NASA'S CONTRIBUTIONS TO AERONAUTICS

VOLUME 2

FLIGHT ENVIRONMENT

OPERATIONS

FLIGHT TESTING AND RESEARCH

CASE 12

Aircraft Icing: The Tyranny of Temperature

By James Banke

The aerospace environment is a realm of extremes: low to high pressures, densities, and temperatures. Researchers have had the goal of improving flight efficiency and safety. Aircraft icing has been a problem since the earliest days of flight and, historically, researchers have artfully blended theory, ground-and-flight research, and the use of new tools such as computer simulation and software modeling codes to ensure that travelers fly in aircraft well designed to confront this hazard.

ONE FEBRUARY EVENING in the late 1930s, a young copilot strode across a cold ramp of the Nashville airport under a frigid moonlit sky, climbing into a chilled American Airlines DC-2. The young airman was Ernest Gann, later to gain fame as a popular novelist and aviation commentator, whose best-remembered book, The High and the Mighty, became an iconic aviation film. His captain was Walter Hughen, already recognized by his peers as one of the greats, and the two men worked swiftly to ready the sleek twin-engine transport for flight. Behind them, eight passengers settled in, looked after by a flight attendant. They were bound for New York, along AM-23, an air route running from Nashville to New York City. Preparations complete, they taxied out and took off on what should have been a routine 4-hour flight in favorable weather. Instead, almost from the moment the airliner's wheels tucked into the plane's nacelles, the flight began to deteriorate. By the time they reached Knoxville, they were bucking an unanticipated 50-mile-per-hour headwind, the Moon had vanished, and the plane was swathed in cloud, its crew flying by instruments only. And there was something else: ice. The DC-2 was picking up a heavy load of ice from the moisture-laden air, coating its wings and engine cowlings, even its propellers, with a wetly glistening and potentially deadly sheen.[1]

1. Ernest K. Gann, *Fate is the Hunter* (New York: Simon & Schuster, 1961), pp. 79–87.

Suddenly there was "an erratic banging upon the fuselage," as the propellers began flinging ice "chunks the size of baseballs" against the fuselage. In the cockpit, Hughen and Gann desperately fought to keep their airplane in the air. Its leading edge rubber deicing boots, which shattered ice by expanding and contracting, so that the airflow could sweep it away, were throbbing ineffectively: the ice had built up so thick and fast that it shrouded them despite their pulsations. Carburetor inlet icing was building up on each engine, causing it to falter, and only deliberately induced back-firing kept the inlets clear and the engines running. Deicing fluid spread on the propellers and cockpit glass had little effect, as did a hot air hose rigged to blow on the outside of the windshield. Worst of all, the heavy icing increased the DC-2's weight and drag, slowing it down to near its stall point. At one point, the plane began "a sudden, terrible shudder," perilously on the verge of a fatal stall, before Hughen slammed the throttles full-forward and pushed the nose down, restoring some margin of flying speed.[2]

After a half hour of desperate flying that "had the smell of eternity" about it, the battered DC-2 and its drained crew entered clear skies. The weather around them was still foreboding, and so, after trying to return to Nashville, finding it was closed, and then flying about for hours searching for an acceptable alternate, they turned for Cincinnati, Hughen and Gann anxiously watching their fuel consumption. Ice—some as thick as 4 inches—still swathed the airplane, so much so that Gann thought, "Where are the engineers again? The wings should somehow be heated." The rudder was frozen in place, and the elevators and ailerons (controlling pitch and roll) moveable only because of Hughen and Gann's constant control inputs to ensure they remained free. At dawn they reached Cincinnati, where the plane, burdened by its heavy load of ice, landed heavily. "We hit hard," Gann recalled,"and stayed earth-bound. There is no life left in our wings for bouncing." Mechanics took "two hours of hard labor to knock the ice from our wings, engine cowlings, and empennage." Later that day, Hughen and Gann completed the flight to New York, 5 hours late. In the remarks section of his log, explaining the delayed arrival, Gann simply penned "Ice."[3]

2. Ibid., pp. 88–93.
3. Ibid., pp. 94–107.

Gann, ever after, regarded the flight as marking his seasoning as an airman, "forced to look disaster directly in the face and stare it down."[4]

Many others were less fortunate. In January 1939, *Cavalier,* an Imperial Airways S.23 flying boat, ditched heavily in the North Atlantic, breaking up and killing 3 of its 13 passengers and crew; survivors spent 10 cold hours in heaving rafts before being rescued. Carburetor icing while flying through snow and hail had suffocated two of its four engines, leaving the flying boat's remaining two faltering at low power.[5] In October 1941, a Northwest Airlines DC-3 crashed near Moorhead, MN, after the heavy weight of icing prevented its crew from avoiding terrain; this time 14 of 15 on the plane died.[6]

Even when nothing went wrong, flying in ice was unsettling. Trans World Airlines Captain Robert "Bob" Buck, who became aviation's most experienced, authoritative, and influential airman in bad weather flying, recalled in 2002 that

> A typical experience in ice meant sitting in a cold cockpit, windows covered over in a fan-shaped plume from the lower aft corner toward the middle front, frost or snow covering the inside of the windshield frames, pieces as large as eight inches growing forward from the windshield's edges outside, hunks of ice banging against the fuselage and the airplane shaking as the tail swung left and right, right and left, and the action was transferred to the rudder pedals your feet were on so you felt them saw back and forth beneath you The side winds were frosted, but you could wipe them clear enough for a look out at the engines. The nose cowlings collected ice on their leading edge, and I've seen it so bad that the ice built forward until the back of the propeller was shaving it! But still the airplane flew. The indicated airspeed would slow, and

4. Ibid., p. 79.

5. Harald Penrose, *Wings Across the World* (London: Cassell, 1980), p. 114; R.E.G. Davies, *British Airways: An Airline and its Aircraft*, v. 1: *The Imperial Years* (McLean, VA: Paladwr Press, 2005), pp. 94, 96.

6. U.S. Civil Aeronautics Board, Bureau of Safety Investigation, *Comparative Safety Statistics in United States Airline Operations*, Pt. 1: *Years 1938–1945* (Washington, DC: CAB BSI Analysis Division, 15 August 1953), p. 29.

> you'd push up the throttles for more power to overcome the loss but it didn't always take, and the airspeed sometimes went down to alarming numbers approaching stall.[7]

Icing, as the late aviation historian William M. Leary aptly noted, has been a "perennial challenge to aviation safety."[8] It's a chilling fact that despite a century of flight experience and decades of research on the ground and in the air, today's aircraft still encounter icing conditions that lead to fatal crashes. It isn't that there are no preventative measures in place. Weather forecasting, real-time monitoring of conditions via satellite, and ice prediction software are available in any properly equipped cockpit to warn pilots of icing trouble ahead. Depending on the size and type of aircraft, there are several proven anti-icing and de-icing systems that can help prevent ice from building up to unsafe levels. Perhaps most importantly, pilot training includes information on recognizing icing conditions and what to do if an aircraft starts to ice up in flight. Unfortunately the vast majority of icing-related incidents echo a theme in which the pilot made a mistake while flying in known icing conditions. And that shows that in spite of all the research and technology, it's still up to the pilot to take advantage of the experience base developed by NASA and others over the years.

In the very earliest days of aviation, icing was not an immediate concern. That all changed by the end of the First World War, by which time airplanes were operating at altitudes above 10,000 feet and in a variety of meteorological conditions. Worldwide, the all-weather flying needs of both airlines and military air service, coupled with the introduction of blind-flying instrumentation and radio navigation techniques that enabled flight in obscured weather conditions, stimulated study of icing, which began to take a toll on airmen and aircraft as they increasingly operated in conditions of rain, snow, and freezing clouds and sleet.[9]

7. Bob Buck [Robert N. Buck], *North Star Over My Shoulder: A Flying Life* (New York: Simon & Schuster, 2002), p. 113. Once America's youngest licensed pilot, Buck authored two influential books on aviation safety, *Weather Flying* (New York: The Macmillan Co., 1978); and *The Pilot's Burden: Flight Safety and the Roots of Pilot Error* (Ames, IA: Iowa State University Press, 1994).
8. William M. Leary, "A Perennial Challenge to Aviation Safety: Battling the Menace of Ice," in Roger D. Launius and Janet R. Daly Bednarek, eds., *Reconsidering a Century of Flight* (Chapel Hill, NC: University of North Carolina Press, 2003), pp. 132–151.
9. See, for example, Wesley L. Smith, "Weather Problems Peculiar to the New York-Chicago Airway," *Monthly Weather Review* vol. 57, no. 12 (Dec. 1929), pp. 503–506.

The NACA's interest in icing dated to the early 1920s, when America's aviation community first looked to the Agency for help. By the early 1930s, both in America and abroad, researchers were examining the process of ice formation on aircraft and means of furnishing some sort of surface coatings that would prevent its adherence, particularly to wings, acquiring data both in actual flight test and by wind tunnel studies. Ice on wings changed their shape, drastically altering their lift-to-drag ratios and the pressure distribution over the wing. An airplane that was perfectly controllable with a clean wing might prove very different indeed with just a simple change to the profile of its airfoil.[10] Various mechanical and chemical solutions were tried. The most popular mechanical approach involved fitting the leading edges of wings, horizontal tails, and, in some cases, vertical fins with pneumatically operated rubber "de-icing" boots that could flex and crack a thin coating of ice. As Gann and Buck noted, they worked at best sporadically. Other approaches involved squirting de-icing fluid over leading edges, particularly over propeller blades, and using hot-air hoses to de-ice cockpit windshields.

Lewis A. "Lew" Rodert—the best known of ice researchers—was a driven and hard-charging NACA engineer who ardently pursued using heat as a means of preventing icing of wings, propellers, carburetors, and windshields.[11] Under Rodert's direction, researchers extensively instrumented a Lockheed Model 12 light twin-engine transport for icing research and, later, a larger and more capable Curtiss C-46 transport. Rodert and test pilot Larry Clausing, both Minnesotans, moved the NACA's ice research program from Ames Aeronautical Laboratory (today the NASA Ames Research Center) to a test site outside Minneapolis. There, researchers took advantage of the often-formidable weather conditions to assemble a large database on icing and icing conditions, and

10. Thomas Carroll and William H. McAvoy, "The Formation of Ice Upon Airplanes in Flight," NACA TN-313 (1929); Montgomery Knight and William C. Clay, "Refrigerated Wind Tunnel Tests on Surface Coatings for Preventing Ice Formation," NACA TN-339 (1930); W. Bleeker, "The Formation of Ice on Aircraft," NACA TM-1027 (1942) [trans. of "Einige Bermerkungen über Eisansatz an Flugzeugen," *Meteorologische Zeitschrift* (Sep. 1932), pp. 349–354.

11. For samples of Rodert's work, see Lewis A. Rodert, "An Investigation of the Prevention of Ice on the Airplane Windshield," TN-754 (1940); Lewis A. Rodert and Alun R. Jones, "A Flight Investigation of Exhaust-Heat De-Icing," NACA TN-783 (1940); Lewis A. Rodert, "The Effects of Aerodynamic Heating on Ice Formations on Airplane Propellers," TN-799 (1941); Lewis A. Rodert and Richard Jackson, "Preliminary Investigation and Design of an Air-Heated Wing for Lockheed 12A Airplane," NACA ARR A-34 (1942).

on the behavior of various modifications to their test aircraft. These tests complemented more prosaic investigations looking at specific icing problems, particularly that of carburetor icing.[12]

The war's end brought Rodert a richly deserved Collier Trophy, American aviation's most prestigious award, for his thermal de-icing research, particularly the development and validation of the concept of air-heated wings.[13] By 1950, a solid database of NACA research existed on icing and its effects upon propeller-driven airplanes.[14] This led many to conclude that the "heroic era" of icing research was in the past, a judgment that would prove to be wrong. In fact, the problems of icing merely changed focus, and NACA engineers quickly assessed icing implications for the civil and military aircraft of the new gas turbine and transonic era.[15] New high-performance interceptor fighters, expected to accelerate quickly and climb to high altitudes, had icing problems of their own, typified by inlet icing that forced performance limitations and required imaginative solutions.[16] When first introduced into service, Bristol's otherwise-impressive Britannia turboprop long-range transport had persistent problems caused by slush ice forming in the induction system of its Proteus turboprop engines. By the time the NACA evolved into the

12. George W. Gray, *Frontiers of Flight: The Story of NACA Research* (New York: Alfred A. Knopf, 1948), pp. 308–316; and Henry A. Essex, "A Laboratory Investigation of the Icing Characteristics of the Bendix-Stromberg Carburetor Model PD-12F5 with the Pratt and Whitney R-1830-C4 Intermediate Rear Engine Section," NACA-WR-E-18 (1944); William D. Coles, "Laboratory Investigation of Ice Formation and Elimination in the Induction System of a Large Twin-Engine Cargo Aircraft," NACA TN-1427 (1947).

13. Edwin P. Hartman *Adventures in Research: A History of Ames Research Center 1940-1965*, NASA SP-4302 (Washington, DC: GPO, 1970), pp. 69–73; and Glenn E. Bugos, "Lew Rodert, Epistemological Liaison, and Thermal De-Icing at Ames," in Pamela E. Mack, ed., *From Engineering Science to Big Science: The NACA and NASA Collier Trophy Research Project Winners,* NASA SP-4219 (Washington, DC: NASA, 1998), pp. 29–58.

14. For example, G. Merritt Preston and Calvin C. Blackman, "Effects of Ice Formations on Airplane Performance in Level Cruising Flight," NACA TN-1598 (1948); Alun R. Jones and William Lewis, "Recommended Values of Meteorological Factors to be Considered in the Design of Aircraft Ice-Prevention Equipment," NACA TN-1855 (1949); Carr B. Neel, Jr., and Loren G. Bright, "The Effect of Ice Formations on Propeller Performance, NACA TN-2212 (1950).

15. James P. Lewis, Thomas F. Gelder, Stanley L. Koutz, "Icing Protection for a Turbojet Transport Airplane: Heating Requirements, Methods of Protection, and Performance Penalties," NACA TN-2866 (1953).

16. Porter J. Perkins, "Icing Frequencies Experienced During Climb and Descent by Fighter-Interceptor Aircraft," NACA TN-4314 (1958); and James P. Lewis and Robert J. Blade, "Experimental Investigation of Radome Icing and Icing Protection," NACA RM-E52J31 (1953).

National Aeronautics and Space Administration in 1958, the fundamental facts concerning the types of ice an aircraft might encounter and the major anti-icing techniques available were well understood and widely in use. In retrospect, as impressive as the NACA's postwar work in icing was, it is arguable that the most important result of NACA work was the establishment of ice measurement criteria, standards for ice-prevention systems, and probabilistic studies of where icing might be encountered (and how severe it might be) across the United States. NACA Technical Notes 1855 (1949) and 2738 (1952) were the references of record in establishing Federal Aviation Administration (FAA) standards covering aircraft icing certification requirements.[17]

NASA and the Aircraft Icing Gap

At a conference in June 1955, Uwe H. von Glahn, the NASA branch chief in charge of icing research at the then-Lewis Research Center (now Glenn Research Center) in Cleveland boldly told fellow scientific investigators: "Aircraft are now capable of flying in icing clouds without difficulty . . . because research by the NACA and others has provided the engineering basis for ice-protection systems."[18]

That sentiment, in combination with the growing interest and need to support a race to the Moon, effectively shut down icing research by

17. As referenced in U.S. National Transportation Safety Board, "In-Flight Icing Encounter and Loss of Control Simmons Airlines, d.b.a. American Eagle Flight 4184 Avions de Transport Regional (ATR) Model 72-212, N401AM, Roselawn, Indiana October 31, 1994," NTSB/AAR-96/01 (Washington, DC: NTSB, 1996), pp. 97–99.

18. William M. Leary, *"We Freeze to Please": A History of NASA's Icing Research Tunnel and the Quest for Flight Safety*, NASA SP-2002-4226 (Washington, DC: NASA, 2002), p. 60. Glahn did much notable work in icing research; see Uwe H. von Glahn and Vernon H. Gray, "Effect of Ice and Frost Formations on Drag of NACA 65-212 Airfoil for Various Modes of Thermal Ice Protection," NACA TN-2962 (1953); Uwe H. von Glahn and Vernon H. Gray, "Effect of Ice Formations on Section Drag of Swept NACA 63A-009 Airfoil with Partial Span Leading Edge Slat for Various Modes of Thermal Ice Protection," NACA RM-E53J30 (1954); Uwe H. von Glahn, Edmund E. Callaghan, and Vernon H. Gray, "NACA Investigation of Icing-Protection Systems for Turbojet-Engine Installations," NACA RM-E51B12 (1951); Uwe H. von Glahn, Thomas F. Gelder, and William H. Smyers, Jr., "A Dye-Tracer Technique for Experimentally Obtaining Impingement Characteristics of Arbitrary Bodies and Method for Determining Droplet Size Distribution," NACA TN-3338 (1955); Vernon H. Gray and Uwe H. von Glahn, "Aerodynamic Effects Caused by Icing of an Unswept NACA 65A004 Airfoil," NACA TN-4155 (1958); Vernon H. Gray, Dean T. Bowden, and Uwe H. von Glahn, "Preliminary Results of Cyclical De-Icing of a Gas-Heated Airfoil," NACA RM-E51J29 (1952).

the NACA, although private industry continued to use Government facilities for their own cold-weather research and certification activities, most notably the historic Icing Research Tunnel (IRT) that still is in use today at the Glenn Research Center (GRC). The Government's return to icing research began in 1972 at a meeting of the Society of Automotive Engineers in Dallas, during which an aeronautics-related panel was set up to investigate ice accretion prediction methods and define where improvements in related technologies could be made. Six years later the panel concluded that little progress in understanding icing had been accomplished since the NACA days. Yet since the formation of NASA in 1958, 20 years earlier, aircraft technology had fundamentally changed. Commercial aviation was flying larger jet airliners and being asked to develop more fuel-efficient engines, and at the same time the U.S. Army was having icing issues operating helicopters in icy conditions in Europe. The Army's needs led to a meeting with NASA and the FAA, followed by a July 1978 conference with 113 representatives from industry, the military, the U.S. Government, and several nations. From that conference sparked the impetus for NASA restarting its icing research to "update the applied technology to the current state of the art; develop and validate advanced analysis methods, test facilities, and icing protection concepts; develop improved and larger testing facilities; assist in the difficult process of standardization and regulatory functions; provide a focus to the presently disjointed efforts within U.S. organizations and foreign countries; and assist in disseminating the research results through normal NASA distribution channels and conferences."[19]

While icing research programs were considered, proposed, planned, and in some cases started, full support from Congress and other stakeholders for the return of a major, sustained icing research effort by NASA did not come until after an Air Florida Boeing 737 took off from National Airport in Washington, DC, in a snowstorm and within seconds crashed on the 14th Street Bridge. The 1982 incident killed 5 people on the bridge, as well as 70 passengers and 4 crewmembers. Only five people survived the crash, which the National Transportation Safety Board blamed on a number of factors, assigning issues related to icing as a major cause of the preventable accident. Those issues included faulting

19. Leary, *"We Freeze to Please"*, p. 72.

the flight crew for not activating the twin engine's anti-ice system while the aircraft was on the ground and during takeoff, for taking off with snow and ice still on the airfoil surfaces of the Boeing aircraft, and for the lengthy delay between the final time the aircraft was de-iced on the tarmac and the time it took the crew to be in position to receive takeoff clearance from the control tower and get airborne. While all this was happening the aircraft was exposed to constant precipitation that at various times could be described as rain or sleet or snow.[20]

The immediate aftermath of the accident—including the dramatic rescue of the five survivors who had to be fished out of the Potomac River—was all played out on live television, freezing the issue of aircraft icing into the national consciousness. Proponents of NASA renewing its icing research efforts suddenly had shocking and vivid proof that additional research for safety purposes was necessary in order to deal with icing issues in the future. Approval for a badly needed major renovation of the IRT at GRC was quickly given, and a new, modern era of NASA aircraft icing investigations began.[21]

Baby, It's Cold Out There

Not surprisingly, ice buildup on aircraft is bad. If it happens on the ground, then pilots and passengers alike must wait for the ice to be removed, often with hazardous chemicals and usually resulting in flight delays that can trigger a chain reaction of schedule problems across the Nation's air system. If an aircraft accumulates ice in the air, depending on the severity of the situation, the results could range from mild annoyance that a de-icing switch has to be thrown to complete aerodynamic failure of the wing, accompanied by total loss of control, a spiraling dive from high altitude, a premature termination of the flight and all lives on board, followed by the reward of becoming the lead item on the evening news.

Icing is a problem for flying aircraft not so much because of the added weight, but because of the way even a tiny amount of ice can begin to disrupt the smooth airflow over the wings, wreaking havoc with the wing's ability to generate lift and increasing the amount of drag, which

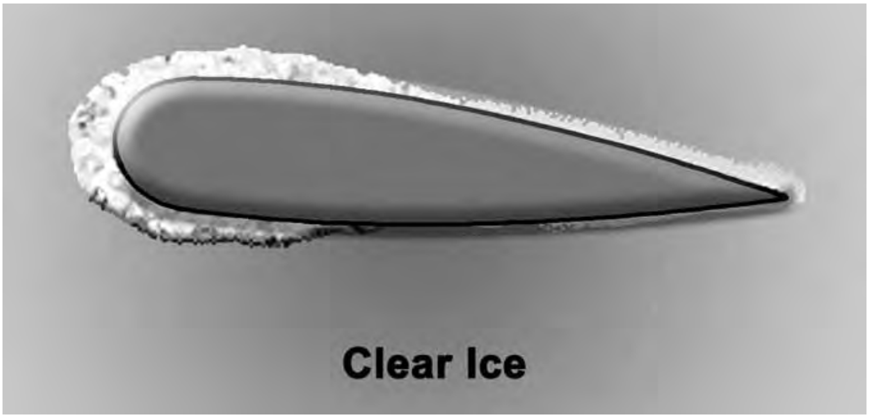
20. National Transportation Safety Board, *Collision with 14th Street Bridge Near Washington National Airport, Air Florida Flight 90, Boeing 737-222, N62AF, Washington, D.C., January 13, 1982,* NTSB/AAR-82-8 (1982).
21. Leary, "*We Freeze to Please*", p. 82.

slows the aircraft and pitches the nose down. This prompts the pilot to pull the nose up to compensate for the lost lift, which allows even more ice to build up on the lower surface of the wing. And the vicious circle continues, potentially leading to disaster. Complicating the matter is that even with options for clearing the wing of ice—discussed shortly—ice buildup can remain and/or continue on other aircraft surfaces such as antennas, windshields, wing struts, fixed landing gear, and other protrusions, all of which can still account for a 50-percent increase in drag even if the wing is clean.[22]

From the earliest experience with icing during the 1920s and on through the present day, researchers have observed and understood there to be three primary categories of aircraft ice: clear, rime, and mixed. Each one forms for slightly different reasons and exhibits certain properties that influence the effectiveness of available de-icing measures.[23]

Clear ice is usually associated with freezing rain or a special category of rain that falls through a region of the atmosphere where temperatures are far below the normal freezing point of water, yet the drops remain in a liquid state. These are called super-cooled drops.

Such drops are very unstable and need very little encouragement to freeze. When they strike a cold airframe they begin to freeze, but it is



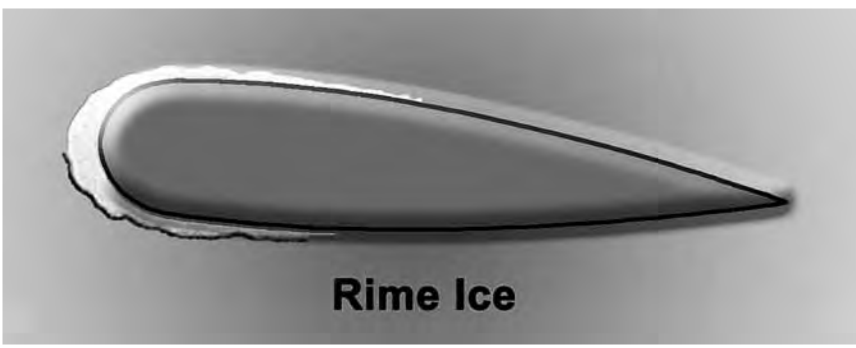
A graphic depicting clear ice buildup on an airfoil.

22. R.J. Ranaudo, K.L. Mikkelsen, R.C. McKnight, P.J. Perkins, Jr., "Performance Degradation of a Typical Twin Engine Commuter Type Aircraft in Measured Natural Icing Conditions," NASA TM-83564 (1984).

23. R. John Hansman, Kenneth S. Breuer, Didier Hazan, Andrew Reehorst, Mario Vargas, "Close-Up Analysis of Aircraft Ice Accretion," NASA TM-105952 (1993).

not an instant process. The raindrop freezes as it spreads out and continues to make contact with an aircraft surface whose skin temperature is at or below 32 degrees Fahrenheit (0 degrees Celsius). The slower the drop freezes, the more time it will have to spread out evenly and create a sheet of solid, clear ice that has very little air enclosed within. This flowback phenomenon is greatest at temperatures right at freezing. Because of its smooth surface, clear ice can quickly disrupt the wing's ability to generate lift by ruining the wing's aerodynamic shape. This type of ice is quite solid in the sense that if any of it does happen to loosen or break off, it tends to come off in large pieces that have the ability to strike another part of the aircraft and damage it.[24]

Rime ice proves size makes a difference. In this case the supercooled liquid water drops are smaller than the type that produces



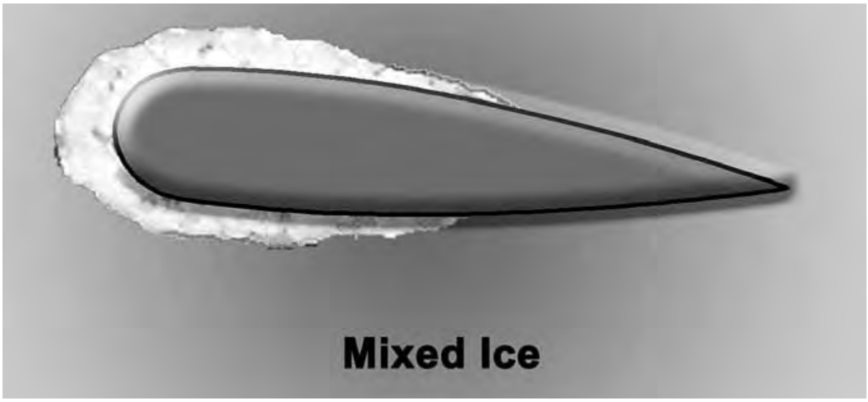
A graphic depicting rime ice buildup on an airfoil.

clear ice. When these tiny drops of water strike a cold aircraft surface, most of the liquid drops instantly freeze and any water remaining is not enough to create a sheet of ice. Instead, the result is a brittle ice that looks milky white, is opaque, has a rough surface due to its makeup of ice crystals and trapped air, and doesn't accumulate as quickly as clear ice. It does not weigh as much, either, and tends to stick to the leading edge of the wing and the cowl of the engine intakes on a jet, making rime ice just as harmful to the airflow and aerodynamics of the aircraft.[25]

Naturally, when an aircraft encounters water droplets of various sizes, a combination of both clear and rime ice can form, creating the

24. Civil Aviation Authority of New Zealand, "Aircraft Icing Handbook" (2000), p. 2.

25. R.C. McKnight, R.L. Palko, and R.L. Humes, "In-flight Photogrammetric Measurement of Wing Ice Accretions," NASA TM-87191 (1986).



A graphic depicting mixed ice buildup on an airfoil.

third category of icing called mixed ice. The majority of ice encountered in aviation is of this mixed type.[26]

Aircraft must also contend with snow, avoiding the wet, sticky stuff that makes great snowballs on the ground but in the air can quickly accumulate not only on the wings—like ice, a hazard in terms of aerodynamics and weight—but also on the windshield, obscuring the pilot's view despite the best efforts of the windshield wipers, which can be rendered useless in this type of snow. And on the ground, frost can completely cover an aircraft that sits out overnight when there is a combination of humid air and subfreezing temperatures. Frost can also form in certain flying conditions, although it is not as hazardous as any of the ices.[27]

Melting Your Troubles Away

As quickly as the hazards of aircraft icing became known in the early days of aviation, inventive spirits applied themselves to coming up with ways to remove the hazard and allow the airplane to keep flying. These ideas at first took the form of understanding where and when icing occurs and then simply not flying through such conditions, then ways to prevent ice from forming in the first place—proactive anti-icing—were considered, and at the same time options for removing ice once it

26. John R. Hansman, Jr., "The Influence of Ice Accretion Physics on the Forecasting of Aircraft Icing Conditions," NASA Joint University Program for Air Transportation Research, NASA NTRS 90N20928 (1990).
27. M. Dietenberger, P. Kumar, and J. Luers, "Frost Formation on an Airfoil: A Mathematical Model 1," NASA-CR-3129 (1979).

had formed—reactive de-icing—were suggested and tested in the field, in the air, and in the wind tunnel. Of all the options available, the three major ones are the pneumatic boot, spraying chemicals onto the aircraft, and channeling hot bleed air.[28]

A King Air equipped with a de-icing boot on its wing leading edge shows how the boot removes some ice, but not on areas behind the boot.

The oldest of the de-icing methods in use is the pneumatic boot system, invented in 1923 by the B.F. Goodrich Corporation in Akron, OH. The general idea behind the boot has not changed nearly a century later: a thick rubber membrane is attached to the leading edge of a wing airfoil. Small holes in the wing behind the boot allow compressed air to blow through, ever so slightly expanding the boot's volume like a balloon. Any time that ice builds up on the wing, the system is activated, and when the boot expands, it essentially breaks the ice into pieces, which are quickly blown away by the relative wind of the moving aircraft. Again, although the general design of the boot system has not

28. John J. Reinmann, Robert J. Shaw, and W.A. Olsen, Jr., "NASA Lewis Research Center's Program on Icing Research," NASA TM-83031 (1983).

changed, there have been improvements in materials science and sensor technology, as well as changes in the shape of wings used in various sizes and types of aircraft. In this manner, NASA researchers have been very active in coming up with new and inventive ways to enhance the original boot concept and operation.[29]

One way to ensure there is no ice on an aircraft is to remove it before the flight gets off the ground. The most common method for doing this is to spray some type of de-icing fluid onto the aircraft surface as close to takeoff as possible. The idea was first proposed by Joseph Halbert and used by the United Kingdom Royal Air Force in 1937 on the large flying boats then operated by Imperial Airways.[30] Today, the chemicals used in these fluids usually use a propylene glycol or ethylene glycol base and may include other ingredients that might thicken the fluid, help inhibit corrosion on the aircraft, or add a color to the mixture for easier identification. Often water is added to the mixture, which although counterintuitive makes the liquid more effective. Of the two glycols, propylene is more environmentally friendly.[31]

The industry standard for this fluid is set by the aeronautics division of the Society of Automotive Engineers, which has published standards for four types of de-icing fluids, each with slightly different properties and intentions for use. Type I has a low viscosity and is usually heated and sprayed on aircraft at high pressure to remove any snow, ice, or frost. Due to its viscosity, it runs off the aircraft very quickly and provides little to no protection as an anti-icing agent as the aircraft is exposed to snowy or icy conditions before takeoff. Its color is usually orange.[32] Type II fluid has a thickening agent to prevent it from running very quickly off the aircraft, leaving a film behind that acts as an anti-icing agent until the aircraft reaches a speed of 100 knots, when the fluid breaks down from aerodynamic stress. The fluid is usually light yellow. Type III fluid's properties fall in between Type I and II, and it is intended for smaller,

29. A.E. Albright, D.L. Kohlman, W.G. Schweikhard, and P. Evanich, "Evaluation of a Pneumatic Boot Deicing System on a General Aviation Wing," NASA TM-82363 (1981).

30. "The Early Years—1930s," Killfrost, Inc. of Coral Springs, FL (2009).

31. J. Love, T. Elliott, G.C. Das, D.K. Hammond, R.J. Schwarzkopf, L.B. Jones, and T.L. Baker, "Screening and Identification of Cryopreservative Agents for Human Cellular Biotechnology Experiments in Microgravity," 2004 ASGSB Meeting, Brooklyn, NY, Nov. 2004.

32. Society of Automotive Engineers, "Deicing/Anti-icing Fluid, Aircraft, SAE Type 1," AMS 1224 (Rev. J) (2009).

slower aircraft. It is popular in the regional and business aviation markets and is usually dyed light yellow. Type IV fluids are only applied after a Type I fluid is sprayed on to remove all snow, ice, and frost. The Type IV fluid is designed to leave a film on the aircraft that will remain for 30 to 80 minutes, serving as a strong anti-icing agent. It is usually green.[33]

A Type 4 de-icing solution is sprayed on a commercial airliner before takeoff.

NASA researchers have worked with these fluids for many years and found uses in other programs, including the International Space Station. And during the late 1990s, a team of engineers from the Ames Research Center (ARC) at Moffett Field, CA, came up with an anti-icing fluid that was nontoxic—so much so that it was deemed "food grade" because its ingredients were approved by the U.S. Government for use in food—namely ice cream—and promised to last longer as an anti-icing agent for aircraft, as well as work as an effective de-icing agent. Although it

33. Society of Automotive Engineers, "Fluid, Aircraft Deicing/Anti-Icing, Non-Newtonian (Pseudoplastic), SAE Types II, III, and IV," AMS 1228 (Rev. G) (2009).

has not found wide use in the aviation industry, NASA did issue a license to a commercial firm who now sells the product to consumers as "Ice Free," a spray for automobile windshields that can provide protection from snow or ice forming on a windshield in temperatures down to 20 degrees Fahrenheit (-7 degrees Celsius).[34]

The third common technique for dealing with ice accretion is the hot bleed air method. In this scheme, hot air is channeled away from the aircraft engines and fed into tubes that run throughout the aircraft near the areas where ice is most likely to form and do the most damage. The hot air warms the aircraft skin, melting away any ice that is there and discouraging any ice from forming. The hot gas can also be used as the source of pressurized air that inflates a rubber boot, if one is present. While the idea of using hot bleed air became most practical with the introduction of jet engines, the basic concept itself dates back to the 1930s, when NACA engineers proposed the idea and tested it in an open-air-cockpit, bi-wing airplane. The in-flight experiments showed that "a vapor-heating system which extracts heat from the exhaust and distributes it to the wings is an entirely practical and efficient method for preventing ice formation."[35]

As for melting ice that can accrete on or in other parts of an aircraft, such as windshields, protruding Pitot tubes, antennas, and carburetors on piston engines, electrically powered heaters of one kind or another are employed. The problem of carburetor ice is especially important and the one form of icing most prevalent and dangerous for thousands of General Aviation pilots. NASA has studied carburetor ice for engines and aircraft of various configurations through the years[36] and in 1975 surveyed the accident database and found that between 65 and 90 accidents each year involve carburetor icing as the probable cause. And when there are known carburetor icing conditions, between 50 and 70 percent of engine failure accidents are due to carburetor icing. Researchers found the problem to be particularly acute for pilots

34. "Preventing Ice Before it Forms," *Spinoff* 2006 (Washington, DC: NASA, 2006), pp. 46–47.
35. Theodore Theodorsen and William C. Clay, "Ice Prevention on Aircraft by Means of Engine Exhaust Heat and a Technical Study of Heat Transmission from a Clark Y Airfoil," NACA TR-403 (1933).
36. William D. Coles, "Laboratory Investigation of Ice Formation and Elimination in the Induction System of a Large Twin-Engine Cargo Aircraft," NACA TN-1427 (1947). Henry A. Essex, "A Laboratory Investigation of the Icing Characteristics of the Bendix-Stromberg Carburetor Model PD-12F5 with the Pratt and Whitney R-1830-C4 Intermediate Rear Engine Section," NACA WR-E-18 (1944).

with less than 1,000 hours of total flying time and overall exposed about 144 persons to death or injury each year.[37]

Icing's Electromagnetic Personality

Influenced by increasing fuel prices, the search for more profitability in every way, and a growing environmental movement, NASA's aeronautics researchers during the 1980s sought to meet all of those needs in terms of propulsion, airframe design, air traffic control, and more. On the subject of aircraft icing, all three of the traditional de-icing methods provided some drawbacks. The pneumatic boot added weight and disrupted the intended aerodynamics of an otherwise unequipped wing airfoil. Spraying chemicals onto the aircraft, whether on the ground or seeped through the leading edge in flight, contributed toxins to the environment. And bleeding off hot air to warm the interior of the wing and other aircraft cavities reduced the performance of the engines and added to the empty weight of the aircraft. Based on an idea first suggested in 1937 by Rudolf Goldschmidt, a German national living in London, NASA researchers investigated an Electro-Impulse De-Icing (EIDI) system that promised applications both on fixed-wing aircraft and on helicopters.[38]

First tested during the 1970s, the EIDI system researched during the 1980s consisted of flat-wound coils of copper ribbon wire positioned near the skin inside the leading edge of a wing, but leaving a tiny gap between the skin and the coil. The coils were then connected a high-voltage bank of capacitors. When energy was discharged through the wiring, it created a rapidly forming and collapsing electromagnetic field, which in turn set up a sort of a vibration that rippled across the wing, creating a repulsive force of several hundred pounds for just a fraction of a second at a time. The resulting force "shattered, de-bonded and expelled ice instantaneously."[39]

Ground tests in GRC's IRT and flight tests on aircraft such as NASA's Twin Otter and Cessna 206 during 1983 and 1984 conclusively proved the EIDI system would work. The results set up a 1985 symposium with

37. R.W. Obermayer and T.W. Roe, "A Study of Carburetor/Induction System Icing in General Aviation Accidents," NASA CR-143835 (1975).
38. G.W. Zumwalt, R.L. Schrag, W.D. Bernhart, and R.A. Friedberg, "Analyses and Tests for Design of an Electro-Impulse De-Icing System," NASA CR-174919 (1985).
39. G.W. Zumwalt and R.A. Friedberg, "Designing an Electro-Impulse De-Icing System," AIAA Paper 86-0545 (1986).

more than 100 people in attendance representing 10 companies and several Government agencies. As participants observed test runs in the GRC IRT, program engineers stressed that EIDI operated on low energy (in some cases with less power than required to power landing lights), caused no aerodynamic penalties, required minimum maintenance, and compared favorably in terms of weight and cost with existing de-icing systems. Although it was hailed as the de-icing system of the future, the EIDI never found widespread acceptance or lived up to its expectations.[40]

However, in 1988 an ARC engineer by the name of Leonard A. Haslim won NASA's Inventor of the Year Award by coming up with the Electro-Expulsive Separation System (EESS), an apparent combination of the best of the EIDI and traditional rubber boot de-icing systems. In this configuration, the electrically conducting copper ribbons are embedded into the boot with tiny slits in the boot separating each conductor. When a burst of energy is discharged through the system, each conductor pair repels one another in an instant and causes the slits in the boot to expand explosively, instantly breaking free any ice on the wing. In addition to the advantages the EIDI system offers, the EESS can remove ice when it is only as thin as a layer of frost, preventing the possibility of larger chunks of ice breaking free of the leading edge and then causing damage if the ice strikes the tail or tail-mounted engines. With applications for removing ice from large ship superstructures or bridges, the EESS was licensed to Dataproducts New England, Inc. (DNE), to make the product available commercially.[41]

Tail Plane Icing Program

Following the traumatic loss of TWA Flight 800 in 1996, then-President Clinton put together a commission on aviation safety, from which NASA in 1997 began an Aviation Safety Program to address very specific areas of flying in a bid to reduce the accident rate, even as air traffic was anticipated to grow at record rates. The emphasis on safety came at a time when a 4-year program led by NASA with the help of the FAA to understand the phenomenon known as ice-contaminated tail plane stall, or ICTS, was a year away from wrapping up. The successful Tail Plane Icing Program provided immediate benefits to the aviation community and today is considered by veteran NASA

40. G.W. Zumwalt, "Electro-Impulse De-Icing: A Status Report," AIAA Paper 88-0019 (1988).
41. "Breaking the Ice," Spinoff 1989 (Washington, DC: NASA, 1989) pp. 64–65.

researchers as one of the Agency's most important icing-related projects ever conducted.[42]

According to a 1997 fact sheet prepared by GRC, the ICTS phenomenon is "characterized as a sudden, often uncontrollable aircraft nose down pitching moment, which occurs due to increased angle-of-attack of the horizontal tail plane resulting in tail plane stall. Typically, this phenomenon occurs when lowering the flaps during final approach while operating in or recently departing from icing conditions. Ice formation on the tail plane leading edge can reduce tail plane angle-of-attack range and cause flow separation resulting in a significant reduction or complete loss of aircraft pitch control." At the time the program began there had been a series of commuter airline crashes in which icing was suspect or identified as a cause. And while there was a great deal of knowledge about the effects of icing on the primary wing of an aircraft and how to combat it or recover from it, there was little information about the effect of icing on the tail or how pilots could most effectively recover from a tail plane stall induced by icing. As the popularity of the smaller, regional commuter jets grew following airline deregulation in 1978, the incidents of tail plane icing began to grow at a relatively alarming rate. By 1991, when the FAA first had the notion of initiating a review of all aspects of tail plane icing, there had been 16 accidents involving turboprop-powered transport and commuter-class airplanes, resulting in 139 fatalities.[43]

42. Interview of Jaiwon Shin, Associate Administrator for NASA's Aeronautics Research Mission Directorate, by Jim Banke, Orlando, FL, 5 Jan. 2010 Shin's own contributions to the study of aircraft icing have been substantial. For a sampling of his work, see Jaiwon Shin, "Characteristics of Surface Roughness Associated with Leading Edge Ice Accretion," NASA TM-106459 (1994); Jaiwon Shin, "The NASA Aviation Safety Program: Overview," NASA TM-2000-209810 (2000); Jaiwon Shin and Thomas H. Bond, "Results of an Icing Test on a NACA 0012 Airfoil in the NASA Lewis Icing Research Tunnel," NASA TM-105374 (1992); Jaiwon Shin, Hsun H. Chen, and Tuncer Cebeci, "A Turbulence Model for Iced Airfoils and Its Validation," NASA TM-105373 (1992); Jaiwon Shin, Brian Berkowitz, Hsun H. Chen, and Tuncer Cebeci, "Prediction of Ice Shapes and their Effect on Airfoil Performance," NASA TM-103701 (1991); Jaiwon Shin, Peter Wilcox, Vincent Chin, and David Sheldon, "Icing Test Results on an Advanced Two-Dimensional High-Lift Multi-Element Airfoil," NASA TM-106620 (1994); Thomas H. Bond and Jaiwon Shin, "Results of Low Power Deicer Tests on the Swept Inlet Component in the NASA Lewis Icing Research Tunnel," NASA TM-105968 (1993); and Thomas H. Bond, Jaiwon Shin, and Geert A. Mesander, "Advanced Ice Protection Systems Test in the NASA Lewis Icing Research Tunnel," NASA TM-103757 (1991).

43. Dale Hiltner, Michael McKee, Karine La Noé, and Gerald Gregorek, "DHC-6 Twin Otter Tail Plane Airfoil Section Testing in the Ohio State University 7x10 Wind Tunnel," NASA-CR-2000-2099921/VOL1 (2000).

Following a review of all available data on tail plane icing and incidents of the tail stalling on turboprop-powered commuter airplanes as of 1991, the FAA requested assistance from NASA in managing a full-scale research program into the characteristics of ICTS. And so an initial 4-year program began to deal with the problem and propose solutions. More specifically the goals of the program were to collect detailed aerodynamic data on how the tail of a plane contributed to the stability of an aircraft in flight, and then take the same measurements with the tail contaminated with varying severity of ice, and from that information develop methods for predicting the effects of tail plane icing and recovering from them. To accomplish this, a series of wind tunnel tests were performed with a tail section of a De Havilland of Canada DHC-6 Twin Otter aircraft (a design then widely used for regional transport), both in dry air conditions and with icing turned on in the tunnel. Flight tests of a full Twin Otter were made to complement the ground-based studies.[44]

As is typical with many research programs, as new information comes in and questions get answered, the research results often generate additional questions that demand even more study to find solutions. So following the initial tail plane icing research that concluded in 1997, a year later NASA's Ohio-based Field Center initiated a second multiphase program to continue the icing investigations. This time the work was assigned to Wichita State University in Kansas, which would coordinate its activities with support from the Bombardier/Learjet Company. The main goal was of the combined Government/industry/university effort was to expand on the original work with the Twin Otter by coming up with methods and criteria for testing multiple tail plane configurations in a wind tunnel, and then actually conduct the tests to generate a comprehensive database of tail plane aerodynamic performance with and without ice contamination for a range of tail plane/airfoil configurations. The resulting database would then be used to support development and verification of future icing analysis tools.[45]

From this effort pilots were given new tools to recognize the onset of tail plane icing and recover from any disruptions to the aircraft's

44. Gerald Gregorek, John J. Dresse, and Karine La Noé, "Additional Testing of the DHC-6 Twin Otter Tail Plane Airfoil Section Testing in the Ohio State University 7x10 Low Speed Wind Tunnel," NASA-CR-2000-29921/VOL2 (2000).

45. Judith Foss Van Zante, and Thomas P. Ratvasky, "Investigation of Dynamic Flight Maneuvers with an Iced Tail Plane," NASA TM-1999-208849 (1999).

aerodynamics, including a full stall. As part of the education process, a Guest Pilot Workshop was held to give aviators firsthand experience with tail plane icing via an innovative "real world" simulation in which the pilots flew with a model of a typical ice buildup attached to the tail surface of a Twin Otter. The event provided a valuable exchange between real-world pilots and laboratory researchers, which in turn resulted in the collaboration on a 23-minute educational video on tail plane icing that is still used today.[46]

Predicting an Icy Future

With its years of accumulated research about all aspects of icing—i.e., weather conditions that produce it, types of ice that form under various conditions, de-icing and anti-icing measures and when to employ them—NASA's data would be useless unless they were somehow packaged and made available to the aviation community in a convenient manner so that safety could be improved on a daily basis. And so with desktop computers becoming more affordable, available, and increasingly powerful enough to crunch fairly complex datasets, in 1983, NASA researchers at what was still named the Lewis Research Center began developing a computer program that would at first aid NASA's in-house researchers, but would grow to become a tool that would aid pilots, air traffic controllers, and any other interested party in the flight planning process through potential areas of icing. The software was dubbed LEWICE, and version 0.1 originated in 1983 as a research code for in-house use only. As of the beginning of 2010, version 2.0 is the official current version, although a version 3.2.2 is in development, as is the first 0.1 version of GlennICE, which is intended to accurately predict ice growth under any weather conditions for any aircraft surface.[47]

LEWICE, which spelled out is the Lewis Ice Accretion Program, is a freely available desktop software program used by hundreds of people in the aviation community for purposes of predicting the amount, type, and shape of ice an aircraft might experience given a particular weather forecast, as well as what kind of anti-icing heat requirements may be necessary to prevent any buildup of ice from beginning. The software

46. The video is available online via YouTube at *http://www.youtube.com/watch?v=_ifKduc1hE8&feature=PlayList&p=18B9F75B0B7A3DB9&playnext=1&playnext_from=PL&index=3*.
47. William B. Wright, Mark G. Potapczuk, and Laurie H. Levinson, "Comparison of LEWICE and GlennICE in the SLD Regime," NASA TM-2008-215174 (2008).

runs on a desktop PC and provides its analysis of the input data within minutes, fast enough that the user can try out some different numbers to get a range of possible icing experiences in flight. All of the predictions are based on extensive research and real-life observations of icing collected through the years both in flight and in icing wind tunnel tests.[48]

At its heart, LEWICE attempts to predict how ice will grow on an aircraft surface by evaluating the thermodynamics of the freezing process that occurs when supercooled droplets of moisture strike an aircraft in flight. Variables considered include the atmospheric parameters of temperature, pressure, and velocity, while meteorological parameters of liquid water content, droplet diameter, and relative humidity are used to determine the shape of the ice accretion. Meanwhile, the aircraft surface geometry is defined by segments joining a set of discrete body coordinates. All of that data are crunched by the software in four major modules that result in a flow field calculation, a particle trajectory and impingement calculation, a thermodynamic and ice growth calculation, and an allowance for changes in the aircraft geometry because of the ice growth. In processing the data, LEWICE applies a time-stepping procedure that runs through the calculations repeatedly to "grow" the ice. Initially, the flow field and droplet impingement characteristics are determined for the bare aircraft surface. Then the rate of ice growth on each surface segment is determined by applying the thermodynamic model. Depending on the desired time increment, the resulting ice growth is calculated, and the shape of the aircraft surface is adjusted accordingly. Then the process repeats and continues to predict the total ice expected based on the time the aircraft is flying through icing conditions.[49]

The basic functions of LEWICE essentially account for the capabilities of the software up through version 1.6. Version 2.0 was the next release, and although it did not change the fundamental process or models involved in calculating ice accretion, it vastly improved the robustness and accuracy of the software. The current version was extensively tested on different computer platforms to ensure identical results and also incorporated the very latest and complete datasets based on the most

48. Jaiwon Shin, Brian Berkowitz, Hsun Chen, and Tuncer Cebeci, "Prediction of Ice Shapes and their Effect on Airfoil Performance," NASA TM-103701 (1991).
49. William B. Wright and Adam Rutkowski, "Validation Results for LEWICE 2.0," NASA CR-1999-208690 (1999).

recent research available, while also having its prediction results verified in controlled laboratory tests using the Glenn IRT. Version 3.2—not yet released to date—will add the ability to account for the presence and use of anti-icing and de-icing systems in determining the amount, shape, and potential hazard of ice accretion in flight. Previously these variables could be calculated by reading LEWICE output files into other software such as ANTICE 1.0 or LEWICE/Thermal 1.6.[50]

According to Jaiwon Shin, the current NASA Associate Administrator for the Aeronautics Research Mission Directorate, the LEWICE software is the most significant contribution NASA has made and continues to make to the aviation industry in terms of the topic of icing accretion. Shin said LEWICE continues to be used by the aviation community to improve safety, has helped save lives, and is an incredibly useful tool in the classroom to help teach future pilots, aeronautical engineers, traffic controllers, and even meteorologists about the icing phenomenon.[51]

Learning to Fly with SLDs

From the earliest days of aviation, the easiest way for pilots to avoid problems related to weather and icing was to simply not fly through clouds or in conditions that were less than ideal. This made weather forecasting and the ability to quickly and easily communicate observed conditions around the Nation a top priority of aviation researchers. Working with the National Oceanic and Atmospheric Administration (NOAA) during the 1960s, NASA orbited the first weather satellites, which began equipped with black-and-white television cameras and

50. For these programs and their validation, see William B. Wright, "Users Manual for the Improved NASA Lewis Ice Accretion Code LEWICE 1.6," NASA CR-1995-198355 (1995); William B. Wright, "User Manual for the NASA Glenn Ice Accretion Code LEWICE Version 2.0," NASA CR-1999-209409 (1999); William B. Wright, "User Manual for the NASA Glenn Ice Accretion Code LEWICE Version 2.2.2," NASA CR-2002-211793 (2002); William B. Wright, "Further Refinement of the LEWICE SLD Model," NASA CR-2006-214132 (2006); William B. Wright, "User's Manual for LEWICE Version 3.2," NASA CR-2008-214255 (2008); William B. Wright and James Chung, "Correlation Between Geometric Similarity of Ice Shapes and the Resulting Aerodynamic Performance Degradation-A Preliminary Investigation Using WIND," NASA CR-1999-209417 (1999); William B. Wright, R.W. Gent, and Didier Guffond, "DRA/NASA/ONERA Collaboration on Icing Research Pt. II—Prediction of Airfoil Ice Accretion," NASA CR-1997-202349 (1997); William B. Wright, Mark G. Potapczuk, and Laurie H. Levinson, "Comparison of LEWICE and GlennICE in the SLD Regime," NASA TM-2008-215174 (2008).

51. Banke, Shin interview.

have since progressed to include sensors capable of seeing beyond the range of human eyesight, as well as lasers capable of characterizing the contents of the atmosphere in ways never before possible.[52]

Post-flight image shows ice contamination on the NASA Twin Otter airplane as a result of encountering Supercooled Large Droplet (SLD) conditions near Parkersburg, WV.

Our understanding of weather and the icing phenomenon, in combination with the latest navigation capabilities—robust airframe manufacturing, anti- and de-icing systems, along with years of piloting experience—has made it possible to certify airliners to safely fly through almost any type of weather where icing is possible (size of the freezing rain is generally between 100 and 400 microns). The exception is for one category in which the presence of supercooled large drops (SLDs) are detected or suspected of being there. Such rain is made up of water droplets that are greater than 500 microns and remain in a liquid state even though its temperature is below freezing. This makes the drop very unstable, so it will quickly freeze when it comes into contact with a cold object such as the leading edge of an airplane. And while some

52. Andrew Reehorst, David J. Brinker, and Thomas P. Ratvasky, "NASA Icing Remote Sensing System Comparisons from AIRS II," NASA TM-2005-213592 (2005).

of the SLDs do freeze on the wing's leading edge, some remain liquid long enough to run back and freeze on the wing surfaces, making it difficult, if not impossible, for de-icing systems to properly do their job. As a result, the amount of ice on the wing can build up so quickly, and so densely, that a pilot can almost immediately be put into an emergency situation, particularly if the ice so changes the airflow over the wing that the behavior of the aircraft is adversely affected.

This was the case on October 31, 1994 when American Eagle Flight 4184, a French-built ATR 72-212 twin-turboprop regional airliner carrying a crew of 4 and 64 passengers, abruptly rolled out of control and crashed in Roselawn, IN. During the flight, the crew was asked to hold in a circling pattern before approaching to land. Icing conditions existed, with other aircraft reporting rime ice buildup. Suddenly the ATR 72 began an uncommanded roll; its two pilots heroically attempted to recover as the plane repeatedly rolled and pitched, all the while diving at high speed. Finally, as they made every effort to recover, the plane broke up at a very low altitude, the wreckage plunging into the ground and bursting into flame. An exhaustive investigation, including NASA tests and tests of an ATR 72 flown behind a Boeing NKC-135A icing tanker at Edwards Air Force Base, revealed that the accident was all the more tragic for it had been completely preventable. Records indicated that the ATR 42 and 72 had a marked propensity for roll-control incidents, 24 of which had occurred since 1986 and 13 of which had involved icing. The National Transportation Safety Board (NTSB) report concluded:

> The probable cause of this accident were the loss of control, attributed to a sudden and unexpected aileron hinge moment reversal that occurred after a ridge of ice accreted beyond the deice boots because: 1) ATR failed to completely disclose to operators, and incorporate in the ATR 72 airplane flight manual, flightcrew operating manual and flightcrew training programs, adequate information concerning previously known effects of freeing precipitation on the stability and control characteristics, autopilot and related operational procedures when the ATR 72 was operated in such conditions; 2) the French Directorate General for Civil Aviation's (DGAC's) inadequate oversight of the ATR 42 and 72, and its failure to take the necessary corrective action to ensure continued

12

> airworthiness in icing conditions; and 3) the DGAC's failure to provide the FAA with timely airworthiness information developed from previous ATR incidents and accidents in icing conditions, as specified under the Bilateral Airworthiness Agreement and Annex 8 of the International Civil Aviation Organization.
>
> Contributing to the accident were; 1) the Federal Aviation Administration's (FAA's) failure to ensure that aircraft icing certification requirements, operational requirements for flight into icing conditions, and FAA published aircraft icing information adequately accounted for the hazards that can result from light in freezing rain and other icing conditions not specified in 14 Code of Federal Regulations 9CFR) part 25, Appendix C; and 2) the FAA's inadequate oversight of the ATR 42 and 72 to ensure continued airworthiness in icing conditions. [53]

This accident focused attention on the safety hazard associated with SLD and prompted the FAA to seek a better understanding of the atmospheric characteristics of the SLD icing condition in anticipation of a rule change regarding certifying aircraft for flight through SLD conditions, or at least long enough to safely depart the hazardous zone once SLD conditions were encountered. Normally a manufacturer would demonstrate its aircraft's worthiness for certification by flying in actual SLD conditions, backed up by tests involving a wind tunnel and computer simulations. But in this case such flight tests would be expensive to mount, requiring an even greater reliance on ground tests. The trouble in 1994 was lack of detailed understanding of SLD precipitation that could be used to recreate the phenomenon in the wind tunnel or program computer models to run accurate simulations. So a variety of flight tests and ground-based research was planned to support the decision-making process on the new certification standards.[54]

53. National Transportation Safety Board, *In-Flight Icing Encounter and Loss of Control Simmons Airlines, d.b.a. American Eagle Flight 4184 Avions de Transport Regional (ATR) Model 72-212, N401AM Roselawn, Indiana October 31, 1994*, v. 1: *Safety Board Report*, NTSB/AAR-96/01 (Washington, DC: NTSB, 1996), p. 210.

54. Dean R. Miller, Mark G. Potapczuk, and Thomas H. Bond, "Update on SLD Engineering Tools Development," NASA TM-2004-213072 (2004).

One interesting approach NASA took in conducting basic research on the behavior of SLD rain was to employ high-speed, close-up photography. Researchers wanted to learn more about the way an SLD strikes an object: is it more of a direct impact, and/or to what extent does the drop make a splash? Investigators also had similar questions about the way ice particles impacted or bounced when used during research in an icing wind tunnel such as the one at GRC. With water droplets less than 1 millimeter in diameter and the entire impact process taking less than 1 second in time, the close-up, high-speed imaging technique was the only way to capture the sought-after data. Based on the results from these tests, follow-on tests were conducted to investigate what effect ice particle impacts might have on the sensing elements of water content measurement devices.[55]

NASA's Twin Otter ice research aircraft, based at the Glenn Research Center in Cleveland, is shown in flight.

Another program to understand the characteristics of SLDs Supercooled Large Droplets involved a series of flight tests over the Great Lakes during the winter of 1996–1997. GRC's Twin Otter icing research aircraft was flown in a joint effort with the FAA and the National Center for Atmospheric Research (NCAR). Based on weather forecasts

55. Dean R. Miller, Christopher J. Lynch, and Peter A. Tate, "Overview of High Speed Close-Up Imaging in an Icing Environment," NASA TM-2004-212925 (2004).

and real-time pilot reports of in-flight icing coordinated by the NCAR, the Twin Otter was rushed to locations where SLD conditions were likely. Once on station, onboard instrumentation measured the local weather conditions, recorded any ice accretion that took place, and registered the aerodynamic performance of the aircraft in response to the icing. A total of 29 such icing research sorties were conducted, exposing the flight research team to all the sky has to offer—from normal-sized precipitation and icing to SLD conditions, as well as mixed phase conditions. Results of the flight tests added to the database of knowledge about SLDs and accomplished four technical objectives that included characterization of the SLD environment aloft in terms of droplet size distribution, liquid water content, and measuring associated variables within the clouds containing SLDs; development of improved SLD diagnostic and weather forecasting tools; increasing the fidelity of icing simulations using wind tunnels and icing prediction software (LEWICE); and providing new information about SLD to share with pilots and the flying community through educational outreach efforts.[56]

Thanks in large measure to the SLD research done by NASA in partnership with other agencies—an effort NASA Associate Administrator Jaiwon Shin ranks as one of the top three most important contributions to learning about icing—the FAA is developing a proposed rule to address SLD icing, which is outside the safety envelope of current icing certification requirements. According to a February 2009 FAA fact sheet: "The proposed rule would improve safety by taking into account supercooled large-drop icing conditions for transport category airplanes most affected by these icing conditions, mixed-phase and ice-crystal conditions for all transport category airplanes, and supercooled large drop, mixed phase, and ice-crystal icing conditions for all turbine engines."[57]

As of September 2009, SLD certification requirements were still in the regulatory development process, with hope that an initial, draft rule would be released for comment in 2010.[58]

56. Dean R. Miller, Thomas Ratvasky, Ben Bernstein, Frank McDonough, and J. Walter Strapp, "NASA/FAA/NCAR Supercooled Large Droplet Icing Flight Research: Summary of Winter 1996-1997 Flight Operations," NASA TM-1998-206620 (1998).

57. Laura Brown, "FAA Icing Fact Sheet: Flying in Icing Conditions," NTSB Docket No. SA-533, Exhibit No. 2-GGG (2009).

58. "FAA Presentation—Icing Requirements and Guidance," NTSB Docket No. SA-533, Exhibit No. 2-JJJ (2009).

Flaming Out on Ice

And just when the aircraft icing community thought it had seen everything—clear ice, rime ice, glazed ice, SLDs, tail plane icing, and freezing rain encountered within the coldest atmospheric conditions possible—a new icing concern was recently discovered in the least likely of places: the interior of jet engines, where parts are often several hundred degrees above freezing. Almost nothing is known about the mechanism behind engine core ice accretion, except that the problem does cause loss of power, even complete flameouts. According to data compiled by Boeing and cited in a number of news media stories and Government reports, there have been more than 100 dramatic power drops or midair engine stoppages since the mid 1990s, including 14 instances since 2002 of dual-engine flameouts in which engine core ice accretion turned a twin-engine jetliner into a glider. "It's not happening in one particular type of engine and it's not happening on one particular type of airframe," said Tom Ratvasky, an icing flight research engineer at GRC. "The problem can be found on aircraft as big as large commercial airliners, all the way down to business-sized jet aircraft."[59]

The problem came to light in 2004, when the first documented dual-engine flameout occurred with a U.S. business jet due to core ice accretion. The incident was noted by the NTSB, and during the next 2 years Jim Hookey, an NTSB propulsion expert, watched as two more Beechjets lost engine power despite no evidence of mechanical problems or pilot error. One of those incidents took place over Florida in 2005, when both engines failed within 10 seconds of each other at 38,000 feet. Despite three failed attempts to restart the engines the pilots were able to safely glide in to a Jacksonville airport, dodging thunderstorms and threatening clouds all the way down. Hookey took the unusual step of interviewing the pilots and became convinced the cause of the power failures was due to an environmental condition. It was shortly after that realization that both the NTSB and the FAA began pursuing icing as a cause.[60]

Hookey employed some commonsense investigative techniques to find commonality among the incidents he was aware of and others that were suspect. He contacted the engine manufacturers to request they take another look at the detailed technical reports of engines that had failed

59. Phone interview of Tom Ratvasky by Jim Banke, Cape Canaveral, FL, 7 April 2009.

60. Andy Pasztor, "Airline Regulators Grapple with Engine-Shutdown Peril," *The Wall Street Journal*, Page A1, 7 April 2008.

and then also look at the archived weather data to see if any patterns emerged. By May 2006, the FAA began to argue that the engine problems were being caused by ice crystals being ingested into the engine. The NTSB concurred and suggested how ice crystals can build up inside engines even if the interior temperatures are way above freezing. The theory is that ice particles from nearby storms melt in the hot engine air, and as more ice is ingested, some of the crystals stick to the wet surfaces, cooling them down. Eventually enough ice accretes to cause a problem, usually without warning. In August 2006, the NTSB sent a letter to the FAA detailing the problem as it was then understood and advising the FAA to take action.[61]

Part of the action the FAA is taking to continue to learn more about the phenomenon, its cause, and potential mitigation strategies is to partner with NASA and others in conducting an in-flight research program. "If we can find ways of detecting this condition and keeping aircraft out of it, that's something we're interested in doing," said Ratvasky, who will help lead the NASA portion of the research program. Considering the number and type of sensors required, the weight and volume of the associated research equipment, the potentially higher loads that may stress the aircraft as it flies in and around fairly large warm-weather thunderstorms, the required range, and the number of people who would like to be on site for the research, NASA won't be able to use its workhorse Twin Otter icing research aircraft. A twin-turbofan Lockheed S-3B Viking aircraft provided to NASA by the U.S. Navy originally was proposed for this icing research program, but the program requirements outgrew the jet's capabilities. As of early 2010, the Agency still was considering its options for a host aircraft, although it was possible that the NASA DC-8 airborne science laboratory based at the Dryden Flight Research Center (DFRC) might be pressed into service. In any case, it's going to take some time to put together the plan, prepare the aircraft, and test the equipment. It may be 2012 before the flight research begins. "It's a fairly significant process to make sure we are going to be doing this program in a safe way, while at the same time we meet all the research requirements. What we're doing right now is getting the instrumentation integrated onto the aircraft and then doing the appropriate testing to qualify the instrumentation before we go fly all the way across the

61. National Transportation Safety Board, Letter to the Federal Aviation Administration, Safety Recommendation A-06-56 through -59 (Washington, DC: NTSB, 2006).

world and make the measurements we want to make," Ratvasky said. In addition to NASA, organizations providing support for this research include the FAA, NCAR, Boeing, Environment Canada, the Australian Bureau of Meteorology, and the National Research Council of Canada.[62]

In the meantime, ground-based research has been underway and safety advisories involving jet engines built by General Electric and Rolls-Royce has resulted in those companies making changes in their design and operations to prevent the chance of any interior ice buildup that could lead to engine failure. Efforts to unlock the science behind internal engine icing also is taking place at Drexel University in Pennsylvania, where researchers are building computer models for use in better understanding the mechanics of how ice crystals can accrete within turbofan engines at high altitude.[63]

While few technical papers have been published on this subject—none yet appear in NASA's archive of technical reports—expect the topic of engine ingestion of ice crystals and its detrimental effect on safe operations to get a lot of attention during the next decade as more is learned, rules are rewritten, and potential design changes in jet engines are ordered, built, and deployed into the air fleet.

Slip, Sliding Away

Before an aircraft can get into the winter sky and safely avoid the threat of icing, it first must take off from what the pilot hopes is a long, wide, dry runway at the beginning of the flight, as well as at the end of the flight. Likewise, NASA's contributions to air safety in fighting the tyranny of temperature included research into ground operations. While NASA did not invent the plow to push snow off the runway, or flamethrowers to melt off any stubborn runway snow or ice, the Agency has been active in studying the benefits of runway grooves since the first civil runway was introduced in the United States at Washington National Airport in December 1965.[64]

Runway grooves are intended to quickly channel water away from the landing strip without pooling on the surface so as to prevent

62. Banke, Ratvasky interview.

63. Manuel A. Rios, Yung I. Cho, "Analysis of Ice Crystal Ingestion as a Source of Ice Accretion," AIAA-2008-4165 (2208).

64. R.C. McGuire, "Report on Grooved Runway Experience at Washington National Airport," NASA Washington Pavement Grooving and Traction Studies (1969).

NASA's Aircraft Landing Dynamics Facility (ALDF) at Langley Research Center. This facility is used to test landing gear and how it acts when they touch the runway at high speed. ALDF achieved a 200-knot design speed.

hydroplaning. The 3-mile-long runway at the Shuttle Landing Facility is probably the most famous runway in the Nation and known for being grooved. Of course, there is little chance of snow or ice accumulating on the Central Florida runway, so when NASA tests runway surfaces for cold weather conditions it turns to the Langley Aircraft Landing Dynamics Facility at NASA's Langley Research Center (LaRC) in Hampton, VA. The facility uses pressurized water to drive a landing-gear-equipped platform down a simulated runway strip, while cameras and sensors keep an eye on tire pressure, tire temperature, and runway friction. Another runway at NASA's Wallops Flight Facility also has been used to test various surface configurations. During the mid-1980s, tests were performed on 12 different concrete and asphalt runways, grooved and non-grooved, including dry; wet; and snow, slush, and ice-covered surface conditions. More than 200 test runs were made with two transport aircraft, and more than 1,100 runs were made with different ground test vehicles. Ground vehicle and B-737 aircraft friction tests were conducted on grooved and non-grooved surfaces under wet conditions. As expected, grooved runway surfaces had significantly greater friction properties than non-grooved surfaces, particularly at higher speeds.[65]

65. Thomas J. Yager, William A. Vogler, and Paul Baldasare, "Evaluation of Two Transport Aircraft and Several Ground Test Vehicle Friction Measurements Obtained for Various Runway Surface Types and Conditions. A Summary of Test Results From Joint FAA/NASA Runway Friction Program," NASA TP-2917 (1990).

NASA's Cool Research Continues

With additional research required on SLDs and engine core ice accretion, new updates always in demand for the LEWICE software, and the still-unknown always waiting to be discovered, NASA maintains its research capability concentrated within the Icing Branch at GRC. The branch performs research activities related to the development of methods for evaluating and simulating the growth of ice on aircraft surfaces, the effects that ice may have on the behavior of aircraft in flight, and the behavior of ice protection and detection systems. The branch is part of the Research and Technology Directorate and works closely with the staff of the Icing Research Tunnel and the Twin Otter Icing Research Aircraft. Its mission is to develop validated simulation methods—for use in both computer programmed and real-world experiments—suitable for use as both certification and design tools when evaluating aircraft systems for operation in icing conditions. The Icing Branch also fosters the development of ice protection and ice detection systems by actively supporting and maintaining resident technical expertise, experimental facilities, and computational resources. NASA's Aircraft Icing Project at GRC is organized into three sections: Design and Analysis Tools, Aircraft Ice Protection, and Education and Training.[66]

Design and Analysis Tools

The Icing Branch has a continuing, multidisciplinary research effort aimed at the development of design and analysis tools to aid aircraft manufacturers, subsystem manufacturers, certification authorities, the military, and other Government agencies in assessing the behavior of aircraft systems in an icing environment. These tools consist of computational and experimental simulation methods that are validated, robust, and well documented. In addition, these tools are supported through the creation of extensive databases used for validation, correlation, and similitude. Current software offerings include LEWICE, LEWICE 3D, and SmaggIce. LEWICE 3D is computationally fast and can handle large problems on workstations and personal computers. It is a diverse, inexpensive tool for use in determining the icing characteristics of arbitrary aircraft surfaces. The code can interface with most

66. Mario Vargas, "Icing Branch Current Research Activities in Icing Physics," in NASA Glenn Research Center staff, *Proceedings of the Airframe Icing Workshop,* NASA CP-2009-215797 (Cleveland, OH: NASA Glenn Research Center, 2009).

3-D flow solvers and can generate solutions on workstations and personal computers for most cases in less than several hours.[67]

SmaggIce is short for Surface Modeling and Grid Generation for Iced Airfoils. It is a software toolkit used in the process of predicting the aerodynamic performance ice-covered airfoils using grid-based Computational Fluid Dynamics (CFD). It includes tools for data probing, boundary smoothing, domain decomposition, and structured grid generation and refinement. SmaggIce provides the underlying computations to perform these functions, a GUI (Graphical User Interface) to control and interact with those functions, and graphical displays of results. Until 3-D ice geometry acquisition and numerical flow simulation become easier and faster for studying the effects of icing on wing performance, a 2-D CFD analysis will have to play an important role in complementing flight and wind tunnel tests and in providing insights to effects of ice on airfoil aerodynamics. Even 2-D CFD analysis, however, can take a lot of work using the currently available general-purpose grid-generation tools. These existing grid tools require extensive experience and effort on the part of the engineer to generate appropriate grids for moderately complex ice. In addition, these general-purpose tools do not meet unique requirements of icing effects study: ice shape characterization, geometry data evaluation and modification, and grid quality control for various ice shapes. So, SmaggIce is a 2-D software toolkit under development at GRC. It is designed to streamline the entire 2-D icing aerodynamic analysis process from geometry preparation to grid generation to flow simulation, and to provide unique tools that are required for icing effects study.[68]

Aircraft Ice Protection

The Aircraft Ice Protection program focuses on two main areas: development of remote sensing technologies to measure nearby icing conditions, improve current forecast capabilities, and develop systems to transfer and display that information to flight crews, flight controllers, and dispatchers; and development of systems to monitor and assess aircraft performance, notify the cockpit crew about the state of the

67. Colin S. Bidwell and Mark G. Potapczuk, "Users Manual for the NASA Lewis Three-Dimensional Ice Accretion Code: LEWICE 3D," NASA TM-105974 (1993).
68. Marivell Baez, Mary Vickerman, and Yung Choo, "SmaggIce User Guide," NASA TM-2000-209793 (2000).

aircraft, and/or automatically alter the aircraft controlling systems to prevent stall or loss of control in an icing environment. Keeping those two focus areas in mind, the Aircraft Ice Protection program is subdivided to work on these three goals:

- Provide flight crews with real-time icing weather information so they can avoid the hazard in the first place or find the quickest way out.[69]
- Improve the ability of an aircraft to operate safely in icing conditions.[70]
- Improve icing simulation capabilities by developing better instrumentation and measurement techniques to characterize atmospheric icing conditions, which also will provide icing weather validation databases, and increase basic knowledge of icing physics.[71]

In terms of remote sensing, the top level goals of this activity are to develop and field-test two forms of remote sensing system technologies that can reduce the exposure of aircraft to in-flight icing hazards. The first technology would be ground based and provide coverage in

69. Richard H. McFarland and Craig B. Parker, "Weather Data Dissemination to Aircraft," NASA, Langley Research Center, Joint University Program for Air Transportation Research, 1988–1989, pp. 119–127.
70. Sharon Monica Jones, Mary S. Reveley, Joni K. Evans, and Francesca A. Barrientos, "Subsonic Aircraft Safety Icing Study," NASA TM-2008-215107 (2008).
71. For simulation, see Laurie H. Levinson, Mark G. Potapczuk, and Pamela A. Mellor, "Software Development Processes Applied to Computational Icing Simulation," NASA TM-1999-208898 (1999); Thomas B. Irvine, John R. Oldenburg, and David W. Sheldon, "New Icing Cloud Simulation System at the NASA Glenn Research Center Icing Research Tunnel," NASA TM-1999-208891 (1999); Mark G. Potapczuk and John J. Reinmann, "Icing Simulation: A Survey of Computer Models and Experimental Facilities," NASA TM-104366 (1991); Mark G. Potapczuk, M.B. Bragg, O.J. Kwon, and L.N. Sankar, "Simulation of Iced Wing Aerodynamics," NASA TM-104362 (1991); Thomas P. Ratvasky, Billy P. Barnhart, and Sam Lee, "Current Methods for Modeling and Simulating Icing Effects on Aircraft Performance, Stability and Control," NASA TM-2008-215453 (2008); Thomas P. Ratvasky, Kurt Blankenship, William Rieke, and David J. Brinker, "Iced Aircraft Flight Data for Flight Simulation Validation," NASA TM-2003-212114 (2003); Thomas P. Ratvasky, Richard J. Ranaudo, Kurt S. Blankenship, and Sam Lee, "Demonstration of an Ice Contamination Effects Flight Training Device," NASA TM-2006-214233 (2006); Thomas P. Ratvasky, Billy P. Barnhart, Sam Lee, and Jon Cooper, "Flight Testing an Iced Business Jet for Flight Simulation Model Validation," NASA TM-2007-214936 (2007).

a limited terminal area to protect all vehicles. The second technology would be airborne and provide unrestricted flightpath coverage for a commuter class aircraft. In most cases the icing hazard to aircraft is minimized with either de-icing or anti-icing procedures, or by avoiding any known icing or possible icing areas altogether. However, being able to avoid the icing hazard depends much on the quality and timing of the latest observed and forecast weather conditions. And once stuck in a severe icing hazard zone, the pilot must have enough information to know how to get out of the area before the aircraft's ice protection systems are overwhelmed. One way to address these problem areas is to remotely detect icing potential and present the information to the pilot in a clear, easily understood manner. Such systems would allow the pilot to avoid icing conditions and also allow rapid escape from icing if severe conditions were encountered.[72]

Education and Training

To support NASA's ongoing goal of improving aviation safety, the Education and Training Element of the Aircraft Icing Project continues to develop education and training aids for pilots and operators on the hazards of atmospheric icing. A complete list of current training aids is maintained on the GRC Web site. Education materials are tailored to several specific audiences, including pilots, operators, and engineers. Due to the popularity of the education products, NASA can no longer afford to print copies and send them out. Instead, interested parties can download material from the Web site[73] or check out the latest catalog from Sporty's Pilot Shop, an internationally known source of professional materials and equipment for aviators.[74]

Icing Branch Facilities

NASA's groundbreaking work to understand the aircraft icing phenomenon would have been impossible if not for a pair of assets available at GRC. The more historic of the two is the Icing Research Tunnel (IRT),

72. Andrew Reehorst, David Brinker, Marcia Politovich, David Serke, Charles Ryerson, Andrew Pazmany, and Frederick Solheim, "Progress Towards the Remote Sensing of Aircraft Icing Hazards," NASA TM-2009-215828 (2009).

73. The GRC Web site can be found at *http://icebox.grc.nasa.gov/education/index.html.*

74. Judith Foss Van Zante, "Aircraft Icing Educational and Training Videos Produced for Pilots," Glenn Research Center Research and Technology Report (1999).

which began service in 1944 and, despite the availability of other wind tunnels with similar capabilities, remains one of a kind. The other asset is the DHC-6 Twin Otter aircraft, which calls the main hangar at GRC its home.

Jack Cotter inspects a Commuter Transport Engine undergoing testing in the Icing Research Tunnel while Ray Soto looks on from the observation window. The Icing Research Tunnel, or IRT, is used to simulate the formation of ice on aircraft surfaces during flight. Cold water is sprayed into the tunnel and freezes on the test model.

For ground-based research it's the IRT, the world's largest refrigerated wind tunnel. It has been used to contribute to flight safety under icing conditions since 1944. The IRT has played a substantial role in developing, testing, and certifying methods to prevent ice buildup on gas-turbine-powered aircraft. Work continues today in the investigation of low-power electromechanical deicing and anti-icing fluids for use on the ground, deicing and anti-icing research on Short Take Off and Vertical Landing (STOVL) rotor systems and certification of ice protection systems for military and commercial aircraft. The IRT is a closed-loop, refrigerated wind tunnel with a 6- by 9-foot test section. It can generate airspeeds from 25 to more than 400 miles per hour. Models placed in the tunnel can be subjected to droplet sprays of varying sizes to produce the natural icing conditions.[75]

75. For a detailed history of the IRT, see the previously cited William Leary, *"We Freeze to Please: A History of NASA's Icing Research Tunnel and the Quest for Flight Safety"*, NASA-SP-2002-4226 (2002).

For its aerial research, the Icing Branch utilizes the capabilities of NASA 607, a DHC-6 Twin Otter aircraft. The aircraft has undergone many modifications to provide both the branch and NASA a "flying laboratory" for issues relating to the study of aircraft icing. Some of the capabilities of this research aircraft have led to development of icing protection systems, full-scale iced aircraft aerodynamic studies, software code validation for ground-based research, development of remote weather sensing technologies, natural icing physics studies, and more.[76]

Partners on Ice

As it is with other areas involving aviation, NASA's role in aircraft icing is as a leader in research and technology, leaving matters of regulations and certifications to the FAA. Often the FAA comes to NASA with an idea or a need, and the Agency then takes hold of it to make it happen. Both the National Center for Atmospheric Research and NOAA have actively partnered with NASA on icing-related projects. NASA also is a major player in the Aircraft Icing Research Alliance (AIRA), an international partnership that includes NASA, Environment Canada, Transport Canada, the National Research Council of Canada, the FAA, NOAA, the National Defense of Canada, and the Defence Science and Technology Laboratory (DSTL)-United Kingdom. AIRA's primary research goals complement NASA's, and they are to

- Develop and maintain an integrated aircraft icing research strategic plan that balances short-term and long-term research needs,
- Implement an integrated aircraft icing research strategic plan through research collaboration among the AIRA members,
- Strengthen and foster long-term aircraft icing research expertise,
- Exchange appropriate technical and scientific information,
- Encourage the development of critical aircraft icing technologies, and
- Provide a framework for collaboration between AIRA members.

76. Thomas P. Ratvasky, Kurt Blankenship, William Rieke, and David J. Brinker, "Iced Aircraft Flight Data for Flight Simulation Validation," NASA TM-2003-212114 (2003).

Finally, among the projects NASA is working with AIRA members includes the topics of ground icing, icing for rotorcraft, characterization of the atmospheric icing environment, high ice water content, icing cloud instrumentation, icing environment remote sensing, propulsion system icing, and ice adhesion/shedding from rotating surfaces—the last two a reference to the internal engine icing problem that is likely to make icing headlines during the next few years.

The NACA-NASA role in the history of icing research, and in searching for means to frustrate this insidious threat to aviation safety, has been one of constant endeavor, constantly matching the growth of scientific understanding and technical capabilities to the threat as it has evolved over time. From crude attempts to apply mechanical fixes, fluids, and heating, NACA and NASA researchers have advanced to sophisticated modeling and techniques matching the advances of aerospace science in the fields of fluid mechanics, atmospheric physics, and computer analysis and simulation. Through all of that, they have demonstrated another constant as well: a persistent dedication to fulfill a mandate of Federal aeronautical research dating to the founding of the NACA itself and well encapsulated in its founding purpose: "to supervise and direct the scientific study of the problems of flight, with a view to their practical solution."

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12

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12

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