SAE INTERNATIONAL

AEROSPACE INFORMATION REPORT

AIR4367™ REV. B

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Superseding AIR4367A

(R) Aircraft Inflight Ice Detectors and Icing Rate Measuring Instruments

RATIONALE

AIR4367 needed updates to incorporate new technologies and to align with the significant updates to AS5498.

TABLE OF CONTENTS

1. SCOPE

This document provides information regarding ice detector technology and design. The SAE document AS5498 provides detailed information regarding the requirements, specifications, qualification, and certification of icing detection systems. This document is not meant to replace AS5498, but to enhance it by considering unique aspects of sensing technology and, in particular, those that may not be certificated at the time of this revision. To that end, an effort has been made not to duplicate information contained in AS5498. Icing rate information is included where applicable. The primary application is associated with ice forming on the leading edges of airfoils and inlets while the aircraft is in flight. Information related to detection of ice over cold fuel tanks and icing at low-velocity operation is included. The material is primarily applicable to fixed-wing aircraft. Unique requirements for engine inlets and rotorcraft are also provided.

1.1 Purpose

The purpose of this document is to provide information regarding various in situ icing sensing technologies and issues a user of these technologies should consider regarding the method of operation, performance, design, verification, and installation of aircraft ice detectors and icing rate indicators. The intent is not to duplicate AS5498, but to supplement it in areas that may not have been deemed appropriate for such a standards document. More details on requirements and installed performance considerations are provided in AS5498.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

Many of the referenced documents are available online.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR1168/4 SAE Aerospace Applied Thermodynamics Manual, Ice, Rain, Fog, and Frost Protection

AR5624 Aircraft Inflight Icing Terminology

AS5498 Minimum Operational Performance Specification for In-flight Icing Detection Systems

2.1.2 U.S. Department of Transportation, Federal Aviation Administration (FAA) Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

Title 14 of the US Code of Federal Regulations, Part 23 Airworthiness Standards: Normal Category Airplanes (14 CFR Part 23).

Title 14 of the US Code of Federal Regulations, Part 25 Airworthiness Standards: Transport Category Airplanes (14 CFR Part 25).

Title 14 of the US Code of Federal Regulations, Part 27 Airworthiness Standards: Normal Category Rotorcraft (14 CFR Part 27).

Title 14 of the US Code of Federal Regulations, Part 29 Airworthiness Standards: Transport Category Rotorcraft (14 CFR Part 29).

2.1.3 AGARD Publications

Available from http://www.rta.nato.int/.

AGARD Advisory Report No. 127 Aircraft Icing, November 1978.

AGARD Advisory Report No. 166 Rotorcraft Icing - Status and Prospects, August 1981.

AGARD Advisory Report No. 223 Rotorcraft Icing - Progress and Potential, September 1981.

2.1.4 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM F3310 Standard Specification for Non-Essential Ice Detectors for Aircraft

2.1.5 Other Applicable Documents

Hansman, R. J. Jr. and Kirby, M. S., Real Time Measurement of Ice Growth During Simulated and Natural Icing Conditions Using Ultrasonic Pulse-Echo Techniques, AIAA Paper 86-0410, January 6-9, 1986.

Magenheim, B and Rocks, J. K., A Microwave Ice Accretion Measurement Instrument (MIAMI), AIAA Paper 82-0385, May 1983.

NASA Tech Brief, Vol. 19, Issue 7, pg 48, July 1995.

NASA Tech Brief, Vol. 25, Issue 7, pg 48, July 2001.

Sinnar, A., Infrared Icing Monitoring Technique for Aircraft/Helicopter Application, SAE/AHS Icing Technology Workshop, Cleveland, Ohio, September 21-22, 1992.

Stallabrass, J. R., Review of Icing Protection for Helicopters, NRC LR-334, 1962.

2.2 Related Publications

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

Jackson, D.G, J.Y. Liao and J.A. Severson: An Assessment of Goodrich Ice Detector Performance in Various Icing Conditions: 03FAAID-36, SAE International, FAA In-flight Icing/Ground De-icing International Conference and Exhibition, Chicago, June 2003.

Jackson, Darren G. and Goldberg, Joshua I.: Ice Detection Systems: A Historical Perspective, SAE International publication 2007-01-3325, SAE Aircraft & Engine Icing International Conference: September 2007, Seville, Spain.

2.2.2 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

RTCA DO-160 Environmental Conditions and Test Procedures for Airborne Equipment, July 29, 1997

RTCA DO-178 Software Considerations in Airborne Systems and Equipment Certification, December 1992

RTCA DO-254 Design Assurance Guidance for Electronic Hardware, April 2000

2.2.3 U.S. Department of Defense (DOD) Publications

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, https://quicksearch.dla.mil/.

MIL-HDBK-310 Global Climatic Data for Developing Military Products

MIL-HDBK-5400 Electronic Equipment, Airborne, General Guidelines for

MIL-STD-704 Aircraft Electrical Power Characteristics

2.2.4 U.S. Department of Transportation, Federal Aviation Administration (FAA) Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov. The FAA Icing Handbook is available through National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, Tel: 800-553-6847 or 703-605-6000, www.ntis.gov.

Title 14 of the US Code of Federal Regulations, Part 33 Airworthiness Standards: Aircraft Engines (14 CFR Part 33).

DOT/FAA/CT-88/8-I, "Aircraft Icing Handbook," March 1991.

Advisory Circular 20-73A (or later revision), Aircraft Ice Protection, August 16, 2006.

2.2.5 Other Publications

American Meteorological Society Glossary of Meteorology, 2001 (available from American Meteorological Society, Boston, MA).

ASTM F3120 Standard Specification for Ice Protection for General Aviation Aircraft

Cober, S.G., G.A. Isaac and A.V. Korolev: Assessing the Rosemount icing detector with in-situ measurements. J. Atmos. Oceanic Tech., 18, 515-528, 2001.

Eurocontrol, Aeronautical Information Manual, October 1996.

Jackson , D.G., D.J. Cronin, J.A. Severson and D.G. Owens: Ludlam Limit Considerations on Cylinder Ice Accretion: Aerodynamics and Thermodynamics, AIAA-2001-0679, 39th Aerospace Sciences Meeting & Exhibit, Reno, Nevada, 2001.

Mason, J.G., Strapp, J.W., Chow, P.: The Ice Particle Threat to Engines in Flight, AIAA 2006-206, 44th Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2006.

Mazin, I.P., A. V. Korolev, A. Heymsfield, G. A. Isaac, S. G. Cober: Thermodynamics of an Icing Cylinder for Measurements of Liquid Water Content in Supercooled Clouds. J. Atmos. Oceanic Tech., 18, 543-558, 2001.

NASA TM 78118, Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development, Nov. 1977.

Maris, J. M.: Real-time Airfoil Performance Monitoring and Stall Detection, The SETP Canada Symposium, Ottawa, Canada, 1999.

Maris, J. M.: Airfoil Performance Monitoring Using the Turbulence Intensity Parameter, FAA International Conference in Aircraft Inflight Icing, 1996.

Gordon, L.: Combating the Stall, Skies Magazine, April 12, 2019.

2.3 Definitions

Terminology used in this document is consistent with AIR5504. Specific definitions are listed below where multiple definitions exist or are absent in AIR5504.

CLEAR AIR: Air in which no visible liquid water drops, snow, ice crystals, etc., are present (refer to AIM).

ICING RATE INDICATOR: A device that provides an indication of the rate that ice is accreting on the device's sensing element.

NOTE: Ice accretion rate on any specific aircraft surface may differ from the icing rate indicator due to the influence of the local geometry. Usually the icing rate indicator is correlated to the aircraft surface to account for the difference.

INDUCTIVE TRANSDUCER: A device that provides an indication of a change in resonance resulting from a change in self-inductance.

MICROWAVE: A very short wavelength or high frequency (1 to 100 GHz).

NONICING CONDITIONS: Above-freezing conditions or clear air; for engine inlets, temperatures above 10 °C (50 °F).

NONINTRUSIVE: Flush with the aerodynamic surface, causing no disturbance to the flow field.

PIEZOELECTRIC: The property of a material (usually ceramic) that causes it to change dimensions and vibrate when subjected to a high-frequency electric field. In ice detectors, the shift in resonant frequency is used to indicate ice buildup.

ROTORCRAFT: Aircraft powered by a rotor operating approximately in a horizontal plane, or an aircraft where the rotor can be moved from a horizontal plane to a vertical plane. They are also known as helicopters, rotary wing aircraft, or tiltrotor aircraft. (Some distinguishing features pertinent to ice detection are low forward velocity and rotor downwash.)

SENSITIVITY: The ability to detect slight amounts (or slight differences in amounts) of ice accretion.

2.4 Abbreviations

AGARD: Advisory Group for Aerospace Research and Development

AIAA: American Institute of Aeronautics and Astronautics

AIR: Aerospace Information Report (SAE)

AIM: Aeronautical Information Manual

AISLIS: Advanced Icing Severity Level Indicating System

APMS: Aerodynamic Performance Monitoring System

AS: Aerospace Standard (SAE)

CFR: Title 14 of the US Code of Federal Regulations

DOT: Department of Transportation

EM: Electromagnetic

FAA: Federal Aviation Administration

FAAIH: HFAA Icing Handbook

FIDS: Flight Icing Detection System

FPD: Freezing point depressant

LWC: Liquid water content

MVD: Median volumetric diameter

NACA: National Advisory Committee for Aeronautics

NASA: National Aeronautics and Space Administration

NRC: National Research Council

OAT: Outside air temperature

RTCA: Radio Technical Commission for Aeronautics

TAT: Total air temperature

TM: Technical memorandum

µm: Micrometer or micron (one-thousandth millimeter)

3. ICING INSTRUMENTATION CLASSIFICATIONS

Icing instrumentation systems provide information to the flight crew and/or airplane systems concerning inflight icing. Components of the system may be intrusive or non-intrusive to the airflow. The system may be directly or indirectly sensitive to the physical phenomena of inflight icing. Icing instrumentation systems are divided into two types: Flight Icing Detection Systems (FIDS) and Aerodynamic Performance Monitoring Systems (APMS). FIDS are further divided into those that detect ice accretion and those that detect icing conditions. .

Icing instrumentation systems may include a processing unit to perform signal processing, sensor monitoring, data communication, or other functions. The processing unit may either be integrated with or separate from the sensor(s). Icing instrumentation systems may be connected to a device to provide information to the cockpit crew and/or communicate with other onboard equipment or systems.

When considering the type of icing instrumentation best suited for a particular application, it is important to distinguish between different classes, because each option has its appropriate implementation. For the desired application, consider if it is better to use a device that:

- Requires pilot monitoring, or can alert the pilot and/or aircraft systems without pilot attention (passive versus active)
- Protrudes from the side of the aircraft or not (intrusive versus non-intrusive)
- Directly measures on an area of interest or monitors that area remotely (measure versus monitor)
- Simply indicates “icing,” or indicates the type of icing (detect versus differentiate)

3.1 Flight Icing Detection Systems

A FIDS that detects ice accretion informs the flight crew and/or systems about the presence of ice accretions on a reference airplane surface, i.e., the FIDS sensing element surface. FIDS that detect ice accretion may also inform the crew or a system about ice thickness, ice accretion rate, LWC, cloud droplet size, and/or accretion location. FIDS that detect ice accretion may be located on or remote from the monitored airplane surfaces.

A FIDS that detects icing conditions provides information to the flight crew and/or airplane systems concerning atmospheric icing conditions. The output of a FIDS that detects icing conditions informs the flight crew and/or airplane systems about the presence of atmospheric conditions that are conducive to the accretion of ice on airplane surfaces. A FIDS that detects icing conditions is not necessarily sensitive to the presence of ice accretions.

3.2 Aerodynamic Performance Monitoring System

An Aerodynamic Performance Monitoring System (APMS) informs the flight crew and/or airplane systems about aerodynamic performance degradation, which may be due to ice accretions, over monitored surfaces. This aerodynamic performance degradation may result in degraded airplane performance and handling qualities. An APMS is not directly sensitive to ice accretions.

3.3 Classification by Sensing Method

Flight Icing Detection Systems that detect ice accretion include the following classes:

- Makes a measurement on a sensing surface separated from the surface of interest (e.g., probe type sensors)
- Makes a measurement on a sensing surface which is part of the surface of interest (e.g., flush mounted sensors)
- Makes a remote measurement on a sensing surface which is part of the surface of interest (e.g., observation of the wing from the fuselage)

Flight Icing Detection Systems that detect icing conditions include the following classes:

Directly sensitive to environmental inflight icing conditions:

- Methods that measure directly the characteristics of the Atmospheric conditions that might be conducive to ice accretion on the aircraft surfaces. For example, techniques may remotely measure liquid water drops size, liquid water drop concentration and/or ice crystals in the airflow (e.g., Drops or ice crystals Imaging, optical sensors, Lidar, Radar, Radiometer, etc.).

Indirectly sensitive to environmental inflight icing conditions:

- Methods that indirectly measure the characteristics of the environmental inflight icing conditions by measuring the induced effect of the conditions on a sensing element. Such techniques may be sensitive to the presence of ice and/or water and/or heat exchange and/or aerodynamic degradation.

3.4 Ice Detection Implementation

3.4.1 Primary Detection Systems

A primary ice detection system is the only required means of providing its function and may automatically implement actions required for safe inflight icing operations without flight crew intervention (an automatic primary ice detection system may or may not provide ice accretion or environmental inflight icing conditions information to the flight crew). A primary ice detection system may also provide ice accretion or environmental inflight icing conditions information to the flight crew and the flight crew is required to manually implement aircraft flight manual procedures to ensure safe inflight icing operations. A primary ice detection system may provide icing environment characteristics information.

3.4.2 Advisory Ice Detection Systems

For an aircraft using an advisory system, activation of the ice protection system is the responsibility of the pilot, typically using visual cues (e.g., visible moisture, ice on protrusions visible from the cockpit, etc.) and a TAT near freezing (e.g., 10 °C [50 °F] or below). An advisory ice detection system provides advisory ice accretion or environmental inflight icing conditions information used by the flight crew in the decisions that aircraft and/or engine icing is present and that implementation of aircraft flight manual procedures for inflight icing operations is required. This advisory information cannot be the only available ice detecting cue, but is used with other aircraft flight manual identified icing detecting cues to confirm aircraft and engine icing. The ice detection system is used only as an additional “advisory” indication. This allows lower reliability requirements for the ice detection system relative to meeting the requirements of CFR 14 section 1309 of parts 23, 25, 27, or 29 (or equivalent regulation).

3.4.3 Non-Required Safety Enhancing Equipment (NORSEE)

Ice detectors can also be certified as non-required safety enhancing equipment under FAA NORSEE rules. In this category, the ice detector may not be relied on by the pilot and is only allowed to interface with aircraft power and a method of display for the indication of ice. More information can be found in ASTM F3310.

4. ICE DETECTION METHODS

A number of methods can be used to detect ice formation on aircraft. This section describes concepts that have been certificated or qualified as well as those in various stages of development. The list is not meant to be exhaustive. More detailed information can be found in DOT/FAA/CT-88/8-1, AGARD Advisory Report No. 127, Stallabrass [1962], Magenheim [1983], and Hansman [1986].

Only ice detector concepts are described in this section. Most concepts can be leveraged to provide icing rate if a signal proportional to ice thickness can be generated. Accretion-based detectors and icing rate sensors generally require periodic deicing and cannot detect during the deicing sequence. Usually during this time the icing status (or icing rate) just prior to deicing is reported. While this report does not cover methods for choosing a type of ice detector for a specific application, it should be noted that different techniques have different limitations (e.g., local aerodynamic effects for accretion-based devices and sunlight contamination for optical devices), many of which can be overcome by proper integration with the aircraft.

4.1 Passive Techniques

4.1.1 Visual

One of the simplest methods of detecting icing conditions is for the pilot to note ice accretion on the unprotected portion of the windshield, windshield wiper, engine inlet/spinner, or some protruding element in the pilot's field of view (windshield wiper bolt, for example). Other common methods are for the pilot to monitor the temperature and the presence of visible moisture or to watch instruments for response changes indicative of icing such as torque in a rotorcraft. Icing rate information can be inferred from the visual observations. It is possible to differentiate drop diameters if a surface in the field of view of the pilot is capable of inertially separating impinging drops.

4.1.2 Audible

Audible cues include listening for the sound of atmospheric particles impacting the aircraft (more specific to ice crystal conditions) or the sound of ice being shed from surfaces such as propellers.

4.1.3 Tactile

Tactile methods include sensing the increased vibration of a rotorcraft that has accumulated ice in flight.

4.1.4 Illumination

For night ice detection, airplane-mounted illumination of airplane surfaces that are critical relative to ice accumulation is usually provided. A red light shining upward on the inside of a windshield has also been used. Normally the red light shines through the windshield and is inconspicuous to the pilot. When ice is accumulated, the red light diffuses and provides an indication of ice accumulation. Similar concepts have been used in illuminating a translucent rod in the pilot field of view that highlights ice accumulation. Use of a hand-held flashlight has not been considered acceptable due to associated flight crew workload. With lighting, the daytime techniques can be used in nighttime.

4.2 Active Techniques

4.2.1 Ice Accretion Devices

4.2.1.1 Obstruction

The obstruction-type ice detector consists of a scraper rotating on a surface. As ice accretes on the surface, the torque required to rotate the scraper increases. At a preset torque, a signal is generated causing the surface to be deiced electrically. Icing rate can be determined by the slope of the torque versus time curve.

4.2.1.2 Differential Pressure

This concept uses a probe to sense total air pressure through several small orifices (0.4 mm [0.016 inch]) on its forward face. This pressure is sensed by one side of a differential pressure sensing device with aircraft total pressure fed to the opposite side. As ice blocks the total pressure orifices, the pressure is bled to static and a differential pressure signal is created. This concept was originally developed by the National Advisory Committee for Aeronautics (NACA) in the early 1950s.

4.2.1.3 Latent Heat

Two types of ice detectors use the latent heat-of-fusion to indicate the presence of ice. Either detector can be used as an icing rate detector by using suitable electronics to interpret the output signal.

The first uses a periodic current pulse through a resistance element to heat a probe. If ice has accreted on the probe, the temperature increase will be temporarily halted at 0 °C (32 °F). Electronic equipment senses and indicates this condition. Figure 1 illustrates one implementation of this concept which is currently used on the B-1B aircraft.

The second concept provides indication of icing conditions by measuring the power required to maintain a probe at a predetermined temperature (typically 90 °C (194 °F)). The instrument must be "zeroed" in non-icing conditions. The increase in power caused by the impingement of water drops indicates the presence of water; icing conditions may be assumed below a TAT of 10 °C (50 °F).

© Ultra Electronics

Figure 1 - Self-contained, engine-inlet ice detector (B-1B aircraft) using latent heat principle

4.2.1.4 Vibration

Ice on a vibrating surface has three effects:

a. Increased mass decreases the resonant frequency

b. Increased stiffness increases the resonant frequency

c. Increased damping decreases the amplitude of oscillation

Ice detectors have been manufactured using the first two physical principles and the technology can provide icing rate data.

The most common ice detector in use today uses an axially vibrating cylindrical probe as a sensor. The probe is oriented generally perpendicular to the air stream. As ice accretes, the mass increases and the resonant frequency decreases. The device is intrusive by design. A derivative of this design uses a flush diaphragm vibrated at its natural frequency. As ice accretes, the increased stiffness predominates, increasing the resonant frequency. This derivative may be suitable in applications where a non-intrusive solution is desired.

Piezoelectric, magnetostrictive, or inductive transducers are most commonly used to put the sensor in oscillation and read the resonant frequency. The working frequency of such a device is normally between 15 and 100 kHz, with a typical frequency change due to ice of approximately 100 Hz (for ice detection devices) to 50 kHz (for ice thickness measurement devices). Ice detectors using these principles can detect and measure the thickness from 0.13 mm (0.005 inch) up to 25.4 mm (1.0 inch) of ice. Combining the rate of change of frequency with airspeed information can allow this technique to calculate the liquid water content of the icing condition being encountered to tolerances of approximately ±30%.

Figure 2 shows a flush-mounted magnetostrictive ice detection system used on an MD-80 commercial transport aircraft. One sensing unit on each wing is used to detect ice on the wing upper surface.

Figure 3 illustrates an application of the magnetostrictive vibratory principle used on aircraft to sense inflight icing. The electronics are integrated into a single unit, which uses a magnetostrictive probe to collect and sense ice. The decrease in resonant frequency due to the mass of ice on the sensor is used as an indication of icing. Alternate application may locate the sensing element in the engine with the electronic processor located in another section of the aircraft. As in Figure 2, the effect of ice mass is used to indicate icing.

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Figure 2 - Flush-mounted MD-80 wing upper surface ice detector using a magnetostrictive vibrated diaphragm

© Collins Aerospace

Figure 3 - Ice detector using magnetostrictive vibratory principle

4.2.1.5 Microwave

One implementation of microwaves to detect ice is a microwave transducer that consists of a resonant surface waveguide embedded non-intrusively into the surface on which the ice accretes. The surface waveguide is constructed from dielectrics, such as polyethylene, with dielectric properties similar to that of ice. When ice accretes on the dielectric surface, it acts as a part of the waveguide, effectively thickening it and changing its phase constant. In this implementation, the waveguide is designed to be resonant in the absence of ice by suitably adjusting the dimensions of its metallic boundaries but allowing its single dielectric surface to be exposed to the surface on which ice accretes. The accretion of ice causes a change in the phase constant, lowering its resonant frequency. Instrumentation calculates the ice thickness from the shift in resonant frequency. The device can act as an ice detector, an icing rate meter, and as an LWC meter.

Ice thickness up to 25 mm (1 inch) has been measured using this technology in the laboratory. In theory, even larger thicknesses are possible. This implementation has been successfully flight tested behind a tanker aircraft on a Cessna Crusader 303 aircraft under a nonoperating pneumatic boot. The microwave concept has no moving parts and has a very high resolution, making it adaptable for either detection of incipient icing conditions or accurate measurement of icing rate. The device can operate with a protective cover and survive extremely harsh environments. The microwave device can be designed to ignore the effects of water and other liquid contaminants, or these effects can be measured with suitable instrumentation. For more detailed information, refer to Magenheim [1983].

4.2.1.6 Electromagnetic (EM) Beam Interruption

This concept uses an EM source placed on one side of a flattened tube, directed at a sensor on the opposite side of the tube. As ice accretes on the tube, the signal is blocked, and an electronic unit senses the interruption in sensor signal.

Various source/sensor combinations can be used such as visible light, infrared, laser, and nuclear beam. This concept has been used to provide icing-rate information.

4.2.1.7 Pulse-Echo (Ultrasonic)

High-frequency sound waves are reflected at an ice/air interface. To use this phenomenon to detect ice, a small piezoelectric transducer has been mounted flush with an aircraft surface (e.g., a wing leading edge). The transducer emits ultrasonic waves at the surface. If ice is present, the reflected waves will be received by the transducer and processed electronically. The ice thickness can be determined from the time delay between pulse emission and reception and the speed of sound in ice. Accurate and sensitive indications of ice have been obtained for both rime and glaze ice. By using the proper signal processing, minimum ice thickness and icing rate can be determined. This concept has a distinct advantage of being applicable to non-intrusive ice detectors. For more detailed information, refer to Hansman [1986].

4.2.1.8 Impedance

This technology can provide ice detection coverage over a broad area of the wing leading edge in a non-intrusive manner. It is installed on the surface on which ice forms with wide area sensing. The system utilizes impedance measurement technology to determine the presence of ice and is certified for the Piper Malibu/Mirage PA-46-310P and PA-46-350P. Performance benefits of the system include:

- Can be installed integral to leading edge or placed directly on the surface.
- Direct measurement of ice build-up on areas of interest.
- Ice detection capability over flat or curved surfaces.
- Sensor detection area can be tailored for each specific application.
- Detection of as little as 0.020 inch of nominal ice buildup.
- Integration capability with the aircraft ice protection system.

- Installation without airplane structural changes.
- Aerodynamically flush.
- App C and O (SLD) ice feedback capability.

4.2.1.8.1 System Development Overview

The system is designed to detect the presence of ice on the surface of concern using impedance measurement technology.

In a wing application the system configuration could have a flush mounted sensor in each wing and a controller. In flight, the sensors provide wide-area ice detection coverage capability while being insensitive to rain, snow, crystal, hail and other environmental conditions.

The sensor signals are automatically and continuously monitored by the controller which analyzes the impedance sensor signals and determines the presence of ice. The wing ice data can be transmitted to the ice protection system by discrete or RS422 interface.

The sensors are mounted in or on the airfoil. The sensor uses electrodes that are flush to the airfoil surface to produce an effective ice sensing area that extends chordwise around the leading edge. It allows ice to be detected during different AOA excursions.

Each device also has a corresponding temperature sensor that is used for sensor signal analysis and system diagnostics.

4.2.1.8.2 Airfoil Material Compatibility

The technology is compatible with airfoils made from aluminum alloys and composite materials. The sensor packet can be bonded directly to the surface or built integral to the leading edge assembly.

4.2.1.8.3 System Coverage

The desired electrode surface area defines the active sensing area. The electrode sensor can be 51 to 914 mm (2 to 36 inches) in length and 25 mm (1 inch) in width for effective area coverage of 1275 to 22850 mm^2 (2 to 36 in^2).

4.2.1.8.4 Sensor Location

The impedance sensor packet can be installed in any location defined by the customer. The recommended practice is to install the sensors in a location that accumulates ice before other locations on the airfoil/structure.

4.2.1.9 Optically Occluding

This concept consists of an optical source that directs radiation at an optical receiver. An example of this type of detector is shown in Figure 4. An accreting surface is in close proximity to the radiated beam and accreting ice is sensed when it blocks the path of the beam. This concept can also be used to compute icing rate.

© Curtis Wright

Figure 4 - Ducted optically occluding ice detector system

4.2.1.10 Optically-Refractive

This approach senses light refracted from accreted ice. An example of this type of detector is shown in Figure 5. Intrusive to the airstream and hermetically sealed, it uses un-collimated light to monitor the opacity and optical index-of-refraction of whatever substance is on the probe. It is desensitized to ignore a film of water. It has no moving parts, and is completely solid.

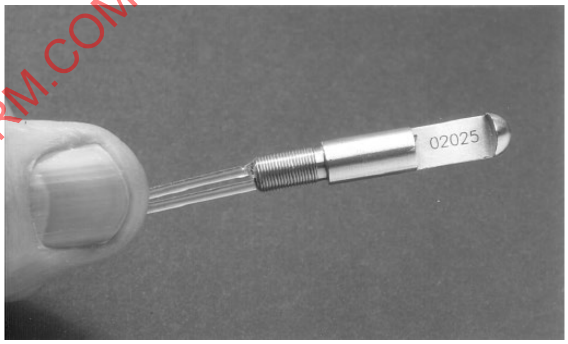

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Figure 5A - With no mounting hardware

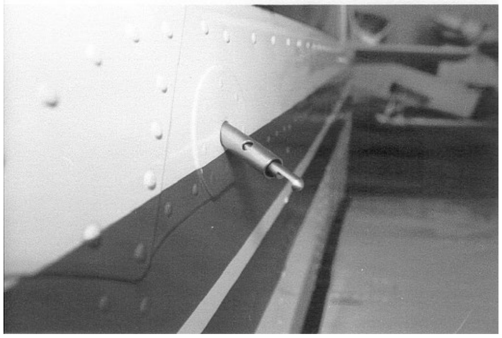

Figure 5B - Probe embedded into an aircraft outside air temperature gauge

Figure 5 - Refractive-based ice detecting transducer

The transducer probe works as a combined optical spectrometer and optical switch. A change in opacity registers as rime ice. A change in index-of-refraction registers as clear ice. The wavelength of the transducer's excitation light is not visible to the human eye, so as not to be construed as any kind of navigational running light.

The detector can be installed on any type air vehicle with enough air speed to keep water from accumulating on the optics, and can be embedded into host aerospace systems such as antennas or anti-icing systems.

Optically-refractive ice detectors can be small, lightweight, sensitive, robust, and low powered. Installation typically requires the detector probe to be mounted in the airstream beyond the boundary layer. Probes may require periodic cleaning with a solvent such as isopropyl alcohol.

Transducer probe deicing can be hastened by incorporating an electric heating element. This type of detector can offer substantial adjustment range of drive level and returned signal amplification, and can be applied to operate in a wide variety of applications and sensitivities, down to 0.025 mm (0.001 inch) of ice.

4.2.1.11 Optical Absorption

This working principle is based on the absorption of one of the two wavelengths used to illuminate an ice accretion area, or ice catch area. When the ice catch area is clean of ice the contrast between the two reflected wavelengths is 0. When ice is present the contrast goes up to 0.6 depending on the ice thickness. The detection threshold is a few micrometers.

Successive measurements of the ice thickness over time give an indication of the ice accretion rate and the severity of the encountered icing conditions. The LWC may be deduced from the ice accretion measurement and the true airspeed. The ice catch area is heated to clean the ice for the next detection cycle, or to detect exit of icing conditions.

During each detection cycle the ice catch area is cooled down a few degrees below zero to maintain a margin below the Ludlam limit, and detect icing conditions before accretion occurs on critical surfaces. This last feature is of great interest for the certification of a primary ice detection system including these detectors.

Operational in icing conditions specified in FAA 14 CRF Part 25 Appendix C and Appendix O, the detector is not disturbed by ice crystals to detect and announce the water part of mixed phase icing conditions. It has also demonstrated during flight test and during icing wind tunnel test campaigns its ability to detect ice crystals. An image of the device is shown in Figure 6.

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Figure 6 - Optical absorption based ice detector

4.2.1.12 Infrared

The Infrared Icing Monitoring Technique uses light absorption by the ice/water layer at multiple wavelengths to detect and measure accretion thickness of both ice and water. The selection of wavelengths at which ice absorption coefficients differ substantially from those of water allows detection and measurement of ice/water thickness from a few micrometers to several centimeters. Retroreflectors, flush-mounted at desired detection sites, receive and reflect the attenuated light beam back to a light emitter/receiver unit for signal processing. This non-intrusive and remote sensing technique is suitable for use on an aircraft to detect both static and inflight icing conditions, and to automatically actuate a de/anti-icing system at optimum time intervals. For more detailed information, refer to Sinnar [1992] and NASA Tech Briefs [1995] and [2001].

4.2.1.13 Thermal Flow

The thermal flow concept is implemented into a surface-type ice detector sensor that measures the heat flow change through the surface of a wing, occurring when wing surface contaminants, such as frost, deicing fluids, and ice, build up on the surface. The change in condition, detected by the sensor, is brought into the signal processor, where it is compared to a calculated heat flow value for a dry wing surface using ambient air and fuel temperature sensor inputs. The difference in the heat flow characteristics of the wing is calibrated to indicate specific conditions, such as ice.

4.2.1.14 Ultrasonic

Separate transmitting and receiving transducers are used to establish and measure flexural elastic waves in a surface subjected to ice. This implementation yields a measure of the average ice thickness in a particular region (from centimeters to meters in length). Laboratory tests have demonstrated accurate ice measurement up to 10 mm (0.39 inch) in a reliable, non-intrusive installation. The concept provides the capability for self-test on the ground and in flight.

4.3 Icing Conditions Devices

4.3.1 Optical Interferometry

This optical technique, developed about 30 years ago, is a known technique for measuring size of spherical droplets in a plane (two-dimensional analysis), commonly called Interferometric Laser Imaging for Droplet Sizing (ILIDS), or Interferometric Particle Imaging (IPI), or also Mie Scattering Imaging (MSI).

According to this technique, the water droplets are illuminated by a laser sheet and observed at a specific angle. Two luminous points, called glare points, are visible on the surface of the droplets and create an interference pattern in the form of parallel fringes when they are imaged outside the focal plane. The interfringe, the distance between two successive fringes, is proportional to the distance between the two glare points, representing the droplet diameter. When a non-spherical solid ice crystal is illuminated by the laser sheet, a multitude of glare points are visible on the surface of the crystal. The out-of-focus image does not show fringes, but instead a speckle pattern whose grain is inversely proportional to the largest dimension of the visible particle.

The icing condition detector implementing this technology acquires non-focal plane images of a portion of the space illuminated by a laser sheet. Interferometric fringes or the speckle patterns are segmented by image processing to identify the presence and amount of droplets or ice crystals. A spatial frequency analysis of the segmented regions gives the size of the particles, whether liquid or solid. Thanks to this technology it is possible to discriminate App O and App C conditions and calculate LWC and IWC. An image of the device is shown in Figure 7.

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Figure 7 - Interferometry-based ice detector

4.3.2 Optical Scatter

Optical scattering techniques for ice detection look at the change in properties of light when an active light source, such as a laser or Light Emitting Diode (LED), is reflected by water droplets or ice crystals. A variety of techniques apply Mie theory of scattering and absorption to determine properties of the icing cloud. These include one or a combination of the following:

Forward scatter: the icing cloud is between the light source and the detector in a pitch/catch arrangement.

Backscatter: the detector is co-located with the light source and analyzes light reflected directly back.

Side scatter: the detector is in a location/angle somewhere between forward scatter and backscatter.

Some optical scatter devices use pulsed light sources. With sufficiently fast electronics, the speed of light can be used to determine the time and therefore the distance that the light traveled before reflecting back off a particle, making it a type of LIght Detection And Ranging (LIDAR) device. This allows for range-gating of the data collected. Water content can be determined by analyzing the amount of reflected light as a function of range (distance).

By polarizing the light source and analyzing whether there is a change in polarization upon reflection from an icing particle, an optical scattering device can determine whether the particle is liquid or solid water. Information on particle size can also be determined by looking at the intensity of the reflection or by examining the difference in absorption of more than one wavelength of light. An image of the device is shown in Figure 8.

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Figure 8 - Optical scatter-based ice detector

4.4 Aerodynamic Performance Monitors

Aerodynamic Performance Monitors aka Airfoil Performance Monitors (APM) directly measure the turbulence intensity ratio “R” on the suction surface of an airfoil, and use this non-dimensional parameter as a proxy for airfoil “aerodynamic stress.” Through extensive experimentation, the R parameter has been found to correlate closely with the airfoil’s lift-curve slope and maximum lift coefficient, even with contamination such as leading-edge icing present. Evaluations have been conducted for frost conditions, simulated using 40-grit sandpaper, through moderate ice, to critical ridge-ice formations. Although APM systems do not measure the icing directly, they do reflect the aerodynamic consequences of ice accretion in terms of the maximum lift coefficient that contaminated airfoil can produce. APM systems can also be used in conjunction with ice-detector and angle-of-attack systems to give a complete picture of the airfoil performance. APM systems can be used to monitor wing, tail, or fin airfoils. APM systems typically have no moving parts, and can use a variety of pressure and velocity transducers to extract the turbulence intensity parametric data from the locally-sensed airflow. Images of the device are shown in Figure 9.

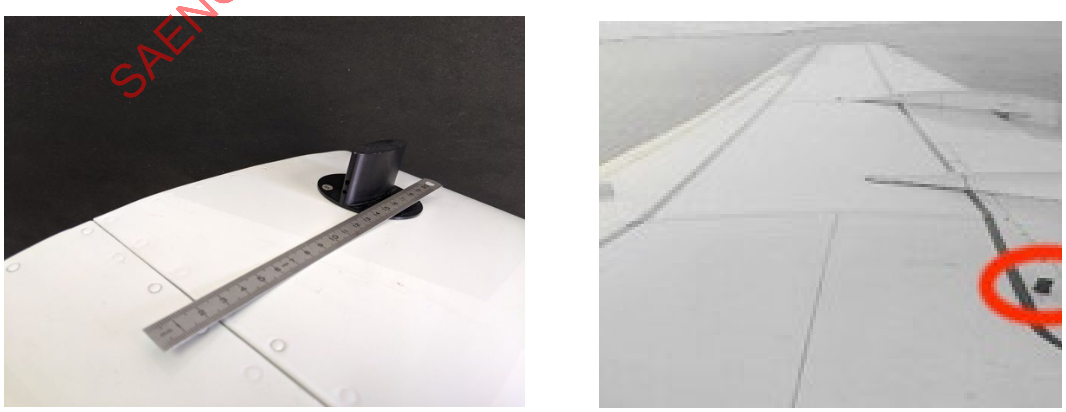

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Figure 9 - Aerodynamic performance monitor