9 Ice & Rain Protection (ATA 30)

9.1 Definition

> *Those units and components which provide a means of preventing or disposing of formation of ice and rain on various parts of the aircraft. Includes alcohol pump, valves, tanks, propeller/rotor anti-icing system, wing heaters, water line heaters, pitot heaters, scoop heaters, windshield wipers and the electrical and heated air portion of windshield ice control. Does not include the basic windshield panel. For turbine type power plants using air as the anti-icing medium, engine anti-icing is... [part of the power plant]* (**ATA 100**)

9.2 System Classification

Ice & rain protection may be classified as follows:

- nontransparent surfaces: ice protection (leading edges, radome, inlets, etc.):
    - pneumatic boot systems
    - thermal ice protection systems:
        - hot air systems
        - electrical resistance systems
    - fluid systems
    - electro impulse de-icing (EIDI) systems
    - microwave systems
- external components: ice protection (antennas, sensors, drain masts, etc.)
- internal components: ice protection (water lines, etc.)
- windshield: ice and fog protection
- windshield: rain removal
- ice detection

External and internal components are generally protected against icing by electrical resistance systems. Some technical solutions for windshield ice protection serve at the same time also for windshield rain removal.

The two main ice **protection principles** are *deicing* and *antiicing*. Various **technical solutions** exist to do the job. Some ice protection technical solutions can perform both: *deicing* and *antiicing*. Other technical solutions only manage deicing (Table 9.1).

The terms *deicing* and *antiicing* are defined in **AIR 1168/4**:

- **Deicing** is the periodic shedding, either by mechanical or thermal means, of small ice buildups by destroying the bond between the ice and the protected surface.
- **Antiicing** is 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.

Table 9.1 Ice protection technical solutions and protection principles

ice protection technical solutions	deicing	antiicing
pneumatic boot systems	x	O
hot air systems	x	X
electrical resistance systems	x	(x)
fluid systems	x	(x)

X solution usually applied to protection principle
(x) solution usually not applied to protection principle
o solution can not be applied to protection principle

9.3 Icing Fundamentals

From our daily experience we know that water freezes to ice below 0°C (32 °F) and melts again above 0 °C. When it comes to aircraft icing, we learn that this need not be so. Small droplets can still be in the liquid phase below(!) 0 °C. Most droplets will have turned to ice below -20 °C (-4 °F), though very small and pure droplets may reach temperatures as low as -40 °C (-40 °F) and still remain liquid. Below -40 °C finally all water in the air will be frozen. (Liquid) water below 0 °C is called *supercooled water*. Supercooled water can exist because the water has been totally undisturbed during cooling – nothing has caused it to turn to ice. When an aircraft hits the droplet, however, the droplet receives the necessary input for the phase change and turns to ice. The phase change from water to ice usually requires some latent heat extraction, but when the droplets are supercooled water, the heat extraction has already taken place. The ice will be slightly warmer than the supercooled water was just a second earlier. Summing up: **Supercooled water turns instantly to ice due to the interaction with the aircraft**. The result will be *ice accretion* on the aircraft surface if the surface is below 0 °C.

Aircraft icing is thus **possible** if

1. the air contains water (clouds are an indication of water in the air)
2. the air temperature is below 0°C
3. the air temperature is above -40°C
4. the aircraft surface is below 0°C.

There are **other icing mechanisms** besides the standard one just discussed:

- *Icing* will occur *during descent* from high altitudes if the aircraft encounters humid air even above 0 °C. The aircraft surface will be below 0 °C due to a long flight at high altitudes. The fuel in the wings will also be below freezing. The fuel is in close contact with the skin as a consequence of integral fuel tank design (see Section 7: Fuel). The fuel does not warm up quickly and is likely to remain below 0 °C until landing.

- *Carburetor icing* can occur at temperatures between -7 °C (20 °F) and +21 °C (70 °F) when there is visible moisture or high humidity. Carburetor icing is caused by cooling from vaporization of fuel, combined with the expansion of air as it flows through the carburetor.
- *Water and slush* that the aircraft picks up *during taxi out* can freeze at higher altitudes with detrimental effects to the aircraft.
- *Frost, ice, and snow* that have settled on an aircraft *on the ground* have to be removed before takeoff. **Ground deicing** equipment and procedures have been developed (see **AC 135-16**).

The **two basic forms of ice** built-up on the aircraft surface are *clear ice* and *rime ice* (Figure 9.1):

- **Clear ice** forms between 0 °C to –10 °C usually from larger water droplets or freezing rain, and can drastically change the form of the leading edge. It can spread over the surface.
- **Mixed ice** forms between -10 °C to -15 °C. A mixture of clear ice and rime ice has the bad characteristics of both types and can form rapidly.
- **Rime ice** forms between -15 °C to -20 °C from small droplets that freeze immediately when contacting the aircraft surface. This type of ice is brittle, rough looking, and colored milky white.

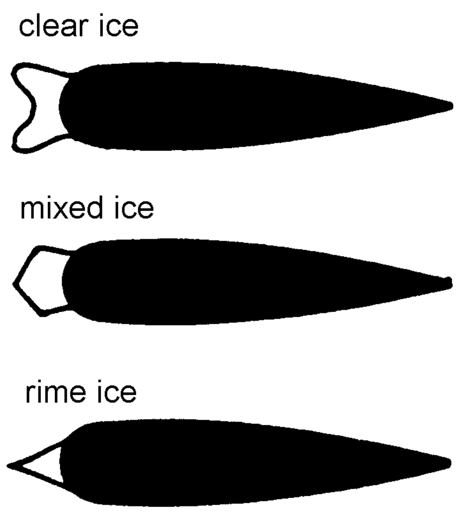

Figure 9.1 Ice shapes on the leading edge of airfoils

In order to **calculate** the **total water catch** of the wing, let us cut off a piece of a wing with a spanwise extension Δy and maximum thickness t. This piece of wing will fly at a speed v through a unit volume of air with a certain mass of supercooled water. The mass of supercooled water per volume is called *liquid water content* (LWC) and is something like a density we name ρ_{LWC}. We consider $t \cdot \Delta y$ as the area of an imaginary sieve at an angle perpendicular to its flight path. The mass flow rate of supercooled water through the sieve would be $\dot{m} = v\, t\, \Delta y\, \rho_{LWC}$. The impingement of water on the leading edge of the wing will, however, be different from the flow through the sieve as shown in Figure 9.2. The air and with it very small droplets pass around the wing; only larger droplets hit the surface. This phenomenon is expressed by the *water catch efficiency* E_m. The imaginary sieve shows an efficiency E_m = 1. The *total water catch* of a piece of wing is calculated by including E_m:

$$\dot{m} = v\, t\, \Delta y\, \rho_{LWC}\, E_m \quad .$$

E_m is a function of aircraft speed and droplet size, airfoil shape and thickness, viscosity, and density of the air:

- High aircraft speeds and a large droplet size cause an increase in water catch efficiency.
- High aircraft velocities, however, lead to aerodynamic heating of the leading edges. This reduces icing.
- Thin wings divert the flow less and increase the water catch efficiency.

AIR 1168/4 presents detailed methods to calculate E_m.

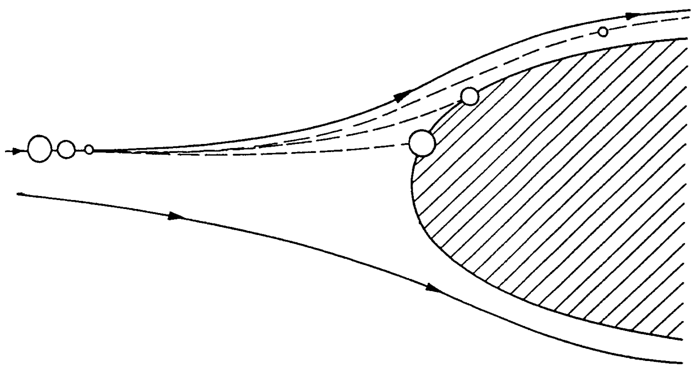

Figure 9.2 Flow around a wing leading edge:
- Streamlines of dry airflow
- Trajectories of differently sized droplets

A **simplified method to calculate the water catch efficiency** E_m is presented here based on Figure 3F-3 of **AIR 1168/4** as a function of aircraft speed v and wing thickness t (Figure 9.3)

$$E_m = 0.00324 \left(\frac{v}{t} \right)^{0.613} \qquad \text{for } v \text{ in m/s and } t \text{ in m} .$$

This equation is based on typical airfoils with a relative thickness of 6 ... 16% at an angle of attack $\alpha = 4°$. The *mean effective drop diameter* d_{med} = 20 µm, altitude h = 10000 ft. Other altitudes from sea level to h = 20000 ft will result in an error less than 10%.

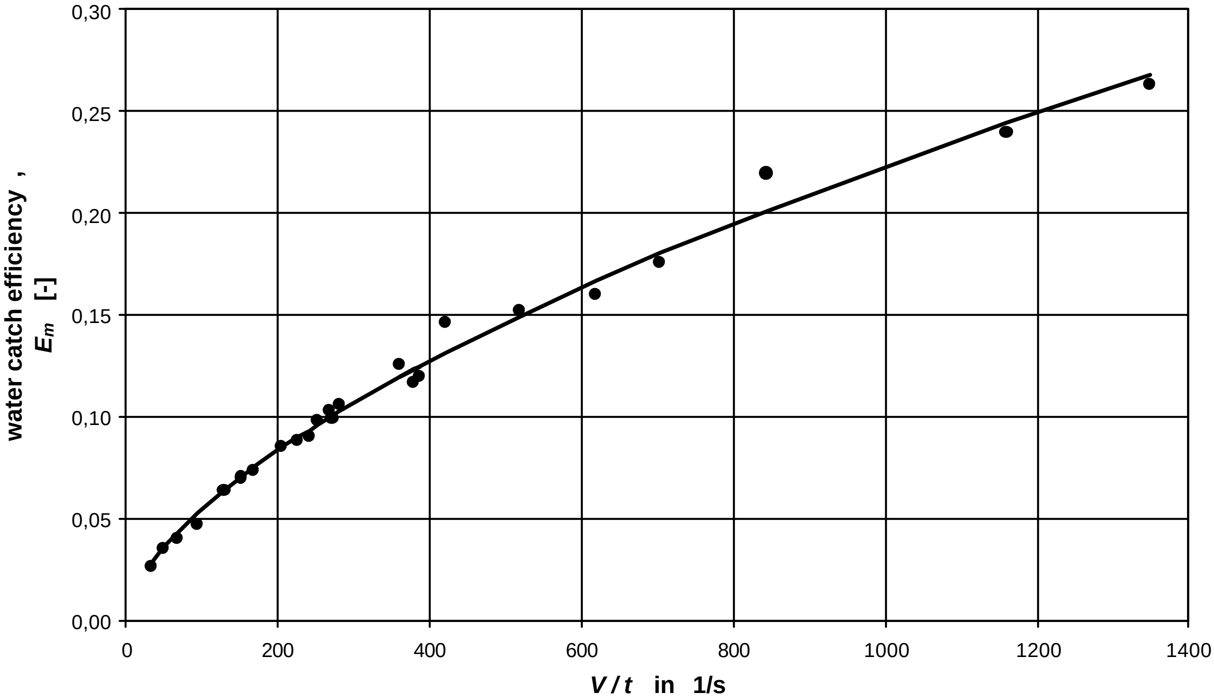

Figure 9.3 Water catch efficiency E_m as a function of aircraft speed v and wing thickness t for typical applications. The diagram is calculated from **AIR 1168/4**, Figure 3F-3 (●)

ACJ-25, section 1419 assumes for certification a typical *mean effective drop diameter* d_{med} = 20 µm. The *liquid water content* (LWC) that an aircraft is supposed to meet continuously in flight ranges from ρ_{LWC} = 0.2 g/m³ at -30 °C to ρ_{LWC} = 0.8 g/m³ at 0 °C.

The **detrimental effects of icing on the aircraft** are manifold. Ice can...

- ... alter the shape of an airfoil. This can change the angle of attack at which the aircraft stalls, and cause the aircraft to stall at a significantly higher airspeed. Ice can reduce the amount of lift that an airfoil will produce and increase drag several-fold.
- ... partially block control surfaces or limit control surface deflection.
- ... add weight to the aircraft. The aircraft may not be able to maintain altitude. The stall speed is higher.
- ... block the pitot tube and static ports.
- ... cause the breakage of antennas on the aircraft.
- ... cause a tailplane stall. The airplane will react by pitching down, sometimes in an uncontrollable manner.
- ... reduce propeller efficiency. Ice that is hurled away from the propeller is a hazard to everything in its plane of rotation.

- ... endanger the internal parts of a jet engine.

In order to protect the aircraft properly against these effects, ice protection may become necessary in areas shown in Figure 9.4.

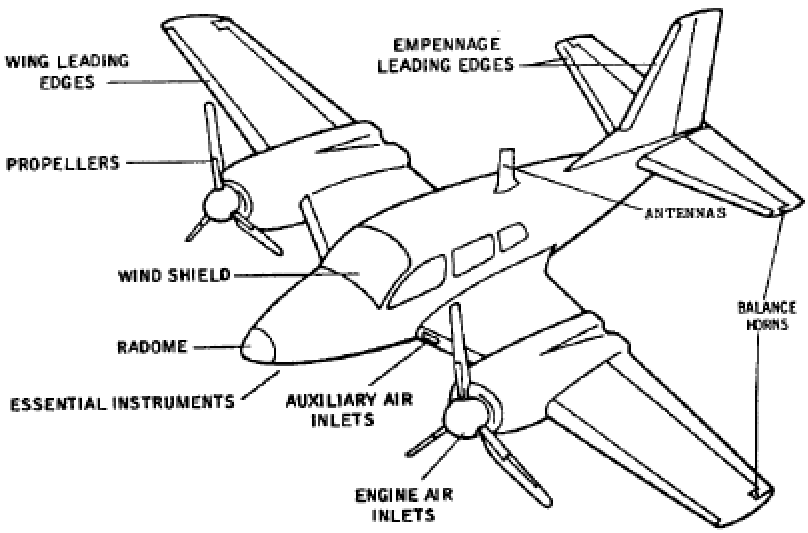

Figure 9.4 Areas of the airframe that may require ice protection (**FAA 1993**)

The **design of ice protection systems** will always have to be based on the *certification requirements*. For transport category aircraft, the fundamental statement reads: "If certification for flight in icing conditions is desired, the airplane must be able to safely operate in the continuous maximum and intermittent maximum icing conditions ..." (**FAR Part 25**, **JAR-25**, section 1419). Icing conditions are given in Appendix C of these documents.

Critical parts of the aircraft (like the wing) will probably need some kind of ice protection device. Other parts of the aircraft (like the empennage) may fulfill the requirements without being protected.

9.4 Pneumatic Boot Systems

Pneumatic boot systems have been the standard ice protection method for piston engine aircraft since the 1930s. The **boot surfaces** remove ice accumulations mechanically by alternately inflating and deflating tubes within a boot that covers the surface to be protected (Figure 9.5). Inflation of the tubes under the accreted ice breaks the ice into particles and destroys the ice bond to the surface. Aerodynamic forces, and centrifugal forces on rotating airfoils then remove the ice. In principle, this method of deicing is designed to remove ice after it has accumulated rather than to prevent its accretion in the first place. Thus, by definition a pneumatic boot system cannot be used as an antiicing device. Conventional pneumatic boots are constructed of fabric-reinforced synthetic rubber or other flexible material. The material is wrapped around and bonded to the leading-edge surfaces to be de-iced on wings or empennage. Total thickness of typical pneumatic boots is usually less than 1.9 mm (0.075 in). Pneumatic boots require very little power and are a lightweight system of reasonable cost. The tubes in the pneumatic boot are usually oriented spanwise but may be oriented chordwise. The inflatable tubes are manifolded together in a manner to permit alternate or simultaneous inflation as shown in Figure 9.5. Alternate inflation is less commonly used.

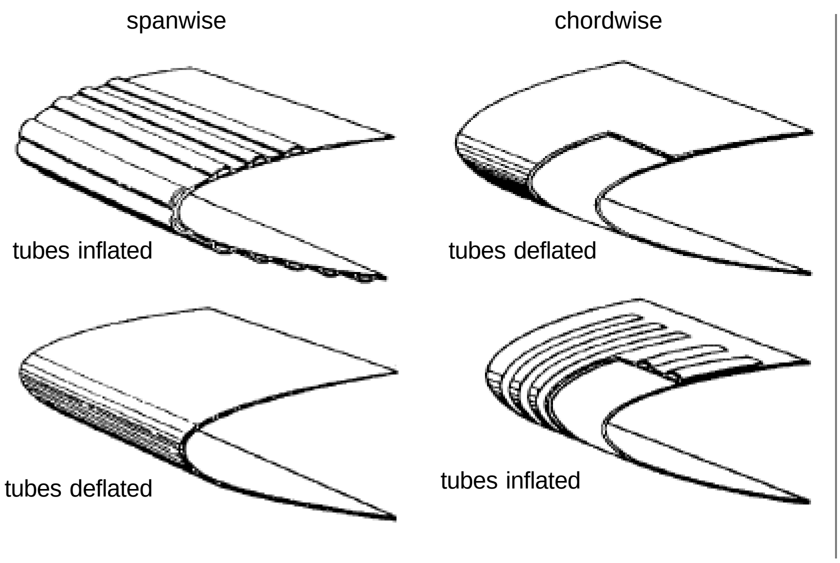

Figure 9.5 Inflatable deicing boots (**FAA 1993**)

In addition to the boots, the primary **components of a pneumatic system** are a regulated pressure source, a vacuum source, and an air distribution system. Miscellaneous components may include check and relief valves, air filters, control switches and timer, and electrical interfaces, including fuses and circuit breakers. A regulated pressure source is required to insure expansion of all tubes in the system to design limits and within design rise times. Pneumatic boots should inflate and deflate rapidly to function effectively. The time to reach full pressure should be about 5 to 6 seconds. If tube expansion is too slow, deicing effectiveness is lessened. The vacuum source is essential to insure positive deflation and keep the tubes collapsed during nonicing flight conditions to minimize the aerodynamic penalty. Air pumps generally multiply the atmospheric pressure by a fixed factor, so the pressure delivered becomes a function of altitude. Therefore, for air pump systems, the pressure produced at service ceiling altitude is a design condition.

Some aerodynamic **drag penalty** is to be expected with pneumatic boot deicing systems on an airfoil, but it can be lessened by recessing the surface leading edge to offset the boot thickness. Pneumatic boot deicing systems have been in use for many years, and their repair, inspection, **maintenance**, and replacement are well understood. Pneumatic boot material deteriorates with time and periodic inspection is recommended to determine the need for replacement. System **weight and power** requirements are minimal.

Ice bridging is the formation of an arch of ice over the boot, which is not removed by boot inflation. In the lore of flight of early piston-powered air transports, it used to be recommended that some ice should be allowed to accrete before the deicing system was turned on in order to avoid ice bridging. The aircraft flight manual (AFM) for modern aircraft now requires that the system be activated at the first sign of ice formation. Ice bridging for modern, properly functioning deicing boots has not been reported. (**FAA 1993**)

9.5 Hot Air Systems

Hot air systems and *electrical resistance systems* are **thermal ice protection systems**. Thermal ice protection systems are classified into three groups:

1. **Evaporative anti-icing systems** supply sufficient heat to evaporate all water droplets impinging upon the heated surface.
2. **Running-wet antiicing systems** provide only enough heat to prevent freezing on the heated surface. Beyond the heated surface of a running-wet system, the water can freeze, resulting in runback ice. For this reason, running-wet systems must be used carefully so as not to permit buildup for runback ice in critical locations. For example, a running-wet system may be used for a turbine engine inlet duct where the runback is permitted to enter the engine.
3. **Cyclic de-icing systems** periodically shed small ice buildups by melting the surface-ice interface with a high rate of heat input. When the adhesion at the interface becomes zero, aerodynamic or centrifugal forces remove the ice.

An evaporative antiicing system uses the most energy of the three ice protection principles presented, cyclic deicing uses the least energy.

Hot air systems are used on most of the large jet transports because of the availability of hot air from the engines and the relative efficiency and reliability of these systems. Hot air is used to antiice or deice leading-edge wing panels and high-lift devices, empennage surfaces, engine inlet and air scoops, radomes, and selected components. Details of the hot air system are given below, using the Airbus A321 as an example.

9.6 Electrical Resistance Systems

Electrical resistance systems are thermal ice protection systems. They may also be classified as *evaporative*, *running wet*, or *cyclic*.

Electrical resistance systems have a wide range of application:

- **External components** protected with an electrical resistance system will use the evaporative technique.
- **Internal components** like water lines are simply heated above 0 °C to prevent freezing.
- **Nontransparent surfaces** will most probably use cyclic deicing because the electrical loads would otherwise become unbearable.

Electrical resistance systems use electrical **resistance heaters** in the form of foil, film, resistance wire, or mesh imbedded in fiberglass, plastic, rubber, or metal to heat the surface or component.

Electrical Deicing Systems for Nontransparent Surfaces

Electrical deicing systems for nontransparent surfaces may use **parting strips** to divide the total protected area into smaller sequentially heated areas. The spanwise and chordwise parting strips must prevent any ice bridging from one shedding zone to another (Figure 9.6). Parting zones reduce the total instantaneous power requirement and maintain a stable load on the electrical system. Aircraft wings with about 30° or more sweepback will normally use only chordwise parting strips.

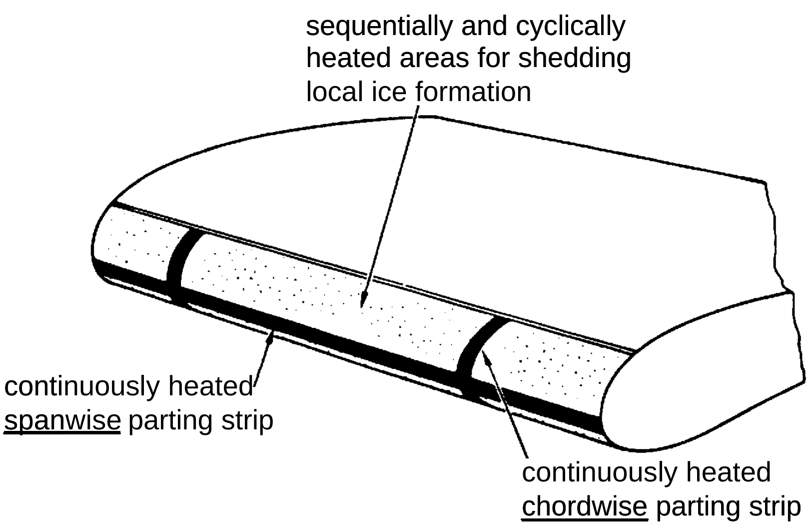

Figure 9.6 Arrangement of an area with an electric cyclic deicing systems

For efficient deicing protection, the correct **amount of heat** must be supplied. If there is too little heat, the ice may not shed as required, perhaps causing large chunks of ice to shed. If too much heat is supplied, there can be too much melting, resulting in undesirable amounts of runback ice. It has been found desirable to have a high specific heat input applied over a short period.

The **off-time** of a shedding zone depends upon the rate at which the surface cools to 0 °C (32 °F). It also depends upon the icing rate. The off-time may be tailored to the maximum ice thickness allowed for the application and can be as long as 3 to 4 minutes for fixed-wing aircraft.

The biggest **disadvantage** of an electrical resistance system for large surfaces is the high power demand. If additional generators are installed just for the purpose of ice detection, the system will get very heavy.

9.7 Fluid Systems

Fluid ice protection systems operate on the **principle** that the surface to be protected is coated with a fluid that acts as a freezing point depressant (FPD). Current systems use a glycol-based fluid. When supercooled water droplets impinge on a surface, they combine with the FPD fluid to form a mixture with a freezing temperature below the temperature of the ambient air. The mixture then flows aft and is either evaporated or shed from the trailing edge of the surface. FPD fluid is distributed onto the surface leading edge by pumping it through porous material or by spraying the fluid onto the surface.

The use of a freezing point depressant can provide **antiicing or deicing** protection. The antiicing mode is the normal mode of operation in light to moderate icing conditions. The deicing mode is a condition allowing ice to accumulate and bond to the wing surface. When the fluid ice protection system is turned on, a flow is introduced between the ice and the surface to weaken the bond so that the ice is shed by aerodynamic forces.

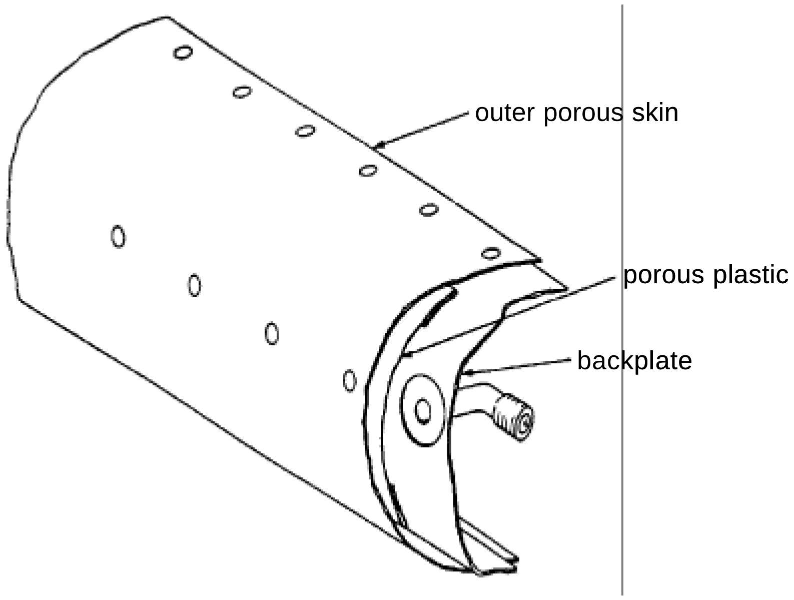

Figure 9.7 Construction of a typical porous panel (**FAA 1993**)

FPD fluid is stored in a tank. A pump meters the system's fluid flow requirements. Porous panels are constructed typically of sintered stainless steel mesh or laser-drilled titanium for the outer skin, a stainless steel or titanium backplate to form a reservoir, and a porous plastic liner to provide uniform control of panel porosity (Figure 9.7).

The principle **disadvantage** of the fluid protection system is the fluid storage requirement. The stored fluid weight may be significant when compared to other candidate ice protection systems. The system has a finite period of protection, dependent on fluid supply. (**FAA 1993**)

9.8 Windshield Ice and Fog Protection

Windshield panels are usually provided with antiicing protection on those aircraft that are required to operate in all weather conditions. The most widely used system is an **electrical resistance system** for *antiicing*, whereby electric current is passed through a transparent conductive film or resistance wire that is part of the laminated windshield. The heat from the antiicing film or resistance wire also achieves internal *defogging*. Electrical heat may also be used to maintain the windshield layers of glass and plastic near the optimum temperature for *resistance against bird strikes*.

Where electric power seems not to be the adequate solution, an **external hot air blast** system can be an alternative. This system may also be used for *rain removal*.

9.9 Windshield Rain Protection

Rain-removal systems are designed to allow the pilots to have a clear view out of the cockpit at the airport and during departure and approach. The systems are not commonly used during flight at altitude. Rain may be removed by the use of *windshield wipers*. Alternatively, an *external hot air blast* can clear the windshield. In addition to either one of the two systems, a chemical *rain repellent* may be used.

Windshield wipers perform adequately, although their ability is limited. High oscillation rates are desirable to keep up with high rates of rain impingement during heavy rainfall. Sufficient blade pressure on the windshield must be maintained to produce satisfactory wiping when the aerodynamic forces are high at high aircraft speeds. Unfortunately, wipers also cause considerable aerodynamic drag.

An **external hot air blast** operates on the principle of blanketing the outside surface of the windshield with a protective wall of high-velocity, high-temperature air. The air blast prevents water impingement by deflecting many of the incoming raindrops. Water on the surface that has penetrated the air blast will be evaporated.

Rain repellent may be sprayed on the windshield to form a transparent film that reduces the adhesive force between the water and the glass. The water draws up into beads that cover only a portion of the glass. The high velocity slipstream continually removes the beads. Depending on the rain intensity, the rain impingement breaks down the repellent film, causing the window to return gradually to a wettable condition. Unless the windshield is wiped off frequently, the effectiveness of repeated repellent application decreases. Windshield wipers spread the repellent and improve its efficiency. Rain repellent used together with an external hot air blast is used in the critical landing phase when engine bleed air pressure is low and the jet blast is reduced.

9.10 Ice-Detection Systems

Some method of ice detection is necessary so that the ice protection system is operated only when necessary. Two methods exist: *visual detection* and *electronic detection*.

Visual detection is achieved by the flight crew monitoring such things as windshield wipers, wing leading edges, pylons, or landing lights that could serve as an ice datum. Those surfaces of the airplane directly exposed to stagnation flow conditions usually accumulate the largest quantity of ice. Wing and engine scan lights are used to monitor the engine intakes and the wing leading edges at night.

Electronic ice detectors consist of a probe extending into the free stream. The probe vibrates at a known frequency. When ice starts to build on the probe, the frequency will decrease. This will be detected by an attached controller. The controller will energize a heating element in the probe to remove the ice so that the probe can check again for icing conditions.

9.11 Example: Airbus A321

The ice and rain protection system lets the aircraft operate normally in ice conditions or heavy rain. Ice protection is given by the use of hot air or electrical power to make the necessary areas of the aircraft hot. The areas supplied by hot air are (Figure 9.8):

- the leading edge of the slats 3, 4, and 5 on each wing
- the engine air intakes.

The engine bleed air system supplies the hot air to the anti-ice system.

The items with electrical heaters are:

- the cockpit windshield and side windows
- the *total air temperature* (TAT) probes
- the *angle of attack* (alpha) probes
- the pitot and static probes of the *air data system* (ADS)
- the wastewater drain masts.

Rain is removed from the windshield with windshield wipers.

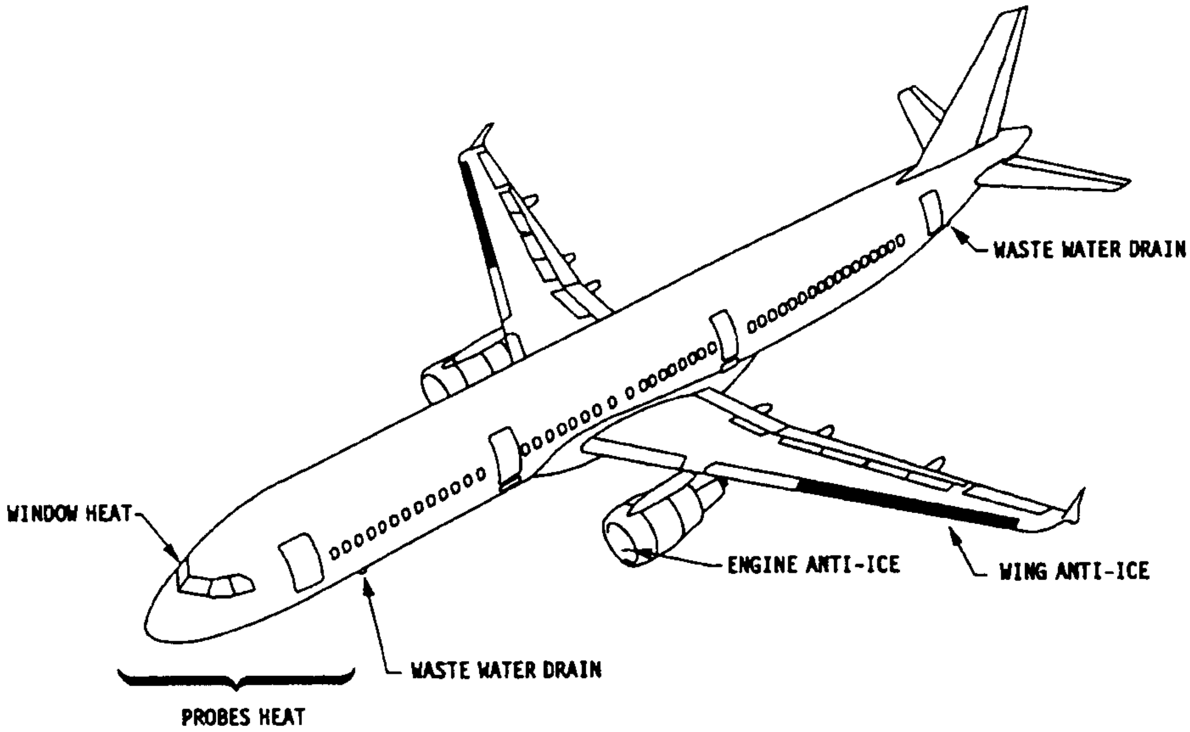

Figure 9.8 A321 ice and rain protection component locations

The A321 wing ice protection system is a hot air evaporative antiice system. Only slats 3, 4, and 5 on the outboard wing need to be ice protected. The hot air is bled from the engine. Each engine supplies its related wing. On both wings, an *antiice valve* isolates the antiice system from the bleed air supply. When the crossfeed valve is open, it is possible to supply the two wings from only one engine bleed-air system. Lagged ducts connect the antiice valve to a telescopic duct at slat 3. A piccolo tube runs along slat 3, 4, and 5 and supplies the hot air to the leading edge. A piccolo tube is a tube with calibrated holes that ensures that hot air is evenly distributed along the leading edge, although bleed pressure decreases towards the wing tip. The bleed air in the slats is released overboard through the holes in the bottom surface of the slat. The operation of the antiice valve is controlled by the WING push-button switch on the ANTI ICE overhead panel in the cockpit.

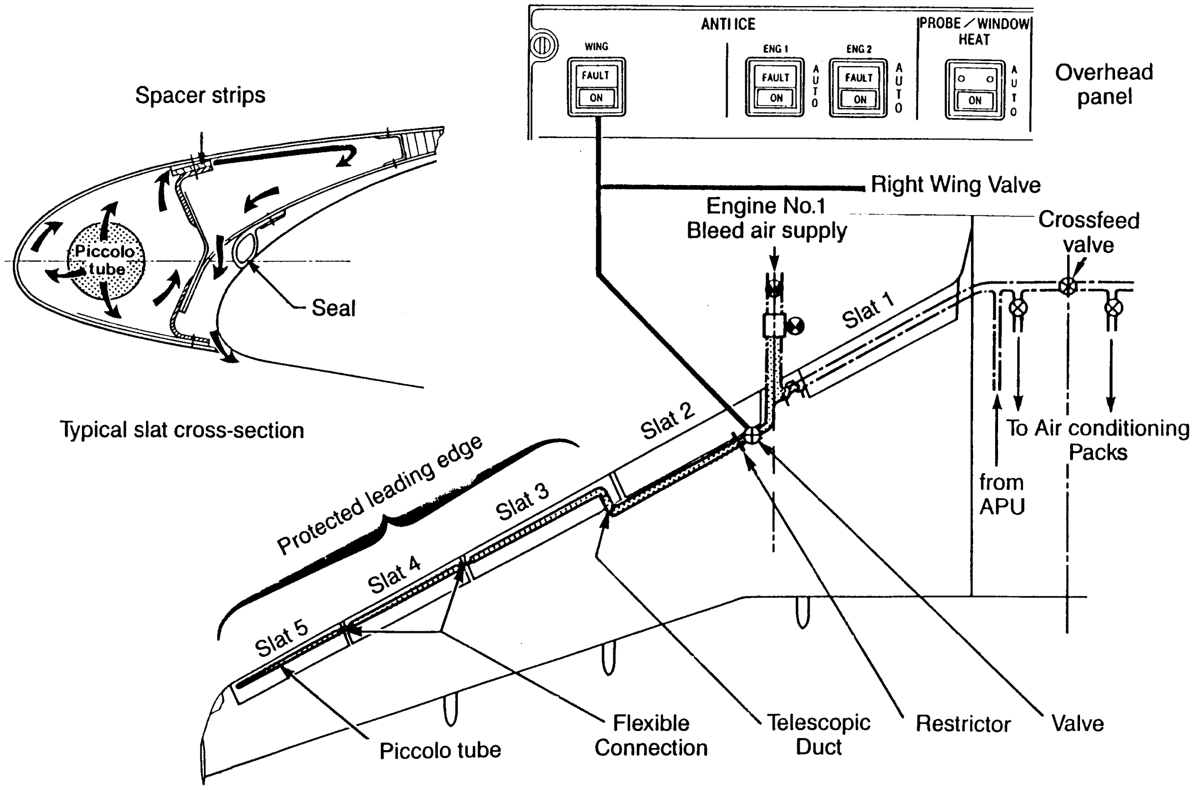

Figure 9.9 A321 wing antiice