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SAE The Engineering Society For Advancing Mobility Land Sea Air and Space ®
400 COMMONWEALTH DRIVE, WARRENDALE, PA 15096

# AEROSPACE INFORMATION REPORT

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# ROTOR BLADE ELECTROTHERMAL ICE PROTECTION DESIGN CONSIDERATIONS

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1. SCOPE:

This Aerospace Information Report (AIR) identifies and summarizes the various factors that should be considered during design, development, certification, or testing of helicopter rotor blade ice protection. Although various concepts of ice protection are mentioned in this report, the text is limited generally to those factors associated with design and substantiation of cyclic electrothermal ice protection systems as applicable to the protection of helicopter rotor blades. Other systems are described briefly in Appendix A. Applications consider main rotor blades, conventional tail rotor blades, and other types of antitorque devices. The information contained in this report is also limited to the identification of factors that should be considered and why the factor is important. Specific design, analysis and test methodologies are not included. For additional information refer to the references in Section 7.

2. PURPOSE:

The information in this AIR should be useful to designers, manufacturers, procuring agencies, and certificating authorities to avoid time consuming and expensive redesign due to oversight. This document was prepared by Subcommittee AC-9C, Aircraft Icing Technology, of the Aircraft Environmental Systems Committee with information compiled by individuals who have experience with helicopter rotor blade ice protection design, analysis, and testing and who, in some cases, have gained knowledge through negative results.



3. DEFINITIONS AND BACKGROUND:

3.1 Icing Definitions:

3.1.1 Icing Intensity: The relationship of the icing intensity terms of trace, light, moderate, and severe to the corresponding cloud liquid water content (LWC) is defined[4] as:

| Icing Intensity Term | Cumuliform Cloud LWC ($gm/m^3$) | Stratiform Cloud LWC ($gm/m^3$) | SAE Recommendation LWC ($gm/m^3$) |
|---|---|---|---|
| Trace | $<0.07$ | $<0.11$ | $<0.10$ |
| Light | 0.08-0.49 | 0.12-0.68 | 0.10-0.50 |
| Moderate | 0.50-1.00 | 0.69-1.33 | 0.50-1.00 |
| Severe (heavy) | $>1.00$ | $>1.33$ | $>1.00$ |

A further definition[4] of icing intensity applies to the effects on a fixed wing transport aircraft. These definitions are not useful for design or operational purposes, but are provided here for information.

a. Trace Icing: Ice becomes perceptible. Rate of accumulation slightly greater than rate of sublimation. It is not hazardous even though deicing/anti-icing equipment is not utilized, unless encountered for an extended period of time (over 1 h).

3.1.1 (Continued)

b. Light Icing: The rate of accumulation may create a problem if flight is prolonged in this environment (over 1 h). Occasional use of deicing/anti-icing equipment removes/prevents accumulation. It does not present a problem if the deicing/anti-icing equipment is used.

c. Moderate Icing: The rate of accumulation is such that even short encounters become potentially hazardous and use of deicing/anti-icing equipment or diversion is necessary.

d. Severe Icing: The rate of accumulation is such that deicing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary.

While these terms are still used frequently, the definition of icing intensity is subjective and the deicing system designer should use one of the quantitative certifying or qualifying agency envelopes such as found in FAR 25 Appendix C.

3.1.2 Ice Classification: The following terms are used to describe the types of ice that may occur:

Rime - Opaque ice formed during flight in clouds by the rapid freezing of small supercooled water droplets producing a streamlined spear shape. This type of ice occurs below the Ludlam Limit (see below).

Glaze or Clear - Transparent ice formed during flight in clouds by the slower freezing of supercooled water droplets. This is most likely to occur at ambient temperatures near freezing when the droplets may flow along the surface or remain liquid before freezing occurs. The ice formed during freezing rain is also an example of glaze ice. This type of ice may occur at conditions above the Ludlam Limit, reducing the apparent LWC.

Glime - A mixture of glaze and rime, generally with rough surfaces and runback ice.

Hoarfrost - Ice crystals deposited directly from water vapor onto surfaces that are below freezing.

Wet Snow - Snow existing at near freezing ambient temperatures. Wet snow tends to cling to exposed surfaces and may create an ice-like formation similar to the double horn shape, but is more likely to form a narrow hard ridge on the stagnation line.

Ice Crystal - Frozen supercooled water droplets. May exist in the form of snow crystals or ice nodules such as sleet.

Freezing Rain - Precipitation in the form of large above-freezing water droplets which become supercooled and freeze upon contact with a below-freezing surface within a below-freezing air mass.

3.1.2 (Continued)

Mixed Icing Conditions - Mixture of supercooled water droplets and ice crystals existing within the same cloud environment.

Ludlam Limit - The point at which some supercooled water droplets no longer freeze within their catchment area and the forward growth of ice is diminished.

Natural Icing - Icing that occurs during flight in a cloud formed by nature.

Artificial and Simulated Ice - These terms have been used differently by many authorities on icing. The following convention has been followed consistently by many authorities in many documents, but the opposite meaning is also widely accepted and used.

Artificial Icing: Real ice, but formed by artificial means, such as a spray rig or tanker.

Simulated Ice: Ice shapes that are fabricated from wood, epoxy, or other materials.

3.2 Physics of Ice Accretion: An understanding of the physics of ice collection is important; such knowledge will allow determination of the area of airfoil to be heated and the rate that ice can collect and, therefore, the rate that ice must be removed. The following is a list of the terms associated with icing and the interrelationship with airfoils and other leading edge surfaces:

Supercooled Clouds - Clouds containing water droplets that have remained in the liquid state even though the ambient temperature is below freezing. Supercooled water droplets will freeze upon or soon after impact with another object. Water droplets can remain in the liquid state at ambient temperatures as low as -40°F (-40°C). Note that water in a supercooled form has been observed to -65°F (-54°C), but this should not be a design consideration. The rate of ice accretion on an aircraft component is dependent upon many factors such as droplet size, liquid water content, ambient temperature, and component size, shape and velocity.

Catch Efficiency - The ratio of the mass of liquid water actually impinging on the surface to the mass of water contained in the swept volume of the body at a given angle of attack (see Appendix B). Catch efficiency is a function of the velocity of the body, droplet size, body geometry, and air density (Fig. 1).

Impingement - The location on the accreting surface that the water droplets initially strike. The limits of impingement, i.e., the locations on the surface where the droplet path becomes tangent to the surface, SU and SL, are used to determine the maximum extent of icing for a specified droplet size. The local impingement on the surface is used to determine the local rate of water catch. The water drop impingement calculation techniques involve the determination of the flow field around the surface and the

3.2 (Continued)

introduction of the water drop particles into this flow field. The flow field definition is generally developed through a potential flow program, which calculates the local Mach numbers and pressure coefficients approaching and surrounding the surface under investigation.

Collection Efficiency - The ratio of the mass of liquid water remaining on the body after any blow-off that may occur to that actually impinging on the body moving through the air. It is subject to the same functions as catch efficiency plus ambient air temperature, surface temperature and body-heat conductivity.

Droplet Trajectory - The path of the water droplet through the free stream toward, onto and around the surface of interest. Droplet trajectories are used to establish the upper and lower limits of impingement on a surface for a specified water droplet size and to establish the local and overall water catch rate. The water drop trajectories may be calculated from the equations relating the inertia and drag forces acting on the water drops, as a function of drop Reynolds numbers and inertia. Reference 5 offers one means of addressing the trajectory calculation procedure. Computer codes have been developed to provide analytical solutions for the particle trajectories.



Liquid Water Content - The liquid water content is the mass of water per unit volume of air. This governs the quantity of ice that can accumulate on an exposed surface or the quantity of water striking the surface. The total water catch on a surface is a function of liquid water content, droplet size, air speed, and surface catch efficiency.

Droplet Diameter - The water droplet diameter determines the particle drag and inertia and, therefore, the trajectory of a particle under the influence of another body. The diameter affects the amount of ice collecting on a surface, the surface catch efficiency, and the freezing fraction. The larger the diameter of the drop, the more the drop inertia tends to keep the drop along the initial undisturbed path, and the more likely the drop is to strike the surface. The freezing fraction is also affected by the drop diameter due to the release of heat of fusion, thus the greater chance of the impinging water leaving the surface or freezing aft of the point of initial impact. Since droplets do not occur in nature as a single diameter, but as a distribution, the reference diameter is generally referred to as median volumetric diameter (MVD). Droplet size (MVD) in natural icing is typically in the 5 to 50 µm range. These droplets are small and have a low mass, therefore, they are strongly influenced by the airflow around the rotor blade (see Fig. 1).

Median Volumetric Droplet Diameter - The drop size for which half the total water volume is contained in drops larger and half in drops smaller than the referenced median diameter.

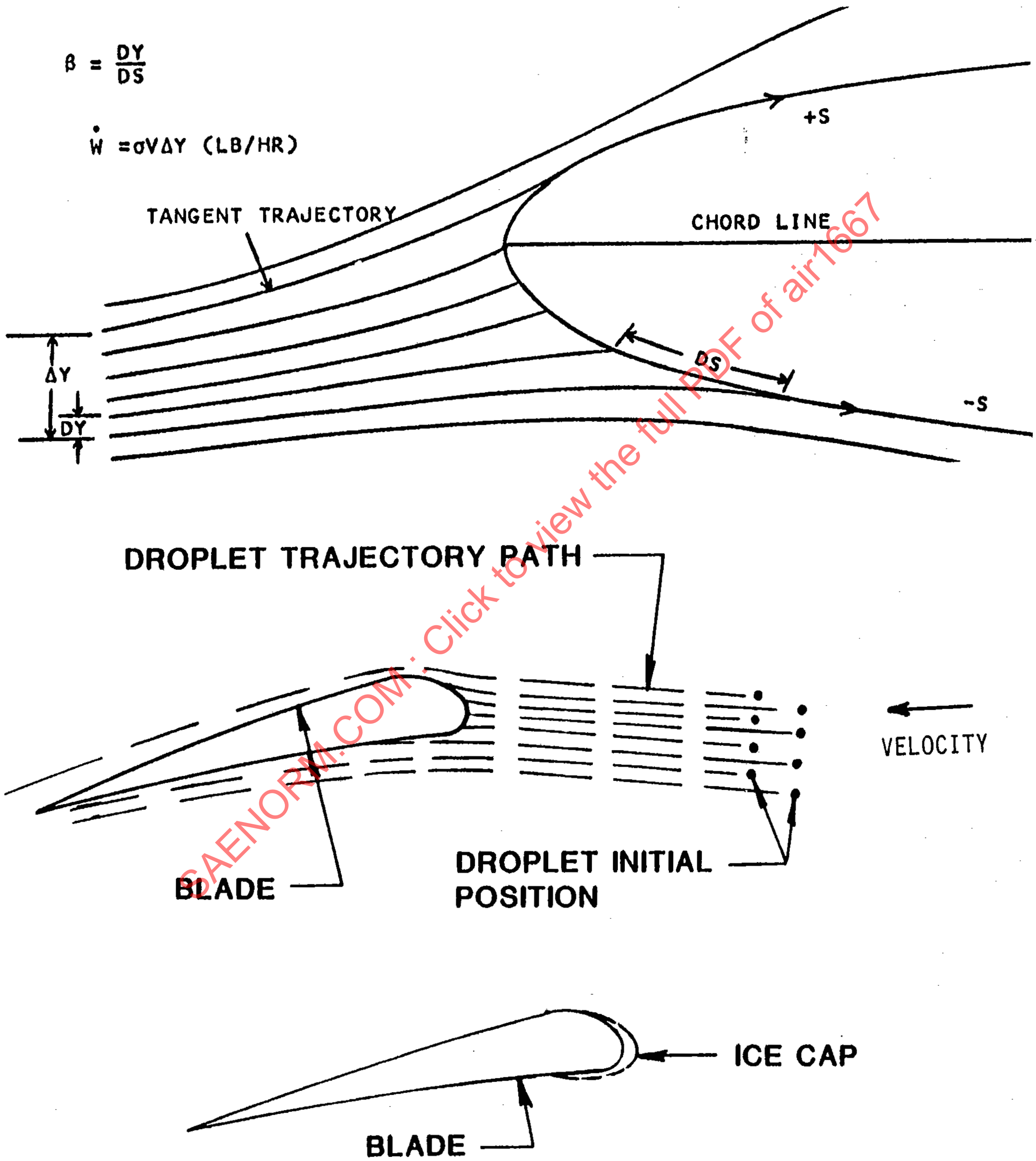



FIGURE 1 - Droplet Trajectory and Impingement

3.2 (Continued)

Temperature - Temperature influences the amount of ice buildup and the shape of the ice in several ways. Lower temperatures reduce the influence of the heat of fusion release and the water droplets freeze faster. Also, lower temperature clouds generally contain only smaller water droplets (except in cases of rapid cloud lifting), and the liquid water content tends to be lower, reducing the mass of water striking the surface.

Freezing Fraction - The amount of impinging water that freezes at the point of impingement. The portion of the impinging water not freezing on contact may freeze aft of the initial contact point. The magnitude of the freezing fraction is a function of the air speed, ambient temperature, local temperature, and water catch rate as well as the surface material's thermal conductivity.

Ice Shapes - Ice shapes range from the aerodynamic rime spear shape typical of the small water drop sizes at low ambient temperatures to the blunt double-horned glaze shape formed at the larger droplet sizes and higher ambient (and kinetic) temperatures. The ice shape is closely related to the freezing fraction in that both are functions of the water droplet size and effective or equilibrium temperature.

Dry Kinetic Heating (Aerodynamic Heating) - The local dry surface temperature rise at the surface at or near the stagnation region. The dry kinetic temperature rise is a function of the relative (or approach) velocity at a surface. For a helicopter rotor blade, the dry kinetic temperature is a function of local velocity and is calculated as a function of both the rotational velocity (at the span station of interest) and the forward flight velocity.

Wet Kinetic Heating (Equilibrium or Datum Heating) - The local wet surface temperature rise at or near the stagnation region. The wet kinetic temperature rise is a function of the local velocity, the impinging water catch, the local heat transfer effects (heat balance due to water impingement, heat of fusion and local pressures) and the freezing fraction. Appendix C includes more details on the method of calculation of the equilibrium or datum temperature.

Rate of Ice Collection - The rate of ice collection on an airfoil is a function of airfoil geometry, airspeed, water droplet diameter, and liquid water content. The water intercepted by the airfoil can be expressed in terms of mass of water per unit time per unit of airfoil span or area. The actual amount of ice forming due to the interception of the water is a function of the freezing fraction. See Appendix B for further information.

Surface Equilibrium (Datum) Temperature - The temperature of an airfoil exposed to icing conditions is a complex function of airspeed, liquid water content, ambient temperature, and altitude. The shape and type of ice (if any) that forms is dependent on the surface temperature.

3.2 (Continued)

The equilibrium temperature ($t_{ok}$), has been widely used to approximate the airfoil temperature under icing conditions. A somewhat improved estimate has been derived by Messinger.[6] These treatments are not adequate from a rigorous thermodynamic standpoint, but are easily understood and have been proven from experience to be quite useful. Provided that the assumptions are adequately taken into account, the temperatures predicted by these models are of practical use to the designer. These equations are described in Appendix C. Even simpler empirical relationships are given in Reference 7.

Shed Ice Trajectory - The path taken by a piece of ice shed from an aircraft surface. This trajectory may be within an engine inlet, or may be external to the aircraft such that it may strike rotor blades or tail surfaces.

3.3 Ice Protection Definitions:

Anti-icing (Active) - The prevention of ice accumulation by direct thermal or chemical means.

Anti-icing (Passive) - The prevention of ice formation by flow deflection or by catchment on an upstream surface (screen in a duct).

Deicing (Active) - The cyclic removal of accreted ice by direct mechanical (including electro-mechanical and vibratory), thermal or chemical means after ice is allowed to accrete.

Deicing (Passive) - The removal of accreted ice by indirect means (i.e., natural shedding, chemical application to enhance natural shedding (icephobic), particle separator/screen, etc.) after ice is allowed to accrete.

3.4 Thermal Deice Versus Anti-Ice: Rotor blade ice protection can be accomplished either through anti-icing or deicing. Deicing is currently the favored method for rotor blade protection because it minimizes power required by allowing some ice accretion to occur prior to system cycling. The application of heat is sufficient to melt the ice bond layer, allowing centrifugal and aerodynamic forces to shed the ice. Tail rotors may be anti-iced if necessary to minimize the consequences of ice shedding from the tail rotor.

Droplets initially in a volume swept by the blade will tend to be deflected out of the initial path by the flow field preceding the blade, but the droplet inertia will cause some droplets to impact the blade. Most frequently, impact of these droplets will occur in the leading edge area, with frequency of impact tapering off in the chordwise direction. The result is the build-up of an ice cap locally around the leading edge of the blade. Deicing takes advantage of this accretion pattern, providing protection only on the area of the blade where significant impingement occurs.

3.4 (Continued)

The advantage of deicing is best shown by comparison with anti-icing systems. Anti-icing prevents formation of ice by maintaining the protected surface above freezing. In the case of a non-evaporative "running wet" system the surface temperature is maintained above 32°F (0°C) to prevent freezing. With such a system, local blade protection will result in water runback from heated to unheated areas where freezing may occur. Since runback icing is usually unacceptable on rotor blades for dynamic and aerodynamic reasons, running wet anti-icing protection cannot be utilized, since such protection requires continuous heating of the entire area of all blades. The alternate to a running wet anti-icing system is an evaporative anti-icing system which applies sufficient energy to evaporate all the water impinging on the protected surface. However, the amount of energy required for an evaporative system is substantial due to the heat of vaporization of water, and there may be material property constraints. Consequently, for a given level of protection, either method of anti-icing requires substantially more power than deicing. For this reason, the use of anti-icing is generally limited to components that cannot tolerate ice accretion and subsequent shedding (such as engine inlets), that are small and require little power (such as Pitot tubes), or that have a small surface area and could cause damage due to ice shedding (such as tail rotors).



## 4. ELECTROTHERMAL ICE PROTECTION SYSTEM

4.1 General Description: The electrothermal deicing system is currently the only proven controllable and repeatable means of positive, active rotor blade ice protection. This deicing technique involves permitting the ice to accrete to a specific thickness on the rotor at a reference spanwise location, then applying power to electrical heaters until the ice is shed. There are a number of possible rotor electrical heater configurations. For example, the heaters may be located in a chordwise pattern around the leading edge, in a spanwise pattern from tip to root, or a combination of both patterns. The chordwise heaters are generally activated in sections from tip to root, while the spanwise heaters are activated around the chord starting at the leading edge and progressing to the next most susceptible area or zone.

The heaters may be constructed of wire elements, etched metal foil, cut metal foil, sprayed metal, or conductive composite materials. The heater construction is generally a function of the particular heater manufacturer. The selection of the deice heater is, to a large degree, determined by the rotor stress field (flatwise and torsional bending and spanwise stress) and the method of blade construction, i.e., the actual blade leading edge assembly method. The heater material must be compatible with basic rotor design parameters and tooling methods. Variations in the local blade heating can be accomplished by changes in the heater resistance, changing the local power density, but the ability to accomplish this easily depends on the heater type and heater orientation selected.

4.1 (Continued)

Power to the rotor deice heaters can be supplied from the main aircraft generating system or from a dedicated electrical supply. Electrical system redundancy may be required. The energy "on-time" and sequence for the heaters is dependent upon the icing severity, collection efficiency of the component, and local power density.

4.2 Generic System Description: The main components of a typical blade deice system installation are shown in Fig. 2. These include main and tail rotor blades with electrical heaters, power supply, power switching/distribution system, deice controller, main and tail rotor slip rings, system power steppers, fault monitoring, ambient temperature sensor, ice detector/rate meter subsystem, and velocity sensing instrumentation.

The extent of rotor blade coverage required can be determined through analysis and/or test and typically starts at 20% blade span and may extend up to 99% blade span. Coverage is generally back to about 15% upper surface chord and 25% lower surface chord. A better estimate of heater coverage may be determined using a particle trajectory code. Once the total area requiring protection is determined, the area is divided into zones to minimize the power required for effective protection.

There are several variations in the design of the electrical heating elements in use today. The two basic concepts employed are the spanwise zone arrangement (Fig. 3) and the chordwise zone arrangement (Fig. 4). The characteristics of rotor blade icing indicate that the leading edge and outboard stations of the rotor are generally the most critical in terms of ice accretion. This is due, in part, to the high collection efficiency of the leading edge and high velocity of the outboard stations. (However, inboard sections are critical for autorotation.) Some recently designed heater element zone arrangements and control systems are tailored to remove ice from these areas in the most efficient manner. The zone arrangements of such systems employ a combination of chordwise and spanwise zones.

4.2.1 Electrical Heaters: Typical main and tail rotor blade heater installations are shown in Figs. 5 and 6, respectively. The heaters may be fabricated of wire conductors woven into a carrier, etched foil bonded to a carrier, sprayed metallic coating applied to a contoured surface, or a conductive composite layer within a composite blade. A suitable dielectric layer is incorporated on each side of the heater to provide insulation from the spar (in the case of a metal spar) and/or from the abrasion strip. The heater can lie within the basic contour of the blade, eliminating any aerodynamic performance penalty. Alternatively, some aircraft have used add-on deice heater assemblies, which are subsequently bonded onto the blade exterior surface, outside of the blade contour. Although this is a less expensive approach, there may be structural, dynamic and aerodynamic performance disadvantages, and erosion protection is required on outboard blade stations.

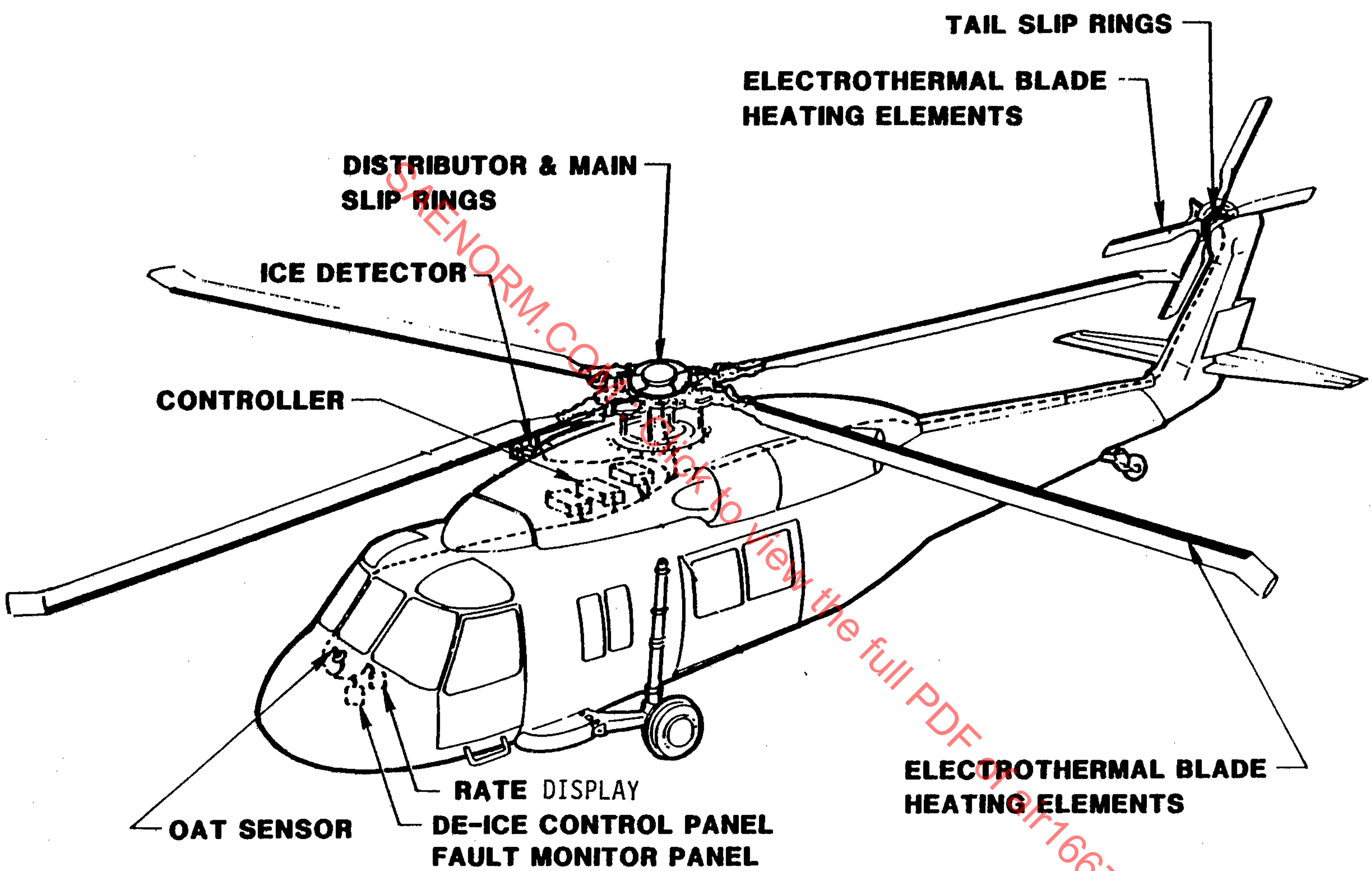



FIGURE 2 - Typical Rotor Blade Deice System

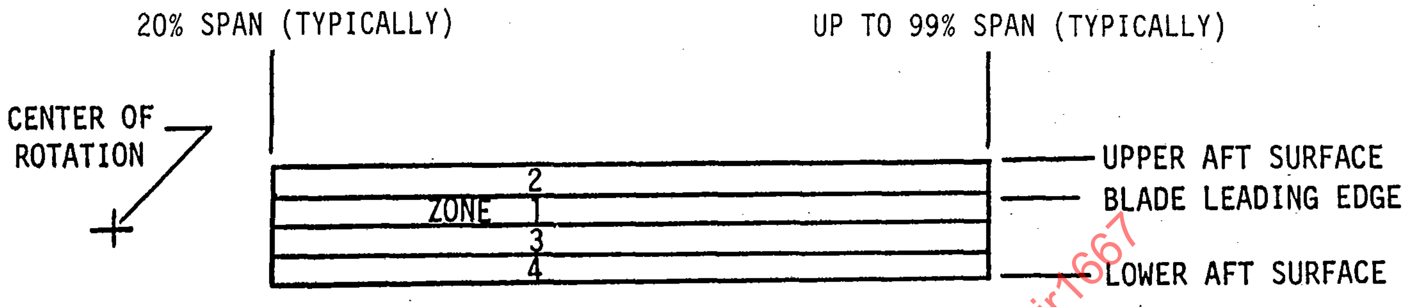



FIGURE 3 - Typical Spanwise Zone Arrangement

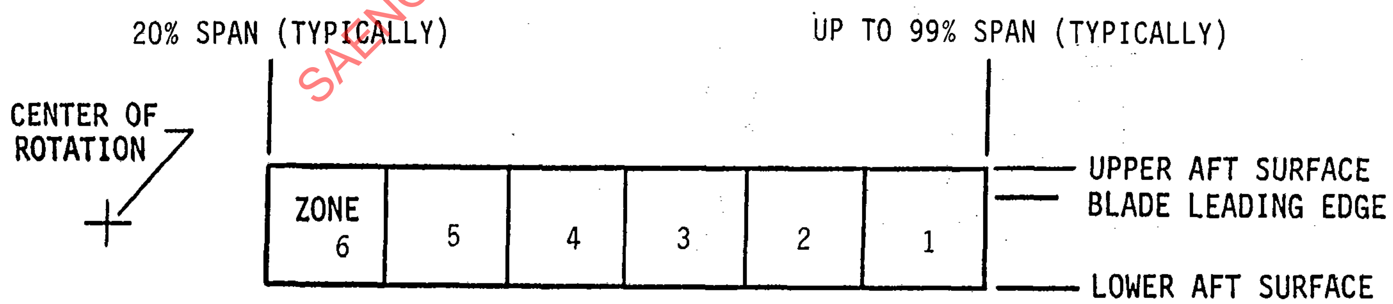



FIGURE 4 - Typical Chordwise Zone Arrangement

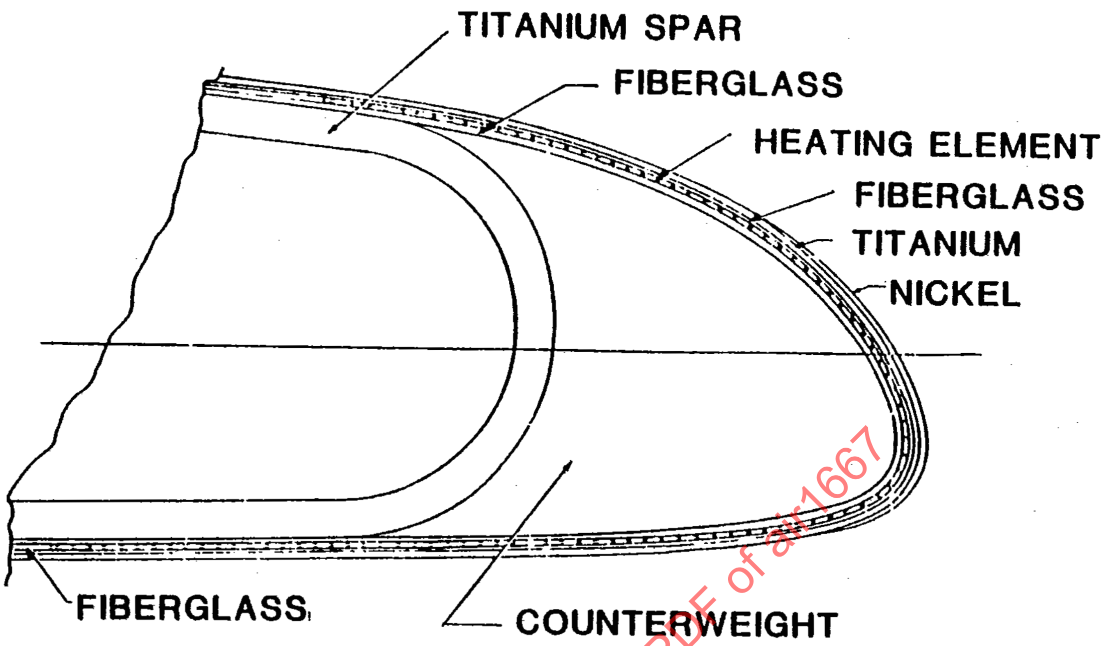



FIGURE 5 - Typical Main Blade Heater Installation

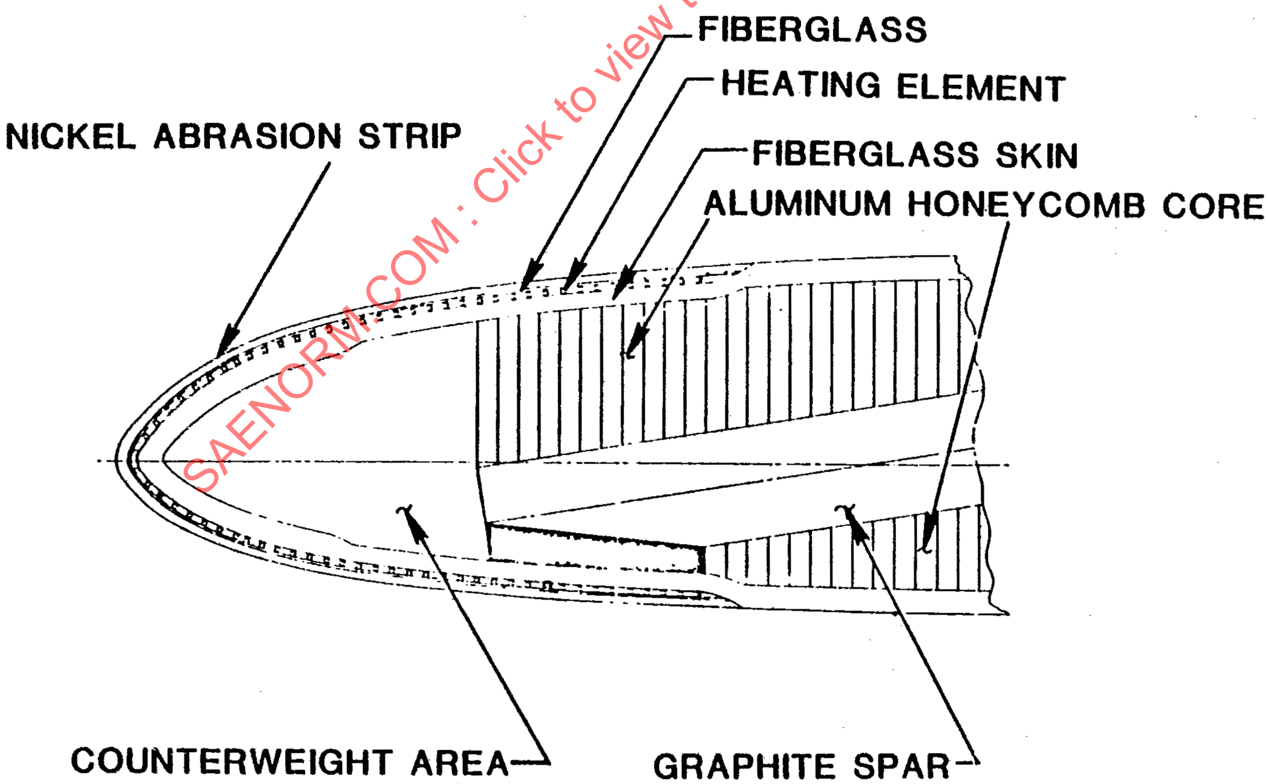



FIGURE 6 - Typical Tail Blade Heater Installation

4.2.2 Deice Power Supply: Deicing power is generally supplied from the helicopter main generator/alternator system. In some configurations, however, use of a dedicated power supply source may be the optimum choice particularly where a decision on use of constant frequency versus variable frequency may be an influencing factor. The electrical system must, however, be sized for the load demand of the deicing system, which in many cases will be equal to, or greater than the total remaining helicopter load. The generator-failed case must be considered during the total electrical power requirement determination. A redundant power source may be required if the rotor deice system must continue to function with one generator/alternator out.

4.2.3 Power Switching/Distribution: Power switching is generally accomplished through a mechanical or solid-state switching device which transmits a power pulse to each heater element in a prescribed sequence as defined in the main deice controller. Deice power must be transferred from a stationary generator or alternator and power switching unit to the rotary wing. The most common system employed is a shaft slip ring assembly illustrated in Fig. 7.

4.2.4 Deice Controller: Control of the deice system, which may include both main and tail rotors, is provided by the deice controller. A controller may provide automatic control, manual control, or combinations of both. Automatic controllers process signals from an outside air temperature (OAT) sensor to establish the heater element on-time, while the element off-time is determined via a signal from the icing rate system. The automatic controller sequences power to the blade, adjusting the cycle timing based on ambient conditions. Manual controllers establish element on-times and off-times based on direct pilot input of desired switch settings. Typically, as a minimum, the pilot must select an OAT range at which he is operating and his estimation of the LWC severity (trace, light, moderate, heavy). Changes in ambient conditions are reflected via changes in the switch settings. Manual control of element on-time is not generally recommended, especially for current blade construction techniques which encompass some form of composite rotor blade technology where it is necessary to prevent possible overheating of the blade resin. Many controllers can operate in either an automatic mode or in a manual mode, with the manual mode typically available as a backup to the automatic system as illustrated in Fig. 8. Some form of over-temperature protection is desirable.

Protective circuitry for the deicing electrical system can be incorporated into the controller. This circuitry can alter or shutdown the deice power sequence in the event of an electrical system failure, while providing system status information to the helicopter instrument panel. A failure, as detected by the controller check circuitry, will result in automatic power sequence shutdown or alteration of the cycle sequence and must illuminate a failure signal on the cockpit control panel. The controller can also include built-in test circuitry. This circuitry, when supplied with the proper signals, can verify correct system operation.

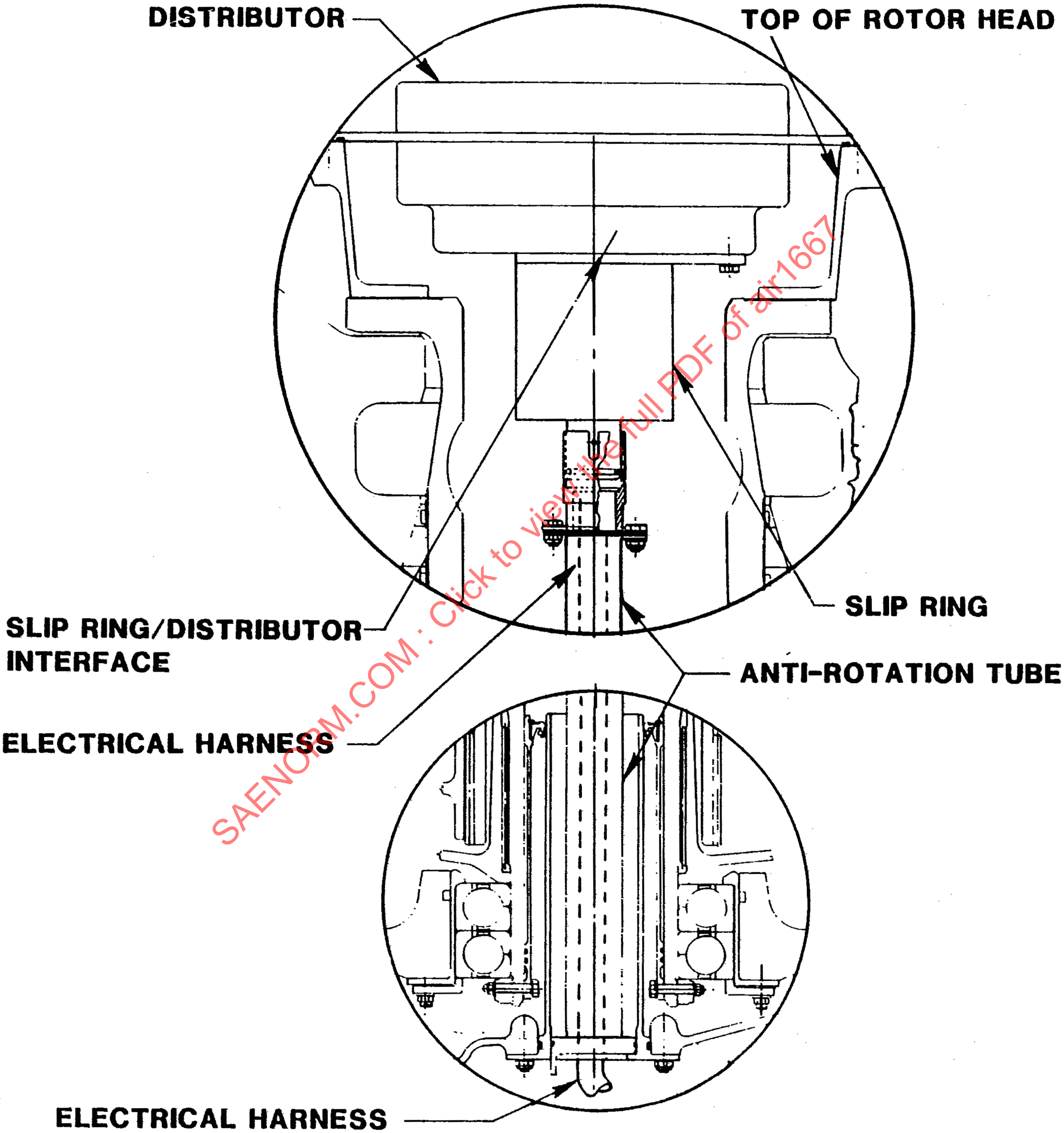
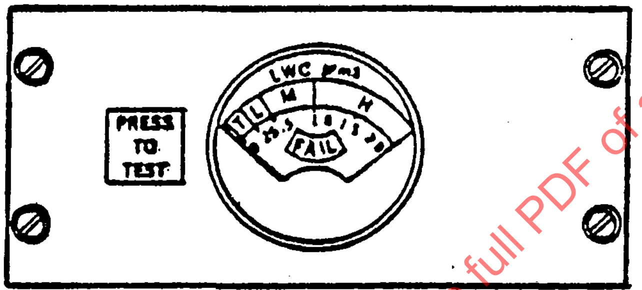
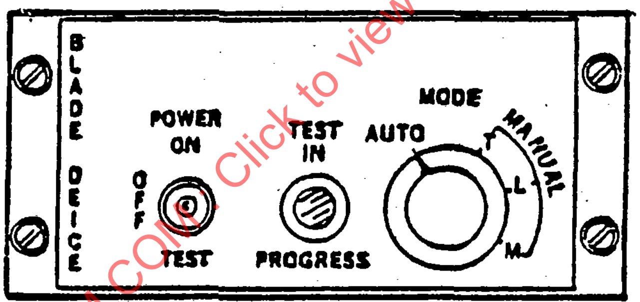


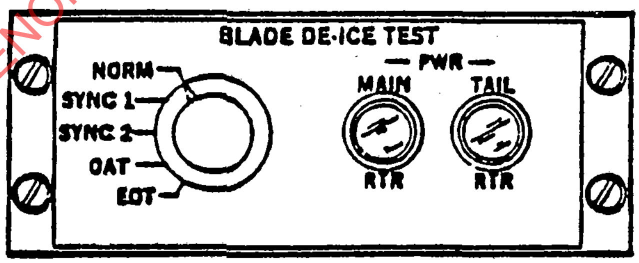

FIGURE 7 - Typical Main Distributor and Slip Ring Installation




LIQUID WATER CONTENT INDICATOR




DEICE CONTROL PANEL




DEICE TEST PANEL

FIGURE 8 - Typical Pilot Control Panel

4.2.4 (Continued)

Automatic controllers normally receive inputs from external sensors such as ice detectors, ambient temperature probes, and free stream velocity sensors to trigger deice cycles and control the individual heater power-on times. The automatic controller may also examine deice system malfunctions and attempt to maintain system function for as long as possible.

The combination deice controller combines the automatic control features with a pilot manual override. Normally with this type of system, the pilot manual input starts the system function and the automatic inputs from the external sensors maintain specific control functions.

The deice controller also generally provides a system status reporting link to the aircraft instrument panel and monitors the electrical protective circuitry of the deice system.

Tail rotor deice control may be provided through the main deice controller by providing a delay in the main rotor power switching when power is being supplied to the tail rotor, or it may have a separate independent controller, with its own cycle and heater time sequencing.

4.2.5 <u>External Sensors</u>: Manual or automatic control of the deice system controller is accomplished using signals from an outside air temperature sensor, ice detector/rate sensor, and/or an aircraft torque meter.

4.2.5.1 <u>Outside Air Temperature Sensing</u>: The outside air temperature (OAT) sensor signal is generally input into the deice controller as the primary source for the deice heater element on-time schedule. (Note that what is commonly referred to in the rotorcraft industry as an OAT sensor actually senses total temperature rather than static temperature. At a flight speed of 64 mps (125 knots) total or measured temperature is about 2°C (3.6°F) higher than the static or true OAT temperature.) To insure accurate temperature readings, the sensor should be protected from ice accumulations, either thermally or through the use of shielding. The OAT sensor location must be selected so that fuselage skin temperatures, solar radiation, or internal compartment temperatures cannot influence the OAT temperature readings.

4.2.5.2 <u>Ice Detection/Ice Rate Sensing</u>: The ice rate sensor, which provides an indication of LWC, is generally used to control the deice element off-time sequence when the deice controller is in the automatic mode. The ice detection device provides the first indication of ice and/or the rate of ice accretion. The control signal for the deice sequence is generally set to activate at a reference ice accretion from the ice detector which equates to a reference thickness on the rotor. Since current ice detectors are fuselage mounted, a relationship between the detector ice signal and the rotor ice accretion must be established.

4.2.5.2 (Continued)

The Aircraft Icing Severity Level Indicating System (AISLIS)[22] uses an ice detector, changes in aircraft torque, and other parameters to infer the loss of performance due to rotor ice accretion. Current research may lead to a blade-mounted ice detector at several locations on the rotor, to provide a direct reading of ice accretion thickness and ice accretion rate. The rotor ice accretion quantity establishes the deice control signal point depending on the rotor tolerance to ice (i.e., the rate of rotor torque rise), the minimum ice thickness necessary to promote clean ice shedding (minimize runback potential), and the maximum ice thickness tolerable from an ice impact damage standpoint (rotor or fuselage damage from shed ice).

The ice detector location must be selected to give a representative and repeatable icing signal. Detector location on a fuselage can be determined by use of computational aerodynamic codes (VSAERO, PANAIR, etc.),[8,9] air flow measurements, tuft studies, and ice catch studies over representative areas of the aircraft. Use of aspirated ice detector configurations provides a means of reducing the detector icing signal variations as a function of aircraft location and airspeed. Location of rotor blade-mounted detectors must consider the effects of kinetic heating. At warmer icing temperatures an inboard blade detector is needed, but an outboard detector would give a better indication of the more severe colder temperature ice. Several icing instruments are discussed in Reference 10.

4.2.5.3 <u>Torque Meter</u>: The engine torque meter has been used to provide an indication of the severity of icing on some aircraft. The pilot can then activate either manual or automatic control of the deice system at a certain torque rise indication. This approach, however, may not indicate a torque rise for inboard ice occuring at conditions just below freezing. This could present a hazard in the event of a multiple engine failure, since autorotative performance may be degraded.

4.3 <u>Basic Description of Typical System Operation</u>: The following describes the main deice system functional units of a typical system and illustrates how these functional units fit into the overall deice operation.

A typical deice system is schematically represented in Fig. 9. Once activated by input from the external sensors (i.e., ice detector, ice rate probe, OAT sensor) or from pilot manual control, the deice system will automatically sequence power to the blades according to the programmed cycle schedule. Based on experience to date, the deice heater element on-time is set by the signal from the outside air temperature sensor while the deice heater element off-time is controlled by the icing rate signal. Manual on-time control can also be set by pilot switch, however this would increase the potential for blade overheating if an incorrect switch position were selected by the pilot.

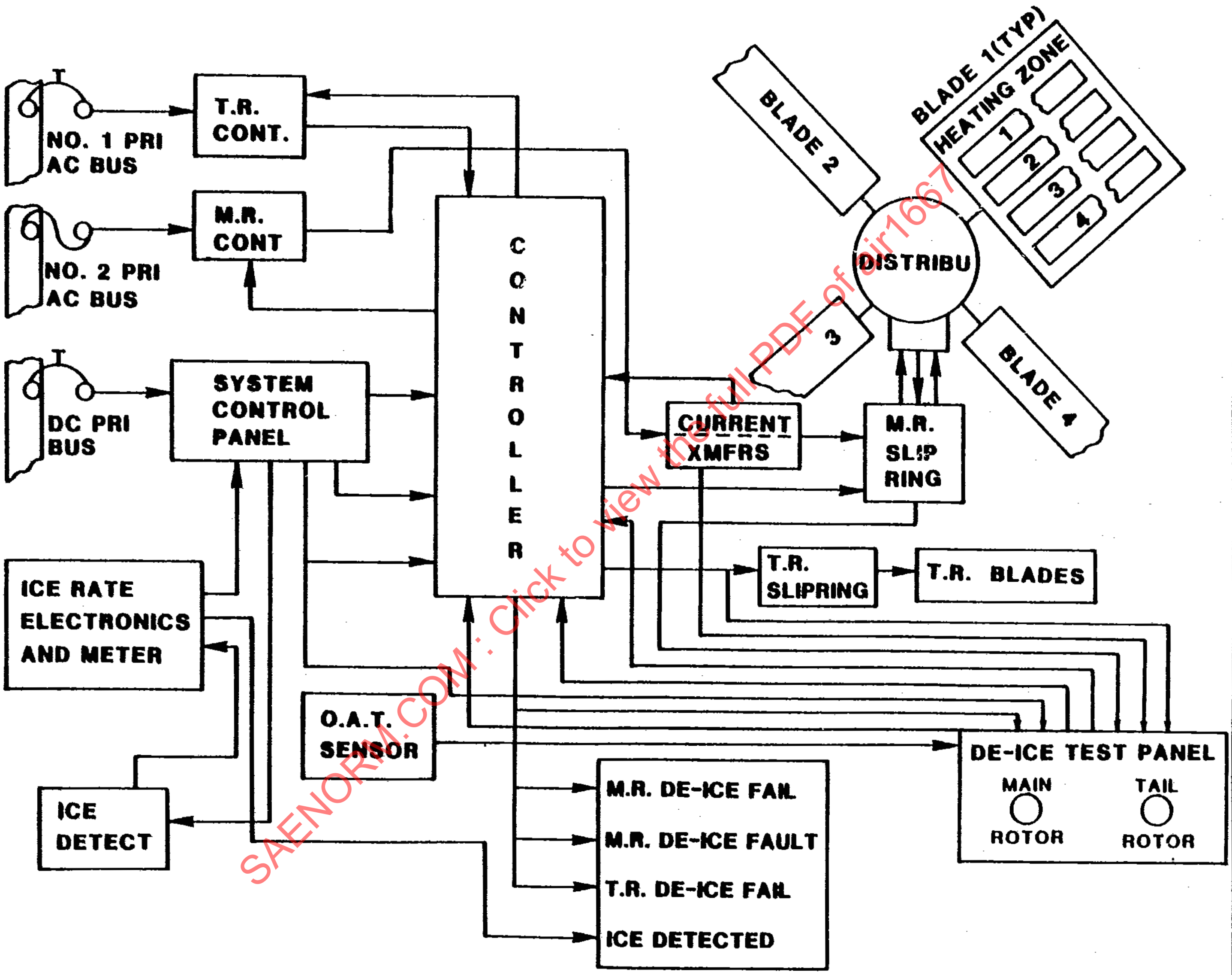



FIGURE 9 - Typical Deice Schematic For Spanwise Zone Arrangment

4.3 (Continued)

When the helicopter enters the icing environment, the ice detector or rate meter senses the accumulation of ice and determines the rate of ice accretion or LWC. During this icing interval, ice is accumulating on the rotors. At a predetermined accretion (generally based on a reference rotor ice thickness, or a rotor torque increase) as indicated by the ice detector or rate meter, the deice controller is activated manually or automatically and sends its command signal to the power distributor to begin the deice cycle. The distributor sequences power to the blade heater zones in response to the controller signal. The off-time (i.e., delay time between element deice cycles) is controlled by the icing rate indication system.

Once a deice cycle is initiated, the cycle will proceed in the programmed manner through each blade heater element starting with the same initial element as shown in Fig. 10. The number of blades on the rotor head generally determines the deice control sequence from blade to blade. For example, on a four-bladed rotor the first element on each of the four blades could be heated, or (more probably) the first element of opposing blades (i.e., blades 1 and 3) could be heated. Power can then be applied element-by-element on blades 1 and 3 until each element had been fired before switching to blades 2 and 4. Alternatively, deicing can occur on the first elements of blades 1 and 3, then the first elements of blades 2 and 4, etc. However, the first example can be expected to provide more effective ice shedding. In the case of an odd number of blades the corresponding elements of each blade are fired simultaneously to prevent asymmetric ice shedding.

When sufficient ice accumulates on the icing rate detector probe, it must deice itself, resulting in a loss of real-time LWC indication for as much as 10 to 20 s. However, most commercially available probes will hold the last existing signal during the probe deice phase.

Under severe icing conditions (high liquid water content and/or cold temperatures), the next rotor deice cycle may be ready to begin at the completion of the current cycle. The condition where the sum of the element on times exceeds the element off-time is called system saturation. At lower icing rates, there may be a considerable time delay before the next cycle. An example of a system saturation plot is shown in Fig. 11. The icing bounds of References 11 and 12 are shown on this figure for below 10 000-ft (3049 m) altitude conditions.



## 5. DESIGN CONSIDERATIONS:

### 5.1 Requirements:

5.1.1 Icing Environment: The design considerations for rotor blade ice protection start with the selection of the system environment in terms of:

- Liquid water content
- Water droplet size
- Ambient temperature
- Airspeed
- Altitude range
- Rotor speed

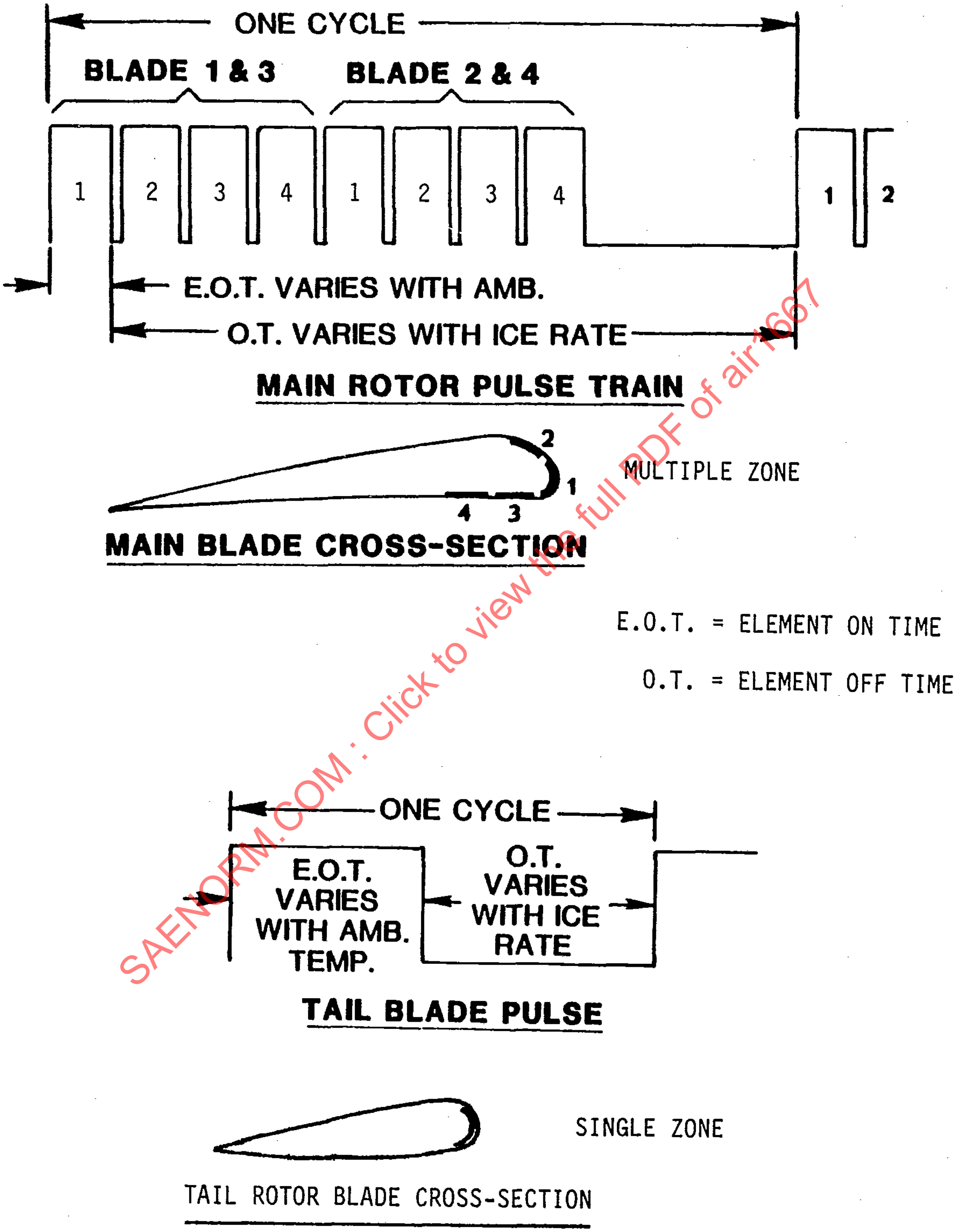





FIGURE 10 - Typical Blade Deice Cycle for Spanwise Zone Arrangement.

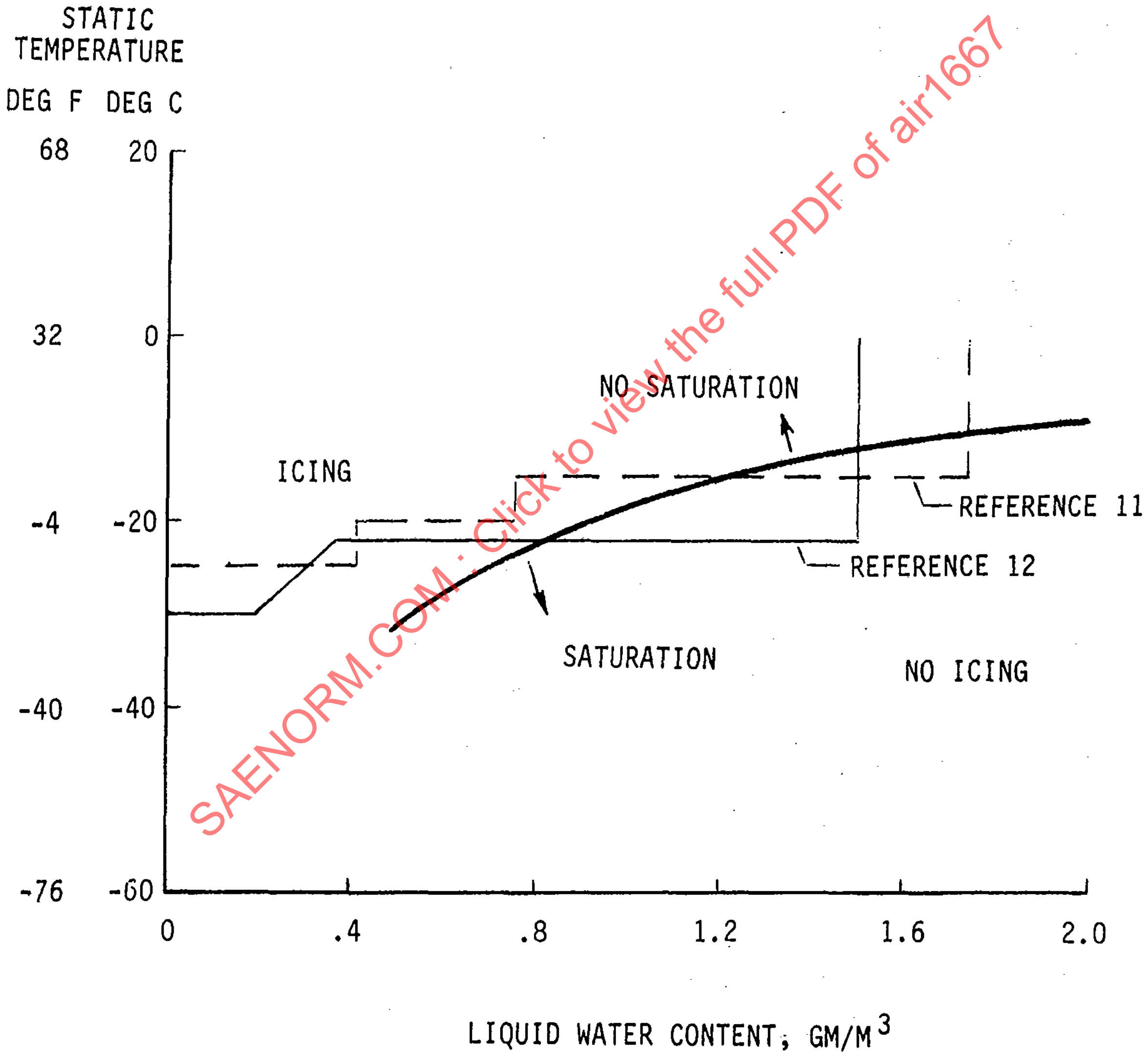





FIGURE 11 - Typical Deice System Saturation Limits

5.1.1 (Continued)

Some of these parameters may be specified in civil or military design requirements for continuous and intermittent rotorcraft operations within the icing environment.[5,11-16] The effect of the icing environment on a rotorcraft differs from that of a fixed wing aircraft. While the main rotor of a helicopter can be compared to the wing of a fixed-wing aircraft, the relative air velocity across the rotor blade varies with the azimuth location and the distance from the hub. In hover, the velocity varies from zero at the hub to a maximum at the tip. In forward flight the relative velocity will be a summation of tangential velocity and forward flight velocity. The tangential velocity near the hub on the retreating blade may be less than the forward flight velocity, resulting in a negative relative velocity (reversed flow) on that portion of the blade. Therefore, ice accretion will vary from the hub to the tip, and around the rotor disk.

5.1.2 System Requirements:

The ice protection system must be designed to permit safe operation within the specified icing environment. Additional requirements may exist concerning reliability and maintainability, system weight and maximum power consumption, lightning protection, erosion protection, cost, crew interface conditions and built-in test equipment (BITE) features.

5.2 Assessment of Icing on Rotor:

5.2.1 Analytical Assessment of Accretion: An analytical assessment of the rotor blade ice accretion characteristics should be made prior to the design of the deice system. This will include the definition of ice shapes and accumulation features on rotor blades over a given range of flight conditions and weather environments. Experimental investigations and analytical programs on both two-dimensional airfoil sections and scaled rotors provide a data base for more detailed assessments, allowing the evaluation of the impact of ice accumulation on the sectional aerodynamic and dynamic characteristics of rotor blades.

An ice accretion analysis should include both hover and forward flight conditions. Several blade stations should be analyzed to sufficiently describe patterns of droplet impingement and catch rates. Calculations to determine the ice collection characteristics of the blade may be based on the established formulas and graphs of Reference 5 or more modern references, such as References 7, 17 and 20. For study of airfoils and conditions not covered by existing empirical data, the designer may use more sophisticated computer programs that address flow field and ice collection properties for specific airfoil geometries.

5.2.1 (Continued)

The designer must also assess the impact of residual ice accumulations during active rotor deicing with consideration for:

Runback ice
Impingement aft of protected area
Exceedance of deice capability (i.e., deice system saturation)
System failure (partial or complete)

5.2.2 Need for Rotor Protection: Ice protection needed for the main and tail rotors will depend upon a number of factors such as the effect of rotor ice on the overall aircraft performance, handling qualities, rotor dynamics, and structural loads. The specific need for the aircraft to operate under icing conditions must be considered. Weight, space, and power allowance for ice protection equipment must be considered when determining the impact of a deicing system on aircraft performance.

5.2.3 Considerations of an Ice Protection System: An ice protection system should consider the type of ice protection required (active system or passive) and the available aircraft energy supply (electrical, bleed air, etc.). Methods other than electrothermal (pneumatic, ice phobic, electromagnetic impulse, chemical) are covered in Appendix A. The types of sensing equipment required and location on the aircraft must be determined, and the relationship between sensor signals and actual rotor blade ice accumulation must be established.

5.2.4 Aerodynamic Degradation: The aerodynamic effects of rotor ice require investigation to determine the magnitude of the aerodynamic degradation and to determine the need for specific ice protection. Many of the factors to be considered include the penalties due to nonuniform ice buildup and shedding, asymmetric ice shedding, and rotor lift, drag, torque (power), flutter and dynamic loads, and pitching moments changes. Autorotation should be feasible.

5.2.5 Dynamic Degradation: Rotor dynamic characteristics may be degraded due to blade center-of-gravity changes and due to vibration and control loads changes due to asymmetric ice shedding.

5.2.6 Other Effects on Aircraft: Ice may affect other parts of the aircraft, either due to impacts from shed ice, or from the icing of other components. The ice protection system must be designed to minimize the damage that could occur from shed ice. The flight envelope (pilot-controlled variables such as forward speed, rate of descent, and maneuver load factor) may be limited to avoid flight conditions that have higher probabilities of inducing damage. Rotor static droop stops must be protected from icing to maintain acceptable operational characteristics.

5.3 Other Considerations:

5.3.1 Erosion: The electrical heater blanket and its encasing insulating material is vulnerable to rain, sand, dust, and impact erosion. The erosion potential is particularly great along the outer half of the rotor because of the high impact velocities generated by rotor rotation. The general practice is to provide a metal leading edge erosion cap such as electro-formed nickel, stainless steel, or titanium along the span. Because the metal itself is subject to erosion in a sand, dust or rain environment, an additional material such as electroplated nickel may be added for longer life.

Blade erosion protection through the use of polyurethane (of various compounds) and polyethylene appears to have application on unheated rotors or sections of rotors. The heat transfer properties of these materials, however, makes use of them questionable for electrothermal deicing application except in very thin layers or for surface heater configurations.

5.3.2 Lightning: The material between the leading edge erosion cap and the deicing blanket must be sufficient to protect the blanket during lightning strikes on the rotor leading edge. The use of electrical conduction paths (such as wire mesh) along the surfaces and in contact with the erosion shield is one approach to leading the charge away from the deice blanket. The system may need some form of isolation to protect the helicopter electrical system. A customer or certifying group must establish the criteria for post-lightning strike operation. The general intent should be to minimize the effect of lightning on the helicopter, with consideration for the requirements or level of protection established for other essential systems and equipment fitted on board for a particular rotorcraft application. A lightning strike may damage the zone(s) affected by the strike.



5.3.3 Impact: The potential for main and tail rotor blade damage due to impact with shed ice (from either main or tail rotor, fuselage, or other external sources) and other foreign objects must be taken into account in determining the proper protection for the rotor deice blankets. Impact damage due to ice has been noted along main rotor lower surfaces (usually in the trailing edge regions) and on the tail rotor surfaces near the leading edge and tip. While no specific ice impact damage to electrical heating blankets has been noted to date, the design should be examined to determine the damage potential. The tail rotor could be anti-iced if ice shedding from the tail rotor became a problem for a particular design.

5.3.4 Dynamic Loads: The deicing blankets are subject to the same dynamic motions as the rotor leading edge region: normal (flatwise), chordwise (inplane), and torsional bending, and blade acceleration. The dynamic environment must be taken into account when evaluating the choice of deicing electrical resistance heater element, and the physical arrangement of the elements.

5.3.4 (Continued)

The deice blanket materials must be evaluated for the following:

Stress-strain characteristics

High temperature limits

Fatigue limits

Thermal cycle fatigue characteristics

Erosion

Foreign object damage (FOD)

Repairability

5.4 Overall Deicing System Assessments: The following lists the items that must be assessed during the design of the over-all deice system:

Reliability and failure modes and effects

Electro-magnetic interference and radio frequency interference

Redundancy requirements

Overheat protection

Ground checkout (BITE) procedures

System checkout procedures

System saturation

Fault/failure detection

Repairability

5.5 System Attributes: The following items must be considered for design and optimization of the overall system:

Electrical power required

Thermal/heat transfer requirements

Heater element-on-time to achieve satisfactory surface temperature

Flight performance requirements

Environmental limits

6. TEST CONSIDERATIONS:

6.1 Component/System Development: Tests of components and subsystems during the design and development of an electrothermal rotor deicing system can supply valuable data to assist the design engineer.

6.1.1 Blade Heater Element Tests: Several types of tests are used to provide design data for blade heaters. Fatigue tests of candidate heater foils or wire matrixes can be accomplished to establish fatigue life of the heater elements, since these must be subjected to the same strain levels as other parts of the blade structure. The heater elements are fabricated in a sample which encloses the heater in the same structural elements which would surround it in the rotor blade. The sample is then subjected to repetitive loads in a tensile fatigue test machine. While being subjected to the repetitive loads, the heater should be energized to simulate the effects of temperature cycling. The above described test is useful for comparing the relative worthiness of various heater element materials, but a more conclusive test may be desired by conducting a fatigue test of a blade segment with the heater element installed in the leading edge of the blade. This test would use a blade segment fatigue test specimen as used for normal qualification fatigue tests common to helicopter qualification programs. During such a test, the heater element should be energized to bring the heater element temperature up to the maximum permissible design values.

Another very important design feature in an electrothermal deicing system is the heat transfer characteristic between the heater element and the blade surface. Tolerance variations in the thickness of materials between the heater element and the blade surface and wire spacing can cause considerable inconsistency in temperatures on the surface. Since the deicing method requires the blade surface to be heated and then allowed to cool rapidly, it is important to know the time required to heat and then cool the blade. Although the blade heating and cooling is affected considerably in flight by the air flow and cloud moisture, much can still be learned from laboratory tests of a blade heater in a sample blade segment. Thermocouples located within the design specimen can provide valuable heat transfer data for optimization of the blade/heater interface, but these thermocouples must be located to avoid local cold spots.

Icing wind tunnel tests of helicopter airfoils and blade sections should be conducted. No icing wind tunnel facility at present is large enough to test a full scale rotating helicopter rotor. Therefore, while cyclical variations in blade angle of attack can be simulated, the considerable effects of centrifugal force cannot be simulated.

6.1.2 Power Transfer System Tests: All electrothermal rotor blade deicing systems to date use the same general electrical power fixed system to rotating system transfer method. A two-channel or three-channel slip ring (VDC or VAC, respectively) converts the fixed to rotating hardware and a solid-state or mechanical-stepping switch routes the electrical power to the appropriate blades heater elements. Slip rings and stepping switch systems should be laboratory tested, simulating actual flight conditions as closely as possible, including temperature effects. The controller should also be tested to determine operating characteristics, and evaluate system performance.

6.1.3 Nonicing Flight Tests: Prior to testing a blade electrothermal deicing system in artificial or natural icing conditions, flight tests in dry air or wet air conditions can be used to determine system operating characteristics.

Choosing the location of an ice detector or icing intensity measuring device on a helicopter can be a critical problem because the complex aerodynamics of a rotorcraft fuselage can cause cloud LWC to be "thinned out" or "enriched" at various boundary layer locations. One solution to this is to make a qualitative test with the aircraft in natural clouds at temperatures well above freezing. In the test, short (approximately 10 in [25 cm]), water-soluble, painted rods are attached to various candidate icing detector locations on the helicopter. When the aircraft is flown into a cloud (approximately 1/2 min) the water droplets will mark the water soluble paint and show the variation of cloud moisture at different locations on the aircraft fuselage. The "richest" moisture location is normally chosen for the initial icing detector location.

Tests of the deicing system, using temperature measuring sensors at various points on the heated blades in non-icing conditions, can provide valuable information for deicing controller settings. The effect of moisture on surface temperature and heat loads during tests in wet air must be considered. Electromagnetic interference (EMI) tests should also be done at this time.

6.1.4 Icing Flight Tests: Flight tests in natural icing conditions are presently required for the certification by civil authorities or qualification by military authorities of rotorcraft for flight into known icing conditions. However, artificial icing tests in wind tunnels, spray rigs, or behind tankers can be used to supplement natural icing flight to optimize the heater element on-times, element off-times, and system sequencing. Care should be taken when operating the rotor deice system in the automatic mode behind a tanker since the test aircraft's icing rate indication may not be fully in the spray and it may not be adequately calibrated for the droplet distribution of the tanker cloud.

6.2 Certification/Qualification Testing: Upon completion of the design, analytical and test substantiation and development, the rotor deicing system should be ready for certification and/or qualification testing.

6.2 (Continued)

Compliance is established when there is reasonable assurance that, while operating in an icing environment, there are no unacceptable degrading effects due to ice accretion. Compliance flight testing may consist of a combination of wind tunnel testing and in-flight spray tanker tests, hover icing spray rig tests, dry or wet air flight tests, and natural icing flight tests.

The amount of testing should be directly tied to the ability to compare the flight test results with the analytical substantiation, model tests and development tests. In the latter, care should be taken to identify the aircraft configuration during the development so that changes and the effect on certification/qualification can be assessed. The testing during this time frame could consist of contractor, contractor/government agency, or government agency. Prior to government agency flights, sufficient analyses and testing must have been done to show that the aircraft is "safe" for testing.

In order to minimize the program costs, the government agency should be cognizant of tests conducted by the contractor and limit his tests to verify the validity of the data taken by the contractor.

As a minimum, the certification/qualification tests should include the following:

a. Demonstration that the system operation and performance is as intended for the icing envelope chosen. This should include failure modes and their effect on system operation.

b. Identification of performance degradation, including autorotation.

c. Evaluation of handling qualities characteristics with ice formations during and following deicing and simulated failures

d. Evaluation of main rotor and rotor control system

e. Evaluation of ice shedding damage during deice cycles

f. Evaluation of engine and secondary inlets, Pitot static systems, horizontal stabilizers, rotor droop stops, fuel and drain vents, etc.

g. Determination of performance and handling qualities recovery after exit from icing conditions

To accomplish these tasks, sufficient instrumentation should be installed to verify the areas of concern. Typical instrumentation could consist of: Icing parameters (liquid water content, droplet diameter), temperatures (including blade temperatures), performance parameters, loads, vibration, handling qualities parameters (control positions, aircraft attitudes, and rates), and deice system performance parameters (blade heater power and cycle times). As testing progresses, some instrumentation may become unnecessary. The use of video and still photography, from test and chase aircraft and on the ground, can be valuable in documenting ice accretion.

6.2 (Continued)

The testing to be conducted should be in both dry air, wet air and in icing conditions. The dry air tests can be used to partially verify the blade thermal analysis. This would be followed by flight in icing conditions to assure compensation has been made for the "insulating" effect of the ice. Once the thermal analysis has been verified at several temperatures, the blade temperature instrumentation would not be required. In addition, the thermal analysis could be done utilizing a suitable icing spray system tanker. A hover spray rig is a good research tool, but forward airspeed is not simulated and the beneficial aerodynamic heating effect will not exist.

The flight tests to verify impingement analysis could likewise be conducted behind a suitable tanker. The advantages of utilizing a tanker are many and include the capability of immersing only a particular part of the aircraft in icing conditions and allowing a more rapid avenue of escape if problems develop. The major disadvantage is that cloud parameters (LWC and droplet diameter) and cloud consistency, and the effects on ice shapes, are difficult to maintain and can vary throughout the cloud. Tanker cloud parameters must be used when correlating with impingement code calculations.

Because of the disadvantages of artificial icing tests, the final tests should be conducted in natural conditions as close as possible to the critical design points. Sufficient correlation with analysis must be shown to assure that the aircraft can operate safely throughout the intended envelope. The natural icing tests would verify any performance degradations for other conditions not previously encountered. In addition, the natural tests will probably be the first time the entire aircraft has been immersed in an icing environment at the same time. Effects on unprotected surfaces, engine inlets, possible damage to other components due to random shedding, etc., should be evaluated.

6.3 Operational/Functional System Performance: As a part of the certification/qualification testing, operational and functional performance of the system should be addressed. During the operational/functional test, a representative flight manual should be available to be evaluated by the test team. This should consist of failure modes and their effect on system performance, method of action to be taken depending on the failure, i.e., "continue flight", "land as soon as possible", or "land immediately". The test should also identify which systems should be operational prior to flight, i.e., minimum equipment list. The majority of the failure modes can be evaluated during tests behind the tanker.

Many single and dual failure modes (failures not affecting system performance) can be verified in bench tests. An example of this type of condition could be the switching sequence which is activated internally in the controller, where the total system performance is not affected.

In summary, certification/qualification testing can be accomplished utilizing suitable artificial icing facilities and dry and wet air testing, with final verification in natural icing conditions.

6.3 (Continued)

However, it may be more desirable to do the entire compliance/qualification in natural conditions. It is not considered feasible at this time to conduct all testing utilizing artificial icing facilities; some natural icing tests are required.

6.4 Icing Test Facilities: In all artificial icing facilities, the test aircraft or component is located in a cold airstream containing the icing cloud which consists either of supercooled water droplets, solid ice particles or a mixture of the two. The cold airstream is obtained either by using cold ambient air or by using cooling provided by a refrigeration system. The icing cloud environment is made up of very small supercooled droplets (10 - 50 µm) produced by special nozzles, generally of the air/water atomizing type using both pressurized air and pressurized water. Care must be taken to avoid the formation of ice crystals. (Note that different size nozzles are used to generate the 300 - 2000 µm droplets to simulate freezing rain and that ice crystals may be created by feeding blocks of ice onto a rotating cutter and directing the particles into the tunnel airstream.)

6.4.1 Wind Tunnels: Existing wind tunnels are well suited for research and development tests. Certification testing of aircraft components can be performed at severe icing conditions, but none of the tunnels can cover the entire certification envelope.[15,16] The altitude and velocity ranges of many tunnels do not permit testing over the full operating range of the helicopter. The tunnel sizes generally only allow components of the helicopter to be tested (i.e., inlets, airfoil sections, instruments, etc.).

Scaling is sometimes used to convert tunnel results to the size, airspeed and altitude of the test aircraft, but these scaling parameters have not yet been adequately verified. If scale model tests are used the results must be validated by acceptable means.

6.4.2 Low Velocity Facilities: There are several facilities with refrigerated cold rooms where the test components can be subjected to a controlled icing environment. The climatic hangar at Eglin AFB, Florida, is large enough to test an entire tiedown aircraft under limited icing conditions. A unique facility at Ottawa, Ontario, Canada, the Helicopter Icing Spray Rig, can provide a realistic artificial icing cloud in which a helicopter can hover.[18]

6.4.3 Aerial Tankers: The U.S. Army Helicopter Icing Spray System (HISS) is a JCH-47C helicopter equipped with a spray system which provides an icing cloud that is approximately 8 ft (2.4 m) in height and 36 ft (11 m) in width.[19]

The USAF operates C-130 and KC-135 aircraft with icing spray systems that can be used to test small areas of an aircraft. However, the operating envelopes of these aircraft and conventional rotorcraft do not overlap sufficiently to warrant their use.

7. REFERENCES:

1. Lewis Research Center, "Selected Bibliography of NACA-NASA Aircraft Icing Publications," NASA TM 81651, August 1981.

2. Korkan, K. D. (editor), "Aircraft Icing Technology Bibliography," Society of Automotive Engineers Aeronautical Information Report (AIR) 4015, May 1987.

3. Advisory Circular, "Hazards Following Ground Deicing and Ground Operations in Conditions Conductive to Aircraft Icing," FAA-AC-20-117, December 1982.

4. "Forecaster's Guide on Aircraft Icing," USAF AWSM 105-39, January 1969.

5. Bowden, D. T., Gensemer, A.E. and Skeen, C.A., "Engineering Summary of Airframe Icing Technical Data," FAA Technical Report ADS-4, December 1963.

6. Messinger, B.L., "Equilibrium Temperature of an Unheated Surface as a Function of Airspeed," Journal of Aeronautical Sciences (Vol 20, no.1), January 1953.

7. Flemming, R. J. and Lednicer, D.A., "High Speed Ice Accretion on Rotorcraft Airfoils," NASA CR 3910, August 1985.

8. Kim, J.J., "Particle Trajectory Computation on 3-Dimensional Engine Inlet," NASA CR 175023, January 1986.

9. Ackley, S. F. and Templeton, M.K., "Computer Modeling of Atmospheric Ice Accretion," Cold Regions Research and Engineering Laboratory (CRREL) Report 79-4.

10. Olsen, W., Takeuchi, D. and Adams, K., "Experimental Comparison of Icing Cloud Instruments," NASA TM 83340 (AIAA-83-0026), January 1983.

11. Masters, C.O., "A New Characterization of Supercooled Clouds Below 10,000 Feet AGL," DOT/FAA/CT-83/22, June 1983.

12. "Airworthiness Standards: Transport Category Aircraft," Federal Aviation Regulation Part 25, Appendix C, 1987.

13. Peterson, A.A. and Dadone, L.U. "Helicopter Icing Review," Report No. FAA-CT-80-210, September 1980.

14. Heinrich, A., et al, "Aircraft Icing Handbook," DOT/FAA/CT-87-7, to be published.

15. "Airworthiness Standards: Transport Category Rotorcraft," Federal Air Regulation Part 29, 1987.

16. "Certification of Transport Category Rotorcraft," AC-29-Change 2, May 1985.

7. (Continued)

17. Flemming, R. J. and Lednicer, D.A., "Correlation of Airfoil Icing Relationships with Two-Dimensional Model and Full Scale Rotorcraft Icing Test Data," AIAA Paper 85-0337, January 1985.

18. Olsen, W., "Survey of Aircraft Icing Simulation Test Facilities in North America," NASA TM 81707, February 1981.

19. Lynch, C.P. and Peterson, A.A., "Helicopter Icing Spray System (HISS) Improvement Program," Boeing Vertol Report D210-11570-1, January 1980.

20. Bragg, M.B., "Rime Ice Accretion and Its Effect on Airfoil Performance," NASA CR 165599, March 1982.

21. Shaw, R.J., Sotos, R.G., and Solano, F.R., "An Experimental Study of Airfoil Icing Characteristics," NASA TM 82790, January 1982.

22. Corley-Byrne, P.L., "Helicopter Icing and Performance Degradation Measurement," Leigh Instruments, Ltd. document ES700615A, January 1987.

## 8. LIST OF SYMBOLS

a Droplet radius, ft

A/B Semi-length/maximum radius of ellipsoid, dimensionless

b Dimensionless parameter

C Airfoil chord length, ft (m)

$c_p$ Specific heat, BTU/lb - °F

$D_d$ Median volumetric droplet diameter, µm

$e_l$ Vapor pressure of saturated air at edge of boundary layer, in Hg

$e_{ok}$ Vapor pressure of air at surface of airfoil, in Hg

$E_m$ Total collection efficiency based upon frontal area projected along the line of flight, dimensionless

g Gravitational constant, 32.2 ft/s$^2$

H Airfoil projected height along line of flight, ft

J Mechanical equivalent of heat, 778 ft-lb/BTU

K Impingement parameter, dimensionless: $K = 2/9 \dfrac{a^2 V_o \rho_w}{C \mu_a g}$

$K_o$ Inertia parameter, dimensionless: $K_o = (\lambda/\lambda_s)K$

$L_s$ Latent heat of evaporation of water, BTU/lb

LWC Liquid water content, g/m$^3$

M Free stream Mach number, dimensionless

n Freezing fraction, dimensionless

p Pressure just outside the boundary layer, in Hg

Pr Prandtl number (for air) 3,600 $c_p \mu/k$

R Rotor radius, ft (m)

$S_U$ Impingement limit on upper surface, ratio to chord length, dimensionless

$S_L$ Impingement limit on lower surface, ratio to chord length, dimensionless

$t_o$ Ambient temperature, °F (°C)

8. (Continued)

$t_{ok}$ Datum temperature or wet air boundary layer temperature, °F (°C)

$t_{se}$ Airfoil surface temperature, °F (°C)

$V$ Local velocity along the surface, fps (mps)

$V_o$ Free stream velocity, fps (mps)

$W_m$ Rate of water catch on airfoil, lb/min/ft of span (gm/sec/m of span)

$\lambda$ Droplet range when projected into still air

$\lambda_s$ Droplet range when projected into still air according to Stokes law

$\alpha$ Angle of attack, deg

$\mu$ Viscosity, lb s/ft$^2$

$\mu_a$ Air viscosity, lb s/ft$^2$

$\beta$ Collection efficiency at any point on airfoil or body, dimensionless

$\gamma$ Ratio of specific heats

$\rho$ Air density, slugs/ft$^3$

$\rho_o$ Free stream air density, slugs/ft$^3$

$\rho_w$ Density of water droplet, slugs/ft$^3$

$\gamma_w$ Specific weight of water, lb/ft$^3$



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## APPENDIX A

## OTHER ICE PROTECTION CONCEPTS

### Ice-Phobic

The ice-phobic concept (the self-shedding of ice due to interface shear reduction or the prevention of ice accumulation) has been under investigation for use on helicopter rotor blades for over 20 years. Various pastes, waxes, low adhesion materials (such as Teflon®, and several types of polyurethane), flexible substrates and other materials have been tested for their ice shedding potential on rotating arm rigs and on helicopter rotors with limited success. The most recent series of ice-phobic material tests on a UH-1H in the National Research Council (NRC) of Canada Helicopter Icing Spray Rig (HISR) and during in-flight icing trials indicated that the blade coatings are highly susceptible to rain erosion, and exhibit a lack of predictable ice shedding.

More work is needed in the ice-phobic material development area. The results of the testing to date has led to conculsions that selected ice-phobic material may show promise for rotor blade application for at least a limited capability for flight in supercooled cloud icing conditions at LWC's less than 0.5 $gm/m^3$ and ambient temperatures above 14°F (-10°C). Such capability may be useful for some applications, however, the FAA has not favorably considered limited approvals in the past and has not shown any inclination to accept limited approvals in the future.

### Pneumatic Boot Deicing

Pneumatic boot deicing has and is currently being used on a number of fixed-wing aircraft (primarly general aviation type) for wing and empennage protection. The pneumatic system employs a series of deformable (stretchable) tubes running in either the chordwise or spanwise direction along the airfoil leading edge. A compressed air source (engine bleed, load compressor, etc.) supplies the pressure source to inflate the tubes at a predetermined ice thickness, thus cracking the ice layer, and to provide a negative pressure to keep the boot contoured to the leading edge during non-operating periods. Aerodynamic, dynamic, and centrifugal forces acting on the cracked ice separate the ice from the pneumatic boot surface.

Testing of pneumatic deicing on a helicopter rotor has been accomplished by the U.S. Army on a UH-1H in icing trials in the NRC HISR and in forward flight behind the Army icing spray tanker (HISS). Tests have indicated that the pneumatic boots can provide satisfactory rotor deicing within the range of icing conditions tested. Additional work is required, however, to reduce the aerodynamic penalties on the rotor, to demonstrate resistance to erosion, and to extend the capabilities under icing conditions.

Fluid Deicing/Anti-icing

Fluid deicing and anti-icing systems have been tested in rotor blade installations for several helicopter applications. In principle, the fluid system distributes and secretes an ice-depressant fluid along the rotor leading edge to provide an ice-free surface (anti-icing) or to weaken the ice bond and permit aerodynamic, dynamic and centrifugal shedding (deicing). The fluid distribution systems may include a series of small holes along the leading edge or may incorporate a porous metal surface to permit fluid distribution to the ice impingement regions. To date, while fixed wing fluid systems are well under way in development, no successful rotor fluid system has been achieved.

Electromagnetic Impulse Deicing (EIDI)

The electromagnetic impulse deicing concept involves the mechanical deformation of an airfoil leading edge skin through the use of a series of spanwise local deflections driven by electromagnetic devices which cause the skin to "ripple" in a propagated wave along the span. The effect is somewhat similar to that of the pneumatic boot, in that the ice is cracked and removed from the surface by aerodynamic, dynamic, and centrifugal forces. The major difference is the "ripple" which, in the case of the pneumatic boot, is produced by a low frequency, high amplitude wave, while the impulse system produces a high frequency, low amplitude wave.

No practical rotor blade installation has occurred for the electromagnetic impulse approach to date. Because the impulse devices must be installed beneath the blade leading edge skin, a unique fabrication approach is required for the blade to accommodate the installation.

Microwave Deicing

The microwave concept involves the transmission of microwave energy along a rotor leading edge cavity wave guide. In theory, the rotor ice will extract a portion of the transmitted energy in sufficient amounts to cause local shedding of the ice. The microwave deicing concept is similar to the electrothermal deicing approach in that both are heating a thin layer at the ice/surface interface in order to reduce and break the bond and permit ice shedding. In theory, the microwave approach should require less electrical energy than the electrothermal because only a small area is being heated at any one time. A practical application of the microwave as a deicer has not surfaced.

Vibratory Deicing

The vibratory deicing concept involves the application of an induced rotor blade excitation at blade natural frequences with amplitudes necessary to fracture the ice interface at the blade leading edge. The blade excitation is provided through forcing function shakers mounted at selected locations at the rotor hub to provide the required vibratory mode shapes to cause ice shedding. In theory, the vibratory concept accomplishes a similar function as the electromagnetic impulse approach. In both cases, the purpose is to introduce a high-frequency, low-amplitude wave along the rotor leading edge surface of sufficient energy to break the ice bond. A practical rotorcraft vibratory deicing system has not been designed and demonstrated.

## APPENDIX B

## RATE OF ICE COLLECTION

The liquid water content (LWC), median volumetric drop diameter (MVD), and outside air temperature (OAT) are used to determine the rate of water (ice) collection on a surface. The collection rate is given by the following equation:

$$W_m = 5.278 \times 10^{-4} \times V_o \times LWC \times H \times E_m \quad \text{(British Units)}$$

$$W_m = V_o \times LWC \times H \times E_m \quad \text{(Standard International Units)}$$

where: $W_m$ = mass of water intercepted - lb/min/ft of span (gm/sec/m of span)

$E_m$ = collection efficiency

LWC = liquid water content - $gm/m^3$

H = projected height - in (m)

$V_o$ = forward speed - kt (m/sec)

The collection efficiency of a surface can be determined either by analysis or test. Potential flow/particle trajectory analysis methods can be used to calculate the theoretical amount of ice catch on various body shapes. Fig. B-1 illustrates airfoil particle trajectories that become tangent to the airfoil surface and shows associated collection efficiencies for a typical helicopter section. An approximate collection efficiency can be established by calculating the inertia parameter ($K_o$) and matching the value with known shapes tested for ice accretion. For example, $K_o$ may be calculated by the method outlined in Reference 20 and illustrated as follows:

$$K_o = \frac{D_d^2 V_o \rho_w}{c\mu} \quad x \quad R^{-2/3} - (\sqrt{6}/R) \text{ Arctan } (R^{1/3}/\sqrt{6})$$

where:

| | | | |
|---|---|---|---|
| C | = effective chord length | - | m |
| $D_d$ | = median volumetric droplet diameter | - | µm |
| $K_o$ | = inertia parameter | - | dimensionless |
| R | = Reynolds number = $\rho D_d V_o/\mu$ | - | dimensionless |
| $V_o$ | = forward speed | - | m/sec |
| µ | = viscosity of air | - | kg/m-sec |