Ice Crystal

Previously inexplicable high-altitude turbine engine flame-outs have been the focus of investigations that are providing a better understanding of the role played by ice crystals and how the incidents can be avoided.

Ice crystals in significant quantities can be lofted into the atmosphere by convective activity typical of thunderstorms, squall lines and tropical storms. The crystals do not build up on the airframe and are invisible to on-board weather radar and ice detectors. Until recently, flight crews generally were unaware of the hazard. As a result, the more than 100 power losses that have been attributed to ice crystal icing over the past two decades have caught pilots off guard.

A report on a study of 46 power-loss events for which sufficient data were available revealed some common characteristics.[1] Most of the events occurred in summer, in relatively warm air above 20,000 ft and near convective weather (Figure 1). Many occurred in instrument meteorological conditions (IMC) with light to moderate turbulence. Several events occurred while pilots were deviating around thunderstorms or areas of significant precipitation shown on their radar displays.

Ice crystals previously were thought to be harmless to airplanes because they would simply bounce off the airframe and engine surfaces, without accreting. Researchers now believe that ice crystals can partially melt, due to compression effects, as they pass through the engine fan section, enter the engine core and create a film of moisture on relatively warm surfaces, such as the

Icing

A nearly undetectable weather hazard can knock out a jet engine.

BY MARK LACAGNINA

forward stator vanes (Figure 2, p. 14). The moisture traps additional ice crystals, and, eventually, the ice buildup is shed into the compressor, causing the engine to surge and stall, and possibly reaching the combustor, causing a flameout.

The report said that 28 of the power-loss events occurred during descent, 17 during cruise, and one during climb. Power typically is set at idle during descent, resulting in minimum airflow through the engines. "The engine's capability to tolerate ice particles is related to the airflow and decreases as density decreases with altitude … where ice particles can constitute a greater proportion of the total airflow in the engine," the report said. Also, the compressor section is more susceptible to ice accretion at low power because of the reduced temperature.

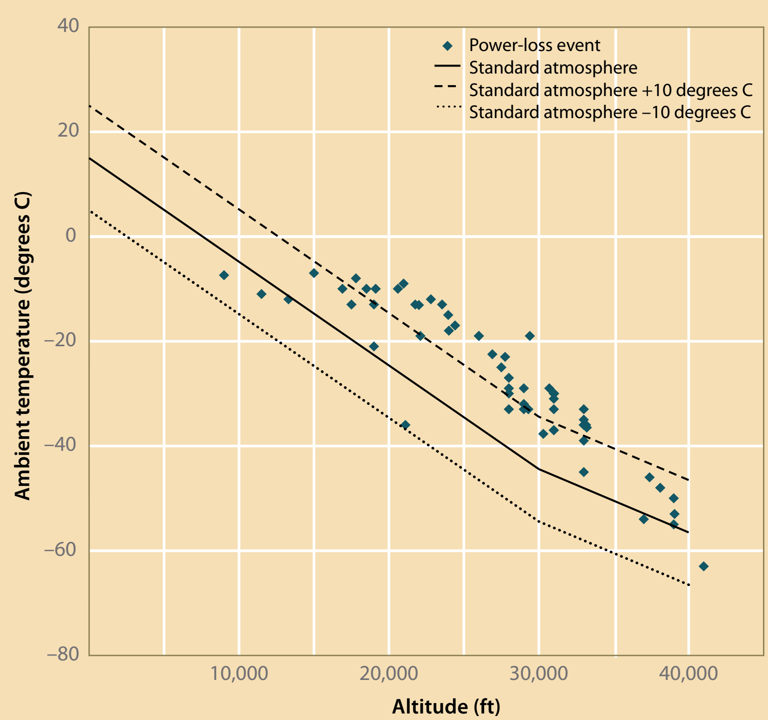
The power-loss events that occurred at high power during cruise and climb likely involved extended exposure to very high concentrations of ice crystals.[2]

'Rain' on the Windshield

Many power losses initially were not thought to be related to ice crystal icing because the pilots said that their airplanes were in heavy rain when the events occurred. This perception was based on observations of rain striking the windshield. However, some pilots also said that the sound was different than rain striking the windshield and that, when the landing lights were turned on, the particles looked different from rain. Only recently have the observations of heavy rain been linked to ice crystals that melted on heated windshields.

Another possible clue to the presence of a high concentration of ice crystals at altitude is anomalous total air temperature (TAT) indications, which include the increase in outside — static — air temperature due to compression. Researchers believe that erratic and erroneously warm TAT

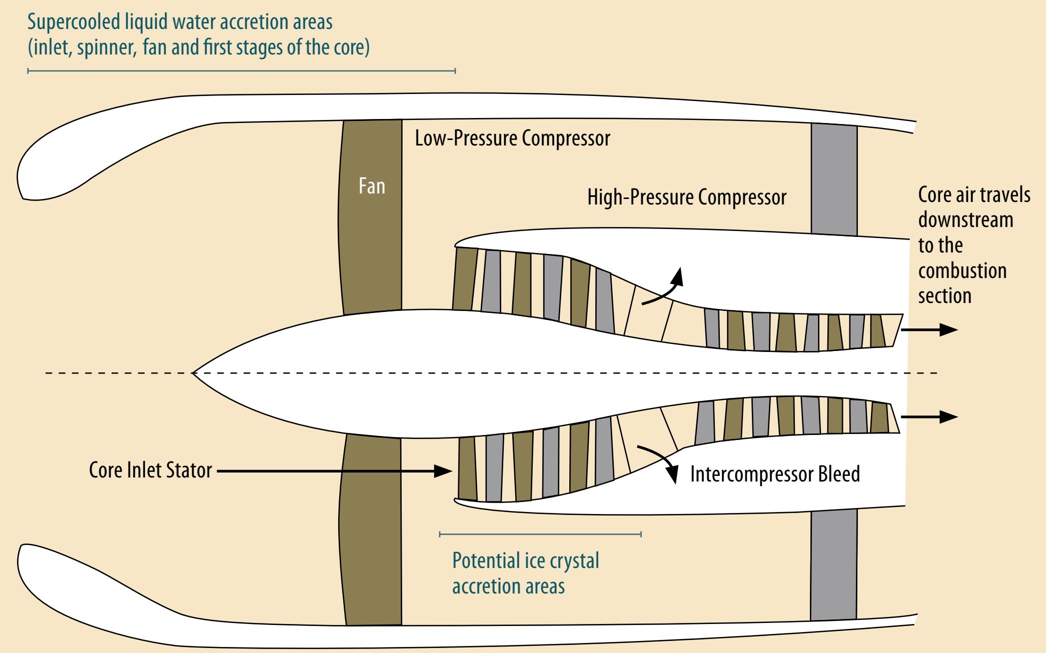
Power-Loss Event Altitudes and Temperatures



Source: Courtesy of Boeing AERO Magazine

Figure 1

Ice Crystal Accretion Area



Source: Courtesy of Boeing AERO Magazine

Figure 2

is believed to be associated with these events, which occurred at altitudes between 11,500 and 36,000 ft and were in or near convective weather systems," the bulletin said.

The FAA recommends that pilots avoid convective weather whenever possible. "Especially avoid flying over strong convective systems," the bulletin said. "If unavoidable, maintain vigilance for recognizing a potential ice crystal encounter … and the potential for adverse engine operation."

The bulletin said that on-board weather radar, ice detectors and visual inspections of the airframe provided no indication of the ice crystal encounters; however, some pilots observed erroneous TAT indications and water droplets on heated windshields at altitudes and ambient temperatures where rain is not possible.

General Electric developed new software for the engine control units (ECUs) on CF6-80C2 and -80E1 engines to increase their resistance to flameout by modifying the variable bleed valve schedule to increase ice extraction from the core flow path. Last year, the FAA issued four airworthiness directives (ADs) requiring installation of the new ECU software. The ADs are "interim actions due to the ongoing investigation," the FAA said. "We may take further rule-making actions in the future based on the results of the investigation and field experience."

indications are caused by ice crystals that build up on heated TAT probes and block airflow through the probes. The report said that TAT anomalies preceded 35 of the power-loss events.

In all 46 events, the engines were restarted. "Even in the rare cases where the engine was damaged, those engines were restarted and operated normally for the remainder of the flight," the report said.

'Serious Threat'

"The ice crystal phenomenon has only recently been identified as a serious potential environmental threat to turbine engines," said the U.S. Federal Aviation Administration (FAA) in a special airworthiness information bulletin, SAIB NE-07-01, issued in October 2006 to owners and operators of Airbus A300s and A330s, Boeing 747s and 767s, and McDonnell Douglas MD-11s.

The bulletin cited 32 incidents since the early 1990s of flameouts, including two dual flameouts, of the General Electric CF6-80C2 and -80E1 engines used on these airplanes. "Exposure to high concentrations of ice crystals

Reducing the Risk

Further rule-making actions were taken in April 2008, when the FAA proposed airplane flight manual (AFM) revisions that specify new conditions in which activation of engine anti-ice systems would be required during descent in 747s, 767s and MD-11s with CF6-80C2 and -80A engines.

In the notices of proposed rule making (NPRMs), the FAA said that 747s and 767s have been involved in "several in-flight flameout events," including four dual flameouts, and that MD-11s have been involved in six events, including two dual flameouts. All the events involved airplanes with CF6-80C2 engines, but the NPRMs include the -80A engines because they have similar compressor designs.

"Each flameout event was in or near convective weather with ice crystal icing," the NPRMs said. "This type of icing does not appear on radar due to its low reflectivity, and neither the airplane ice detector nor visual indications indicate the presence of icing conditions. Therefore, it is often undetected by the flight crew."

Increased engine idle speed and bleed flow when the anti-ice system is activated reduces the risk of flameout. "Engine anti-ice also assists with relighting the engines by turning on the igniters on airplanes that are not equipped with autorelight," the NPRMs said. "In several of the subject engine-flameout events, the engine anti-ice was already on when the engines flamed out. In each flameout event, the engines relit and continued to operate normally for the remainder of the flight."

The AFMs for the 1,064 affected 747s and 767s currently require activation of the engine anti-ice system in airplanes without ice detectors when TAT is between 10 degrees C and minus 40 degrees C. This is not required in airplanes with ice detectors because engine anti-ice is activated automatically when ice is detected. Noting again that ice detectors cannot detect ice crystal icing, the NPRM proposes a requirement for engine anti-ice to be activated manually at all TATs below 10 degrees C.

The NPRM for the 118 affected MD-11s does not state the current requirements for activation of the engine anti-ice system, but it proposes that activation be required when TAT is 6 degrees C and below. At press time, the FAA was still accepting public comments on the proposed ADs.[3]

Rollback Event

A different type of ice crystal icing was identified by the U.S. National Transportation Safety Board (NTSB) as the cause of an uncommanded deceleration — rollback — of the engines on an MD-82 on June 4, 2002. The incident involved blockage of the engine inlet pressure probes while the airplane was cruising at Flight Level (FL) 330 (about 33,000 ft) with the autopilot and autothrottles engaged.

The difference between inlet pressure and discharge pressure — engine pressure ratio (EPR) — is used to measure and set power in the MD-82's Pratt & Whitney JT8D-219 engines. Blockage of the inlet pressure probes resulted in erroneously high EPR measurements, which the autothrottle system responded to by retarding the throttles. According to NTSB, the flight crew did not notice the power reductions and the consequent increase in nose-up pitch trim and decrease in airspeed that occurred over a period of about five minutes.

When the stick shaker activated, the captain disengaged the autopilot and pushed the control column and throttles forward. The engines initially did not respond, but the crew was able to restart them as the airplane descended through 17,000 ft. Originally en route from Denver to Fort Lauderdale, Florida, with 105 passengers, the crew diverted to Wichita, Kansas, and landed without further incident.

Although the MD-82 was clear of clouds when the incident occurred, it had been flown in and out of IMC for the previous 50 nm (93 km). NTSB said that the flight crew had not engaged the engine anti-ice system, as required.

Beechjet Incidents

Ice crystal icing has been identified as the probable cause of several dual flameouts involving Raytheon Beechjet 400 series business jets powered by Pratt & Whitney Canada (PWC) JT15D-5 engines.[4] In each case, the flameouts occurred after power was reduced at high altitude in the vicinity of convective weather.

On July 12, 2004, the pilots of a Beechjet 400A en route from Duncan, Oklahoma, to Fort Myers,

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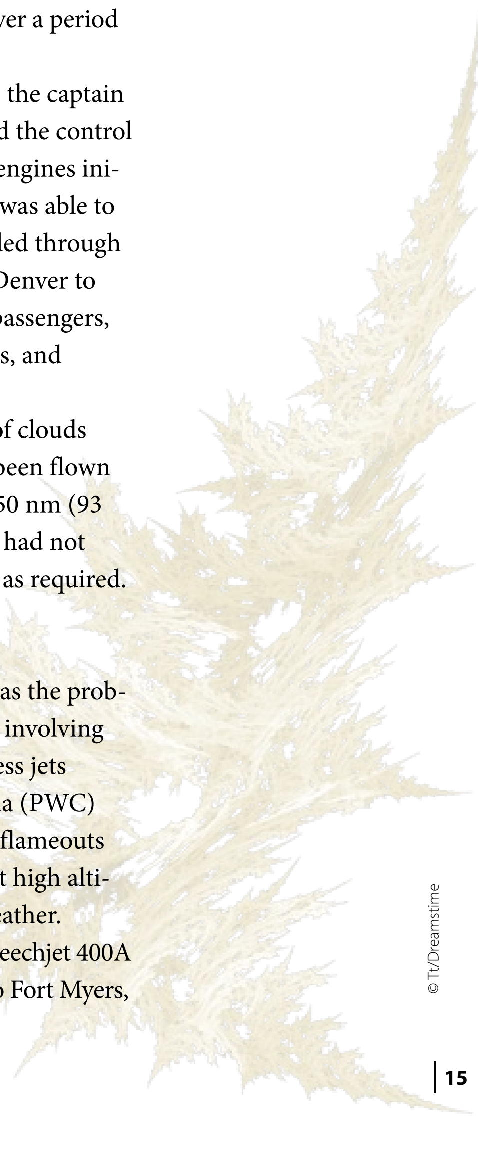

Florida, felt a jolt and heard a bang after beginning a descent in IMC from FL 410 over the Gulf of Mexico. They saw that cabin pressure was decreasing and then discovered that both engines had flamed out. They donned their oxygen masks and declared an emergency, telling air traffic control (ATC) that they were conducting an emergency descent. The copilot flew the airplane and communicated with ATC while the captain attempted to restart the engines. The airplane broke out of the clouds soon after the right engine was restarted at 10,000 ft. The pilots diverted to Sarasota, Florida, and landed without further incident.

On Nov. 28, 2005, Beechjet pilots were not able to restart either engine after they flamed out soon after a descent from FL 380 was initiated in visual meteorological conditions (VMC) during a positioning flight from Indianapolis to Marco Island, Florida. The crew made three attempts to restart the engines. "The pilots stated that they did not make any further attempts to restart the engines because they had descended into IMC and were concerned about draining the battery," said a preliminary report by NTSB, which had not completed its investigation of the incident at press time. The crew diverted to Jacksonville, Florida, and conducted a dead-stick approach and landing. "After they landed and rolled off the runway onto a taxiway, the right landing gear tire deflated," the preliminary report said.

On June 14, 2006, a Beechjet was cruising in VMC at FL 380 — about 3,000 ft over the remnants of a tropical storm — during a flight from Quonset Point, Rhode Island, to Charleston, South Carolina, when ATC issued a heading toward an upsloping cloud deck. The crew decided to activate the engine anti-ice system before entering the clouds. The AFM required power to be reduced below 90 percent N_1 — fan speed — before activating engine anti-ice. But when the throttles were retarded, both engines flamed out. The crew had activated the continuous ignition system before retarding the throttles, and both engines restarted "on their own" as the airplane descended. The crew landed at Norfolk, Virginia, without further incident.

Based on the results of a study performed by PWC during the investigation, NTSB determined that the probable cause of the Sarasota and Norfolk incidents was "high-altitude ice crystals that had accreted on the compressor vanes and were ingested into the high-pressure compressor when the pilots retarded the power levers, causing compressor surges and flameouts of both engines." The safety board also said that a lack of training on ice crystal icing was a contributing factor.

Raytheon subsequently issued Safety Communiqué 269, which provides guidance on how ice can form inside a turbine engine. "Operators should not assume ice formation to be impossible at very low ambient temperatures (i.e., minus 30 degrees C or colder)," the communiqué said. Also, the FAA issued AD 2006-21-02, requiring revision of the Beechjet AFM to require activation of the engine anti-ice system during high-altitude flight in the vicinity of visible moisture and convective storm activity.

Ongoing Investigation

Much of the current information about ice crystal icing is theoretical. Research continues to be performed by the FAA, airplane and engine manufacturers, and other organizations to define and measure the ice crystal environment, develop internal engine icing detectors, identify other engine models that are susceptible to ice crystal icing and to improve engine design to reduce the risk of flameout and rollback.

Boeing Commercial Airplanes, a member of the government/industry team, told *ASW* that progress has been made in developing improved instrumentation, test methods and facilities to measure ice particle size, concentration and extent of distribution in the atmosphere, and to understand the fundamental physics of ice accretion and shedding. "Using satellite and radar images and other meteorological analysis tools, our studies are helping to define how far from the central core of convective storms the events typically occur and thereby allowing us to provide better guidance for flight crews," the company said.

Pilots who encounter this phenomenon are encouraged to report the details to their safety directors so that the information can be shared with researchers. ●

Notes

1. Mason, Jeanne G.; Strapp, J. Walter; Chow, Philip. "The Ice Particle Threat to Engines in Flight." Paper presented at the 44th American Institute of Aeronautics and Astronautics Aerospace Sciences Meeting and Exhibit, Reno, Nevada, U.S., January 2006. Mason is a senior specialist engineer for Boeing Commercial Airplanes; Strapp is a physical scientist at Environment Canada; and Chow is senior principal engineer at Honeywell.
2. Mason, Jeanne. "Engine Power Loss in Ice Crystals Conditions." *Boeing Aero* fourth quarter, 2007.
3. Docket material is available on the Internet at <regulations.gov>. Search for 0402 and 0403, respectively, for the 747/767 and MD-11 dockets.
4. Raytheon Aircraft was acquired in December 2006 by GS Capital Partners and renamed Hawker Beechcraft. The Beechjet's name was changed in 2003 to Hawker 400XP.