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Superseding AIR4367

Aircraft Inflight Ice Detectors and Icing Rate Measuring Instruments

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RATIONALE

Rationale for revising this document was driven by the need to harmonize it with the more recently issued SAE document AS5498, and to provide technical updates. AS5498 defines Minimal Operational Specifications for Inflight Icing Detection Systems, whereas this document provides guidance information on ice detection technologies and applications.

1. SCOPE

This document provides information regarding ice detector technology, design and operating requirements. The SAE document AS5498 Minimal Operational Specification for Inflight Icing Detection Systems 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.

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 publication 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, 400 Commonwealth Drive, Warrendale, PA 15096-001.

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

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AIR5504	Aircraft Inflight Icing Terminology
AS5498	Minimum Operational Performance Specification for In-flight Icing Detection Systems

2.1.2 U.S. Government Publications

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

Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

MIL-HDBK-310	Global Climatic Data for Developing Military Products
MIL- HDBK-5400	Electronic Equipment, Airborne, General Guidelines for
MIL-STD-704E	Aircraft Electrical Power Characteristics

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

Available from FAA, 800 Independence Avenue, SW, Washington, DC 20591. The FAA Icing Handbook is available through National Technical Information Service Springfield, Virginia 22161 (800)-553-6847 or (703)-605-6000.

Advisory Circular 20-73A, Aircraft Ice Protection, August 16, 2006.

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)

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

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

2.1.3 Other Publications

AGARD publications available from http://www.rta.nato.int/. RTCA publications are available from RTCA, Inc., 1828 L Street, NW, Suite 805, Washington, DC 20036-4008 or fax to 202-833-9434.

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 198l

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

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

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

2.2 Applicable References

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

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

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

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

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

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

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

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

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

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

2.3 Definitions

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

ANTI-ICING: The prevention of ice buildup on the protected surface, either by evaporating the impinging water or by allowing it to run back and freeze on noncritical areas (from AIR 1168/4).

ASPIRATED: The use of suction to draw a sample of ambient air for ice detection with low forward velocity.

CIRRUS CLOUD: A high level (20,000 - 30,000 ft.) thin, stratiform ice crystal cloud. Larger ICE CRYSTALS often trail downward in wisps called "mare's tails." Detached cirriform elements in the form of feather-like white patches or narrow bands have little turbulence or potential for icing (from FAAIH).

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

CLEAR ICE: See "Glaze Ice.”

CUMULIFORM CLOUDS: Cumuliform cloud in the form of individual detailed elements which have flat bases and dome-shaped tops.

CUMULUS: A principal cloud type in the form of individual, detailed elements that are generally dense and possess sharp nonfibrous outlines.

DEICING: The periodic shedding of small ice buildups by destroying the bond between the ice and the protected surface, either by mechanical, thermal, or freezing point depressant (FPD) fluid means (from AIR1168/4).

GLAZE ICE: A glossy, clear, or translucent ice formed by relatively slow freezing of supercooled water drops.

ICE DETECTOR: A system that informs the cockpit crew about ice accretion on monitored airplane surfaces (from AS5498).

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.

ICING SEVERITY SYSTEM: A system that provides information regarding the severity of the icing encounter either in terms of LWC or in terms of light, moderate and heavy icing.

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

INTRUSIVE: Regarding a FIDS in which the sensing element is located outside (intrudes beyond) the boundary layer.

LIQUID WATER CONTENT (LWC): The total mass of water contained in liquid cloud drops within a unit volume of cloud, usually given in units of grams of water per cubic meter of air (g/m^3) (from FAAIH).

MEDIAN VOLUMETRIC DIAMETER (MVD): The drop diameter which divides the total water volume present in the drop distribution in half, i.e., half the water volume will be in larger drops and half the volume in smaller drops. The value is obtained by actual drop size measurements.

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

MONITORED SURFACE: The surface of concern regarding an ice hazard (e.g., the leading edge of the wing)

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.

OUTSIDE AIR TEMPERATURE (OAT): The static temperature of the ambient freestream air (outside the aircraft).

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.

REFERENCE SURFACE: The surface where a FIDS sensor makes its measurement (e.g., the intrusive part of a probe system).

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.

STRATIFORM CLOUDS: A cloud species characterized by a flattened appearance and spread out in an extensive horizontal layer; low, middle, or high level layer clouds, characterized by extensive horizontal rather than vertical development (from FAAIH).

STRATUS: A low level (< 6500 ft.) STRATIFORM CLOUD with a uniform, gray, sheet-like appearance resembling fog. No turbulence, but can create serious icing due to distance (from FAAIH).

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
AMS	American Meteorological Society
APMS	Aerodynamic Performance Monitoring System
AS	Aerospace Standard (SAE)
BIT	Built-in-test
CFR	Title 14 of the US Code of Federal Regulations
DOT	Department of Transportation
EM	Electromagnetic
FAA	Federal Aviation Administration
FAAIH	FAA Icing Handbook
FIDS	Flight Icing Detection System
FPD	Freezing point depressant
LWC	Liquid water content
MED	Mean effective diameter
MTBF	Mean time between failure

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
UFR	Undetected failure rate
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. These definitions have been taken from and are consistent with AS5498. Further clarification of these terms can be found in AS5498, sections 1.4 and 1.5.

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.

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:

- FIDS that make a measurement on a reference surface correlated to ice accumulation on a monitored surface (i.e., probe type sensors)
- FIDS that make a direct measurement on a reference surface which is part of a monitored surface (i.e., flush-mounted sensors)
- FIDS that make a remote measurement on a reference surface which is part of a monitored surface (i.e., optical camera methods)

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 (addressed in 4.12). 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.

4.1 Visual

4.1.1 Daytime

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, or some protruding element in the pilot's field of view (windshield wiper bolt, for example). Icing rate information can be inferred from the visual observations.

4.1.2 Nighttime

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 an acrylic 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.

4.2 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.

4.3 Differential Pressure

This concept uses a probe to sense total air pressure through several small orifices (0.4 mm (0.016 in)) 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.

4.4 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).

4.5 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

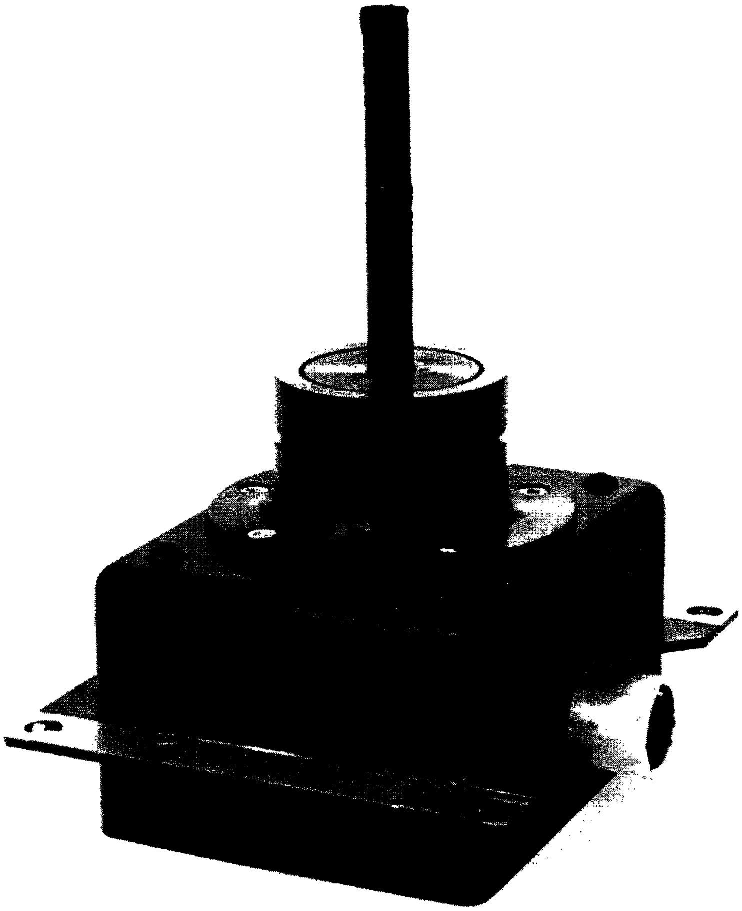

FIGURE 1 - SELF-CONTAINED, ENGINE-INLET ICE DETECTOR (B-1B AIRCRAFT)
USING LATENT HEAT PRINCIPLE

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 derivitive 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 200 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 in) up to 12.7 mm (0.5 in) of ice.

Figure 2 illustrates an application of the magnetostrictive vibratory principle on the B-747 and B-767 commercial transport aircraft. 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.

Figure 3 illustrates an application of the magnetostrictive principle on the MD-11 commercial transport aircraft. The sensing elements are located in the inlets of the wing-mounted engines, and the electronic processors are remotely located in the wing. As in Figure 2, the effect of ice mass is used to indicate icing.

Figure 4 shows a flush-mounted piezoelectric 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 5 shows a similar device using the magnetostrictive principle. In both cases, the increase in resonant frequency due to ice stiffness is used to indicate icing.

FIGURE 2 - SELF-CONTAINED B-747/B-767 ICE DETECTOR USING MAGNETOSTRICTIVE VIBRATORY PRINCIPLE

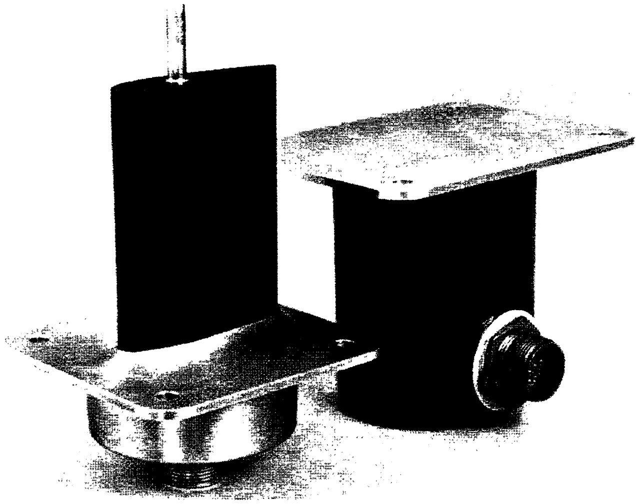

FIGURE 3 - MD-11 ICE DETECTOR SYSTEM USING MAGNETOSTRICTIVE VIBRATION PRINCIPLE (sensing probe assembly left, signal condioner assembly right)

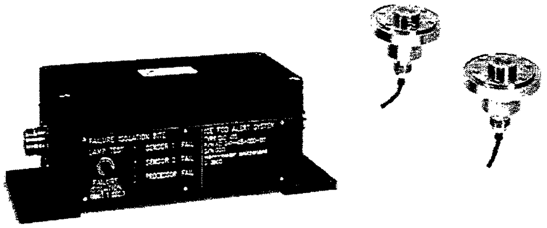

FIGURE 4 - FLUSH-MOUNTED MD-80 WING UPPER SURFACE ICE DETECTOR USING A PIEZOELECTRIC VIBRATED DIAPHRAGM

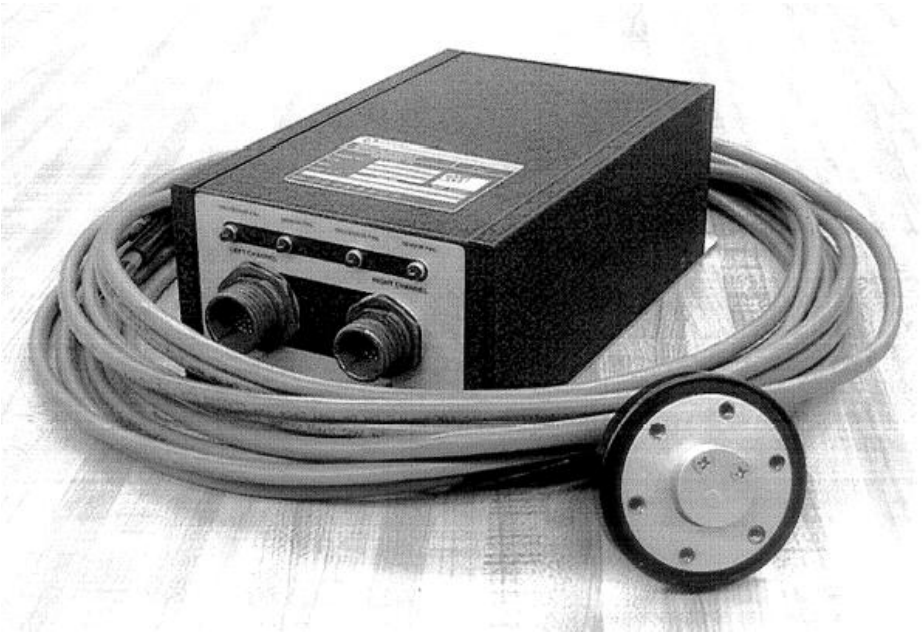

FIGURE 5 - FLUSH-MOUNTED ICE DETECTOR USING A MAGNETOSTRICTIVE VIBRATED DIAPHRAGM

4.6 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 a LWC meter.

Ice thickness up to 25 mm (1 in) 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, see Magenheim [1983].

4.7 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.

4.8 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, see Hansman [1986].

4.9 Capacitance or Total Impedance

A capacitance, or total impedance ice detector, is a surface type ice detector that uses a surface mounted electrical circuit to determine the presence and thickness of ice. This circuit/sensing element has a minimum of one pair of electrical elements. These elements create an electrical field above the surface of interest and the observed capacitance is changed by the dielectric constant of the ice on the surface. Multiple electrical circuits and the resistance of the material above the sensing element can be used to obtain useful information regarding the location, thickness and potentially some properties of the ice.

4.10 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 6. 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.

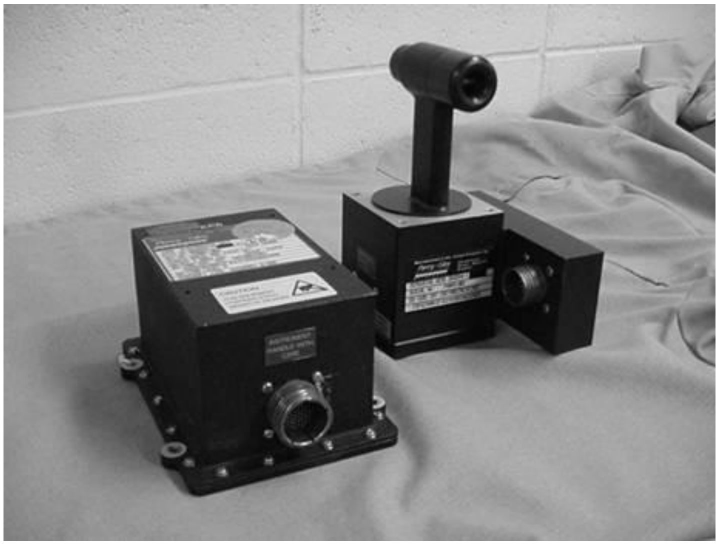

FIGURE 6 – DUCTED OPTICALLY OCCLUDING ICE DETECTOR SYSTEM

4.11 Optically-refractive

This approach senses light refracted from accreted ice. An example of this type of detector is shown in Figure 7. 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.

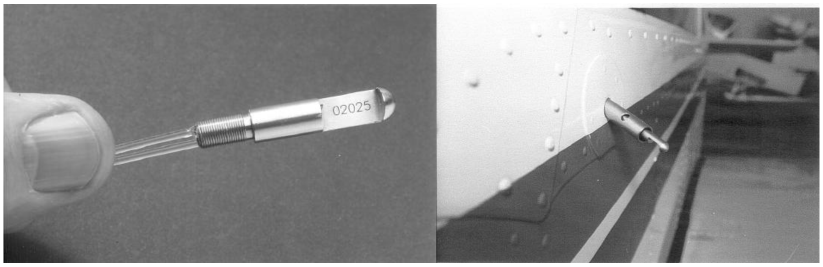

FIGURE 7A - WITH NO MOUNTING HARDWARE

FIGURE 7B - PROBE EMBEDDED INTO AN AIRCRAFT OUTSIDE AIR TEMPERATURE GAUGE

FIGURE 7 – 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 so can be applied to operate in a wide variety of applications and sensitivities, down to 0.001" of ice.

4.12 Advanced Concepts

Three other concepts, under development, are presented.

4.12.1 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, see Sinnar [1992], NASA Tech Brief [1995] and [2001].

4.12.2 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 are calibrated to indicate specific conditions, such as ice.

4.12.3 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 in) in a reliable, non-intrusive installation. The concept provides the capability for self-test on the ground and in flight.

5. DESIGN GUIDANCE

The purpose of this section is to provide general guidance useful in the consideration and evaluation of sensing technologies. In many cases, the operating ranges exceed the minimum performance requirements for certification but are a desirable feature for general aircraft operation. This section is primarily directed toward airfoil ice detectors for aircraft. Special considerations for engine inlets and rotorcraft icing applications are presented in Section 6. The reader is directed to SAE publication AS5498 for minimum performance requirements.

5.1 Environmental Conditions

This section supplements the normal environmental considerations of altitude, ambient temperature, humidity, salt spray, sand and dust, shock, vibration, etc. imposed by the aircraft specification and/or such documents as MIL-HDBK-310, MIL-HDBK-5400, NASA TM 78118 and RTCA DO-160D.

5.1.1 Ambient Temperature

For general use, a FIDS [Flight Ice Detection System] should be designed to operate in all types of icing conditions. FAA/EASA icing standards have possible extents down to -40°C (-40°F). Freezing at ambient temperatures above 0°C (32°F) can occur, for example, due to freezing rain, or the temperature depression that occurs when air drawn into an engine inlet is accelerated through the inlet. Aerodynamic heating can limit ice accretion on accretion-based ice detectors even when the ambient air temperature is less than 0°C; see 5.6.2 Freezing Fraction.

5.1.2 Altitude

An ice detector should be designed to sense ice accretion or icing conditions throughout the altitude range of its intended host aircraft. Note that per FAA 14 CFR Part 25 Appendix C (CS 25 Appendix C), icing conditions shall be considered at altitudes up to 8900 m (29,200 ft).

5.1.3 Liquid Water Content

As a mimimum, ice detectors should be capable of detecting liquid water content over the range specified in FAA 14 CFR Part 25 Appendix C (CS 25 Appendix C), (0.04 to 3.5 g/m^3). Typical icing conditions are associated with stratus clouds having LWC of approximately 0.1 g/m^3. Some of the higher cirrus clouds can have an LWC range from about 0.05 to 0.2 g/m^3 and can exist over extended distances of 80 to 160 km (50 to 100 miles). Even at such very low LWC conditions, ice accumulations of up to 6.4 mm (0.25 in) have been observed on unprotected wings after exposures of 30 to 45 minutes. In contrast, it is not uncommon to encounter LWC of between 2.5 to 3.0 g/m^3 over short 4.8 km (3.0 mile, 2.6 nautical mile) distances in the cumuliform clouds, e.g., thunderstorms. If the ice detector is intended to detect only the onset of icing conditions, an upper limit need not be included.

5.1.4 Drop Size

Ice detectors typically don't have the capability to discriminate drop size, but drop size can affect response. For example, drop size distributions of clouds having a given MVD can be significantly different. Since for a given airspeed, the collection (or accumulation) of drops is dependent on their size, ice detector response can be affected by different distributions with the same MVD. Similarly, response can be affected when drop size distributions encountered in service vary from the calibration distributions. Detector manufacturers usually consider this when specifying uncertainty. The designer can work with the manufacturer if it is desired to quantify the effect more specifically. It is noted that SAE publication AS5498 specifies testing at 3 MVDs to help address this issue. See 5.6.1 for additional discussion on MVDs which exceed current FAA 14 CFR Part 25 Appendix C limits.

5.1.5 Erosion, Hail Impact, and Bird Strike

Ice detectors installed on most aircraft will be subject to impact by rain, ice crystals, sand, dust, hail or birds. Frequency of occurrence and size distribution are published in documents such as MIL-HDBK-310, NASA TM 78118, 14 CFR Part 25, 14 CFR Part 33, and RTCA DO-160D. Consideration should be given to means of preventing unsafe conditions resulting from the ensuing erosion and impact damage. Particular consideration should be made if impact debris could be injested by engines.

5.2 Functional Requirements

5.2.1 Airspeed

Depending on the application, the ice detector used on a transport aircraft normally is required to operate at air velocities ranging from 93 km/h (50 knots) to 830 km/h (450 knots). The helicopter ice detector may be required to operate in hover and at speeds less than 93 km/h (50 knots). The designer needs to consider the airspeed range of the application aircraft.

5.2.1.1 Aspiration

Most accretion-based ice detectors depend on forward velocity to deposit supercooled drops on the sensor. When operating at low forward velocities (e.g., a hovering operation), an aspiration device can be used to draw the air and drops to the sensing device. One simple and reliable means of creating aspiration is the use of high pressure engine bleed air. The effectiveness of aspiration may become limited with increasing flow incidence angles coupled with increasing flow velocities.

5.2.2 Sensitivity

The sensitivity of the ice detector should be sufficient to provide a timely indication of ice accretion. The ice detector should also have adequate range to accommodate the ice protection system being utilized. If the detector is overly sensitive, it may give premature warnings that would cause the pilot to disregard the signal or cause unnecessary operation of the ice protection systems.

5.2.3 Ice Protection

The ice detector may require ice protection capability depending on the application and sensing technology.

5.2.4 False Signal

The ice detector should not produce an icing signal when operated at any normal flight condition due to the presence of water, deicing fluids, oil, grease, cleaning fluid, or accumulations of atmospheric contaminants.

5.2.5 Fail-Safe Design

The ice detection system design should minimize the probability of undetected failure modes in icing conditions.

5.3 Reliability and Credibility

It is important that a clear distinction be made between the reliability of an ice detection system, which is quantified by the mean time between failure (MTBF) and the undetected failure rate (UFR), and the credibility of an ice detection system, which is influenced by the physical measurement principle and the position of the sensor(s).

5.3.1 Primary Detection Systems

When an ice detection system is used as the primary means for determining the need for activation of the ice protection system, it is called a PRIMARY system. The detection system operates continuously, and serves to automatically activate the ice protection system and/or notify the flight crew if icing (or an icing condition) is present. A primary system shall meet the applicable requirements of 14 CFR Parts 23, 25, 27 and 29. Sections .901, .903, .929, .1093, .1301, .1309 and .1419, or the corresponding applicable military requirements (such as MIL-STD-704). To meet the requirements of Section .1309 of 14 CFR Parts 23, 25, 27, and 29, the reliability of a primary ice detector system shall be commensurate with the hazard classification that would result from a failure of the ice detector system, typically determined from a fault hazard analysis. The hazard classification of a system failure to detect ice combined with a failure to annunciate the failed condition to the flight crew shall be assessed. Also, applicable requirements of RTCA DO-178B should be considered for software components of the system.

The credibility of an ice detection system is much more difficult to assess; the measuring system has to be analyzed and tested with respect to a specific sensor position on a given aircraft. The most important credibility criteria are:

a. The installation of the ice sensor on the aircraft should be such that the correlation between the monitored and reference aircraft surfaces allows the sensor to perform its intended function.

b. All the monitored surfaces should be identified and the acceptable threshold of ice detection should be established. The criteria for the ice detection threshold (ice thickness) should result in acceptable aerodynamic performance, engine operability, and structural integrity as a result of ice accretion and shedding.

5.3.1

5.3.2 Advisory Ice Detection Systems

For an aircraft using an advisory system, activation of the ice protection system is the responsibility of the pilot 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). 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).

5.4 Installation

This section outlines considerations which should be evaluated when selecting a mounting location for an ice detector or icing rate system.

5.4.1 Location Considerations

The foremost consideration is that the ice detector (either probe type or surface type) be located in a position where, if icing occurs, the ice detector sensing element performs its intended function.

The ice detector should not be in an area shielded from the moisture laden flow. In general, the best areas for mounting a probe type ice detector share the following characteristics:

The sensing element is:

a. Away from areas of stagnant air

b. Away from areas of flow separation

c. Away from areas that would influence the water droplet trajectories causing either an abnormal concentration or depletion of drops

Ice detectors have been typically mounted on vehicle wing leading edges, in engine inlets, and on the fuselage. When mounted on a fuselage, areas forward of the wing are usually best to obtain the cleanest flow possible. In addition, a side location will be most insensitive to the wide range of angle of attack the aircraft might encounter. When mounting an ice detector in the engine inlet, the nature of any ice shed must be compatible with the engine design. On rotorcraft, downwash can be a significant factor and must be considered.

Ideally, an external flow field study provides a good foundation for selecting an ice detector location. The effect of the full range of angle of attack must be considered if the detector is mounted on a leading edge. On rotorcraft, where ice detector location is the most difficult to determine, computational fluid dynamics or tuft studies can be very helpful in visualizing flow patterns around the vehicle.

5.4.2 Other Installations

The ice detector principle of operation must be considered. If the detector is position-sensitive or requires a special orientation, the installation must accommodate these requirements. Consideration should also be given to the environment that the ice detector electronics will be exposed to as this can affect reliability.

5.5 Verification

A program to substantiate the design, performance, construction, installation and reliability should include analyses and tests by both the system and airframe manufacturers and, possibly, the using agency. The methods used may include normal techniques (e.g., stress analyses, circuit analyses and tests, environmental testing per RTCA DO-160C, software processes per RTCA DO-178B, failure mode and effect analyses, etc.) and unique methods suitable for the application. These latter may include ice impingement analyses, icing tunnel tests of the sensor, natural or tanker ice tests as installed, and bird, hail, and lightning strike tests. Commercial applications require in-flight verification by the FAA.

5.6 Emerging Operating Considerations

5.6.1 SLD and Ice Crystals

Current regulations for aircraft certificated for flight in icing recognize the atmospheric icing environment as defined by FAA Airworthiness Standards listed in 2.1.2.2 (Appendix C of these standards), and comparable non US standards. These standards do not consider some icing conditions which are now recognized to be potentially hazardous. Regulatory agencies and industry have been working to address this, with expanded certification requirements and an expanded definition of the atmospheric icing environment expected.

Though specific guidelines for ice detectors operating outside of Appendix C are not currently defined, operation here cannot be ignored. Specifically, consideration should be given to detector response in conditions which include supercooled large drops (SLD) and/or ice crystals. The Cober [2001], Jackson [2003] and Mazin [2001] references listed in 2.2 offer additional insight.

SLD can be orders of magnitude more massive than drop sizes specified in Appendix C, so inertia influenced trajectories near objects in the air stream (such as a wing or ice detector probe) can be significantly different. The relatively large size of these drops also makes them prone to breakup by aerodynamic forces and to splashing upon impact.

Usually it's desirable for an ice detector to be sensitive to both SLD and the smaller drops specified in Appendix C. A probe type detector capable of discriminating these conditions, however, is not believed to be currently available for commercial application. A surface type detector may be used to discriminate SLD, however, by locating it where SLD will impinge and smaller drops will not. Also, visual cues of ice accretion beyond normal impingement limits (on a windshield for example) can be indicative of SLD.

Glaciated conditions (ice crystals without supercooled liquid water drops) and mixed conditions (a combination of supercooled liquid water drops and ice crystals) may also influence ice detector signal levels. The degree of sensitivity is driven by the sensing technology and the detector design. For example, accretion-based ice detectors are typically insensitive to ice crystals in pure glaciated conditions. There is speculation that in mixed conditions, however, that crystals can become imbedded in accreted ice, or conversely, erode accreted ice, thus influencing detector response (and also ice accretion rate on monitored surfaces).

Historically, there has been little call to detect ice crystals. Recently, however, there have been incidents where ice crystals are believed to have affected turbine engine operation, see Mason et al [2006]. In these situations a detector designed for ice crystal detection may have been well suited. But as noted earlier, such a detector is not believed to be currently available for commercial application.

5.6.2 Freezing Fraction

All ice-accreting bodies including accretion-based ice detectors, may not accrete all impinging water.

Essentially all impinging water freezes when the air temperature is cold enough. At some point as air temperature warms or aerodynamic heating increases, all available water will not freeze. This is the Ludlam Limit Temperature. As air temperature or aerodynamic heating continues to increase, a progressively smaller fraction of water freezes until none freezes. The Critical Temperature is the temperature threshold where no water freezes, and has been expressed historically as either a total temperature or a static temperature. Critical Temperature and Ludlam Limit Temperature vary as a function of the icing condition and are dictated by a fairly complex thermodynamic balance. Reference Jackson et al [2001].

These temperatures are also influenced by accreting body geometry. Users of accretion-based in-flight ice detection systems should consider the possibility that the detector's Critical Temperature could be less than that of a monitored surface at some operating conditions. For example, this might occur at higher angles of attack when local air temperature over sections of a rotor or wing's top surface may be depressed more so than at lower angles.

6. UNIQUE REQUIREMENTS

The following sections provide specific information regarding the use of icing sensing systems with engine inlets and rotorcraft. These issues are not specifically addressed in AS5498 and this additional information is provided for consideration.

6.1 Engine Inlets

The ice detector assembly must be constructed to withstand the harsh operating environment (particularly temperature and vibration) associated with engine inlets. Consideration should be given to the fact that the ice detector installation may be exposed to a heat source (i.e., bleed air) requiring that the sensor be properly isolated to ensure that it will still detect ice. Due to the complex flow characteristics of an engine inlet, care should be given to the proper location of the ice sensor. Also, for this reason, the ice sensor drag and flow disturbance characteristics should be considered. If possible, a location on the top part of the inlet may be preferable as this is usually less prone to damage caused by maintenance activities. Detector failure modes should be considered such that excessive ice that may accrete and shed from a failed detector can be tolerated if it could be ingested into an engine.

Detectors may be remotely located from the engine inlets if the icing conditions between the probe location and the inlets can be correlated.

The operating threshold for an ice detector that activates engine/inlet anti-ice system is design specific. This threshold needs to be an ice buildup on the inlet or surface(s) that is less than the maximum amount of ice that the engine manufacturer certifies the engine to be able to ingest without damage or adverse operating effects.

Ingestion of ice particles in high concentrations can result in engine power loss and damage. This can occur when liquid water is not present in the cloud or when liquid water is present in low concentrations. For more detailed information, see Mason et al [2006]. This phenomenon should be considered when a PIDS is utilized for engine ice protection systems because PIDS are usually designed to detect liquid water only, and not necessarily ice particles.

6.2 Rotorcraft

Complex flow patterns combined with downwash caused by the rotor blades require careful selection of the optimum ice sensor location to ensure best correlation between the detector and the components to be protected. Special consideration should be given to correlation between blade icing and a fuselage mounted sensor indication. Because ice shedding can be a factor, the ice detector should be located in an area safe from shedding ice.The body around the ice detector sensing element must either be anti-iced or have demonstrated that ice accumulation on such body will not interfere with the detector sensitivity, and that the detector does not present a shed ice risk to an engine or other aircraft components. Rotorcraft can be equipped with a primary icing rate measuring system for automatic operation of the rotor ice protection system. These measuring systems can be especially beneficial in night operations when detection of accreted ice through illumination may not be practical.

If accurate icing intensity information is required, it may be necessary to provide sensor aspiration in order to provide a more constant airflow over the sensor, allowing the sensor to operate at low flight speeds as well as minimizing errors over the flight envelope of the aircraft. For more detailed information, see AGARD Advisory Report No. 127, AGARD Advisory Report No. 166 and Stallabrass [1962]. The U.S. Army has developed an Advanced Icing Severity Level Indicating System (AISLIS) for helicopter applications based on the concept described in 4.7. This system monitors rotor speed, vibration level, engine torque, fuel content, static and dynamic pressure, air temperature, and LWC. The crew manually inputs the number of occupants, cargo weight, and aircraft configuration. An on-board computer processes the data and provides an indication of both icing intensity and aircraft performance abnormality (see AGARD Report No. 223).

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