistic expectations for any icing flight tests.

Other useful ways to compare icing rates to 14 CFR Part 25 Appendix C and to natural probabilities for encountering the measured icing rates are illustrated in reference 8.

KNOWN SOURCES OF ERROR.

The performance of the Goodrich model 871FA probes has been studied extensively [6, 10, and 11]. Except for Ludlam Limit effects in some applications and de-icing problems with some probes at low airspeeds, low temperatures, and LWCs larger than about 0.3 g/m^3 [6], the operational problems seem to be few. Attempts to use the Goodrich model 871FA as a LWC meter are often uncertain, usually because of Ludlam Limit effects and the interruptions by the heater cycle.

CALIBRATION. The exact calibration from icing wind tunnel or in-flight tests must be known to obtain correct values of icing rate from the slope of the output voltage [6]. Often, the upper and lower voltage limits are different from the nominal 1-5 V mentioned in the factory literature. This can be seen in both figures 2 and 3. This does not seem to affect the slope (rate of increase of output voltage with accreted ice mass) but a narrower range (2-4.5 V, for example) will shorten the available sampling time each cycle. The important thing is to know whether the

heater is set to activate at the usual 0.5 mm of ice depth or at some other value, as is sometimes the case [6].

LUDLAM LIMIT EFFECTS. One difference with an ice accretion probe is that, depending on the in-cloud temperature, or more precisely, on the TAT or surface temperature of the probe, the greater LWCs in the upper parts of the envelopes may not be measurable in terms of icing rate. This is due to incomplete freezing of the impinging water if the LWC exceeds a certain value for a given air temperature and airspeed. The threshold value of LWC at which incomplete freezing begins is known as the Ludlam Limit [5].

To a first approximation, the Ludlam Limit depends mainly on the LWC, outside air temperature (OAT), and TAS, and not so much on the size of the accreting object. Thus, the (unheated) airframe components will generally not accrete ice if the ice detector does not. A possible exception[3] is runback icing in some cases. For example, when the TAT is near 0°C along the leading edge of a wing, water not freezing there may run back and freeze in a low pressure area (dynamically lowered temperature zone) farther back on the suction side of the airfoil.

PROBE LOCATION CONCERNS. The Goodrich model 871FA probe is designed for convenient mounting on the fuselage, usually toward the nose where the pitot and air temperature sensors are located. Otherwise, a fuselage location farther aft can result in sampling an airstream in which certain droplet sizes have been depleted or increased due to inertial sorting by the deflection of the airstream around the nose of the aircraft. This concern is discussed in references 12 and 13.

Another problem on single-engined, propeller-driven airplanes is the difficulty in obtaining exposures outside the propeller wash, unless the instrument is mounted under a wing outboard of the propeller.

SUMMARY.

Suitable icing rate meters are a valuable (but overlooked) tool for use in documenting and rating icing exposures.

The icing rate is a useful measurement because it is actually an integrated result of all the variables involved, namely LWC, OAT, TAS, drop-size distribution, collection efficiency, and Ludlam limit effects. The icing rate reflects the actual icing situation on the rest of the aircraft regardless of the medium volume diameter (MVD). Also, the icing rate is easier to measure than LWC and drop size individually.

In general, the icing rate on the 1/4-inch cylinder will be an indication of the icing rate on the leading edge of the airframe surfaces. Although the aircraft may be in a high LWC situation, the icing rate could be low or negligible if the TAT is near or above 0°C.

[3] Another exception is when the probe is installed at an aerodynamically incorrect position on the aircraft. In this case, the sensitive element could be either shadowed from certain drop sizes or even exposed to an artificially concentrated flow of cloud droplets, depending on the droplet trajectories in the airstream at the probe location.

If drop sizes are not measured, the main drawback seems to be only that it will be unknown whether the icing exposure is within 14 CFR Part 25 Appendix C, in terms of MVD[4].

Among the benefits of measuring icing rate are the following:

- Icing rates are easily understandable by any icing practitioner
- Test exposures can be conveniently compared to:

  - 14 CFR Part 25 Appendix C (converted to icing rate or icing intensity)
  - Natural icing probabilities
  - Icing intensities (trace, light, moderate, and heavy)
  - Operational requirements in 14 CFR 91.527, 121.341, 125.221, and 135.227

Finally, one of the many recommendations made by a European panel of experts on airborne cloud measurements was "The Rosemount icing detector is considered to be the most reliable detector of supercooled liquid water in clouds and its wider usage is encouraged" [14].

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[4] Conventionally, some measurement of MVD has been required during test exposures in order to know whether the MVD was greater than 15 μm, indicating that the test conditions were within the 14 CFR Part 25 Appendix C envelopes. Often, test results have been arbitrarily disallowed if the MVD were less than 15 μm. Research in the Flight Safety Branch at the FAA Airport and Aircraft Safety R&D Division at the William J. Hughes Technical Center has shown that 75% of the time the MVD is within ±5 μm of 15 μm anyway [see figure 27 in reference 8]. That is, MVDs are not as variable as may have been believed, and the larger the MVD above 15 μm, the rarer it is and the shorter it lasts. This means that it may be possible to assume an MVD of 15 μm for the purposes of natural icing flight tests unless there is some specific reason to have an exact value.

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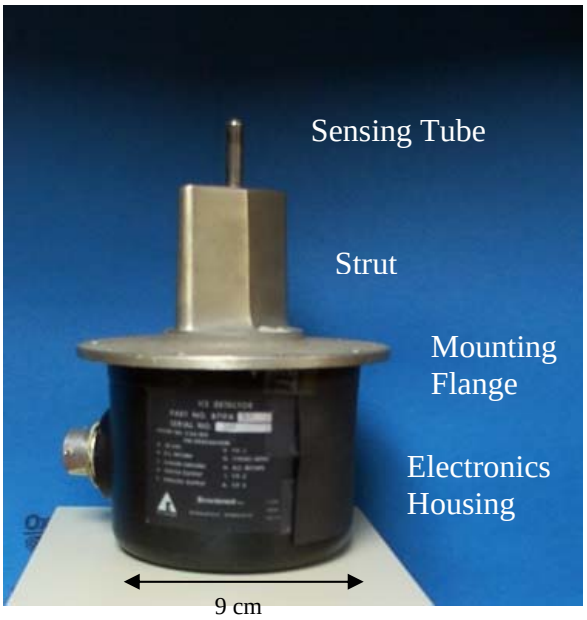

FIGURE 1. THE MODEL 871FA ICING DETECTOR

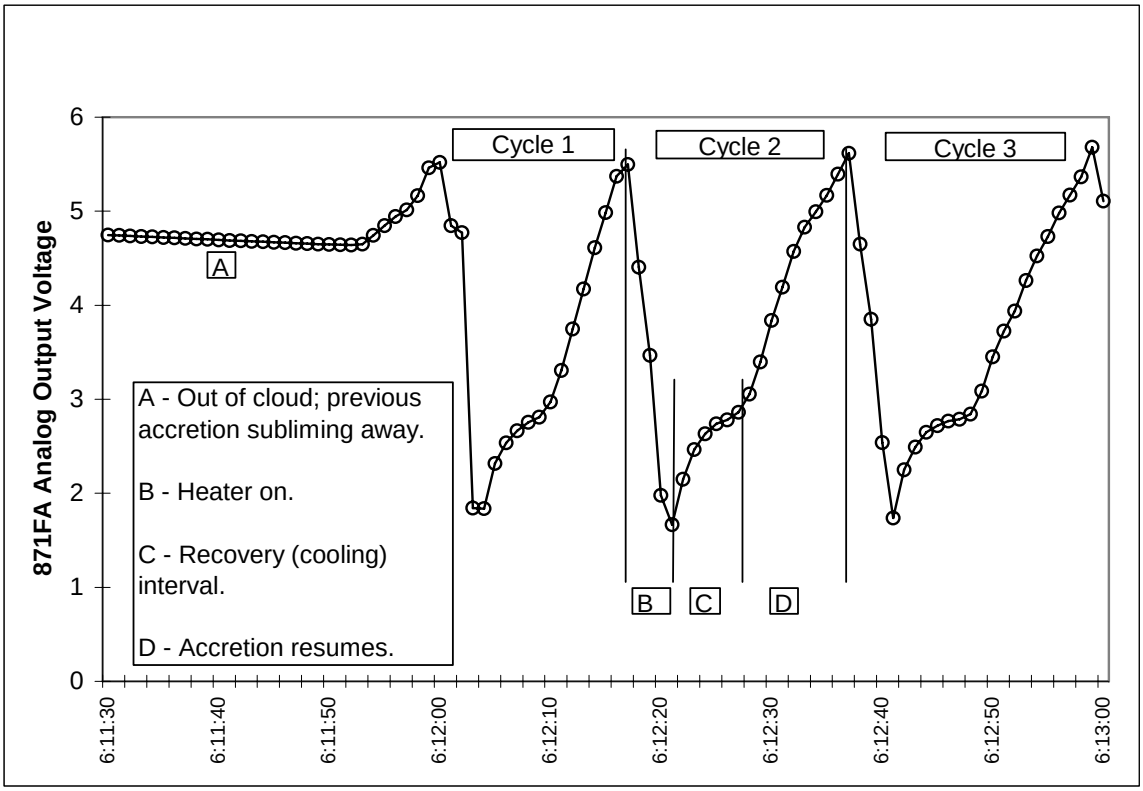

FIGURE 2. ACTUAL EXAMPLE OF THE ANALOG OUTPUT VOLTAGE FROM AN 871FA ICING DETECTOR

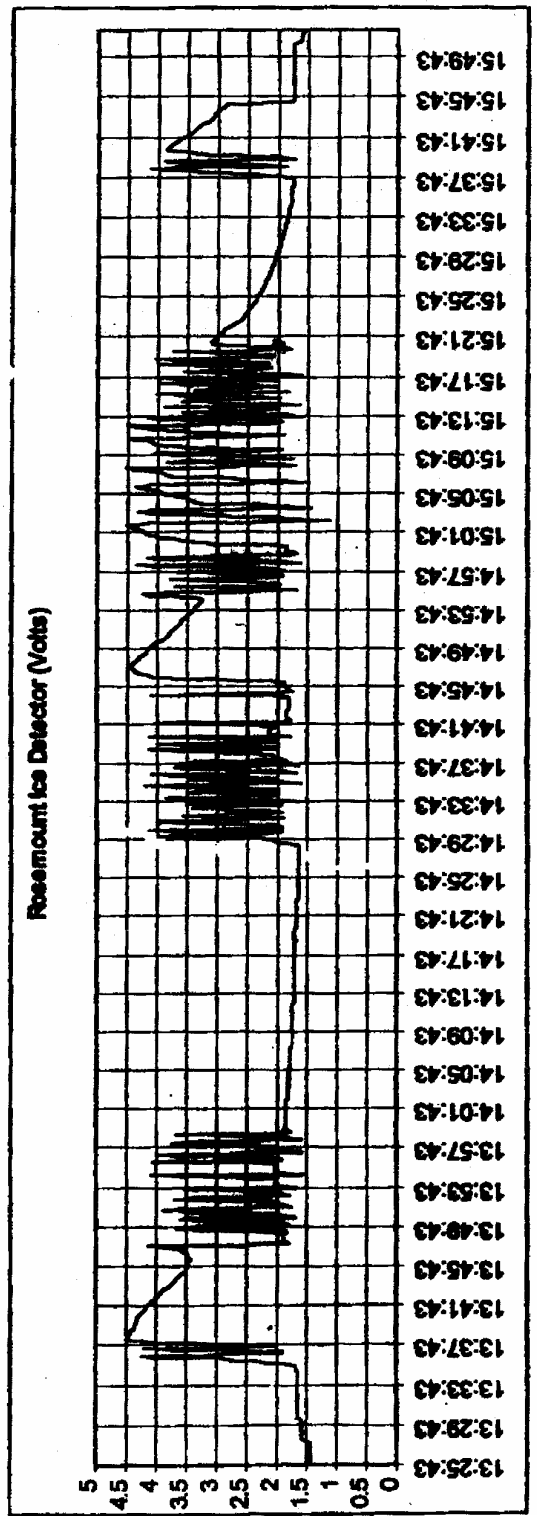

FIGURE 3. ACTUAL EXAMPLE OF THE ANALOG OUTPUT VOLTAGE FROM ANOTHER 871FA DURING AN INTERMITTENT ICING ENCOUNTER

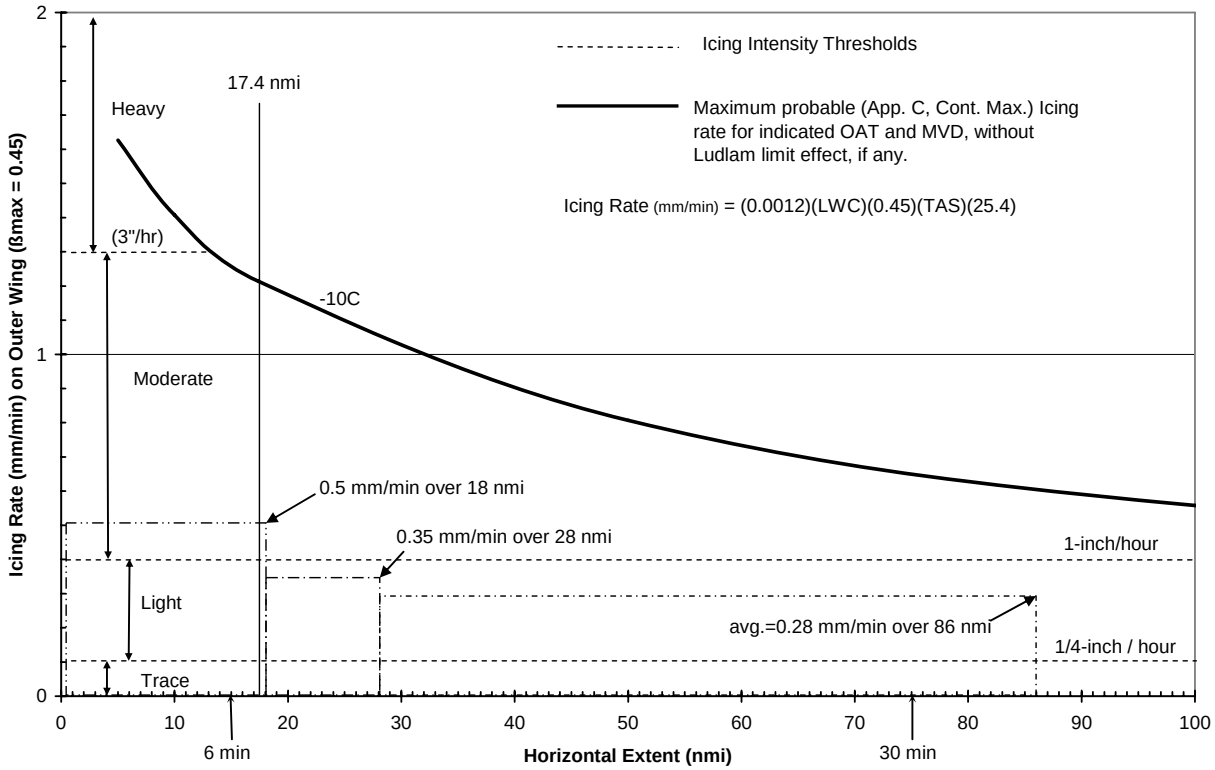

FIGURE 4. COMPARISON OF ICING INTERVALS IN TABLE 2 TO 14 CFR 25 APPENDIX C (CONTINUOUS MAXIMUM) IN TERMS OF ICING RATE ON THE OUTER WING AT 150 kt TAS

(The curve shows the variation of maximum probable icing rate with averaging distance for OAT = -10°C and MVD = 15 µm, as represented by the current design envelopes. Boxed-in areas may be regarded as demonstrated test zones (see text).)

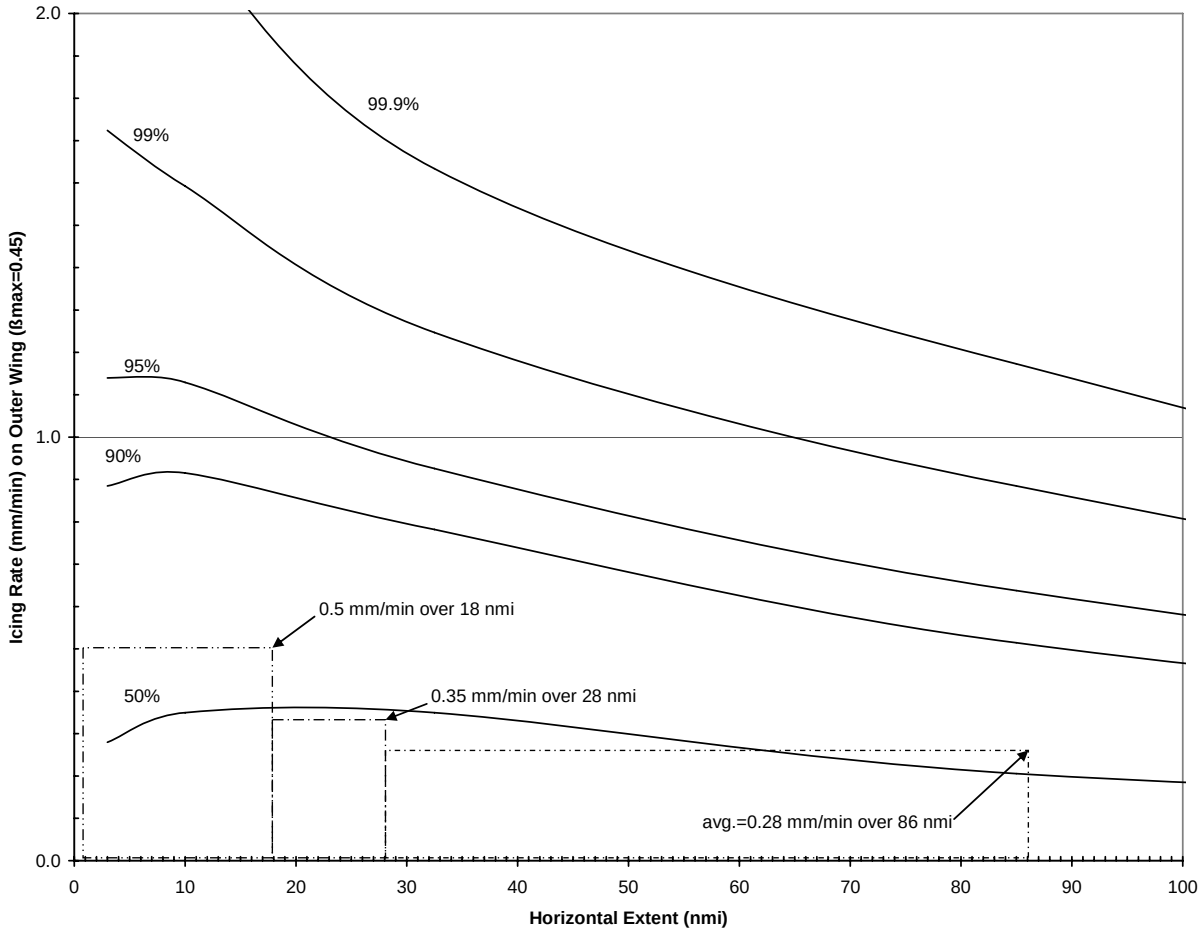

FIGURE 5. COMPARISON OF ICING INTERVALS IN TABLE 2 TO NATURAL PROBABILITIES FOR ICING RATES ON A WING WITH ßmax = 0.45 AT 150 kt (In stratiform icing conditions with average MVDs (15 µm) and in-cloud temperatures of 0° to -10°C. Icing Rate (mm/min) = (0.0012)(LWC)(0.45)(TAS)(25.4) Boxed-in areas may be regarded as demonstrated test zones (see text).)

TABLE 1. TABULAR PRESENTATION OF DATA FROM FIGURE 2

	1	2	3	4	5	6	7	8	9	10	11	12
1	**Suggested Data Presentation for BFG Rosemount Model 871FA Icing Rate Sensor**											
2	Notes:	1) Instantaneous icing rate on 871FA probe computed from: $Rate_{probe}$ (mm/min) = 7.5x(dV/dt),										
3		where	dt(sec) =	1	for the data in this example.							
4		2) Icing rate on a clean, unheated wing computed from ratio: $Rate_{wing} = Rate_{probe} x (Beta_{wing})/(Beta_{probe})$										
5		where	$Beta_{wing}$ =	0.20	for a Lockheed C-130 mid-wing section* at about 200 kt TAS,							
6						* (NACA 64A412 with chord=4.16 m)						
7		and	$Beta_{probe}$ =	0.90	for the 871FA probe at about 200 kt TAS.							
8		3) Other user input:										
9			Baseline =	2.9	volts, is the baseline (un-iced) output voltage for the particular 871FA in use.							
10												
11	(User Input)				Equivalent Rate on Clean, Unheated Component				(User Input)			
12		871FA		Instantaneous	(Lockheed C-130 mid-wing section*)				Pres			Cum.
13	Time	output	dV	Icing Rate	Icing Rate	Icing	Running Avg	Cum. Icing	Alt	OAT	TAS	Distance
14	(hh:mm:ss)	(volts)	(volts)	(mm/min)	(mm/min)	Intensity**	(mm/min)	Depth (mm)	k Ft	degC	kt	nmi
15	6:11:30	4.747							16.8	-23.1	213	0.1
16	6:11:31	4.742	-0.005	-0.04	-0.01	None			16.8	-23.5	214	0.1
17	6:11:32	4.737	-0.005	-0.04	-0.01	None		0.00	16.9	-23.2	215	0.2
18	6:11:33	4.732	-0.005	-0.04	-0.01	None		0.00	16.8	-23.1	214	0.2
19	6:11:34	4.727	-0.005	-0.04	-0.01	None		0.00	16.8	-23.3	218	0.3
20	6:11:35	4.722	-0.005	-0.04	-0.01	None	-0.01	0.00	16.8	-23.1	217	0.4
21	6:11:36	4.717	-0.005	-0.04	-0.01	None	-0.01	0.00	16.8	-23.1	218	0.4
22	6:11:37	4.711	-0.006	-0.04	-0.01	None	-0.01	0.00	16.8	-23.4	218	0.5
23	6:11:38	4.705	-0.006	-0.05	-0.01	None	-0.01	0.00	16.8	-23.6	217	0.5
24	6:11:39	4.700	-0.005	-0.04	-0.01	None	-0.01	0.00	16.8	-23.6	217	0.6
25	6:11:40	4.695	-0.005	-0.04	-0.01	None	-0.01	0.00	16.8	-23.6	217	0.7
26	6:11:41	4.689	-0.006	-0.05	-0.01	None	-0.01	0.00	16.8	-23.6	217	0.7
27	6:11:42	4.684	-0.005	-0.04	-0.01	None	-0.01	0.00	16.8	-23.6	218	0.8
28	6:11:43	4.680	-0.004	-0.03	-0.01	None	-0.01	0.00	16.8	-23.6	216	0.8
29	6:11:44	4.675	-0.005	-0.04	-0.01	None	-0.01	0.00	16.8	-23.6	217	0.9
30	6:11:45	4.669	-0.006	-0.05	-0.01	None	-0.01	0.00	16.8	-23.6	217	1.0
31	6:11:46	4.665	-0.004	-0.03	-0.01	None	-0.01	0.00	16.8	-23.6	216	1.0
32	6:11:47	4.660	-0.005	-0.04	-0.01	None	-0.01	0.00	16.8	-23.6	217	1.1
33	6:11:48	4.656	-0.004	-0.03	-0.01	None	-0.01	0.00	16.8	-23.6	217	1.1
34	6:11:49	4.651	-0.005	-0.04	-0.01	None	-0.01	0.00	16.8	-23.6	218	1.2
35	6:11:50	4.647	-0.004	-0.03	-0.01	None	-0.01	0.00	16.8	-23.6	218	1.3
36	6:11:51	4.643	-0.004	-0.03	-0.01	None	-0.01	0.00	16.8	-23.6	219	1.3
37	6:11:52	4.641	-0.002	-0.01	0.00	None	-0.01	0.00	16.8	-23.6	217	1.4
38	6:11:53	4.651	0.010	0.07	0.02	Trace	0.00	0.00	16.8	-23.6	216	1.4
39	6:11:54	4.742	0.091	0.68	0.15	Light	0.03	0.00	16.8	-23.6	215	1.5
40	6:11:55	4.847	0.105	0.79	0.18	Light	0.07	0.00	16.8	-23.6	216	1.6
41	6:11:56	4.942	0.095	0.71	0.16	Light	0.10	0.01	16.8	-23.6	214	1.6
42	6:11:57	5.014	0.072	0.54	0.12	Light	0.12	0.01	16.8	-23.6	215	1.7
43	6:11:58	5.164	0.150	1.13	0.25	Light	0.17	0.01	16.8	-23.6	218	1.7
44	6:11:59	5.462	0.298	2.24	0.50	Moderate	0.24	0.02	16.8	-23.6	218	1.8
45	6:12:00	5.520	0.058	0.43	0.10	Trace	0.22	0.02	16.8	-23.6	217	1.9
46	6:12:01	4.845	-0.675	de-icing	?	?	0.22	0.03	16.8	-23.6	215	1.9
47	6:12:02	4.771	-0.074	de-icing	?	?	0.22	0.03	16.8	-23.6	216	2.0
48	6:12:03	1.844	-2.927	de-icing	?	?	0.22	0.03	16.8	-23.6	215	2.0
49	6:12:04	1.836	-0.008	recovery	?	?	0.22	0.04	16.8	-23.6	216	2.1
50	6:12:05	2.318	0.482	recovery	?	?	0.22	0.04	16.8	-23.6	216	2.2
51	6:12:06	2.537	0.219	recovery	?	?	0.22	0.04	16.8	-23.6	215	2.2
52	6:12:07	2.664	0.127	recovery	?	?	0.22	0.05	16.8	-23.8	215	2.3
53	6:12:08	2.754	0.090	recovery	?	?	0.22	0.05	16.8	-23.7	217	2.3
54	6:12:09	2.809	0.055	recovery	?	?	0.22	0.06	16.8	-23.8	219	2.4
55	6:12:10	2.971	0.162	1.22	0.27	Light	0.27	0.06	16.8	-23.7	217	2.5
56	6:12:11	3.306	0.335	2.51	0.56	Moderate	0.41	0.07	16.8	-23.6	216	2.5
57	6:12:12	3.748	0.442	3.32	0.74	Moderate	0.52	0.08	16.8	-23.6	217	2.6
58	6:12:13	4.172	0.424	3.18	0.71	Moderate	0.57	0.09	16.8	-23.6	216	2.6
59	6:12:14	4.612	0.440	3.30	0.73	Moderate	0.60	0.11	16.8	-23.6	214	2.7

TABLE 1. TABULAR PRESENTATION OF DATA FROM FIGURE 2 (Continued)

	1	2	3	4	5	6	7	8	9	10	11	12
60	6:12:15	4.984	0.372	2.79	0.62	Moderate	0.67	0.12	16.8	-23.6	217	2.8
61	6:12:16	5.371	0.387	2.90	0.65	Moderate	0.69	0.13	16.8	-23.6	216	2.8
62	6:12:17	5.496	0.125	0.94	0.21	Light	0.58	0.13	16.8	-23.7	217	2.9
63	6:12:18	4.405	-1.091	de-icing	?	?	0.58	0.14	16.8	-23.6	215	2.9
64	6:12:19	3.467	-0.938	de-icing	?	?	0.58	0.15	16.8	-23.6	217	3.0
65	6:12:20	1.979	-1.488	de-icing	?	?	0.58	0.16	16.8	-23.7	217	3.1
66	6:12:21	1.666	-0.313	de-icing	?	?	0.58	0.17	16.8	-23.6	215	3.1
67	6:12:22	2.149	0.483	recovery	?	?	0.58	0.18	16.8	-23.6	214	3.2
68	6:12:23	2.466	0.317	recovery	?	?	0.58	0.19	16.8	-23.6	215	3.2
69	6:12:24	2.633	0.167	recovery	?	?	0.58	0.20	16.8	-23.7	218	3.3
70	6:12:25	2.740	0.107	recovery	?	?	0.58	0.21	16.8	-23.6	218	3.4
71	6:12:26	2.781	0.041	recovery	?	?	0.58	0.22	16.8	-23.6	218	3.4
72	6:12:27	2.860	0.079	recovery	?	?	0.58	0.23	16.8	-23.6	217	3.5
73	6:12:28	3.055	0.195	1.46	0.33	Light	0.33	0.23	16.8	-23.7	215	3.5
74	6:12:29	3.396	0.341	2.56	0.57	Moderate	0.45	0.24	16.8	-23.6	215	3.6
75	6:12:30	3.839	0.443	3.32	0.74	Moderate	0.54	0.25	16.8	-23.8	215	3.7
76	6:12:31	4.192	0.353	2.65	0.59	Moderate	0.56	0.26	16.8	-23.6	215	3.7
77	6:12:32	4.571	0.379	2.84	0.63	Moderate	0.57	0.27	16.8	-23.6	216	3.8
78	6:12:33	4.829	0.258	1.94	0.43	Moderate	0.59	0.28	16.8	-23.6	213	3.8
79	6:12:34	4.995	0.166	1.25	0.28	Light	0.53	0.29	16.8	-23.8	214	3.9
80	6:12:35	5.168	0.173	1.30	0.29	Light	0.44	0.29	16.8	-23.6	215	4.0
81	6:12:36	5.395	0.227	1.70	0.38	Light	0.40	0.30	16.9	-23.6	210	4.0
82	6:12:37	5.617	0.222	1.67	0.37	Light	0.35	0.30	17.1	-24.0	207	4.1
83	6:12:38	4.649	-0.968	de-icing	?	?	0.35	0.31	17.3	-24.3	198	4.1
84	6:12:39	3.852	-0.797	de-icing	?	?	0.35	0.32	17.5	-24.8	191	4.2
85	6:12:40	2.540	-1.312	de-icing	?	?	0.35	0.32	17.7	-25.5	186	4.2
86	6:12:41	1.738	-0.802	de-icing	?	?	0.35	0.33	17.8	-25.7	185	4.3
87	6:12:42	2.250	0.512	recovery	?	?	0.35	0.33	17.9	-26.0	187	4.3
88	6:12:43	2.491	0.241	recovery	?	?	0.35	0.34	17.9	-26.1	190	4.4
89	6:12:44	2.650	0.159	recovery	?	?	0.35	0.34	17.9	-26.2	191	4.4
90	6:12:45	2.719	0.069	recovery	?	?	0.35	0.35	17.9	-26.3	195	4.5
91	6:12:46	2.767	0.048	recovery	?	?	0.35	0.36	18.0	-26.1	199	4.6
92	6:12:47	2.788	0.021	recovery	?	?	0.35	0.36	18.0	-26.3	202	4.6
93	6:12:48	2.843	0.055	recovery	?	?	0.35	0.37	18.0	-26.4	207	4.7
94	6:12:49	3.086	0.243	1.82	0.41	Light	0.41	0.37	18.0	-26.1	212	4.7
95	6:12:50	3.451	0.365	2.74	0.61	Moderate	0.51	0.38	18.0	-26.1	217	4.8
96	6:12:51	3.726	0.275	2.06	0.46	Moderate	0.49	0.39	18.0	-26.1	220	4.9
97	6:12:52	3.938	0.212	1.59	0.35	Light	0.46	0.40	17.9	-26.1	221	4.9
98	6:12:53	4.262	0.324	2.43	0.54	Moderate	0.47	0.41	17.9	-25.9	219	5.0
99	6:12:54	4.524	0.262	1.97	0.44	Moderate	0.48	0.41	17.9	-26.4	218	5.0
100	6:12:55	4.732	0.208	1.56	0.35	Light	0.43	0.42	17.9	-26.7	218	5.1
101	6:12:56	4.981	0.249	1.87	0.41	Light	0.42	0.43	17.9	-26.7	220	5.2
102	6:12:57	5.172	0.191	1.43	0.32	Light	0.41	0.43	17.9	-26.7	221	5.2
103	6:12:58	5.364	0.192	1.44	0.32	Light	0.37	0.44	17.9	-26.6	223	5.3
104	6:12:59	5.681	0.317	2.38	0.53	Moderate	0.39	0.45	17.9	-25.9	225	5.3
105												
106			** Icing Intensities defined as:									
107			**Trace**: 1/4-inch accumulation in 1 hour or longer (less than 0.1 mm/min), (less than 1/4 inch per hour),									
108			**Light**: 1/4-inch accumulation in 15-60 minutes (0.1 - 0.4 mm/min), (1/4 to 1 inch per hour),									
109			**Moderate**: 1/4-inch accumulation in 5-15 minutes (0.4 - 1.3 mm/min), (1 to 3 inches per hour),									
110			**Heavy**: 1/4-inch accumulation in less than 5 minutes (more than 1.3 mm/min), (more than 3 inches per hour).									

Explanation of the procedure and of the formulas in the columns of table 1:

1. User pastes second-by-second recorded values of data into columns 1, 2, 9, 10, and 11.

2. Formulas in columns 3 to 8 and 12 will automatically compute the corresponding values for those columns. Columns 5 to 8 are a way to put the data in perspective and to evaluate the significance of the icing encounter.

3. The formulas operate as follows:

- Column 3 computes the second-by-second difference in the voltage output signal from the 871FA in column 2.

- Column 4 computes the icing rate indicated by the 871FA for a nominal calibration (0.5 mm per 4-volt excursion).

  If the probe in use has a different calibration, the correct calibration should be inserted into the formulas in this column.

- Column 5 computes an expected icing rate on a user-selectable wing section, tailplane, or other components of interest.

  The components will be for the actual aircraft under test. The C-130 midwing is shown only as an example.

  The values for Beta can be easily obtained from LEWICE or similar droplet impingement codes. (See [6] or the appendix in [7] for an introductory explanation and examples for other airplanes.)

  Beta depends mainly on the leading-edge radius of the component and on the airspeed and the droplet sizes in the icing cloud.

  If droplet size is not measured, a standard size of 15 microns can be assumed for the MVD. (These computations automatically account for any Ludlam limit effects due to total air temperatures near or above 0°C, because the Ludlam limit will retard any ice accretion on the 871FA probe too.)

- Column 6 converts the numerical icing rate on the component to an icing intensity according to the definitions given at the bottom of table 1.

- Column 7 computes a 5-sec running average of the icing rate on the component,

- Column 8 estimates a cumulative ice accretion depth on the component for which ice accretion is being computed. It assumes:

  (a) continual accretion (no deicing) during the encounter.

  (b) the running average icing rate during intervals when the 871FA is de-icing itself and recovering to ambient temperature.

  (c) a constant value for Beta. (This assumption is good for up to 1/4 inch (6.4 mm) of ice accretion. After that, Beta may begin to change somewhat and the estimated ice accumulation will be less accurate.)

- Column 12 computes the cumulative distance traveled in the exposure, based on the TAS values given in column 11.

Formulas used in the columns:

Col. 3: RC[-1]-R[-1]C[-1]

Col. 4: IF(dV<-0.01,"de-icing",IF(V<Baseline,"recovery",7.5*dV/dt)),

where *V* and *dV* are the adjacent values in columns 2 and 3, respectively, and *dt* and *Baseline* are constants the user enters in rows 3 and 9, respectively, of column 4.

Col. 5: IF(OR(Rate="de-icing",Rate="recovery"),"?",Rate*Betaw/Betap),

where *Rate* is the adjacent value in column 4, and *Betaw* and *Betap* are the constants the user enters in the 5th and 7th rows, respectively, of column 4.

Col. 6: IF(CompRate="?","?", IF(CompRate>1.27,"Heavy",IF(CompRate>0.423,"Moderate", IF(CompRate>0.106,"Light",IF(CompRate>0,"Trace","None")))))

where CompRate is the adjacent value computed in column 5.

Col. 7: IF(CompRate<>"?",AVERAGE(R[-4]C[-2]:RC[-2]),R[-1]C).

When the 871FA is in heater or recovery mode, the last computed value of the running average is retained as a temporary default value.

Col. 8: IF(CompRate<>"?",CompRate*(dt/60)+R[-1]C,RunAvg*(dt/60)+R[-1]C)

where *RunAvg* is the adjacent value computed in column 7.

Col. 12: (TAS/3600)*dt, where *TAS* is the adjacent value in column 11.

TABLE 2. TABULAR SUMMARY OF DATA IN FIGURE 3

Icing Exposure Record for Flight Tests (hypothetical numbers inserted for illustrative purposes.)

Aircraft model & S/N: B-210, S/N=1416 Component(s) of interest: outer wing LE

Type of ice protection system: boots

Date of Flight Test: Nov. 12, 2007 Flight Number: 2

Location: western Kansas

General cloud type(s) and conditions: deep, widespread stratus & low ceiling:(cloud base = 1000 Ft AGL @ -2C, cloud tops = 4200 Ft AGL @ -12C)

Height of freezing level (AGL): sfc to 500 (feet)

Starting with an ice-free aircraft (and no descent into warm air for de-icing)

	Exposure			On 871FA Icing Rate Meter		On Component of Interest**			Other Conditions					- - Aircraft Performance and Handling - - Level of Effect (1,2,3, or 4) on Aircraft***					Auxiliary Data - - - - - - Average - - - - - -		
No.	Start-End Time (hhmm:)	Duration (min.)	Distance (nmi)	Average Icing rate (mm/min)	Equivalent Intensity* (T,L,M,H)	Average Icing rate (mm/min)	Equivalent Intensity* (T,L,M,H)	Cumulative Ice Depth (mm)	Altitude (Ft, ASL)	OAT deg C	TAS (kt)	No. of IPS cycles during exposure	No. of IPS cycles after exposure	Speed	Power	Climb	Control	Vibration	LWC (g/m3)	MVD (μm)	Engine Pwr or EPR
1	1430 - 1441	11	28	0.7	M	0.35	L	3.9	7500	-11	150	2	1	1	1	untested	1	1			
2	1455 - 1459	4	10	0.4	L	0.2	L	4.7	7400	-10	"	0	1	1	1	"	1	1			
3	1502 - 1514	12	30	0.2	L	0.1	T-L	5.9	7000	-9	"	0	0	1	1	"	1	1			
4	1514 - 1521	7	18	1	M	0.5	L-M	9.4	7500	-11	"	2	1	1	2	2	1	1			
	Sums:	34	86																		

Notes:

* Icing intensity scale is that proposed by FAA Icing Plan Task-1B working group (2001). (T= <0.1 mm/min, L = 0.1 - 0.4 mm/min, M = 0.4 - 1.3 mm/min, H = >1.3 mm/min)

** These amounts are merely approximations for estimation and comparison purposes only. They are computed from the 871FA data simply by using the ratio of the collection efficiencies.. They give a rough idea of what may accumulate if no IPS is active on the component of interest.

*** Level-of-effect scale is that proposed by FAA Icing Plan Task-1B working group (2001). (See separate Table of Effects with definitions.)

TABLE 3. EFFECTS OF ICING ON AIRCRAFT
(From FAA Icing Plan Task-1B Working Group Proposals)

Aircraft Effect	Speed (See Note 1)	Power (See Note 2)	Climb (See Note 3)	Control (See Note 4)	Vibration (See Note 5)
Level 1	Less than 10 knots loss	Less than 10% increase required	No effect or less than 10% loss	No effect	No effect
Level 2	10-19 knots loss	10%-19% increase required	10%-19% loss rate of climb	No effect	No effect
Level 3	20-39 knots loss	20%-39% increase required	20% or more loss rate of climb	Unusually slow or sensitive response from control input	Controls may have slight vibration
Level 4	40 or more knots loss	Not able to maintain speed	Not able to climb	Little or no response to control input	May have intense buffet and/or vibration

Notes:

1. SPEED: Loss of speed due to aircraft icing. This is based on the indicated airspeed which was being maintained prior to encountering ice on aircraft and before applying additional power to maintain original airspeed.

2. POWER: Additional power required to maintain aircraft speed/performance that was being maintained before encountering icing on aircraft. Refers to primary power setting parameter, i.e., torque, rpm, or manifold pressure.

3. CLIMB: Estimated decay in rate of climb (ROC) due to aircraft icing, example10% loss in ROC, 20% loss in ROC, or not able to climb at normal climb speed with maximum climb power applied.

4. CONTROL: Effect of icing to aircraft control inputs. Levels 1 and 2. No noticeable effect on response to control input.

   Level 3. Aircraft is s low to respond to control input. Aircraft may feel sluggish or very sensitive in one or more axes.

   Level 4. Little or no response to control input. Controls may feel unusually heavy or unusually light.

5. VIBRATION/BUFFET: May be felt as a general airframe buffet or sensed through the flight controls. It is not intended to refer to unusual propeller vibration (for airplanes so equipped) in icing conditions.

Although this information is intended to be used for aircraft with approved ice protection systems, this procedure should also be used to report aircraft effects on icing encounters with all aircraft.

This chart is to be used for pilot reporting of icing effects ONLY and NOT to be used as a guide for operating in icing conditions.