National Transportation Safety Board

Washington, D.C. 20594

Safety Recommendation

Date: March 11, 2009

In reply refer to: A-09-17 (Urgent) and -18

Ms. Lynne A. Osmus
Acting Administrator
Federal Aviation Administration
Washington, D.C. 20591

Two recent events involving failure to achieve commanded thrust on Boeing 777-200 airplanes powered by Rolls-Royce RB211 Trent 800 series engines[1] have caused the National Transportation Safety Board to be concerned about the potential for additional failures to occur. Testing following the two events has demonstrated that the Trent 800 series fuel/oil heat exchanger (FOHE)[2] can be overwhelmed by ice formed inside the 777 fuel feed system from normal amounts of water present in jet fuel. This condition can restrict the fuel supply to both engines, resulting in failures to achieve commanded thrust. Procedures intended to mitigate this condition are in place, but the Safety Board is concerned that they are insufficient to prevent additional occurrences and that, until the present FOHE design is replaced by one more tolerant to ice accumulation, additional failure events may occur and could result in accidents and injuries. Although the investigations of these events are ongoing, the Board believes that immediate action is required to address this safety issue.

On January 17, 2008, about 1242 coordinated universal time, a Boeing 777-236ER, registration G-YMMM, powered by two Trent 800 series engines, crashed short of the runway on final approach to Heathrow International Airport, London, United Kingdom. One passenger was seriously injured, and eight passengers and four flight crewmembers sustained minor injuries. The airplane was substantially damaged. The scheduled commercial passenger flight was operated by British Airways as flight BAW038 from Beijing, People's Republic of China, under an instrument flight rules flight plan. The flight crew reported that the airplane was configured for landing, with both autopilot and autothrottle systems engaged, when the No. 2 (right) engine power decreased below the commanded thrust. About 7 seconds later, the No. 1 (left) engine power also decreased. Both engines continued to produce thrust, but less than the thrust commanded. With reduced thrust, the airplane was unable to reach the runway and impacted the

[1] The Boeing 777-200 airplanes are the only airplanes powered by the Rolls-Royce RB211 Trent 800 series engines.

[2] The FOHE heats fuel routed through the main engine pump to prevent the accumulation of ice in the engine fuel metering system.

ground about 1,000 feet short of the runway. The 136 passengers aboard deplaned using the emergency slides.[3]

On November 26, 2008, about 1930 coordinated universal time, a Boeing 777-200ER, registration N862DA, powered by two Trent 800 series engines, experienced a single-engine rollback[4] while in cruise flight at flight level (FL) 390 (about 39,000 feet) en route from Pudong International Airport, Shanghai, People's Republic of China, to Atlanta-Hartsfield International Airport, Atlanta, Georgia. No injuries were reported. The scheduled commercial passenger flight was operated by Delta Air Lines as flight 18 under the provisions of 14 *Code of Federal Regulations* Part 121 under an instrument flight rules flight plan. The flight crewmembers reported that the airplane's autopilot and autothrottle systems were engaged, when, about 1 hour after two maximum climb thrust routine step climbs were performed, they detected that the No. 2 engine was operating below the commanded thrust level. The flight crew descended the airplane to FL310 and performed the 777 engine response non-normal checklist.[5] The engine recovered and responded normally, and the flight continued to Atlanta, where it landed without further incident.[6]

Boeing 777/Trent 800 Series Fuel Delivery and Control System

The Trent 800 series engine draws fuel into the main engine pump, which then routes the fuel to an FOHE. The FOHE heats the fuel to prevent the accumulation of ice in the engine fuel metering system. The heated fuel passes through a fuel metering unit, which regulates the fuel flowing to the engine combustor based on a thrust demand signal received from the electronic engine control (EEC).

The FOHE is designed to both melt ice being carried by the fuel[7] and cool hot engine oil. Inside the FOHE, fuel enters 1,180 small-diameter steel tubes that protrude from the inlet face and extend the length of the unit. FOHEs are designed with this large number of tubes to permit maximum exposure to heat from the hot engine oil: The tubes, and the fuel inside them, are warmed by the hot oil that enters the FOHE just below the inlet face, flows to the bottom of the housing, and then passes across the tubes.

British Airways Flight BAW038

Postaccident inspections of the British Airways airplane found that the EECs of both engines correctly demanded fuel flow increases in response to autothrottle and flight crew

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[3] The United Kingdom Air Accident Investigation Branch (AAIB) is investigating this accident. The National Transportation Safety Board is participating as a representative of the State of Manufacture under the provisions of International Civil Aviation Organization Annex 13. More information about this event can be found on the AAIB's website at <http://www.aaib.gov.uk/publications/interim_reports/boeing_777_236er__g_ymmm.cfm>.

[4] A rollback is an uncommanded reduction in thrust.

[5] Boeing added the engine response checklist to the 777 non-normal procedures following the British Airways accident.

[6] The description of this incident, DCA09IA014, can be found on the Safety Board's website at <http://www.ntsb.gov/ntsb/query.asp>.

[7] Normal levels of water in jet fuel are less than 100 parts per million (ppm), and fuel with up to 260 ppm of water is typically used in component testing.

commands and that the engine fuel metering units properly responded to EEC demands. However, the fuel flows delivered to the engines were lower than the volumes demanded. Specifically, when the flight crew pushed the throttle levers to the full forward position, the EEC of each engine requested fuel volume in excess of 30,000 pounds per hour (pph), but the actual flows were 5,000 pph to the No. 1 engine and 6,000 pph to the No. 2 engine. These findings indicate that rollbacks resulted from restricted fuel flow to each engine.

Damage characteristic of cavitation[8] was found in both main engine pumps. Cavitation damage at this location indicates that the fuel components downstream of the main engine pumps were demanding more fuel than was supplied. The United Kingdom Air Accident Investigation Branch (AAIB) concluded that the rollbacks resulted from nonmechanical fuel flow restrictions upstream of the high-pressure stage of each main engine pump.

Postaccident Fuel System Testing

Extensive research and tests were conducted by Rolls-Royce and Boeing, under the direction of the AAIB and with participation by the Safety Board, to understand the nature and location of the fuel flow restriction. Ice in the fuel was considered because ice can form from water molecules normally present in jet fuel. Research has shown that water molecules entrained in jet fuel will begin to form ice crystals as the fuel cools below 0° C.[9] This research also determined that ice crystals suspended in fuel can begin to adhere to their surroundings and accrete at fuel temperatures between -9° C and -11° C (temperatures often reached on flights that are not exposed to unusually cold conditions). Heat exchangers and filtration systems, like the FOHE in this case, are included in aircraft fuel systems to prevent ice from blocking or otherwise affecting fuel flow to engines.

AAIB-directed laboratory testing at Boeing confirmed that at fuel temperatures between -5° C and -20° C, ice crystals tend to form and adhere to fuel component surfaces. The British Airways thrust rollbacks occurred at about -22° C. Tests showed that ice crystals formed solely from entrained water can restrict fuel passages and that, under certain conditions, substantial amounts of ice will accumulate on the inner surfaces of the fuel feed system. This ice can be released during high fuel flows, such as those that occurred during the final approach of the British Airways flight. When a sufficient amount of ice is released, ice can enter the engine fuel system and collect in a mass on the inlet face of the FOHE. (See the following figure.) The testing demonstrated that, after high fuel flows, the FOHE can be presented with ice concentrations well beyond the amounts for which the engine fuel system was certified to withstand. Further, ice in sufficient concentrations could block a large enough portion of the FOHE inlet face to restrict fuel flow so that the thrust demanded could not be supported and a rollback could occur.

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[8] Cavitation is the vacuum created when the discharge capacity of the pump exceeds the replacement in the suction line.

[9] For more information, see SAE International Aerospace Information Report 790 Revision C, August 2006.

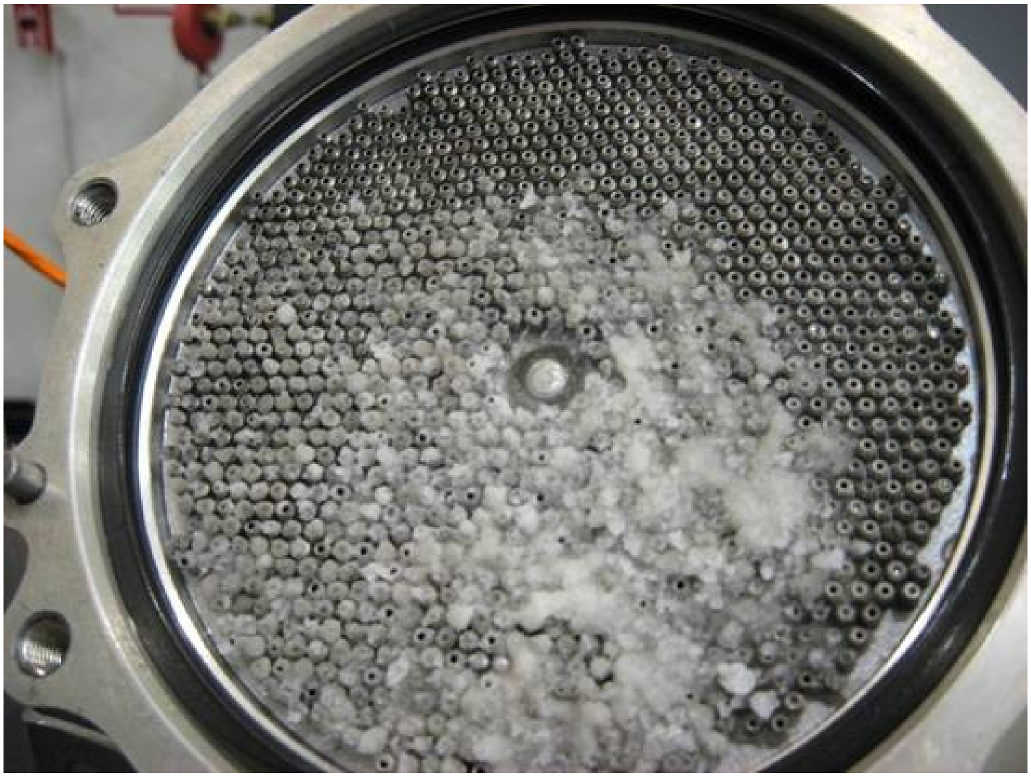

Figure. Ice on the inlet face of a Rolls-Royce RB211 Trent 800 series FOHE.

Testing also found that reducing the volume of the fuel flow through the FOHE can clear ice from the face of the FOHE within a few seconds. A reduced fuel flow through the FOHE reduces the amount of fuel available for oil-to-fuel heat transfer in the FOHE, and this causes more heat from the oil to be retained. Heat from the oil then spreads further up the FOHE tubes to the face and to the ends of the tubes protruding from the face, melting the ice collected on the face and tubes. In fact, fuel volume tests showed that temporarily reducing fuel flows by moving the power levers to minimum idle will melt ice that may be blocking the FOHE.

Operational Changes in Response to the British Airways Accident

On September 12, 2008, the AAIB published its second interim report on the British Airways accident and included several safety recommendations.[10] In conjunction with the report, Boeing issued a flight crew operations manual bulletin addressing the prevention of long-term ice accumulation in the Trent 800 series engines fuel system during extreme cold operations.[11] The bulletin instructed flight crews to follow specific refueling instructions before long-range flights when the ground fuel temperature was below 0° C. The bulletin also included a cold fuel operations supplementary procedure that specified flight crews should perform an ice accumulation clearing procedure 3 hours before descent if the fuel temperature was below -10° C by briefly increasing the thrust of each engine to maximum climb thrust. Finally, based on the

[10] The report is available online at <http://www.aaib.gov.uk/publications/interim_reports/boeing_777_236er__g_ymmm.cfm>.

[11] See Boeing Flight Crew Operations Manual Bulletin No. TBC-11, published September 29, 2008.

results of the tests described above, Boeing added an engine response non-normal procedure to the airplane flight manual that instructed flight crews to temporarily reduce fuel flows by moving the power levers to minimum idle to clear ice from the FOHEs if the engines did not reach commanded thrust after performing the cold fuel operations supplementary ice-clearing procedure or after operating at a high-thrust setting. The manual changes were mandated by the Federal Aviation Administration in Airworthiness Directive 2008-19-04, issued September 29, 2008.

Delta Air Lines Flight 18

Analysis of the flight data recorder (FDR) data downloaded from the Delta Air Lines airplane and an evaluation of the No. 2 main engine pump confirmed that the flight experienced a rollback similar to the dual engine rollback that occurred during the British Airways accident flight.[12] In addition, FDR data allowed investigators to positively establish that the fuel flow to the engine was restricted at the FOHE during the event.

FDR data indicate that, after high fuel flows were commanded during a routine maximum climb thrust step climb, a 30° C increase in the No. 2 engine oil temperature occurred and persisted for 55 minutes, while the oil in the other engine experienced no such increase in temperature. During that time, the airplane performed a second routine step climb, followed by 35 minutes of cruise flight, during which the rollback occurred.[13] After the rollback, the flight crew descended and reduced engine power (in accordance with Boeing's engine response non-normal procedure), and the engine recovered. However, the response was delayed due to the flight crew's confusion about the title of the procedure. After the recovery, the oil temperature in the No. 2 dropped and experienced normal variations, varying as the other engine did, for the remainder of the flight.

This period of elevated oil temperature indicated that the effectiveness of the oil cooling function of the FOHE was reduced before and during the rollback. A blockage of the FOHE will result in an increase in engine oil temperature because decreased fuel flow through the FOHE reduces the amount of fuel available to cool the engine oil. When the No. 2 engine fuel flow returned to normal after the blockage cleared, the engine oil temperature dropped, indicating that the FOHE oil cooling effectiveness was restored. Therefore, the oil temperature excursion that occurred during the Delta event is evidence that the FOHE was restricted for about 55 minutes before and during the rollback.

The Safety Board also notes that, although the British Airways airplane was operated for long periods of cruise flight at unusually low temperatures, the Delta flight was not. In fact, the British Airways flight experienced fuel temperatures as low as -34° C, whereas the lowest measured fuel temperature during the Delta Air Lines flight was -22° C; both the British Airways

[12] The data show that fuel flow decreased to 5,000 pph for 23 minutes, despite continuous autothrottle requests for increased fuel flow. In addition, severe cavitation marks were found in the main engine pump, indicating that for an extended period, fuel components downstream of the high-pressure pump were demanding more fuel than was supplied.

[13] Before the rollback, there was likely ice on the face of the FOHE that resulted in a drop in FOHE effectiveness, but it was not enough to cause a thrust rollback. The rollback likely occurred after additional ice accumulated at the face of the FOHE, increasing the blockage.

and the Delta rollbacks occurred when the measured fuel temperature was about -22° C. Critical fuel icing temperatures, those between -5° C and -20° C, are commonly encountered by long-range transport airplanes. Therefore, the Safety Board concludes that there is risk of ice crystal blockage of FOHEs on Trent 800 series engines installed on 777-200s at temperatures commonly encountered by long-range transport airplanes.

Revised Operational Changes Following the Delta Event

Following the Delta event, Boeing revised its operating procedures to require that the cold fuel operations supplemental procedure be performed 2 hours before descent rather than 3 hours to reduce the time available after the procedure for the buildup of ice. In addition, flight crews are now required to retard the throttles to minimum idle speed for 30 seconds during initial descent. Because the flight crew on the Delta flight was confused about the applicability of the engine response non-normal procedure and to ensure that the procedure is used when needed, the procedure was modified such that it is accomplished if an engine fails to reach commanded thrust and fuel system icing is suspected.

The Delta event shows that the original procedural changes were insufficient to prevent the occurrence of FOHE-related failures to achieve commanded thrust. The Safety Board also notes that if the modification of the ice-clearing procedure had been in place before the Delta event, the procedure likely would not have prevented the single-engine rollback because it occurred just over 3 hours before the top of descent. Although the engine response non-normal procedure may be effective in clearing ice accumulations from the FOHE face and in restoring normal operation, it is not an acceptable substitute for immediate development of an engineering solution to prevent the occurrence. Failures to achieve commanded thrust expose airplanes to unacceptable hazards, even if engine thrust can be recovered. The Safety Board is especially concerned that ice might accumulate on the FOHE during critical flight phases, such as during approach, when reducing power as required in the procedure could result in a dangerous loss of altitude. In fact, loss of altitude can be dangerous at any phase of flight, in part because it could expose an airplane to rising terrain and hazardous weather. In addition, a partial blockage of the FOHE during approach could result in the inability to achieve maximum thrust power, which would be hazardous should a missed approach or runway obstruction require a go-around.

The AAIB and Safety Board investigations of these events are ongoing; however, tests have shown that ice can restrict fuel flow at the Trent 800 series engine FOHE and result in rollbacks or other failures to achieve commanded thrust when high-fuel flows are commanded. The British Airways event demonstrated that this condition can restrict the fuel supply to both engines, resulting in dual engine rollback. Current operational mitigations, which require power reductions, may not prevent additional occurrences at critical flight altitudes when reducing power would require an unacceptable decrease in altitude or when power must be immediately available for a go-around. Therefore, until the current FOHEs are replaced by FOHEs more tolerant to ice accretion, additional failures to achieve commanded thrust could occur and could result in a serious accident and, possibly, injuries and deaths.

The Safety Board is aware that on February 23, 2009, Rolls-Royce issued a memo to operators stating its intent to redesign the FOHE on Trent 800 series engines. The Safety Board is encouraged by this proposed permanent solution; however, because the adequacy of the design, the speed and appropriateness of the FOHE testing, and the installation of the redesigned FOHE are critical to the flight safety of Boeing 777-200 airplanes powered by Rolls-Royce RB211 Trent 800 series engines, the Safety Board believes that the FAA and European Aviation Safety Agency should take an oversight role and direct the development and installation of the new FOHE design.

Therefore, the National Transportation Safety Board recommends that the Federal Aviation Administration:

> Require that Rolls-Royce redesign the RB211 Trent 800 series engine fuel/oil heat exchanger (FOHE) such that ice accumulation on the face of the FOHE will not restrict fuel flow to the extent that the ability to achieve commanded thrust is reduced. (A-09-17) (Urgent)
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> Once the fuel/oil heat exchanger (FOHE) is redesigned and approved by certification authorities, require that operators of Boeing 777-200 airplanes powered by Rolls-Royce RB211 Trent 800 series engines install the redesigned FOHE at the next scheduled maintenance opportunity or within 6 months after the revised FOHE design has been certificated, whichever comes first. (A-09-18)

The Safety Board has issued two related safety recommendations to the European Aviation Safety Agency.

In response to the recommendations in this letter, please refer to Safety Recommendations A-09-17 (Urgent) and -18. If you would like to submit your response electronically rather than in hard copy, you may send it to the following e-mail address: correspondence@ntsb.gov. If your response includes attachments that exceed 5 megabytes, please e-mail us asking for instructions on how to use our Tumbleweed secure mailbox procedures. To avoid confusion, please use only one method of submission (that is, do not submit both an electronic copy and a hard copy of the same response letter).

Acting Chairman ROSENKER and Members HERSMAN, HIGGINS, and SUMWALT concurred with these recommendations.

[Original Signed]
By: Mark V. Rosenker
Acting Chairman