A buildup of ice came loose during final approach.

SNOWBALLS

Flow restrictions caused by ice that dislodged from fuel pipes and smothered the fuel/oil heat exchangers resulted in rollbacks of both engines when a Boeing 777-200ER was on final approach to London Heathrow Airport the afternoon of Jan. 17, 2008. The flight crew was unable to increase thrust, and the aircraft was damaged beyond economic repair when it touched down hard short of the runway (*ASW*, 11/09, p. 26).

One of the 136 passengers was seriously injured, and 34 passengers and 12 of the 13 cabin crewmembers received minor injuries.

In its final report on the accident, the U.K. Air Accidents Investigation Branch (AAIB) said, "Ice had formed within the fuel system from water that occurred naturally in the fuel while the aircraft operated with low fuel flows over a long period. … Certification requirements with which the aircraft and engine fuel systems had to comply did not take account of this phenomenon, as the risk was unrecognized at that time."

Based on the findings of the accident investigation, the AAIB issued 18 safety recommendations, several of which called for actions to mitigate the risk of the buildup and sudden release of ice in aircraft fuel systems, a phenomenon the report called a "snowball."

Extreme Cold

The accident occurred at the conclusion of a British Airways flight from Beijing. The flight crew had received a 44-hour rest period before beginning the trip, and each pilot had taken about three hours of rest in the aircraft's crew rest area during the 10.5-hour flight.

The commander, 43, had 12,700 flight hours, including 8,450 hours in type. Two copilots were assigned to the flight. The senior copilot, 41, had 9,000 flight hours, including 7,000 hours in type. The other copilot, 35, had 5,000 flight hours, with 1,120 hours in type.

Before departing from China at 0209 coordinated universal time (UTC), the pilots discussed the need to monitor fuel temperature because of the unusually cold air temperatures forecast at altitude.

During the flight, the crew conducted a series of relatively gentle step climbs, using the autopilot's vertical speed mode to avoid large power increases that might disturb the passengers. The aircraft reached its final cruise altitude, Flight Level (FL) 400 (approximately 40,000 ft), over Sweden.

The lowest outside air temperature (OAT) en route was minus 74˚ C (minus 101˚ F), about 13˚ C (23˚ F) below average. The lowest OAT at which the aircraft's Rolls-Royce Trent 895-17 engines are certified to operate is minus 75˚ C (minus 103˚ F), the report said.

Despite the low OATs, however, the crew did not receive a low fuel temperature warning, which is generated when the fuel temperature nears the freezing point, or minus 47˚ C (minus 53˚ F) for the Jet A-1 in the 777's tanks. The lowest fuel temperature observed was minus 34˚ C (minus 29˚ F).

Transfer of Control

The commander flew the aircraft with the autopilot and autothrottles engaged during the descent from cruise altitude. The London weather was mild for the season, with visual meteorological conditions and a surface temperature of 10˚ C (50˚ F).

Air traffic control held the aircraft at FL 110 for five minutes before issuing radar vectors for the instrument landing system (ILS) approach to Runway 27L.

The approach was stabilized, and "at 1,000 ft AAL [above airfield level] and 83 seconds before touchdown, the

in the Fuel System

BY MARK LACAGNINA

aircraft was fully configured for the landing," the report said. "At approximately 800 ft AAL, the [senior] copilot took control of the aircraft in accordance with the briefed procedure."

The procedure called for transfer of control from the commander to the copilot if the copilot established visual contact with the runway before the aircraft reached decision height; otherwise, the commander would fly the missed approach. The copilot spotted the runway when the 777 was about 2.5 nm (4.6 km) from the threshold.

Shortly after the copilot took control, the autothrottle system commanded an increase in power from both engines. The engines initially responded, but engine pressure ratio (EPR) — the ratio of outlet pressure to intake pressure — for the right engine then decreased to 1.03, or just above flight idle, when the aircraft was at 720 ft AAL. Seven seconds later, left-engine EPR decreased to 1.02.

No Response

The aircraft was below 400 ft AAL when the crew noticed that airspeed was decreasing below the target of 135 kt and that the engines were producing only slightly more than flight idle thrust. These anomalies likely distracted the copilot from disengaging the autopilot at the intended altitude.

"The engines failed to respond to further demands for increased thrust from the autothrottle [system] and manual movement of the thrust levers to fully forward," the report said. "The airspeed reduced as the autopilot attempted to maintain the ILS glideslope."

Master caution and low-airspeed warnings were generated when airspeed dropped to 115 kt. "The airspeed stabilized for a short period; so, in an attempt to reduce drag, the commander retracted the flaps from flap 30 to flap 25," the report said.[1]

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Despite fuel and oxygen leaks, there was no fire.

After the brief stabilization, airspeed again began to decrease. As the 777 descended through 200 ft AAL, airspeed was about 108 kt. The stick shaker activated 10 seconds before touchdown, and the copilot pushed his control column forward.

"This caused the autopilot to disconnect as well as reducing the aircraft's nose-high pitch attitude," the report said. However, the aircraft was only 150 ft above the ground — too low to build sufficient airspeed. Just before impact, the copilot pulled back on his control column.

Descent rate was about 1,400 fpm and peak vertical acceleration was 2.9 g when the aircraft touched down in a grassy area about 330 m (1,083 ft) short of the runway threshold at 1242 UTC. The landing gear collapsed, and the 777 slid, turned right and came to a stop off the side of the runway threshold. Significant leakages of fuel and oxygen occurred, but there was no fire.

"The cabin crew supervised the emergency evacuation of the cabin, and all occupants left the aircraft via the slides, all of which operated correctly," the report said. "One passenger was seriously injured, having suffered a broken leg as a result of detached items from the right main landing gear penetrating the fuselage."

Unique Combination

The report said that an analysis of data from 35,000 flights by aircraft with Rolls-Royce engines showed that the 777's Beijing-to-London flight was unique in having combined the lowest overall cruise fuel flow, the highest overall approach fuel flow and the lowest fuel temperature during approach.

Average fuel flow to each engine during the 9.5-hour cruise portion of the flight was about 7,000 pounds per hour (pph). "From the top of descent to the time of being fully configured for landing, fuel flow had not exceeded 7,300 pph for either engine," the report said. Fuel temperature during the approach was minus 22° C (minus 8° F).

The autothrottle system commanded four thrust increases during the approach. "Of the four thrust commands, it was the second that resulted in the highest delivery of fuel flow, reaching a peak of 12,228 pph for the left engine and 12,032 pph for the right," the report said. "Peak fuel flows during the first and third thrust commands were lower, at about 9,500 pph and 9,000 pph, respectively."

The rollbacks occurred after the fourth thrust command. Fuel flows reached 8,300 pph for the right engine and 11,056 pph for the left engine before they gradually decreased below 6,000 pph, which was suitable to maintain near-flight-idle thrust. The fuel flows stabilized at these values despite attempts by the autothrottles and the pilots to apply full thrust.

Troublesome Ingredient

The aircraft had departed from Beijing with 79,000 kg (174,163 lb) of fuel. There was as much as 5 kg (11 lb) of water in the fuel — a normal amount, according to the report.

"Water is always present to some extent in aircraft fuel systems and may be introduced during refueling or by condensation from moist air which has entered the fuel tanks through the tank vent system," the report said. "The water in the fuel can take one of three forms: dissolved, entrained (suspended) or free."

As fuel cools, dissolved water is released from solution and takes the form of tiny entrained droplets. Further cooling causes the droplets to freeze as ice crystals that initially drift within the fuel and then adhere to each other and to cold surfaces — inside fuel pipes, for example. This type of ice is relatively soft and easily dislodged.

Free water is denser than fuel and settles as droplets or puddles to the bottoms of tanks, filters and stagnation points in the fuel-delivery system. The ice formed from free water is hard and clings to tank linings and other structures.

The fuel/oil heat exchangers in most large turbofan engines are designed to prevent ice from forming on sensitive downstream components such as fuel-metering units. Inside the 777's heat exchangers, fuel is pumped through more than 1,000 small tubes, around which hot engine oil flows (Figure 1). The fuel is warmed, and the oil is cooled.

Heat exchangers in large jet transports are sufficiently effective that icing inhibitors commonly are not added to the fuel. Although icing inhibitors are approved for use in 777s, none had been used when the accident aircraft was refueled.

Recipe for Snowballs

Extensive testing during the investigation showed that the combination of low fuel flow during cruise and the high fuel flow and low fuel temperature during approach fostered an accretion of soft ice in fuel pipes located within the engine pylons. The ice was released by the fuel flow spikes — and possibly turbulence, pitch changes and other factors — during the approach. It then flowed downstream and coated the fuel inlet faces inside the fuel/oil heat exchangers, blocking most of the fuel tubes.

Eleven months after the Heathrow accident, another 777-200ER was 9.5 hours into a flight from China to the United States when the right engine rolled back after power was increased for a step climb to FL 390. "The power reduction persisted for 23 minutes despite several autothrottle commands for increased thrust," the report said. Power was restored after the throttles were retarded to idle for descent. The U.S. National Transportation Safety Board determined that the incident was caused by ice that restricted fuel flow in the fuel/oil heat exchanger.

Fuel temperature when this incident occurred was minus 22° C, the same as when the accident occurred at Heathrow.

The photograph in Figure 1 shows fuel-inlet icing that occurred during post-accident tests. At the time, the heat exchangers on Rolls-Royce Trents differed from those on other engines in that the tubes protruded slightly from the inlet faces. This was found to have been a factor in the blockage. The engine manufacturer recently modified the fuel inlet faces so that they are smooth.

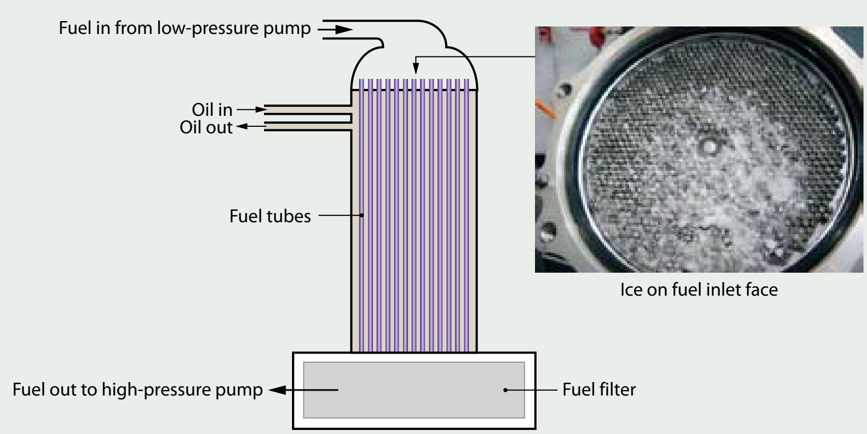
More Research Needed

Noting that most of what is known about fuel system icing is based on research conducted in the 1950s, the report said that the investigation of the Heathrow accident "has established that the risk from fuel system icing is complex and is dependent on a number of interactions that are not fully understood."

Accordingly, the AAIB called on the U.S. Federal Aviation Administration and the European Aviation Safety Agency to jointly conduct research on ice formation and release in aircraft fuel systems. The AAIB also recommended research on the feasibility of expanding the use of ice inhibitors in jet fuel.

This article is based on AAIB Aircraft Accident Report 1/2010, "Report on the Accident to Boeing 777-236ER, G-YMMM, at London Heathrow Airport on 17 January 2008." The report is available at <www.aaib.gov.uk/home/index.cfm>.

Boeing 777 Fuel/Oil Heat Exchanger



Sources: U.K. Air Accidents Investigation Branch and U.S. Federal Aviation Administration

Figure 1

Note

1. The flap retraction moved the touchdown point about 50 m (164 ft) forward, just enough to clear the ILS antenna. "The effects of contact with the ILS antenna are unknown, but such contact would probably have led to more substantial structural damage to the aircraft," the report said.