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Thank you for downloading this collection of AAIB documents from the investigation into the 17 January 2008 crash of a British Airways 777 at London's Heathrow Airport.

Accident Data

AAIB Reference Number: EW/C2008/01/01
Aircraft Type and Registration: Boeing 777-236, G-YMMM
No & Type of Engines: 2 Rolls-Royce RB211 Trent 895-17 turbofan engines
Year of Manufacture: 2001
Date & Time: 17 January 2008 at 1243 hrs
Location: RWY 27L, London Heathrow Airport
Type of Flight: Commercial Air Transport (passenger)
Persons on Board: Crew – 16, Passengers - 136
Injuries: Crew - 4 (minor); Passengers - 1 (serious), 8 (minor)
Nature of Damage: Aircraft Damaged Beyond Economic Repair

Included in this File: This file includes the contents of the key updates issued by the AAIB prior to the publication of the final accident report.

Additional Information: Additional information about this accident, including links to AirSafe.com podcasts and other content related to this investigation, is located at http://777.airsafe.org/.

Podcast: The podcast *The Conversation at AirSafe.com* at http://podcast.airsafe.org/ highlights current online issues of high interest to airline passengers and the airline safety community. This free podcast is available on iTunes and other major podcast providers. The podcast information page is at http://podcast.airsafe.org

The AirSafe.com News: For information about changes to the site or additions to the podcast, or to sign up to get notified of such changes or additions, please visit the AirSafe.com News site at http://fatalevents.blogspot.com/.

Feedback: You may send comments, questions, interview requests, or suggestions to the author through the feedback form at http://feedback.airsafe.org/.

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Initial Report Provided by the Air Accidents Investigation Branch on 18 January 2008

Title: Accident to Boeing 777-236, G-YMMM at London Heathrow Airport on 17 January 2008
Source: http://www.aaib.dft.gov.uk/latest_news/accident__heathrow_17_january_2008___initial_report.cfm
Date Downloaded: 21 January 2008

Following an uneventful flight from Beijing, China, the aircraft was established on an ILS approach to Runway 27L at London Heathrow. Initially the approach progressed normally, with the Autopilot and Autothrottle engaged, until the aircraft was at a height of approximately 600 ft and 2 miles from touch down. The aircraft then descended rapidly and struck the ground, some 1,000 ft short of the paved runway surface, just inside the airfield boundary fence. The aircraft stopped on the very beginning of the paved surface of Runway 27L. During the short ground roll the right main landing gear separated from the wing and the left main landing gear was pushed up through the wing root. A significant amount of fuel leaked from the aircraft but there was no fire. An emergency evacuation via the slides was supervised by the cabin crew and all occupants left the aircraft, some receiving minor injuries.

The AAIB was notified of the accident within a few minutes and a team of Inspectors including engineers, pilots and a flight recorder specialist deployed to Heathrow. In accordance with the established international arrangements the National Transportation Safety Board (NTSB) of the USA, representing the State of Design and Manufacture of the aircraft, was informed of the event. The NTSB appointed an Accredited Representative to lead a team from the USA made up of investigators from the NTSB, the FAA and Boeing. A Boeing investigator already in the UK joined the investigation on the evening of the event, the remainder of the team arrived in the UK on Friday 18th January. Rolls-Royce, the engine manufacturer is also supporting the investigation, an investigator having joined the AAIB team.

Activity at the accident scene was coordinated with the Airport Fire and Rescue Service, the Police, the British Airports Authority and British Airways to ensure the recovery of all relevant evidence, to facilitate the removal of the aircraft and the reinstatement of airport operations.

The flight crew were interviewed on the evening of the event by an AAIB Operations Inspector and the Flight Data Recorder, Cockpit Voice Recorder and Quick Access Recorder were removed for replay. The CVR and FDR have been successfully downloaded at the AAIB laboratories at Farnborough and both records cover the critical final stages of the flight. The QAR was downloaded with the assistance of British Airways and the equipment manufacturer. All of the downloaded information is now the subject of detailed analysis.

Examination of the aircraft systems and engines is ongoing.

Initial indications from the interviews and Flight Recorder analyses show the flight and approach to have progressed normally until the aircraft was established on late finals for Runway 27L. At approximately 600 ft and 2 miles from touch down, the Autothrottle demanded an increase in thrust from the two engines but the engines did not respond. Following further demands for increased thrust from the Autothrottle, and subsequently the flight crew moving the throttle levers, the engines similarly failed to respond. The aircraft speed reduced and the aircraft descended onto the grass short of the paved runway surface.

The investigation is now focused on more detailed analysis of the Flight Recorder information, collecting further recorded information from various system modules and examining the range of aircraft systems that could influence engine operation.

Accident Update Provided by the Air Accidents Investigation Branch on 23 January 2008

Title: Accident to a Boeing 777-236, G-YMMM, on 17 January 2008 - Initial Report Update 23 January 2008
Source:
http://www.aaib.dft.gov.uk/latest_news/accident_to_boeing_777_236__g_ymmm__at_heathrow_airport_on_17_january_2008___initial_report_update.cfm
Date Downloaded: 24 January 2008

Since the issue of the Air Accidents Investigation Branch (AAIB) 1st Preliminary Report on Friday 18 January 2008 at 1700 hrs, work has continued on all fronts to identify why neither engine responded to throttle lever inputs during the final approach. The 150 tonne aircraft was moved from the threshold of Runway 27L to an airport apron on Sunday evening, allowing the airport to return to normal operations.

The AAIB, sensitive to the needs of the industry including Boeing, Rolls Royce, British Airways and other Boeing 777 operators and crews, is issuing this update to provide such further factual information as is now available.

As previously reported, whilst the aircraft was stabilised on an ILS approach with the autopilot engaged, the autothrust system commanded an increase in thrust from both engines. The engines both initially responded but after about 3 seconds the thrust of the right engine reduced. Some eight seconds later the thrust reduced on the left engine to a similar level. The engines did not shut down and both engines continued to produce thrust at an engine speed above flight idle, but less than the commanded thrust.

Recorded data indicates that an adequate fuel quantity was on board the aircraft and that the autothrottle and engine control commands were performing as expected prior to, and after, the reduction in thrust.

All possible scenarios that could explain the thrust reduction and continued lack of response of the engines to throttle lever inputs are being examined, in close cooperation with Boeing, Rolls Royce and British Airways. This work includes a detailed analysis and examination of the complete fuel flow path from the aircraft tanks to the engine fuel nozzles.

Further factual information will be released as and when available.

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Air Accidents Investigation Branch

Department for Transport

AAIB Bulletin S1/2008 *SPECIAL*

ACCIDENT

Aircraft Type and Registration:	Boeing 777-236 ER, G-YMMM	
No & Type of Engines:	2 Rolls-Royce RB211 Trent 895-17 turbofan engines	
Year of Manufacture:	2001	
Date & Time (UTC):	17 January 2008 at 1242 hrs	
Location:	Runway 27L, London Heathrow Airport	
Type of Flight:	Commercial Air Transport (Passenger)	
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Injuries:	Crew - 4 (Minor)	Passengers - 1 (Serious) 8 (Minor)
Nature of Damage:	Aircraft damaged beyond economic repair	
Commander's Licence:	Airline Transport Pilot's Licence	
Commander's Age:	43 years	
Commander's Flying Experience:	12,700 hours (of which 8,500 hours were on type) Last 90 days - 85 hours Last 28 days - 52 hours	
Information Source:	Inspectors Investigation All times in this report are UTC	

This bulletin contains facts which have been determined up to the time of issue. This information is published to inform the aviation industry and the public of the general circumstances of accidents and must necessarily be regarded as tentative and subject to alteration or correction if additional evidence becomes available.

The investigation

The Air Accidents Investigation Branch (AAIB) was informed of the accident at 1251 hrs on 17 January 2008 and the investigation commenced immediately. The Chief Inspector of Air Accidents has ordered an Inspector's Investigation to be conducted into the circumstances of this accident under the provisions of The Civil Aviation (Investigation of Air Accidents and Incidents) Regulations 1996.

In accordance with established international arrangements, the National Transportation Safety Board (NTSB) of the USA, representing the State of Design and Manufacture of the aircraft, has appointed an Accredited Representative to participate fully in the investigation. The NTSB Accredited Representative is supported by a team which includes additional investigators from the NTSB, the Federal Aviation Administration and Boeing; Rolls-Royce, the engine manufacturer, is also participating fully in the investigation. British Airways, the operator, is cooperating with the investigation and providing expertise as required and the CAA and the EASA are being kept informed of developments.

Because of the interest within the aviation industry, and amongst the travelling public, it is considered appropriate to disseminate the results of the initial investigation as soon as possible. This Bulletin is in addition to the Initial Report, published on 18 January 2008, and a subsequent update published on 23 January 2008. As the investigation has developed, additional data has been derived from non-volatile memory within specific systems of the aircraft. This has allowed previously reported data to be refined.

One Safety Recommendation has been made.

History of the flight

The aircraft was on a scheduled flight from Beijing, China, to London (Heathrow) and departed Beijing at 0209 hrs; the flight was uneventful until the later stages of the approach into Heathrow. During the descent, from Flight level (FL) 400 the aircraft entered the hold at Lamborne at FL110; it remained in the hold for approximately five minutes, during which time it descended to FL90. The aircraft was radar vectored for the ILS approach to Runway 27L at Heathrow and subsequently stabilised on the ILS with the autopilot and autothrottles engaged. At 1,000 ft the aircraft was fully configured for the landing, with the landing gear down and flap 30 selected. The total fuel on board was indicating 10,500 kg, which was distributed almost equally between the left and right main fuel tanks, with a minor imbalance of about 300 kg. The fuel cross-feed valves indicated that they were closed and they had not been operated during the flight. The first officer took control for the landing at a height of approximately 780 ft, in accordance with the briefed procedure, and shortly afterwards the autothrottles commanded an increase in thrust from both engines. The engines initially responded but, at a height of about 720 ft, the thrust of the right engine reduced. Some seven seconds later, the thrust reduced on the left engine to a similar level. The engines did not shut down and both engines continued to produce thrust at an engine speed above flight idle, but less than the commanded thrust. The engines failed to respond to further demands for increased thrust from the autothrottles, and subsequent movement of the thrust levers fully forward by the flight crew. The airspeed reduced as the autopilot attempted to maintain the ILS glide slope and by 200 ft the airspeed had reduced to about 108 kt. The autopilot disconnected at approximately 175 ft, the aircraft descended rapidly and its landing gear made contact with the ground some 1,000 ft short of the paved runway surface just inside the airfield boundary fence. During the impact and short ground roll the nose gear collapsed, the right main landing gear separated from the aircraft and the left main landing gear was pushed up through the wing. The aircraft came to rest on the paved surface in the undershoot area of Runway 27L. A significant amount of fuel leaked from the aircraft after it came to rest, but there was no fire. The cabin crew supervised the emergency evacuation and all occupants left the aircraft via the slides, all of which operated correctly; eight of the passengers received minor injuries and one suffered a broken leg.

Aircraft information

The aircraft was serviceable on departure from Beijing and there were no relevant reported defects. It departed with 79,000 kg of Jet A-1 fuel on board, and the planned arrival fuel at London (Heathrow) was 6,900 kg.

Weather

The recorded weather at Beijing, prior to departure, indicated no significant weather and a surface temperature of -7ºC.

The aircraft's flight plan required it to climb initially to 10,400 m (FL341) before descending back to 9,600 m (FL315) at POLHO (on the border between China and Mongolia) because of 'Extreme Cold'. However, to accommodate a request from ATC the crew accepted a climb to a cruise altitude of 10,600 m (FL348), and closely monitored the fuel temperature. The ambient temperature at FL348 was approximately -65ºC and the associated total air temperature[1] (TAT) was -37ºC. Shortly after crossing the Ural mountains, the aircraft climbed to FL380. There was a region of particularly cold air, with ambient temperatures as low as -76ºC, in the area between the Urals and Eastern Scandinavia. The Met Office described the temperature conditions during the flight as 'unusually low compared to the average, but not exceptional'. The lowest TAT recorded during the flight was -45ºC, and the minimum recorded fuel temperature was -34ºC. The fuel temperature in flight must not reduce to a temperature colder than at least 3ºC above the fuel freezing point of the fuel being used. The specified freezing point for Jet A-1 fuel is -47ºC; analysis of fuel samples taken after the accident showed the fuel onboard the aircraft had an actual freezing point of -57ºC.

On arrival at Heathrow, the surface wind was from 210º at 10 kt, the visibility was greater than 10 km, the cloud was scattered at 800 ft and broken at 1,000 ft, the surface temperature was +10ºC and the dew point was +8ºC. The flight crew reported that they were visual with the runway at about 1,000 ft agl.

Recorded data

The aircraft was fitted with a Digital Flight Data Recorder (DFDR), a Cockpit Voice Recorder (CVR) and a Quick Access Recorder (QAR). The CVR and DFDR were successfully downloaded at the AAIB laboratories at Farnborough and both records covered the critical final stages of the flight. The QAR was downloaded with the assistance of British Airways and the equipment manufacturer. Data from the non-volatile memory of various systems were also available.

The recorded data indicates that there were no anomalies in the major aircraft systems. The autopilot and the autothrottle systems behaved correctly and the engine control systems were providing the correct commands prior to, during, and after, the reduction in thrust.

Engineering examination

The aircraft was recovered from the accident site to a

Footnote

[1] TAT is measured by a specially designed temperature probe, on the surface of the aircraft, that brings the air to rest causing an adiabatic increase in temperature. TAT is higher than static (or ambient) air temperature and is the value to which the fuel temperature will drift.

secure location for detailed examination. There were no indications of any pre-existing problems with any of the aircraft systems.

During the impact the right main landing gear separated from the aircraft rupturing the rear right wall of the centre fuel tank. The two front wheels of the right main landing gear broke away and struck the rear right fuselage penetrating the cabin at seat height adjacent to rows 29/30. Additionally, the right main landing gear damaged the wing-to-body fairing and penetrated the rear cargo hold, causing damage to, and leakage from, the passenger oxygen cylinders.

The engines, their control systems and the fuel system were the focus of a detailed examination.

Engines

Examination of the engines indicated no evidence of a mechanical defect or ingestion of birds or ice.

Data, downloaded from the Electronic Engine Controllers (EECs) and the QAR, revealed no anomalies with the control system operation. At the point when the right engine began to lose thrust the data indicated that the right engine EEC responded correctly to a reduction in fuel flow to the right engine, followed by a similar response from the left EEC when fuel flow to the left engine diminished. Data also revealed that the fuel metering valves on both engines correctly moved to the fully open position to schedule an increase in fuel flow. Both fuel metering units were tested and examined, and revealed no pre-existing defects.

Both engine low pressure fuel filters were clean. The fuel oil heat exchangers (FOHE) in both engines were free of blockage. The right FOHE was clear of any debris, however the left engine FOHE had some small items of debris on its fuel inlet bulkhead. The high pressure filters were clean. The variable stator vane controllers and the fuel burners were examined and found to be satisfactory.

Detailed examination of both the left and right engine high pressure fuel pumps revealed signs of abnormal cavitation on the pressure-side bearings and the outlet ports. This could be indicative of either a restriction in the fuel supply to the pumps or excessive aeration of the fuel. The manufacturer assessed both pumps as still being capable of delivering full fuel flow.

Fuel system

Several fuel samples were taken from the fuel tanks, pipe lines and filter housings prior to the examination of the fuel system and these are currently being examined at specialist laboratories. Initial results confirm that the fuel conforms to Jet A-1 specifications and that there were no signs of contamination or unusual levels of water content. A sump sample taken from the left and right main fuel tanks shortly after the accident revealed no significant quantities of water. Samples from the centre tank had been contaminated by fire fighting foam and hydraulic fluid: this contamination was a consequence of the rupture of the right rear wall of the centre tank.

A detailed examination of the fuel tanks revealed no pre-existing defects except for a loose union in the left main tank at its inner wall; the union formed part of the centre tank to left main tank fuel scavenge line. Some small items of debris were discovered in the following locations:

1. Right main tank – a red plastic sealant scraper approximately 10 cm x 3 cm under the suction inlet screen.

2. Left main tank, water scavenge inlet - a piece of black plastic tape, approximately 5 cm square; a piece of brown paper of the same size and shape, and a piece of yellow plastic.

3. Right centre tank override pump – a small piece of fabric or paper found in the guillotine valve of the pump housing.

4. Left centre tank water scavenge jet pump – small circular disc, 6 mm in diameter, in the motive flow chamber.

The relevance of this debris is still being considered. Examination of the fuel surge tanks showed no signs of blockage of the vent scoops and flame arrestors. Neither pressure relief valve had operated; the relief valves were tested and found to be operate normally.

The fuel boost pumps, and their associated low pressure switches, were tested and examined and found to be satisfactory. A pressure and suction test of the engine fuel feed manifold, from the fuel boost pumps to the engine, did not reveal any significant defects. Similarly, a visual examination of the fuel feed lines, using a boroscope, did not reveal any defects or restrictions. A test of the fuel quantity processor unit (FQPU) was satisfactory and its non-volatile memory did not reveal any defects stored prior to the accident. A test of the fuel temperature probe, located in the left main fuel tank, was satisfactory.

Maintenance

The aircraft's fuel tanks were last checked for water[2] in the fuel on the 15 January 2008 at Heathrow; this was prior to its refuelling for the outboard sector to Beijing.

Access by maintenance personnel, to the aircraft's fuel tanks, had last taken place during maintenance activity in 2005. The last scheduled maintenance activity on the aircraft was on the 13 December 2007.

Spar valves

On examination, both of the engine spar valves were found to be OPEN, allowing the fuel leak evident at the accident site.

The spar valves are designed to shut off the fuel supply to the engines following the operation of the fuel control switches or after operation of the fire handles in the cockpit. Their function is to cut off the fuel flow to the engine in the event of an engine fire or an accident. Each valve has two separate electrical wire paths which can be used to supply power to shut the valve; the first is via a run/cut-off relay, controlled by the fuel control switches, the other is directly from the fire handles.

The wiring on G-YMMM was as originally designed and manufactured, and such that when the fire handle was operated, it isolated the power supply to the run/cut-off relay. When tested, the run/cut-off relays for the left and right engines were still in the valve OPEN position, despite the fuel control switches being set to cut-off. The fire handles had also been pulled and the engine fire bottles had been fired. Therefore the fire handles had been operated prior to the fuel control switches.

The left spar valve circuit breaker (CB) had been tripped. This was due to damaged wiring to the valve as a result of the left main landing gear being forced upward through the conduit at the initial impact. The tripping of the CB meant there was no means of electrically closing the left spar valve. Similar damage was also evident to the right spar valve wiring, however, in this instance the CB had remained set.

Footnote

[2] A check for water in the fuel tank is carried out by draining fluid from the sump drains located at the lowest point of each fuel tank in its 'on-ground' attitude.

Examination and tests of the wiring identified that, in the case of the right engine, the valve CLOSE wire from the run/cut-off relay was still continuous. This could have allowed the valve to operate had the fuel switch been operated before the fire handle.

Boeing had issued a Service Bulletin (SB 777-28-0025) which advised the splicing together of the wires for the fuel control switches and the fire handles to avoid the need to sequence their operation. An FAA airworthiness directive requires this SB to be completed by July 2010. This had not yet been incorporated on G-YMMM; however, had it been incorporated, the right spar valve should have closed when the fuel control switch was operated.

The evacuation checklist for the Boeing 777, issued by Boeing, shows operation of the fuel control switches to cut-off prior to operation of the fire handles. This sequence allows for both CLOSE paths to the spar valve to be exploited and increases the likelihood that the spar valves close before electrical power to the spar valves is isolated. However, if the fire handle is operated first, then only a single path is available.

The operator's evacuation checklist, for which Boeing had raised no technical objection, required the commander to operate the fuel control switches whilst the first officer operated the fire handles, this was in order to reduce the time required to action the checklist. These actions were carried out independently, with no measure in place to ensure the correct sequencing. The evacuation drill was placarded on the face of the control column boss, directly in front of each pilot.

An evacuation checklist with the division of independent tasks between the crew leaves a possibility that the fire handles could be operated before the fuel control switches which, with fire handle to spar valve wire damage, could leave the engine fuel spar shut-off valves in an OPEN position. This occurred in this accident, and resulted in the loss of fuel from the aircraft. This was not causal to the accident but could have had serious consequences in the event of a fire during the evacuation. It is therefore recommended that:

Safety Recommendation 2008-009

Boeing should notify all Boeing 777 operators of the necessity to operate the fuel control switch to cut-off prior to operation of the fire handle, for both the fire drill and the evacuation drill, and ensure that all versions of its checklists, including electronic and placarded versions of the drill, are consistent with this procedure.

Boeing has accepted this recommendation. On 15 February 2008 Boeing issued a Multi Operator Message, which advised operators to ensure that "evacuation and engine fire checklists specifiy that the fuel control switches are placed in the cut-off position prior to the operation of the fire handles". This advice only relates to those aircraft that have not had Boeing SB 777-28-0025 incorporated. Boeing also recommends that operators review their engine fire and evacuation checklists (Quick Reference Handbook, Electronic and Placard) to make sure that they are consistent with this advice.

Continuing investigation

Investigations are now underway in an attempt to replicate the damage seen to the engine high pressure fuel pumps, and to match this to the data recorded on the accident flight. In addition, comprehensive examination and analysis is to be conducted on the entire aircraft and engine fuel system; including the modelling of fuel flows taking account of the environmental and aerodynamic effects.

Published February 2008

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Air Accidents Investigation Branch

Department for Transport

AAIB Bulletin S3/2008 *SPECIAL*

ACCIDENT

Aircraft Type and Registration:	Boeing 777-236 ER, G-YMMM
No & Type of Engines:	2 Rolls-Royce RB211 Trent 895-17 turbofan engines
Year of Manufacture:	2001
Date & Time (UTC):	17 January 2008 at 1242 hrs
Location:	Runway 27L, London Heathrow Airport
Type of Flight:	Commercial Air Transport (Passenger)
Persons on Board:	Crew - 16 Passengers - 136
Injuries:	Crew - 4 (Minor) Passengers - 1 (Serious), 8 (Minor)
Nature of Damage:	Aircraft damaged beyond economical repair
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	43 years
Commander's Flying Experience:	12,700 hours (of which 8,500 hours were on type) Last 90 days - 85 hours Last 28 days - 52 hours
Information Source:	Inspector's Investigation

All times in the report are in UTC

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The investigation

In view of the sustained interest within the aviation industry, and amongst the travelling public, it is considered appropriate to publish an update on the continuing investigation into the accident involving a Boeing 777, G-YMMM, which occurred on 17 January 2008. This report is in addition to the Initial Report, published on 18 January 2008, a subsequent update published on 23 January 2008 and a Special Bulletin published on 18 February 2008.

History of the flight

The flight from Beijing to London (Heathrow) was uneventful and the engine operation was normal until the final approach. The aircraft was configured for a landing on Runway 27L and both the autopilot and the autothrottle were engaged. The autothrottles commanded an increase in thrust from both engines and the engines initially responded. However, at a height of about 720 ft the thrust of the right engine reduced to approximately 1.03 EPR (engine pressure ratio); some seven seconds later the thrust on the left engine reduced to approximately 1.02 EPR. The reduction in thrust on both engines was the result of a reduced fuel flow and all engine parameters after the thrust reduction were consistent with this. Parameters recorded on the Quick Access Recorder, Flight Data Recorder and non-volatile memory from the Electronic Engine Controller (EEC) indicate that the engine control system detected the reduced fuel flow and commanded the fuel metering valve to open fully. The fuel metering valve responded to this command and opened fully but with no appreciable change in the fuel flow to either engine.

Engineering examination

Extensive examination of the aircraft and detailed analysis of the recorded data have revealed no evidence of an aircraft or engine control system malfunction. There is no evidence of a wake vortex encounter, a bird strike or core engine icing. There is no evidence of any anomalous behaviour of any of the aircraft or engine systems that suggests electromagnetic interference. The fuel has been tested extensively; it is of good quality, in many respects exceeding the appropriate specification, and shows no evidence of contamination or excessive water. Detailed examination of the fuel system and pipe work has found no unusual deterioration or physical blockages. The spar valves and the aircraft fuel boost pumps were serviceable and operated correctly during the flight. The high pressure (HP) fuel pumps from both engines have unusual and fresh cavitation damage to the outlet ports consistent with operation at low inlet pressure. The evidence to date indicates that both engines had low fuel pressure at the inlet to the HP pump. Restrictions in the fuel system between the aircraft fuel tanks and each of the engine HP pumps, resulting in reduced fuel flows, is suspected.

Environmental conditions

During the flight there was a region of particularly cold air, with ambient temperatures as low as -76ºC, in the area between the Urals and Eastern Scandinavia. The Met Office described the temperature conditions during the flight as 'unusually low compared to the average, but not exceptional'. The lowest total air temperature recorded during the flight was -45ºC, and the minimum recorded fuel temperature was -34ºC. The specified fuel freezing temperature for Jet A-1 is not above -47ºC; analysis of fuel samples taken after the accident showed the fuel onboard the aircraft complied with the Jet A-1 specification and had a measured fuel freezing temperature of -57ºC. The aircraft was operated within its certified flight envelope throughout the flight.

Continuing investigation

The focus of the investigation continues to be the fuel system of both the aircraft and the engines, in order to understand why neither engine responded to the demanded increase in power when all of the engine control functions operated normally. Under the direction of the AAIB, extensive full scale engine testing has been conducted at Rolls-Royce, Derby, and fuel system testing is ongoing at Boeing, Seattle.

The engine test cell at Rolls-Royce was altered to enable the introduction of calibrated restrictions at various locations in the engine and aircraft fuel feed systems to replicate the engine fuel and control system response. The primary challenge at Boeing is to create the environmental conditions experienced on the flight over Siberia, at altitudes up to 40,000 ft, in which to test a representation of the aircraft fuel system. These tests are collectively aimed at understanding and, if possible, replicating the fuel system performance experienced on the day and the potential for formation of restrictions. In addition, work has commenced on developing a more complete understanding of the dynamics of the fuel as it flows from the fuel tank to the engine.

A data analysis team, working with statisticians from QINETIQ, are reviewing and analysing the recorded data from a large sample of flights on similar aircraft. No individual parameter from the flight of G-YMMM has been identified to be outside previous operating experience. The analysis is concentrating on identifying abnormal combinations of parameters.

The Federal Aviation Administration, the European Aviation Safety Agency, the Civil Aviation Authority and British Airways are being kept fully briefed on the progress of the investigation.

Operational changes

No operational changes are currently recommended by either the AAIB, Boeing or Rolls-Royce.

Published May 2008

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The flight from Beijing to London (Heathrow) was uneventful and the engine operation was normal until the final approach. The aircraft was configured for a landing on Runway 27L and both the autopilot and the autothrottle were engaged. The autothrottles commanded an increase in thrust from both engines and the engines initially responded. However, at a height of about 720 ft the thrust of the right engine reduced to approximately 1.03 EPR (engine pressure ratio); some seven seconds later the thrust on the left engine reduced to approximately 1.02 EPR. The reduction in thrust on both engines was the result of a reduced fuel flow and all engine parameters after the thrust reduction were consistent with this. Parameters recorded on the Quick Access Recorder, Flight Data Recorder and non-volatile memory from the Electronic Engine Controller (EEC) indicate that the engine control system detected the reduced fuel flow and commanded the fuel metering valve to open fully. The fuel metering valve responded to this command and opened fully but with no appreciable change in the fuel flow to either engine.

Engineering examination

Extensive examination of the aircraft and detailed analysis of the recorded data have revealed no evidence of an aircraft or engine control system malfunction. There is no evidence of a wake vortex encounter, a bird strike or core engine icing. There is no evidence of any anomalous behaviour of any of the aircraft or engine systems that suggests electromagnetic interference. The fuel has been tested extensively; it is of good quality, in many respects exceeding the appropriate specification, and shows no evidence of contamination or excessive water. Detailed examination of the fuel system and pipe work has found no unusual deterioration or physical blockages. The spar valves and the aircraft fuel boost pumps were serviceable and operated correctly during the flight. The high pressure (HP) fuel pumps from both engines have unusual and fresh cavitation damage to the outlet ports consistent with operation at low inlet pressure. The evidence to date indicates that both engines had low fuel pressure at the inlet to the HP pump. Restrictions in the fuel system between the aircraft fuel tanks and each of the engine HP pumps, resulting in reduced fuel flows, is suspected.

Environmental conditions

During the flight there was a region of particularly cold air, with ambient temperatures as low as -76ºC, in the area between the Urals and Eastern Scandinavia. The Met Office described the temperature conditions during the flight as ‘unusually low compared to the average, but not exceptional’. The lowest total air temperature recorded during the flight was -45ºC, and the minimum recorded fuel temperature was -34ºC. The specified fuel freezing temperature for Jet A-1 is not above -47ºC; analysis of fuel samples taken after the accident showed the fuel onboard the aircraft complied with the Jet A-1 specification and had a measured fuel freezing temperature of -57ºC. The aircraft was operated within its certified flight envelope throughout the flight.

Continuing investigation

The focus of the investigation continues to be the fuel system of both the aircraft and the engines, in order to understand why neither engine responded to the demanded increase in power when all of the engine control functions operated normally. Under the direction of the AAIB, extensive full scale engine testing has been conducted at Rolls-Royce, Derby, and fuel system testing is ongoing at Boeing, Seattle.

The engine test cell at Rolls-Royce was altered to enable the introduction of calibrated restrictions at various locations in the engine and aircraft fuel feed systems to replicate the engine fuel and control system response. The primary challenge at Boeing is to create the environmental conditions experienced on the flight over Siberia, at altitudes up to 40,000 ft, in which to test a representation of the aircraft fuel system. These tests are collectively aimed at understanding and, if possible, replicating the fuel system performance experienced on the day and the potential for formation of restrictions. In addition, work has commenced on developing a more complete understanding of the dynamics of the fuel as it flows from the fuel tank to the engine.

A data analysis team, working with statisticians from QINETIQ, are reviewing and analysing the recorded data from a large sample of flights on similar aircraft. No individual parameter from the flight of G-YMMM has been identified to be outside previous operating experience. The analysis is concentrating on identifying abnormal combinations of parameters.

The Federal Aviation Administration, the European Aviation Safety Agency, the Civil Aviation Authority and British Airways are being kept fully briefed on the progress of the investigation.

Operational changes

No operational changes are currently recommended by either the AAIB, Boeing or Rolls-Royce.

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Air Accidents Investigation Branch

Department for Transport

AAIB Interim Report

Accident to Boeing 777-236ER, G-YMMM at London Heathrow Airport on 17 January 2008

ACCIDENT

Aircraft Type and Registration:	Boeing 777-236ER, G-YMMM	
No & Type of Engines:	2 Rolls-Royce RB211 Trent 895-17 turbofan engines	
Year of Manufacture:	2001	
Date & Time (UTC):	17 January 2008 at 1242 hrs	
Location:	Runway 27L, London Heathrow Airport	
Type of Flight:	Commercial Air Transport (Passenger)	
Persons on Board:	Crew - 16	Passengers - 136
Injuries:	Crew - 4 (Minor)	Passengers - 1 (Serious) 8 (Minor)
Nature of Damage:	Aircraft damaged beyond economic repair	
Commander's Licence:	Airline Transport Pilot's Licence	
Commander's Age:	43 years	
Commander's Flying Experience:	12,700 hours (of which 8,500 hours were on type) Last 90 days - 85 hours Last 28 days - 52 hours	
Information Source:	Inspectors Investigation	
	All times in this report are UTC	

This bulletin contains facts which have been determined up to the time of issue. This information is published to inform the aviation industry and the public of the general circumstances of accidents and must necessarily be regarded as tentative and subject to alteration or correction if additional evidence becomes available.

The investigation

The Air Accidents Investigation Branch (AAIB) was informed of the accident at 1251 hrs on 17 January 2008 and the investigation commenced immediately. The Chief Inspector of Air Accidents has ordered an Inspectors' Investigation to be conducted into the circumstances of this accident under the provisions of The Civil Aviation (Investigation of Air Accidents and Incidents) Regulations 1996.

In accordance with established international arrangements, the National Transportation Safety Board (NTSB) of the USA, representing the State of Design and Manufacture of the aircraft, has appointed an Accredited Representative to participate in the investigation. The NTSB Accredited Representative is supported by a team which includes additional investigators from the NTSB, the Federal Aviation Administration and Boeing; Rolls-Royce, the engine manufacturer, is also participating fully in the investigation. British Airways, the operator, is cooperating with the investigation and providing expertise as required. The Civil Aviation Authority (CAA) and the European Aviation Safety Agency (EASA) are being kept informed of developments.

In view of the sustained interest within the aviation industry, and amongst the travelling public, it is considered appropriate to publish an update on the continuing investigation into this accident. This report is in addition to the Initial Report, published on 18 January 2008, a subsequent update published on 23 January 2008 and Special Bulletins published on 18 February 2008 and 12 May 2008.

History of the flight

The flight from Beijing to London (Heathrow) was uneventful and the operation of the engines was normal until the final approach. The aircraft was correctly configured for a landing on Runway 27L and both the autopilot and the autothrottle were engaged. The autothrottles commanded an increase in thrust from both engines and the engines initially responded. However, at a height of about 720 ft the thrust of the right engine reduced to approximately 1.03 EPR (Engine Pressure Ratio); some seven seconds later the thrust on the left engine reduced to approximately 1.02 EPR. The reduction in thrust on both engines was the result of less than commanded fuel flows and all engine parameters after the thrust reduction were consistent with this. Parameters recorded on the Quick Access Recorder (QAR), Flight Data Recorder (FDR) and Non-Volatile Memory (NVM) from the Electronic Engine Controllers (EECs) indicate that the engine control system detected the reduced fuel flows and commanded the Fuel Metering Valves (FMVs) to open fully. The FMVs responded to this command and opened fully but with no appreciable change in the fuel flow to either engine.

The aircraft had previously operated a flight on 14 January 2008 from Heathrow to Shanghai, with the return flight arriving on 15 January 2008. The aircraft was on the ground at Heathrow for 20 hours before the departure to Beijing on the 16 January 2008. Prior to these flights G-YMMM had been in maintenance for two days, during which the left engine EEC was replaced and left engine ground runs carried out.

Flight Data

In accordance with regulatory requirements, the aircraft was equipped with a 25 hour duration FDR and a 120 minute Cockpit Voice Recorder (CVR). The aircraft was also equipped with a QAR, which recorded data into a removable solid state memory device. These were successfully replayed.

The FDR provided a complete record of both the accident flight and the preceding flight; Heathrow to Beijing, which was operated on 16 January 2008. The FDR also contained the latter stages of the flight from Shanghai to Heathrow, which arrived on 15 January 2008.

The QAR record had ended about 45 seconds[1] prior to initial impact. Although the QAR record had not included the final seconds of the approach and touchdown, it recorded the position of both engine FMVs, a parameter not recorded on the FDR, and included the initial onset of the fuel flow reduction to both engines and the subsequent FMV movements to their fully open positions.

A time history of Total Air Temperature (TAT), Static Air Temperature (SAT), fuel temperature and other salient parameters during the accident flight are shown in Figure 1. Figure 2 shows a time history of the relevant parameters during the final approach and the accident sequence.

Whilst taxiing out at Beijing the TAT was -6°C (21°F), and the fuel temperature, measured in the left main fuel tank, was -2°C (28°F). The aircraft took off at 0209 hrs. The total fuel quantity at takeoff was 78,700 kg, with 28,900 kg in both the left and right main tanks and 20,900 kg in the centre tank. The aircraft climbed to a pressure altitude of 10,590 m (34,750 ft), where, at 0232 hrs, it levelled off into the cruise portion of the flight. The TAT had reduced to -25°C (-13°F) with the fuel temperature remaining at -2°C (28°F) at this time. Engine fuel flows during the takeoff phase had peaked at 24,176 pounds per hour (pph) for the left engine and 23,334 pph for the right engine, with both engines being fed with fuel from the centre tank. This slight difference in fuel flows is not considered to be significant.

Two hours into the cruise the TAT had progressively reduced to -33°C (-27°F) and the left main tank fuel temperature was about -22°C (-8°F). At this point the engines fuel feed supply switched from the centre tank to their respective main fuel tanks; the total fuel quantity at this point was 58,600 kg, with fuel being distributed 29,000 kg, 800 kg and 28,800 kg across the left main, centre and right main fuel tanks respectively.

During the next three and a half hours the fuel temperature reduced further from -22°C (-8°F) to -32°C (-26°F), in line with further reductions in TAT.

At 0842 hrs the aircraft made the first of two cruise step climbs, climbing from 10,590 m (34,750 ft) to 11,610 m (38,100 ft). The step climb was managed using the vertical speed (VS) mode of the autopilot, with the vertical speed set at 400 fpm. The peak fuel flow during the step climb was 8,688 pph for the left engine and 8,512 pph for the right engine. Prior to the second step climb, the aircraft made a minor flight level change to FL380 as it crossed international air traffic control boundaries.

At 0931 hrs, fuel temperature reduced to its lowest recorded value of -34°C (-29°F). It remained there for about 80 minutes during which the lowest value of TAT of -45°C (-49°F) was recorded.

When the left and right main fuel tank quantities approached 12,200 kg, automatic scavenging of the fuel from the centre fuel tank to the main fuel tanks commenced, as designed, and over a period of half an hour the centre tank quantity indication reduced from 800 kg to zero.

Footnote

[1] The loss of the 45 seconds of QAR data was accounted for due to the system being configured to buffer data in volatile memory before recording it onto the solid state memory.

Just over two hours from touchdown the TAT started to rise, in response to the increasing SAT; this was followed by an associated rise in fuel temperature. About twenty minutes later, the aircraft made its second and final step climb from FL380 to FL400. This was also completed using the VS mode of the autopilot, but with a slightly higher vertical speed of 600 fpm set. During this climb the peak fuel flow was 8,896 pph for the left engine and 8,704 pph for the right engine.

At 1202 hrs the aircraft commenced its descent before levelling at FL110, to enter the hold at Lambourne; it remained in the hold for about five minutes, during which it descended to FL90. In the first few minutes of the descent the fuel flows on both engines reduced to 970 pph, with two peaks to a maximum of 4,900 pph, until the aircraft entered the hold, when the fuel flows increased to 5,500 pph. The aircraft was then radar vectored for an ILS approach to Runway 27L. The aircraft subsequently stabilised on the ILS with the autopilot and autothrottle systems engaged and at a height of about 1,200 ft, the aircraft was configured for landing and 30º of flap was selected. By this time the fuel temperature had risen to -22°C (-8°F).

As the flaps reached the 30º position the airspeed had reduced to the target approach speed of 135 kt and the autothrottle commanded additional thrust to stabilise the airspeed (Figure 2 Point A). In response to variations in the wind velocity and associated airspeed changes, there followed a series of four, almost cyclic, thrust commands by the autothrottle (Figure 2 Points B). It was during the fourth acceleration, and as additional thrust was being commanded, that the right engine, followed some seven seconds later by the left engine, experienced a reduction in fuel flow (Figure 2 Points C). The right engine fuel flow reduction occurred at a height of about 720 ft and the left engine at about 620 ft.

Of the four thrust commands it was the second that resulted in the highest delivery of fuel flow, reaching a peak of 12,288 pph for the left engine and 12,032 pph for the right (Figure 2 Point D). These peaks occurred about 26 seconds prior to the reduction in fuel flow to the right engine. Peak fuel flows during the first and third thrust commands were lower, at about 9,500 pph and 9,000 pph respectively.

During the fourth thrust increase, the right engine fuel flow had increased to 8,300 pph before gradually reducing. The recorded EPR then started to diverge from the commanded EPR and the right engine FMV was then fully opened (Figure 2 Point E). Some seven seconds later, the left engine fuel flow, which had increased to 11,056 pph, also started to reduce and the left engine FMV was also moved to its fully open position (Figure 2 Point F). Following the reduction in fuel flow, the left engine fuel flow stabilised at about 5,000 pph and the right at about 6,000 pph. Both engines continued to produce thrust above flight idle. The autothrottle and the flight crew commanded additional thrust, with both thrust levers ultimately being placed fully forward, but there was no increased thrust available from either engine. The actual fuel flows continued to remain significantly below that being commanded.

At 240 ft the aircraft commander selected flap 25 in an attempt to reduce the drag. As the autopilot attempted to maintain the aircraft on the ILS glideslope the airspeed reduced and by 200 ft had reached 108 kt. The stick shaker activated at approximately 170 ft, and shortly afterwards the First Officer made a nose down pitch control input which reduced the aircraft pitch attitude and caused the auto pilot to disconnect. The aircraft's initial impact was at a descent rate of about 1,400 fpm and a peak normal load of about 2.9g. The aircraft then bounced, before commencing a ground slide, during

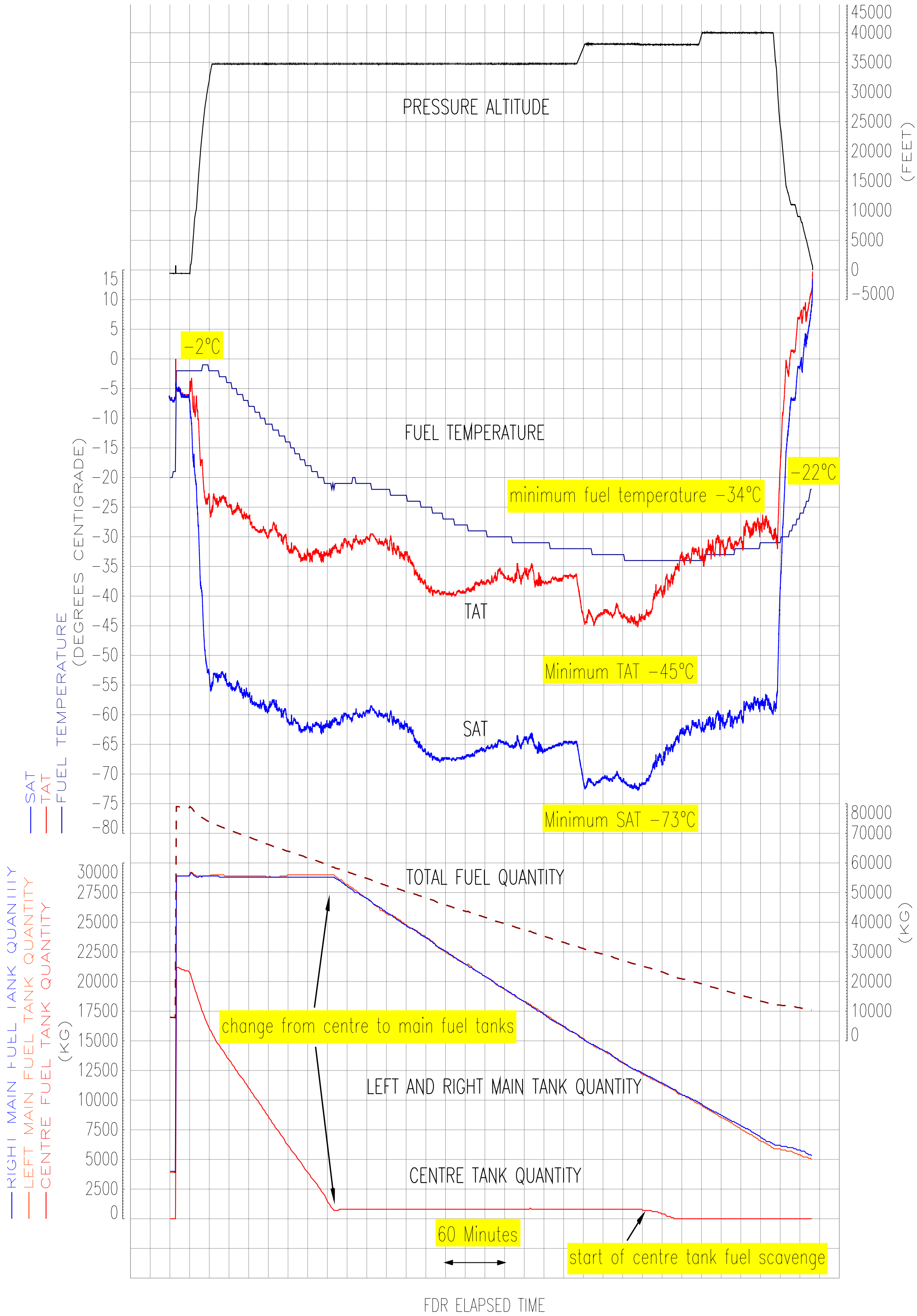

Figure 1

Temperatures

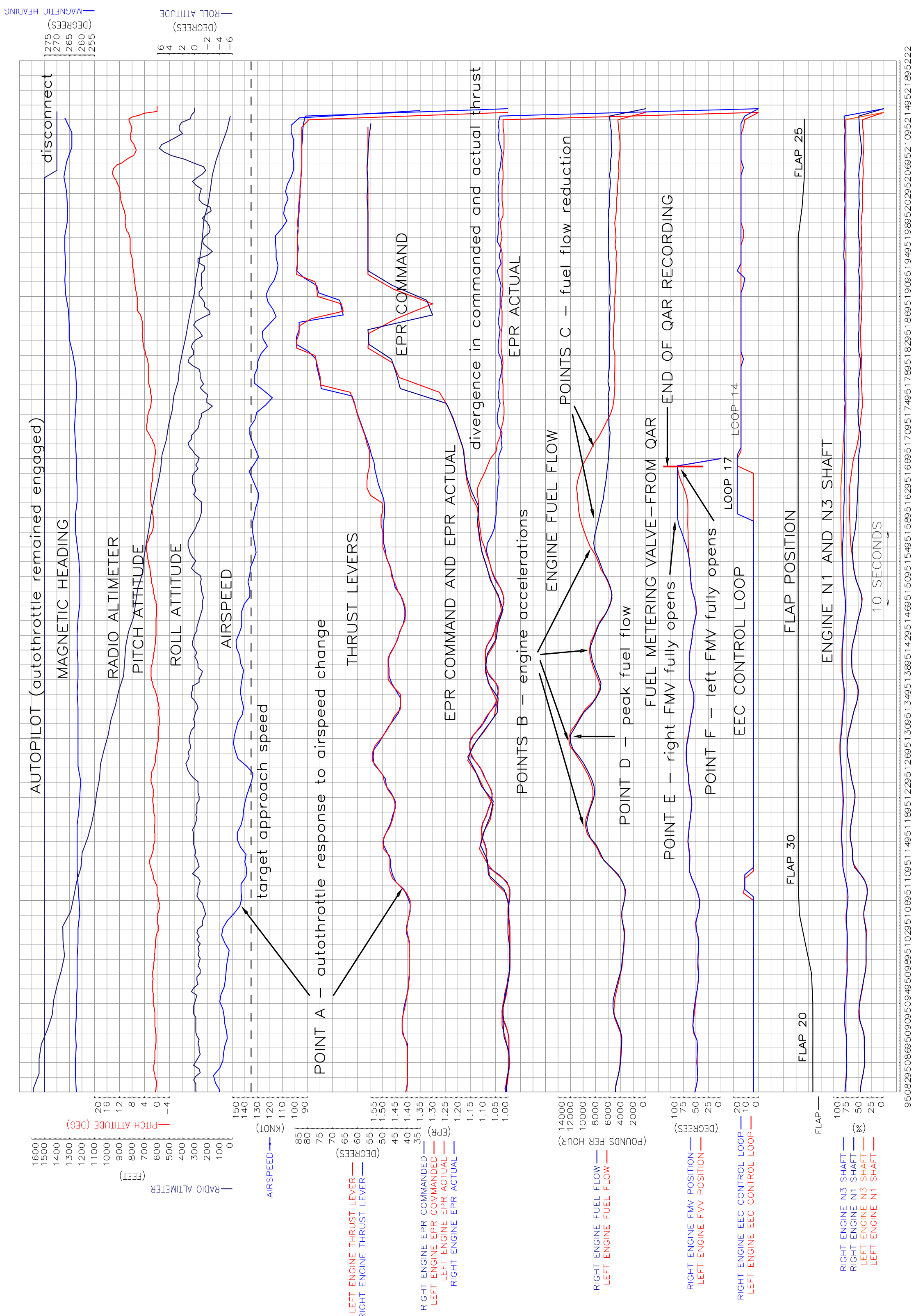

Figure 2

Final approach

which the FDR and CVR records ceased due to loss of electrical power.

The data indicated that throughout the flight, the fuel cross-feed valves were closed and the fuel spar valves open. There was no activation of a low pressure warning from the fuel boost pumps or any impending fuel filter blockage warning.

Fuel system description

The fuel on the Boeing 777-200ER is stored in three fuel tanks: a centre tank, a left main tank and a right main tank; see Figure 3. The centre tank contains two override / jettison pumps (OJ) and each main fuel tank contains two boost pumps, identified as forward (fwd) and aft. Each of the pump inlets is protected by a mesh screen and the pumps are also equipped with a check valve fitted in the discharge port, to prevent fuel in the fuel feed manifold flowing back through the pump. A pressure switch, mounted between the pump's impellor and check valve, monitors the fuel pressure and triggers a warning in the flight deck if the pressure rise across the pump drops to a value between 4 and 7 psi.

The fuel feed manifold runs across the aircraft and connects to the engine fuel feed lines. The manifold is split between the left and right system by two cross-feed valves. When these valves are closed, and the centre tank is the source of the fuel, the left OJ feeds the left engine and the right OJ feeds the right engine. The fuel from the left and right main tanks will supply their respective engines during main tank feed. Spar valves in the fuel manifold provide a means of shutting off the fuel supply to the engines, and they are controlled by the engine run / cutoff switches. The spar valves also move to the closed position when the fire switch is operated.

To prevent large amounts of free water building up in the fuel tanks the aircraft is fitted with a water scavenge system that uses jet pumps operated by motive flow from the OJ and boost pumps. One jet pump is located in each main tank and two in the centre tank. The jet pumps draw fluid from the lowest sections of each tank and inject it close to the inlet of each aft boost pump and both OJ inlets.

The aircraft is equipped with a centre tank fuel scavenge system, which increases the amount of useable fuel in this tank. The system uses jet pumps, provided with motive flow from the boost pumps, to draw fuel from the lowest part of the centre tank and feed it into both main fuel tanks. A float valve mounted in the centre tank turns on the motive flow when the centre tank content is below 15,800 kg. Float valves mounted in each of the main fuel tanks prevent fuel scavenge when the contents of these tanks are above 12,500 kg.

Each tank is vented to atmosphere through channels in the roof of the fuel tanks, which are connected to surge tanks mounted outboard of each of the main tanks. The surge tanks are vented to atmosphere through a flame arrestor and a scoop mounted on the lower surface of each wing. Should the flame arrestor or scoop become blocked, a pressure relief valve will operate and prevent the tanks from becoming over or under pressurised.

If fuel is loaded into the centre tank, the normal operation is to select all OJ and boost pumps ON at the start of the flight. As the OJs operate at a higher delivery pressure than the boost pumps the centre tank will empty first. During this period the boost pumps will provide fuel flow for their internal cooling and lubrication and supply motive flow to the jet pumps. When the centre tank is nearly empty, the pressure in the fuel feed manifold reduces and the main tank boost pump check valves open supplying fuel into the manifold. The flight crew then manually switch OFF the OJ pumps. In the event of low pressure from both the boost pumps in a main tank, the suction feed bypass check valve opens and fuel, via an inlet screen, is drawn from the main fuel tank by the engine Low Pressure (LP) pump.

The airframe fuel system supplies fuel to the LP engine-driven pump. This raises the fuel pressure (and fuel temperature slightly) and pumps the fuel through a Fuel/Oil Heat Exchanger (FOHE) which serves the dual purpose of cooling the engine lubricant and raising the temperature of the fuel such that ice does not affect the downstream components, including the LP filter. The FOHE is of a hybrid cross-flow / counterflow design. The fuel enters the top of the FOHE and passes downward, through a matrix of 1,180 small-diameter tubes that protrude through the inlet face. Hot oil enters the FOHE, just below the inlet face, before being directed to the bottom of the device. The oil then migrates upwards and around the fuel containing tubes. The temperature of the fuel after it has passed through the FOHE is considerably above its entry temperature. Should the LP filter become blocked, a bypass operates to allow unrestricted fuel flow around the filter; there is a flight deck indication if this occurs.

After the LP Filter, the fuel travels to the High Pressure (HP) pump where its pressure is raised higher still to the values needed for injection through the burners in the combustion chamber. The HP fuel is ported into the Fuel Metering Unit (FMU). The FMU contains a Fuel Metering Valve (FMV), which regulates the fuel flow to match a thrust demand and is commanded from the EEC. The fuel from the FMU is routed to the burners via a flowmeter and a relatively coarse HP strainer.

Aircraft examination

General

A comprehensive examination of all the aircraft systems revealed no pre-existing defects with the electrical systems, hydraulics, autoflight systems, navigation systems or the flying controls.

Spar Valves

The flight data shows that the spar valves remained open throughout the flight. Any uncommanded movement would have been recorded on the FDR and warnings would have been enunciated on the flight deck. A detailed examination of the spar valves and their control system revealed no pre-existing defects and a thorough review of the control system indicated that uncommanded and unrecorded movement of the spar valves was not possible. Extensive testing to induce an uncommanded movement, that remained unrecorded, could not identify any such failure modes.

High Intensity Radiated Field (HIRF) and Electro-Magnetic Interference(EMI)

Tests were conducted on the effects of HIRF and EMI on the spar valve control system up to power levels well in excess of published standards and no anomalous behaviour was experienced. In addition, the EECs were originally tested satisfactorily to power levels in excess of those that would have affected other more sensitive aircraft systems. During the accident flight no anomalies were evident with the electrical, navigation or communication systems, which are much more susceptible to such interference. There is therefore no evidence to suggest that HIRF or EMI played any part in this accident.

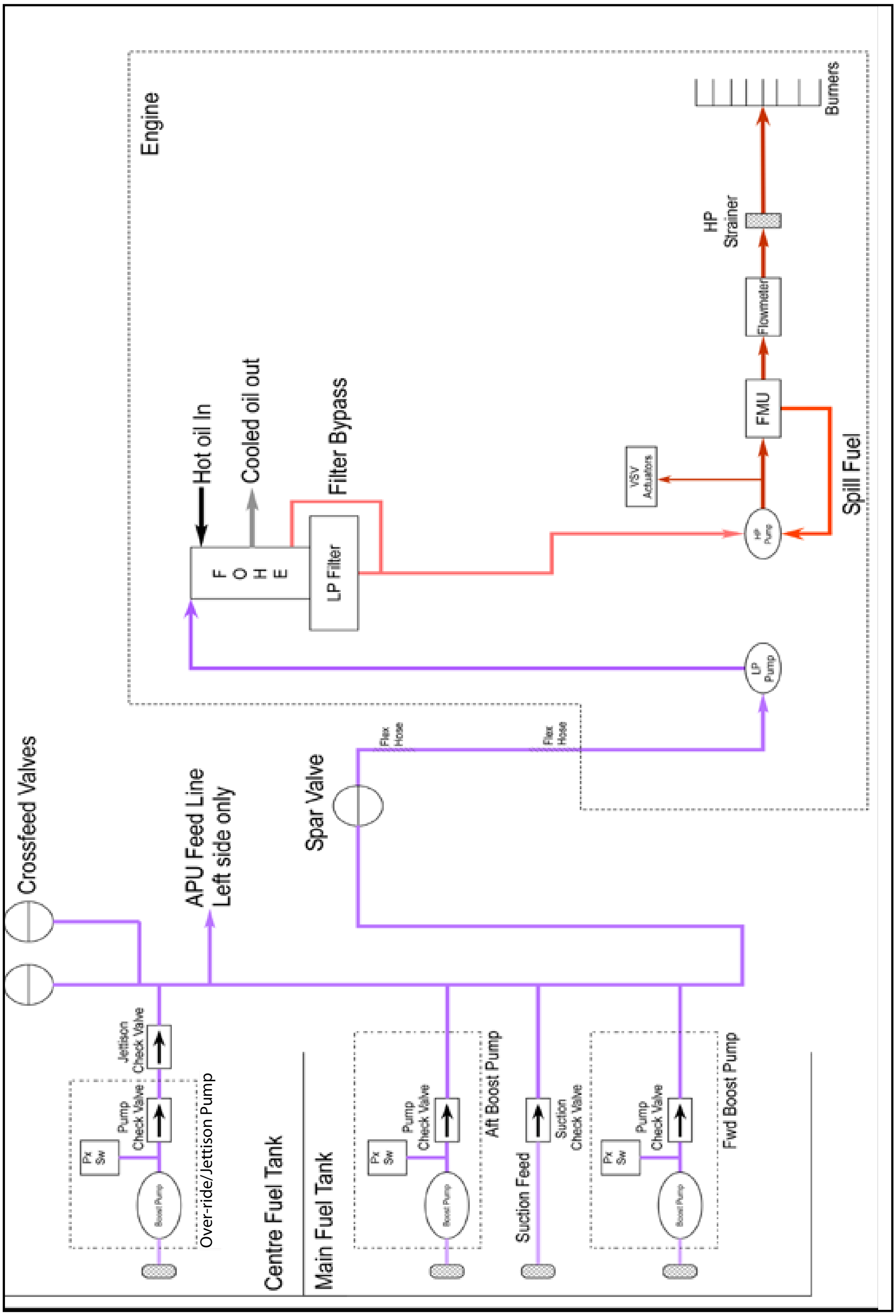

Figure 3

Boeing 777 / Rolls-Royce Trent 800 Fuel System

Fuel System

A pressure and vacuum check was carried out on the aircraft fuel feed system, and all of the pipelines were inspected by videoscope before the main mechanical and electrical components were removed for examination and testing. In addition, the entire left fuel feed system was removed from the aircraft, all the seals were inspected and the system was reassembled at the AAIB facility at Farnborough. The surge tank pressure relief valves, which had not operated in flight, were tested and found to be serviceable and there was no structural deformation to the fuel tanks which would have resulted from a blockage in the vent system.

The examination and testing found no faults in the aircraft fuel system that could have restricted the fuel flow to the engines.

Engines

With the exception of the two EECs and the FOHE/LP filter assemblies, most of the engine control system components, located beneath the engine, were too badly damaged or contaminated with dirt and fire fighting media to be functionally tested. However, all components were strip-examined and individual sub-assemblies tested where possible.

No pre-existing defects or evidence of abnormal operation were found with the exception of signs of abnormal cavitation erosion on the delivery side of both HP pumps. Some small debris was recovered from the left FOHE inlet chamber but this would not have restricted the fuel flow. Both of these observations have been reported in previous AAIB Special Bulletins, 01/2008 and 03/2008.

The EECs, whose NVM was successfully downloaded soon after the accident, have not been tested because to do so would require erasing the installed software and loading special test software. Since the recorded data and the NVM indicate that there were no anomalies with either EEC, testing of these units is not currently planned.

Fuel loading

G-YMMM was refuelled at Beijing with 71,401 kg of No 3 Jet Fuel (Peoples Republic of China), at a fuel temperature of 5°C (41°F); the refuelling was completed 30 minutes before the engines were started for the return flight to Heathrow and the total fuel load was 79,000 kg. At the start of the flight the recorded temperature of the fuel in the left main tank was -2°C (28°F). No 3 Jet Fuel complies with the UK and USA specifications for Jet A-1.

The FDR shows that at the time of the accident the total fuel on the aircraft was 10,500 kg, with 5,100 kg in the left main tank and 5,400 kg in the right main tank. Following the accident, approximately 6,500 to 7,100 kg of fuel had leaked out of fractured engine fuel pipes before the spar valves were manually closed.

Fuel testing

Following the accident, 66 fuel samples were taken from the aircraft and the engines. A number of these samples were tested and critical properties such as the freezing point, density, flash point, viscosity, contamination, fuel additives and presence of water were tested against DEF STAN 91-91 and ASTM D1655 requirements[2]. The fuel samples complied fully with the fuel specifications for Jet A-1. Additional tests were carried out to detect any unusual components that would not normally be found in aviation turbine fuels. No evidence of contamination

Footnote

[2] DEF STAN 91-91 and ASTM D1655 contain the standard specifications for aviation turbine fuels.

was found. The water solubility, which is the fuel's ability to absorb and release water, was considered to be normal.

The properties of the sampled fuel were also consistent with the parameters recorded in the quality assurance certificate for the bulk fuel loaded onto G-YMMM at Beijing.

The fuel sampled from G-YMMM was compared with 1,245 batches of Jet A-1 tested in the UK during 2007. With regard to the distillation range, which is the boiling range of the fuel, the fuel from G-YMMM was approximately in the middle of the sampled range. The freezing point of the fuel sampled from G-YMMM was -57°C (-71°F), which was slightly below the average freezing point but within the normal range for Jet A-1.

Fuel waxing

The freezing point of aviation turbine fuel is established by cooling the fuel until wax has formed and then warming the fuel until the last crystal of wax is seen to disappear. The freezing point of the fuel sampled from G-YMMM was measured using both an automatic and a manual test. Neither test could detect any wax crystals in the fuel at temperatures warmer than -57°C (-71°F).

The Boeing 777 has a fuel temperature probe located in the inboard section of the left main tank. The aircraft manufacturer previously undertook tests to establish the effectiveness of the fuel temperature probe by fitting a number of racks of thermocouples along the inside of the main fuel tanks. The tests established that the coldest fuel in the main fuel tanks is at the inboard section. The tests also established that there was a close correlation between the temperature of the fuel measured by the temperature probe and the rack of thermocouples mounted adjacent to the probe. On the accident flight, the temperature probe measured the minimum fuel temperature as -34°C (-29°F). On long flights the temperature of the fuel in the main wing tanks will tend towards the temperature of the boundary layer around the wing, which can be up to 3°C lower than TAT. On the accident flight the minimum TAT was -45°C (-49°F). Because of the position of the centre fuel tank, the temperature of the fuel in this tank is warmer than the fuel in the main tanks.

In conclusion, the data indicates that the fuel did not reach a low enough temperature to cause the fuel to wax during the accident flight.

Water in fuel

Water is always present, to some extent, in aircraft fuel systems and can be introduced during refuelling or by condensation from moist air which has entered the fuel tanks through the tank vent system. The water can take the form[3] of dissolved water, entrained (suspended) water or free water. Dissolved water occurs when a molecule of water attaches itself to a hydrocarbon molecule. As the fuel is cooled the dissolved water is released and takes the form of either entrained or free water. Entrained water is water that is suspended in the fuel as tiny droplets and can, with time, settle out as free water. Free water takes the form of droplets, or puddles, which collect on the bottom of the fuel tanks or in stagnation points within the fuel delivery system.

The amount of free water is controlled by regularly draining the water out of the fuel tank sumps, an activity known as 'sumping'. Free water is also controlled on the Boeing 777 by the water scavenge system which feeds the free water at the rear of the tanks into the area above the fuel pump inlets as entrained water. Both of these activities rely on the free water not freezing.

Footnote

[3] Aerospace Information Report AIR 790 Rev C.

Water ice in fuel

As the fuel temperature reduces to around -1°C to -3°C (31 to 27°F), entrained water in the fuel will start to freeze and form ice crystals. The density of the ice crystals is approximately the same as the fuel, so the crystals will generally stay in suspension and drift within the fuel. As the fuel temperature is further reduced, it reaches the Critical Icing Temperature, which is the temperature at which the ice crystals will start to stick to their surroundings. When the fuel temperature reduces to approximately -18°C (0°F), the ice crystals adhere to each other and become larger. Below this temperature little is known about the properties of ice crystals in fuel and further research may be required to enable the aviation industry to more fully understand this behaviour.

Fuel System Icing Inhibitor

Fuel System Icing Inhibitor (FSII) is a fuel additive that, when used in concentrations of 0.10% to 0.15% by volume, can prevent the formation of water ice down to a temperature of -40°C (-40°F). FSII is only effective on undissolved water (entrained and free) and, as it is approximately 500 times more soluble in water than fuel, it will migrate into the undissolved water and lower its freezing point. The mixture of water and FSII has a similar density to water and will be either consumed by the engines or can be removed from the fuel tank sumps during normal sumping operations.

FSII is not commonly used in large public transport aircraft and was not detected in the fuel samples taken from G-YMMM. However, aviation turbine fuel containing FSII has been used on aircraft flown by the Royal Air Force, US Air Force and other military forces for about 50 years. The additive was introduced following accidents on the Boeing B-52 aircraft when engine fuel filter icing led to restricted fuel flow and subsequent engine rollbacks[4] and flame outs. FSII is also in use as an alternative to fuel heaters on many small civilian jet aircraft. The additive is approved for use on the Boeing 777 and the FAA has provided information on its use in aircraft through Advisory Circular 20-29B.

Estimated water content of the fuel

It is estimated that the fuel loaded at Beijing would have contained up to 3 ltr (40 parts per million (ppm)) of dissolved water and a maximum of 2 ltr (30 ppm) of undissolved water (entrained or free). In addition, it is estimated that a maximum of 0.14 ltr of water could have been drawn in through the fuel tank vent system during the flight to Heathrow. This water would have been evenly spread throughout the fuel and would have been in addition to any water remaining in the fuel system from previous flights. These quantities of water are considered normal for aviation turbine fuel.

Tests for the presence of water in the fuel

It was not possible to establish the condition of the fuel in the centre tank at the time of the accident as it had subsequently been grossly contaminated with fire fighting foam and water applied by the fire crews immediately following the accident.

A requirement in the fuel specification is that the fuel should be visually inspected to ensure that it is clear, bright and free of water and sediment. In addition to the appearance test, the Karl Fischer test, which uses a chemical method to establish the total amount of water (dissolved and entrained) in the fuel, was carried out on fuel samples taken from the left main tank sump, the APU fuel line and the right engine variable stator vanes.

Footnote

[4] Rollback - uncommanded reduction of engine thrust

With the exception of the samples taken from the engine fuel filters and housings, all the samples that were tested passed the appearance tests. The samples from the engine fuel filters and housings contained a small number of very small droplets of water. These droplets could have resulted from the ingress of fire fighting media through damaged engine components, or might have been free water, which naturally settles in these areas.

The Karl Fischer tests indicated that the total amount of water in the samples, dissolved and entrained, was below 40 ppm, which is a very low level.

During the inspection of G-YMMM approximately 0.25 and 0.1 ltr of free water was recovered from the left and right main fuel tanks respectively, from areas where it could not migrate to the tank sumps. It is normal for free water to collect in large aircraft fuel tanks, and this quantity was considered to be relatively low for a Boeing 777.

Sumping

G-YMMM was last sumped at London Heathrow on 15 January 2008 prior to the flight to Beijing. The aircraft's fuel tanks had also been sumped at London Heathrow whilst on maintenance, on the 14 January 2008.

Prior to the accident the operator had initiated a review of the effectiveness of their sumping programme, which was carried out during routine Daily and Transit checks. The results of the review indicated that the drain valves could freeze and, when the fuel was cold, the flow of fluid through the drains could be very slow. During the review, a number of aircraft were checked in a warm hangar where any ice in the fuel tanks would have melted and migrated to the drains. G-YMMM was sumped in this manner on 14 December 2007.

The review established that whilst the free water does freeze, and could occasionally block the tank drains, there was no evidence of any significant quantities of free water having accumulated in any of the operator's 43 Boeing 777 aircraft.

Testing by aircraft manufacturer

As part of the investigation the manufacturer, under the direction of the AAIB, undertook small scale fuel testing in a climatic chamber and full scale testing on an adapted fuel rig.

Beaker tests

The small scale tests were known as Beaker tests and were undertaken to establish the behaviour of water when introduced into cold-soaked fuel. The test also used a number of simulated fuel system components to establish how ice might accumulate in a fuel system and restrict the fuel flow. The tests concluded that there was a 'stickier' range between -5°C (23°F) and -20°C (-4°F) when ice would more readily stick to its surroundings. The ice took on a more crystalline appearance at -20°C (-4°F) and at temperatures below -25°C (-13°F) the ice did not appear to have the mechanical properties required to bridge and plug orifices.

Fuel rig testing

The fuel rig consisted of a storage tank containing 3,520 ltr (930 US Gal) of Jet A[5] fuel, that could be cooled to -40°C (-40°F), and all the components in the aircraft fuel system from the boost pump inlet screen to the FOHE and engine driven LP pump. The flexible fuel feed pipes from G-YMMM were also fitted to the rig. A constraint of the rig was that the geometry and

Footnote

[5] For the purposes of these tests Jet A and Jet A1 are considered to behave in a similar manner.

length of the pipe runs were not identical to the aircraft configuration.

The aim of the tests was to establish if ice could build up within the fuel delivery system and cause a restriction of the fuel flow. The tests were carried out using either fuel preconditioned with a known quantity of water, or by injecting quantities of ice or water directly into the boost pump inlet.

The tests established that under certain conditions ice can accrete on the inside of some of the fuel pipes and on the boost pump inlet screens. The thickness of this ice appeared to be dependent on the fuel temperature and the fuel flow, but accumulations generated so far have not been sufficient to restrict the flow. However, further testing is required to understand more fully the manner of this accretion.

Testing also established that, under certain conditions, it is possible to partially block the FOHE and restrict the fuel flow to the engine HP fuel pump. The blockages were achieved by injecting water directly into the boost pump inlet. As the water moved through the fuel system it formed ice crystals, which subsequently blocked the ends of a number of the tubes in the FOHE matrix. Smaller amounts of water caused a temporary restriction which quickly cleared as the ice melted, whereas the restriction persisted when larger quantities of water were used. However, this restriction could always be cleared by reducing the fuel flow, which changed the equilibrium between the cold fuel and hot oil in the heat exchanger, such that the ice melted on the inlet face of the FOHE, sufficient to restore the original fuel flow. Variation of the FOHE oil temperature between 75 and 95°C (167 and 203°F) made a small difference to the amount of water required to restrict the FOHE, whereas variations in fuel temperature and fuel flow had a larger affect. During these tests the fuel flow never dropped below that required by the engine for operation at flight idle.

Further tests have shown that icing of the boost pump check valves is unlikely to result in restricted fuel flows. The possibility of air being introduced into the fuel has also been discounted as pressure responses seen on the fuel rig and during engine testing do not correlate with the engine response during the accident.

Tests were undertaken to establish if it was possible for pieces of ice to cause a restriction in the fuel delivery system. Such ice might have formed in the fuel tanks and been drawn into the boost pump inlet, or might have formed from water that had collected in the downstream side of the boost pump check valve housings. Ice injected directly into the boost pump inlet passed into the manifold as small ice particles. Ice was manufactured in a freezer, using the check valve housing as a mould, and positioned in front of the spar valve and close to the inlet of the LP pump in a way that could have caused a restriction to the fuel flow. The results of these limited tests suggest that ice formed in the fuel tank or check valve housings is unlikely to have caused the restricted fuel flow seen on the accident flight; however, further testing is required to confirm this.

Testing continues to investigate other icing scenarios and to establish if it is possible for ice to build up in the aircraft system in sufficient quantity to restrict fuel flow at the point of the build up, or release and thereby restrict fuel flow downstream in the fuel system. Whilst the water injection testing has demonstrated a high level of repeatability of delivering ice to the front face of the FOHE, attempts to generate ice repeatedly on other components in the fuel system have not been successful and have not created a detectable restriction. Problems have also been experienced in maintaining the water concentration in the fuel during the long duration tests as the fuel is recycled through the system.

Electronic Engine Control Unit (EEC)

Before examining the engine's behaviour during the latter stages of the flight, it is necessary to give a broad outline of the operation of the EEC. Since several parameters were both recorded on the QAR and stored in the NVM of the EEC, they provide some evidence of the event and confirm that the EEC was itself reacting correctly.

The most pertinent of the recorded parameters were the FMV commanded and actual positions. These showed that the EECs attempted to counter the shortfall in thrust demanded by the autothrottle by commanding the FMVs on both engines to open fully: the actual position showed that this was achieved. Prior to the rollback, the EECs had been operating in EPR mode. As the FMVs reached fully open, the EECs switched to Control Loop 17 (Absolute Maximum Fuel Flow Limit) as would logically be expected. The right engine remained at this unusual condition for more than the 2 seconds necessary to generate a fault code which was written to the NVM. After about 10 seconds from the start of the rollback of this engine, the EEC switched to Control Loop 14, which is a surge protection logic.

It is important to emphasise that neither engine had surged. Analysis and testing shows that the fluctuations in Burner Pressure (P30), caused by fluctuating fuel flow, would invoke the surge protection logic, which is triggered mostly by an excessive rate of change of P30. Applying Control Loop 14 causes the FMV to close to a lower value of fuel flow (but still significantly more than the fuel system was apparently capable of delivering). If the condition persists for more than 30 seconds, another fault code is generated: the right engine EEC logged such a code.

The left engine also switched to Control Loop 17 but it was not in control for more than 2 seconds before the P30 fluctuations triggered Control Loop 14 and so the fault code was not generated. The variability of this characteristic was reflected during the post-accident engine testing. The response of the EECs was considered to be quite explicable and no abnormalities were apparent.

HP Pump testing

The HP pump manufacturer conducted tests on a new pump in an attempt to replicate the cavitation marks seen on the accident flight pumps. The test revealed that running the pump with an abnormally low inlet pressure and a restricted fuel flow of 5,000 pph for 60 seconds gave identical cavitation marks to those seen on the pumps removed from G-YMMM. These cavitation marks have only been seen by the manufacturer, on one previous in-service pump, which was attributed to a failure of the LP pump drive shaft. The cavitation marks were not an indication of a fault in the pumps, but a symptom of either low inlet pressures or fuel aeration and would not have affected operation of the pump.

Engine testing

In order to validate how an engine reacts to a restricted fuel flow, two test facilities were used: firstly a Systems Test Facility (STF), and secondly a Trent 800 engine mounted in a fully-instrumented engine test cell.

The STF provided valuable data, particularly concerning the manner in which the EEC reacts to the FMV moving to fully open and the fluctuations in fuel flow and P30. However, it had limitations because, although it incorporated almost all of the components which comprise the engine fuel and control system, parameters such as spool speeds and burner pressure had to be synthesised from a mathematical model and the very dynamic conditions which followed the rollback could only be verified using an engine.

Accordingly, a development engine was prepared with the ability to restrict the fuel flow at various locations within the engine and the representative aircraft fuel system. After various iterations, it was found that the best way to apply the restriction was a metal plate with an orifice drilled in it, sized to pass a maximum fuel flow approximating to the average flow of both engines after the rollback.

The testing was accomplished in three distinct phases, the results of each phase informing the next as the overall aim was to match as closely as possible the recorded data from the accident flight. Although the components of the engine were fully representative of those fitted to G-YMMM (in particular the EEC software standard) it was acknowledged that the fuel used was at ambient temperature and, in addition, it was not possible to simulate the effects of airspeed.

Further refinements to the third phase of testing, included programming the power lever to move in a similar manner to the autothrottle thrust demands that preceded the rollback. This was because previous testing had shown that, with the restriction applied several metres upstream from the engine/airframe interface, the engine pump drew fuel from the pipework and thus delayed the onset of rollback, the position of the restriction also appeared to have some effect on the fuel flow and P30 oscillations after rollback. It was hypothesised that, with the restriction in place, it might be possible to achieve the three acceleration / deceleration cycles which preceded the final acceleration and rollback event as fuel in the aircraft pipework was depleted.

Engine Test Conclusions

Data collected during the course of the tests was exhaustive and is still being analysed. However, several important conclusions can be drawn:

- The behaviour of all the engine fuel system control components was consistent with a restriction in fuel flow occurring somewhere upstream of the HP pump.
- The further upstream the restriction was placed from the HP pump, the more acceleration/deceleration cycles could be completed following the introduction of the restriction, before the engine rolled-back.
- The reaction of the EEC to such an event was consistent with its programming logic.
- Upon removal of the restriction, the engine recovered quickly to normal operation.
- The engine and control system response indicated either a fixed restriction in the aircraft system or delivery of a restriction to a downstream fuel system component as the most likely scenarios, and excluded a gradual accretion on the front face of the FOHE or LP pump inlet.

Data mining

A team of statisticians from QinetiQ, together with specialists from the aircraft and engine manufacturer, the operator and the AAIB, are conducting a review of data from the accident flight and from other data sources.

Minimum fuel temperature data has been obtained from approximately 141,000 flights of Boeing 777 aircraft (approximately 13,000 Rolls Royce powered, 114,000 from Pratt and Whitney and 14,000 General Electric). The lowest recorded temperature during the accident flight was -34°C (-29°F). Of the flights sampled, less than 0.2% had fuel temperatures at or below this temperature. The lowest recorded temperature was -39°C (-38°F), which was on a GE powered aircraft, the lowest recorded temperature on a Rolls Royce powered aircraft was -37°C (-34°F). For fuel temperatures below -20°C (-4°F), there were 22,500 flights (approximately 17%).

In addition, data from approximately 13,000 flights on Boeing 777 Rolls Royce powered aircraft has been further analysed in detail. The fuel temperature at takeoff on the accident flight was -2°C (28°F); of the 13,000 flights 118 had takeoff fuel temperatures at or below -2°C (28°F), with the lowest being -11°C (12°F). On the approach prior to the accident the fuel temperature was -22°C (-8°F); 70 flights of the 13,000 flights had approach fuel temperatures at or below this temperature, with the lowest being -28°C (-18°F).

It is therefore clear that the fuel temperatures experienced during the accident flight were low, but were not unique, with other flights experiencing lower temperatures.

Analysis of fuel flow from the 13,000 flights shows that 10% had fuel flows less than 10,000 pph during step climbs (the accident flight did not exceed 8,896 pph), and 10% had had fuel flows greater than 10,000 pph during the approach phase (the accident flight was greater than 12,000 pph). Although these were not unique, they were at the edge of family for the data analysed. However, when analysed in conjunction with the fuel temperature data above, all of these factors make this flight unusual within the 13,000 flights analysed.

Following fuel flow reduction to the engines, the EEC control loop changed to Control Loop 17, an indication that the EEC was commanding maximum fuel flow. The FMV also moved to its fully open position without the expected increase in fuel flow. A retrospective analysis of the aforementioned 13,000 flights has been conducted for cases of EEC Control Loop 17 and for mismatches between the FMV position and the expected fuel flow. This has not revealed any previous occurrences. The aircraft manufacturer, however, has records of six occurrences of EEC Control Loop 17 during the previous 10 years. Explanations were available for all of the occurrences and they were all for reasons not relevant to the accident to G-YMMM.

The data mining work continues and is exploring further combinations of parameters to identify unique features from the accident flight. Included in this work is analysis of fuel flows and temperature.

Operational history of the Boeing 777

The Boeing 777 entered service in May 1995 and has since flown 17.5 million hours and 3.9 million flights. The Trent 800 powered Boeing 777 first entered service in March 1996 and has since flown 6.5 million hours and 1.4 million flights. These figures represent the operational history to July 2008.

Discussion

The examination of the aircraft has not revealed any pre-existing technical reason for the engine rollback and the subsequent lack of engine response. Following the rollback the fuel flow reduced to only 5,000 pph on the left engine and 6,000 pph on the right, whereas the expected fuel flow with the FMV in the fully open position should have been in excess of 38,000 pph. This indicates that the fuel flow was being restricted, and this restriction continued after the initial engine rollback and through to the ground impact.

The only physical evidence found following the accident was the cavitation marks on the pressure outlet ports of the HP pumps on both engines. From testing and in service experience it is concluded that these marks were fresh, and therefore most probably occurred on this flight, and were caused by a restricted fuel flow, leading to low inlet pressure at the HP pump.

The aircraft boost pumps that were supplying fuel from the main fuel tanks to the engine at the time of engine rollback, did not indicate a low pressure at any time during the flight. Subsequent tests of the indication system found it to be serviceable. Therefore, the restriction was most probably downstream of the boost pump low pressure switches and upstream of the HP pump inlet.

Had both boost pumps and suction feed check valves become restricted, then a low pressure in the fuel manifold would have led to air being drawn from the centre tank, via the jettison and override pump check valves. However, testing has shown that aeration causes a different response from the engine to that seen during the event. Furthermore, if a restriction occurred in the fuel manifold, between the centre tank feed and the point at which the boost pump feed lines connect into the manifold, then there would have been adequate fuel supply from the boost pumps downstream, or from the suction feed bypass. Thus, the restriction must have been downstream of the connection of the fwd boost pump feed line to the fuel manifold.

Examination of the fuel system did not reveal any physical restriction in the fuel system and the spar valves remained open throughout the flight. The fuel temperature had reached a low of -34°C (-29°F); whilst this is unusual it is not exceptional and the fuel temperature was not sufficiently low for the fuel to start to wax.

The fuel was tested and found to conform to all the required specifications. No significant quantities of water were found in either the fuel samples or in the aircraft's main fuel tanks.

Testing by the aircraft manufacturer, under the direction of the AAIB, has established that ice can accrete within the fuel system, and that the FOHE can become partially blocked with ice when water is injected into the boost pump inlet whilst cold fuel (below 0ºC) is circulated. However, injecting water in this manner results in concentrations of water that are considerably in excess of current certification requirements; moreover, the quantities of water used have not been quantified against the amount of ice that can form in the fuel system. Indeed, there have been difficulties in the repeatability of accruing ice on some of the fuel system components.

The investigation so far has established that there are two possible scenarios that could have led to a restriction of the fuel flow that match the known data from G-YMMM. The first is that ice accreted over a period of time, most probably at a location downstream of the fwd boost pump connection into the fuel manifold and upstream of the HP pump inlet. This ice would have had to have accrued to an extent to block approximately 95% of the cross sectional area to induce cavitation of the HP pump and result in the observed engine response. Testing by the engine manufacturer has shown that sufficient ice accretion could not have occurred on the face of the FOHE or the LP pump inlet, prior to the final series of accelerations. If it had, then the rollback would have occurred earlier during the first acceleration of the final approach series. A partial restriction upstream of the LP pump is consistent with the accident flight data, but testing has not yet been able to duplicate such a restriction with ice; nevertheless, this possibility is still being evaluated. Testing also established that ice on the face of the FOHE tends to melt at low fuel flows. As the event occurred after the aircraft had flown at a low fuel flow during the descent, it is unlikely, in this scenario, that enough ice had accreted on the face of the FOHE to cause the restriction.

The second scenario is that ice had accreted throughout the fuel feed system, and was then released during an increased fuel flow demand, such as the 12,000 pph achieved during the second acceleration on the final approach. In this case the ice might then travel and be 'caught' in the pipework, spar valve, LP pump inlet or on the face of the FOHE, thereby causing a restriction to the fuel flow.

For ice to accrete within the fuel system it requires long periods at low fuel flows and temperatures below the Critical Icing Temperature. It is known that ice behaves differently as the fuel temperature changes. However, at present it is not fully understood how the ice forms within the aircraft fuel system at different temperatures due to the variability in the results on the fuel rig and differences in the layout between the fuel rig and the actual aircraft fuel system.

Analysis of the flight data on G-YMMM indicated that the system had high fuel flows of 24,000 pph from the centre fuel tank during the takeoff from Beijing. However, when the fuel was being supplied by the boost pumps in the main fuel tanks the maximum fuel flow was 8,896 pph, until the final series of accelerations just prior to the rollback. The last high fuel flow demand on G-YMMM prior to the approach into Heathrow, and when the main fuel tanks were supplying the engines, was during a VNAV commanded step climb on the previous flight into Beijing when the fuel flow reached 10,700 pph. The step climbs on the accident flight had both been completed in VS mode with a low rate of climb selected, which resulted in lower fuel flows.

There has only been one other in-service event of HP pump cavitation, which was as a result of a failure of the LP pump drive. A review of previous recorded occurrences of the EEC entering Control Loop 17 has shown six previous cases, all of which were explicable. There has only been one previous recorded occurrence of the EEC entering Control Loop 14, and this was due to an engine surge. A review of available data has not revealed any other indication of a mismatch between FMV position and fuel flow, similar to that which occurred on the accident flight.

The accident flight was therefore unique in that this has been the only recorded case of a restricted fuel flow affecting the engine performance to the extent of causing HP pump cavitation, Control Loop 17, Control Loop 14 and a mismatch between FMV position and fuel flow demand, and this occurred on both engines within 7 seconds of each other. This is the first such event in 6.5 million flight hours and places the probability of the failure as being 'remote' as defined in EASA CS 25.1309.

Summary

The investigation has shown that the fuel flow to both engines was restricted; most probably due to ice within the fuel feed system. The ice is likely to have formed from water that occurred naturally in the fuel whilst the aircraft operated for a long period, with low fuel flows, in an unusually cold environment; although, G-YMMM was operated within the certified operational envelope at all times.

All aviation fuel contains water which cannot be completely removed, either by sumping or other means. Therefore, if the fuel temperature drops below the freezing point of the water, it will form ice. The majority of flights have bulk fuel temperatures below the freezing point of water and so there will always be a certain amount of ice in the fuel.

To prevent the ice causing a restriction requires either: the fuel system must be designed in such a way that the ice in the fuel does not pose a risk of causing an interruption of the fuel supply to the engine or; prevention of the water from becoming ice in the first instance. Changes to the fuel system design could make the system more tolerant, but would take time to implement and would certainly not be available within the near term. Therefore, to reduce the risk of recurrence interim measures need to be adopted until such design changes to the fuel system are available.

One option would be to prevent the water from becoming ice, such as through the use of FSII. Alternatively, operational changes to reduce the risk of ice formation causing a restricted fuel flow at critical stages of flight could be introduced. Such changes could be implemented quickly, but must not compromise the safe operation of the aircraft.

Although the exact mechanism in which the ice has caused the restriction is still unknown, in detail, it has been proven that ice could cause a restriction in the fuel feed system. The risk of recurrence needs to be addressed in the short term whilst the investigation continues. The FAA and EASA have been fully appraised of the outcome of all testing and analysis developed to date. Therefore:

Safety Recommendation 2008-047

It is recommended that the Federal Aviation Administration and the European Aviation Safety Agency, in conjunction with Boeing and Rolls-Royce, introduce interim measures for the Boeing 777, powered by Trent 800 engines, to reduce the risk of ice formed from water in aviation turbine fuel causing a restriction in the fuel feed system.

However, it should be recognised that throughout the investigation all of the testing and research into the root cause of this accident has been conducted on the Boeing 777 / Trent 800 aircraft engine combination, and it is unknown whether other aircraft / engine combinations that have already been certificated might also be vulnerable to this previously unforeseen threat. Therefore:

Safety Recommendation 2008-048

It is recommended that the Federal Aviation Administration and the European Aviation Safety Agency should take immediate action to consider the implications of the findings of this investigation on other certificated airframe / engine combinations.

Furthermore, the Boeing 777 was certificated in 1995 as meeting both the FAA federal aviation regulations and the JAA airworthiness requirements in force at the time. These regulations required that an aircraft and engine fuel system must be capable of sustained operation throughout its flow and pressure range, and at low temperatures, with a prescribed concentration of water. However, the current requirements do not appear to address the scenarios identified during this investigation, such as the sudden release of accrued ice, which could lead to a restricted fuel flow. Therefore:

Safety Recommendation 2008-049

It is recommended that the Federal Aviation Administration and the European Aviation Safety Agency review the current certification requirements to ensure that aircraft and engine fuel systems are tolerant to the potential build up and sudden release of ice in the fuel feed system.

Further work

The investigation into the cause of this accident continues. Further testing will be carried out to establish more clearly how ice forms within the fuel system and how it might cause the restricted fuel flows seen on this flight. An assessment of the fluid dynamics of the fuel system is also being conducted. The data mining activity is continuing to look at data from other Boeing 777 flights and a comprehensive study of the crashworthiness aspects of the accident is being undertaken.

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Air Accidents Investigation Branch

Department for Transport

AAIB Interim Report 2

Accident to Boeing 777-236ER, G-YMMM at London Heathrow Airport on 17 January 2008

ACCIDENT

Aircraft Type and Registration:	Boeing 777-236ER, G-YMMM		
No & Type of Engines:	2 Rolls-Royce RB211 Trent 895-17 turbofan engines		
Year of Manufacture:	2001		
Date & Time (UTC):	17 January 2008 at 1242 hrs		
Location:	Runway 27L, London Heathrow Airport		
Type of Flight:	Commercial Air Transport (Passenger)		
Persons on Board:	Crew - 16	Passengers -	136
Injuries:	Crew - 4 (Minor)	Passengers -	1 (Serious) 8 (Minor)
Nature of Damage:	Aircraft damaged beyond economic repair		
Commander's Licence:	Airline Transport Pilot's Licence		
Commander's Age:	43 years		
Commander's Flying Experience:	12,700 hours (of which 8,500 hours were on type) Last 90 days - 85 hours Last 28 days - 52 hours		
Information Source:	Inspector's Investigation		

The investigation

This report is an update on the progress of the investigation into the accident to G-YMMM on 17 January 2008, and should be read in conjunction with the initial Interim Report issued on 4 September 2008. That report includes a detailed history of the accident flight, a technical description of the fuel system in the Boeing 777, details of the investigation up to that point and three Safety Recommendations.

The Air Accidents Investigation Branch (AAIB) was informed of the accident at 1251 hrs on 17 January 2008 and the investigation commenced immediately. In accordance with established international arrangements, the National Transportation Safety Board (NTSB) of the USA, representing the State of Design and Manufacture of the aircraft, has appointed an Accredited Representative to participate fully in the investigation. The NTSB Accredited Representative is supported by a team which includes additional investigators from the NTSB, the Federal Aviation Administration and Boeing; Rolls-Royce, the engine manufacturer, is also participating fully in the investigation. British Airways, the operator, is co-operating with the investigation and providing expertise as required. The Civil Aviation Authority (CAA) and the European Aviation Safety Agency (EASA) are being kept informed of developments.

Brief history of the flight

The flight from Beijing, China, to London (Heathrow) was uneventful and engine operation was normal until the final approach. During the approach the autothrottles commanded an increase in thrust from both engines and the engines initially responded. However, at a height of about 720 ft agl the thrust of the right engine reduced to approximately 1.03 EPR (Engine Pressure Ratio); some seven seconds later the thrust on the left engine reduced to approximately 1.02 EPR. The reduction in thrust on both engines (rollback) was the result of a reduced fuel flow and all engine parameters after the thrust reduction were consistent with this.

Related event

On 26 November 2008 an American operator of a Boeing 777-200ER (N862DA), also powered by Rolls-Royce Trent 895 engines, experienced an uncommanded rollback of the right engine whilst in the cruise at FL390. The aircraft was on a flight from Shanghai, China, to Atlanta, USA, when the incident occurred in the vicinity of Great Falls, Montana. The crew executed the applicable Flight Manual procedures, introduced after the G-YMMM accident, following which normal engine control was recovered and the aircraft proceeded to an uneventful landing at Atlanta.

Whilst the phase of flight, environmental conditions and fuel temperature profiles were not common to the G-YMMM accident, many of the characteristics of the engine rollback were similar, including the fuel temperature at the time of the event. Analysis of the data from both events, and the testing undertaken by the aircraft and engine manufacturers, have further enabled the investigation to understand how ice generated within the aircraft fuel feed system might lead to an engine rollback.

Fuel Oil Heat Exchanger restriction tests

It was reported in the AAIB intial interim report that testing has shown that, under certain conditions, it is possible for ice to restrict the fuel flow at the face of the Fuel Oil Heat Exchanger (FOHE). However, during all the testing the fuel flow never fell below that required by an engine at flight idle. Moreover, the restriction could always be cleared by reducing the fuel flow to idle, which resulted in a change in the equilibrium between the cold fuel and hot oil in the heat exchanger, such that the ice melted on the inlet face of the FOHE, sufficient to restore the demanded fuel flow.

Further testing has established that 25 ml of water, when introduced into the fuel flow at the boost pump inlet at an extremely high concentration, can form sufficient ice to restrict the fuel flow through the FOHE. During these tests it was concluded that it was not possible to restrict the fuel flow through the FOHE when the temperature of the fuel in the main tank was above -15°C (5°F) at a fuel flow of 6,000 pounds per hour (pph) and -10°C (14°F) at a fuel flow of 12,000 pph.

It should be emphasised that the FOHE, which is part of the engine fuel system, was shown to comply with all the requirements placed on the engine manufacturer at the time of certification; the tests conducted in the course of the investigation have not, to the knowledge of the AAIB, been proposed or conducted before.

Further testing

Since the publication of the AAIB initial interim report the aircraft manufacturer has undertaken further testing on a fuel rig to establish how ice might accumulate in the aircraft fuel feed system.

Blockage in the aircraft fuel feed system

During the testing, blockage of the fuel boost pump inlet screen was achieved on six occasions sufficient to restrict the flow. The restrictions occurred during the testing and were believed to have occurred as a result of the method by which water was introduced into the fuel to maintain the required concentration; consequently these restrictions were believed to be an artefact of the test set-up. The restrictions were all characterised by a drop in the fuel pressure, sufficient to generate the boost pump low fuel pressure warning, and a reduction in the electrical current draw of the boost pump. The data from the accident flight showed that the boost pump low pressure switches did not trigger throughout the flight, therefore, icing of the inlet screens is unlikely to have caused the particular fuel flow restrictions experienced on G-YMMM.

Observations from the earlier tests showed that, apart from the inlet screens and the FOHE, restrictions did not occur in any of the other fuel system components, or in any of the aircraft fuel feed pipes. During some of the long-duration tests it was observed that, at a low fuel flow, ice could accumulate on the inside of the pipe walls. It was suspected that this ice would clear when the fuel flow was increased. However, on these early tests the geometry, material and lengths of the pipes on the fuel rig were not identical to the aircraft installation, nor were they exposed to the same environment as experienced on the accident flight.

Ice accumulation tests

To establish how ice might have accumulated within the fuel feed system on the accident flight, the fuel rig was reconfigured to include the majority of the right fuel system feed pipes from G-YMMM. The pipes were arranged so that their gradients were representative of the attitude of the aircraft in the cruise. An environmental tank, filled with cold fuel, was used to simulate the environment surrounding the fuel feed pipes in the main fuel tank. An insulated box was built around those fuel pipes which pass through the centre ‘cheek’ tanks and dry ice was used to control the temperature in this area. The pipes located along the top of the strut (engine pylon) were exposed to the ambient conditions of the building in which the fuel rig was located; thermal modelling by the aircraft manufacturer indicated that this would approximate to the temperature in this area during the cruise.

Tests were carried out with fuel flowing for 3, 6 and 7 hours at 6,000 pph, containing a water concentration of approximately 90 parts per million (ppm)[1] and fuel temperatures of 5°C (41°F), -12°C (10°F), -20°C (-4°F) and -34°C (-29°F) respectively. These test conditions were intended to replicate the conditions during the accident flight and to simulate the environment around the fuel feed pipes. The following observations were made:

- When warm fuel (at a temperature of 5°C (41°F)) was fed from the centre tank, ice formed around the inside of the fuel feed pipes that pass through the main fuel tank (fuel at a temperature of -20°C (-4°F)).

- Ice formed around the inside of all the fuel feed pipes from the boost pump discharge port to the front of the strut when fuel flowed for 3 hours at temperatures of -12°C (10°F) and -20°C (-4°F). The thickness of the ice was similar (1 to 2 mm) at both temperatures; however at -12°C (-10°F) the build-up of ice was more consistent and visually there appeared to be more ice throughout the system.

- Very little ice formed on the inside of the fuel feed pipes when the fuel temperature was at -34°C (-29°F).

- There was less repeatability in the amount of ice found in the fuel pipes at the end of the accumulation runs when the duration was increased from 3 to 6 hours. Several tests were carried out, using the same batch of fuel, at a fuel temperature of -20°C (-4°F) with quite different results. The amount of ice within the system ranged from very little ice to a build up of approximately 6 mm along the bottom of the pipe and 1 to 2 mm around the circumference of the pipe (Figure 1). However, it is possible that on some of the runs, ice might have been released before the end of the test.

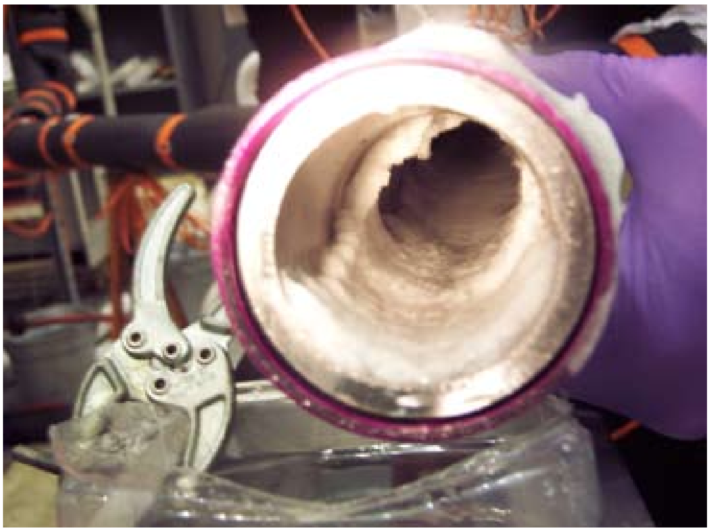

Figure 1

Ice in the flexible hose located at the rear of the strut

- When the fuel temperature was cooled from -12°C (10°F) to -33°C (-27°F), over a 7 hour period, at a similar rate to the accident flight, the amount of ice found in the fuel pipes was consistent with the findings after the 3 hour run at a fuel temperature of -12°C (10°F).

- The ice was soft and easy to move and there appeared to be no difference in the properties of the ice that accumulated at any of the cold test temperatures. However, in the test when the fuel temperature was cooled from -12°C (10°F) to -33°C (-27°F), the surface of the ice took on a 'pebbly' appearance.

Footnote

[1] 90 ppm is an industry standard as defined in SAE ARP 1401 and SAE AIR 790.

- Examination of the melted ice showed that it consisted of a mixture of water and fuel. The quantity of water in the ice deposited along the inside of the fuel pipes in the strut area was greater than the amount found necessary, in previous tests, to restrict the FOHE.

- On two occasions approximately 90 ml of water was recovered from the ice that had accumulated in pipes in the strut area. On another occasion approximately 170 ml of water was recovered from this area; however, the possibility that this sample had been contaminated after the test could not be excluded.

Ice release tests – cold FOHE[2]

Tests were carried out using the environmental test rig to establish whether increasing the flow rate would release sufficient ice, that had accumulated on the inside of the fuel pipes, to cause a restriction at the face of a FOHE. However, because of the limitations of the test rig, and the apparent 'random' process by which ice forms, it was not possible to fully replicate the conditions just prior to the engine rollback on G-YMMM.

The first phase of each test was to accumulate ice within the fuel system using a boost pump to maintain the fuel flow at 6,000 pph, with the fuel conditioned with approximately 90 ppm of water and maintained at a temperature of -20°C (-4°F). This was the approximate fuel temperature at which the rollbacks occurred on G-YMMM and N862DA. It should be noted that it was not possible to establish visually how much ice had accumulated at the end of this phase, without compromising the release test. After the accumulation phase, the fuel flow returning from the end of the strut was diverted through a cold FOHE and the fuel flow was increased.

In the first test, ice was allowed to accumulate for 3 hours before the fuel flow was increased to 10,000 pph for 3 minutes; during this test no pressure drop was detected across the FOHE. On examining the fuel system no ice was found on the face of the cold FOHE and the amount of ice found on the inside of the fuel pipes was similar to the amount found during the previous accumulation tests undertaken at similar conditions.

In order to increase the flow rate above 10,000 pph it was necessary to fit an engine LP pump into the flow path. Under normal operation the LP pump increases the fuel pressure from around 30 to 200 psig, which is sufficient to provide a flow rate of approximately 30,000 pph with the control valve fully open.

During the next two tests, ice was allowed to accumulate for 6 hours before the fuel flow was diverted to the LP pump and cold FOHE. The fuel flow was increased by progressively opening the control valve during which, on both tests, the pressure drop across the FOHE increased and the LP pump outlet pressure reduced. In the first of these tests, as the control valve was gradually moved fully open, the pressure drop across the FOHE began to increase[3] when the fuel flow was between 6,000 and 10,000 pph, indicating that ice had released and started to form a restriction at the FOHE. The fuel flow became restricted to 14,500 pph before decreasing to 11,000 pph, with a corresponding pressure drop of

Footnote

[2] A cold FOHE does not have any hot oil flowing through it and was used in the tests as a strainer to 'catch' any released ice.

Footnote

[3] In normal operation the differential pressure across the FOHE increases slightly with increasing fuel flow. In these tests the pressure differential was higher than would be expected in normal operation.

165 psid across the FOHE. During the next test the pressure drop across the FOHE also began to increase when the flow rate was between 6,000 and 10,000 pph. The fuel flow became restricted to 10,000 pph before decreasing to 6,000 pph, with a pressure drop of 195 psid across the FOHE. Whilst the pressure drop across the FOHE, in both cases, was evidence of the cold FOHE being restricted by ice, the reduction in the boost pump and LP pump outlet pressures, and a reduction in the current drawn by the boost pump, were indications that the fuel flow through the system was also restricted by ice collecting on the boost pump inlet screen.

Following these tests, 35 ml and 55 ml of water was collected from the ice that melted from the face of the FOHE. From a visual inspection of the inside of the fuel pipes, it appeared that in the penultimate test the ice was released from the strut area, whereas in the final test it released from all the fuel pipes.

Ice release tests – hot FOHE[4]

Two further ice release tests were carried out with hot oil at 85°C (167°F) flowing through the FOHE. A clear cap was fitted to the FOHE in order to monitor its face visually.

In the first test there was only a small rise in the pressure drop across the FOHE as the fuel flow was increased above 6,000 pph. However, with the control valve fully open the fuel flow peaked at 14,900 pph before falling back to around 11,000 pph. The drop in the current drawn by the boost pump, and a reduction in the boost pump outlet pressure, indicated that the fuel flow was probably restricted as a result of ice forming on the boost pump inlet screen.

Footnote

4 A hot FOHE has oil flowing through it at a temperature representative of an operating engine.

After removing the bypass loop it was possible to observe the ice entering the FOHE for approximately 15 seconds before the fuel became too cloudy to make visual observations. The size of the ice varied from small flakes up to a piece approximately 21 mm x 15 mm. The appearance and thickness of the ice was consistent with it having been shed from the inside walls of the fuel pipes. On making contact with the face of the FOHE the smaller pieces of ice would 'instantly' melt, whereas it took several seconds for the larger pieces of ice to disappear. Some of the ice was still intact after three seconds but, as the fuel turned cloudy, it was not possible to establish if this ice would melt or grow.

The second test was run at the same conditions as the first test and used the same batch of fuel. In this test the pressure drop across the FOHE began to increase when the fuel flow was at 10,000 pph. The fuel flow peaked at 19,000 pph, with the control valve fully open, and a corresponding pressure drop across the FOHE of 105 psid. Over the following two minutes the fuel flow decreased to 17,000 pph with an increase in the pressure drop across the FOHE to 125 psid. There were no indications that the fuel flow was restricted by icing of the inlet screen and very little ice was found in any of the fuel pipes at the end of the test.

This last test demonstrated the principle that ice can accumulate and release from the inside of the fuel feed pipes in a sufficient quantity to restrict the fuel flow through a hot FOHE. However, the level of restriction during this test was less than that experienced on the accident flight.

Ice release test – effect of temperature in the strut

A test was carried out to establish if the increase in total air temperature (TAT) during the descent might have caused ice to be released from the fuel pipes in the strut. Ice was allowed to accumulate for 6 hours at a fuel flow of 6,000 pph and a temperature of -20°C (-4°F). At the end of this period, hot air was blown into a box surrounding the strut pipes to increase the temperature from approximately 15°C (59°F) to 38°C (100°F). Whilst the frost on the outside of the strut pipes remained intact, the pressure drop across a cold FOHE slowly increased from 20 to 75 psid. After a further hour the fuel flow was increased, but despite the control valve being moved to the fully open position the fuel flow peaked briefly at 10,000 pph before dropping back to 8,000 pph with a corresponding increase in the pressure drop across the FOHE of 170 psid. This was indicative of a restriction at the FOHE.

An inspection of the fuel pipes revealed that, whilst there was no ice in the rigid pipes in the strut, there was some ice in the flexible pipe in the strut and a large amount of ice throughout the rest of the fuel system. Approximately 35 ml of water was collected from the ice on the face of the FOHE.

Water concentration

It was estimated that the fuel uplifted in Beijing at the start of the accident flight might have contained up to 70 ppm[5] of dissolved and entrained (suspended) water; this concentration occurs naturally in aviation jet fuel and would have reduced during the flight as some of the water settled and froze on the bottom of the fuel tank. Fuel samples taken from G-YMMM after the accident indicated that the water concentration in the fuel taken from the left main tank sump, APU line and Variable Stator Vane actuator was approximately 40 ppm. This was comparable with the water concentration in fuel samples taken from the engine fuel filter housings on another Boeing 777 that flew a similar route.

For the accumulation and release tests it was decided to use the industry standard[6] for continuous system operation tests, aiming to condition the fuel with 90 ppm of water.

The water concentration in the fuel used in the accumulation and release tests was established by running at least two Karl Fischer tests on each fuel sample in accordance with the industry standard ASTM D6304. Despite closely metering the amount of water added to the fuel, the results of the testing of fuel samples taken every 30 minutes indicated that the amount of water in the fuel flowing through the pipes varied from approximately 45 to 150 ppm. The discrepancy between the metered and measured water content might be explained by ice collecting, and being released, from the supply tank, pump inlet screen and the feed pipes between the supply tank and the pipes being tested. However, it was also observed, from the results of several Karl Fischer tests carried out on the same sample of fuel, that the measured water concentration could vary by up to 60 ppm.

The variation in the measured water content of the fuel, and the accuracy of the Karl Fischer tests, could not be improved and were, therefore, accepted as test limitations.

Analysis - testing

Fuel system tests

The aircraft manufacturer's tests show that, with normal concentrations of dissolved and entrained (suspended) water present in aviation turbine fuel, ice can form around the inside of the fuel feed pipes. The

Footnote

5 Refer to the initial interim report for details on water concentration in aviation turbine fuels.

Footnote

6 SAE ARP 1401 and SAE AIR 790.

accumulation of ice appears to be dependent on the velocity of the fuel and the fuel and environmental temperatures. The testing established that ice can accumulate in the fuel system when the fuel is at a temperature of +5°C[7] (41°F), -12°C (10°F) and -20°C (-4°F), with ice appearing to accumulate at a lower rate at -20°C (-4°F). Whilst very little ice accumulates at -35°C (-31°F), ice which has accumulated at warmer temperatures will stay attached to the pipe walls as the temperature is reduced to -35°C (-31°F) with no apparent change in its properties. These results are consistent with the earlier 'beaker tests' undertaken by the aircraft manufacturer as well as previous research on the formation of ice in aircraft fuel systems. This work identified that there is a 'sticky range' between approximately -5°C (23°F) and -20°C (-4°F), where ice will adhere to its surroundings with ice being at its most 'sticky' at around -12°C (10°F).

The tests carried out in the environmental fuel test rig demonstrated that increasing the fuel flow can result in the release of a quantity of ice sufficient to restrict the fuel flow through the FOHE. An increase in the TAT, which occurs when the aircraft descends, results in an increase in the temperature in the strut, which the tests proved could also cause ice to be released from the fuel pipes in the strut area.

It was also evident, from all the fuel rig testing, that ice can move through the fuel feed system and under very low flow conditions might collect in areas such as the strut pipes, which form a low point when the aircraft is in its normal cruise attitude, and the LP pump inlet. However, it should be emphasised that the investigation did not identify any features in the aircraft fuel system which would cause a large enough concentration of ice to accumulate and cause a restriction.

Generation of ice

To overcome the difficulties in maintaining the water concentration in cold fuel, the aircraft manufacturer fitted a Perspex box around the boost pump inlet and introduced a mixture of warm fuel and water into the cold fuel, through an atomising nozzle. Nitrogen was then blown across the nozzle to prevent the water freezing and blocking the holes. This produced ice crystals which had formed from a high concentration of entrained (suspended) water, which would then adhere to the inside of the pipes. On the accident flight, the ice crystals would have formed from a lower concentration of entrained water. Some of this entrained water would already be present in the fuel and some would have formed as dissolved water was released as the fuel cooled. These processes may produce varying sizes of water droplet which, with the different concentrations and agitation of the fuel, might influence the properties of the ice crystals and the ice which subsequently formed on the inside of the fuel feed pipes.

In the testing of the FOHE, on the fuel rig, the ice crystals were formed by injecting a mixture of water, at very high concentrations, and fuel directly into the boost pump inlet. These ice crystals would then travel at the same velocity as the fuel through the fuel system and collect on the face of the FOHE, causing a restriction of the fuel flow. However, it is not known if the properties of the ice generated in this manner are the same as the properties of the ice which might release from the inside of the fuel feed pipes. It is also not known if ice released from the inside of the fuel pipes travels through the system at the same velocity as the fuel.

Footnote

[7] Ice will form when fuel at a temperature of +5°C is flowing through cold fuel pipes.

Engine testing

The AAIB initial interim report of 4 September 2008 included an extensive description of the flight data recorded on the accident flight and the analysis. It also described the initial fuel system testing performed at the engine manufacturer.

Tests carried out by the engine manufacturer demonstrated that fluctuations in the P30 burner pressure, fuel flow and spool speeds, recorded on the FDR and QAR during the engine rollback on G-YMMM, were generally more closely matched when a restriction was placed in the fuel feed pipe approximately 25 feet or more from the aircraft to strut interface. These tests were carried out using warm, un-weathered[8] fuel and with fixed 'restrictor' plates and the analysis could not, therefore, consider the dynamics of ice moving through the system, or possible changes in the porosity of the ice as it becomes compressed onto the face of the FOHE. Further, within the extensive testing to date it has not been possible to generate a restriction anywhere within the fuel system, other than at the boost pump inlet screens[9] and on the face of the FOHE.

Engine oil temperature recorded data

If the fuel path in an FOHE becomes substantially blocked for any reason, then its heat transfer efficiency will become degraded. This is because the fuel has to flow down a greatly reduced number of tubes at a higher velocity to maintain the overall flow rate. This loss of efficiency would imply that the engine oil temperature should rise accordingly, such as was seen during the N862DA event. The oil temperature, which is sensed at the scavenge outlet, takes some time to register variations but experience has shown that the oil pressure sensor, which is sensitive to changes in viscosity due to temperature changes, is quicker to react.

During early analysis of the G-YMMM recorded data, attempts were made to interpret the oil temperature parameters but this was hampered by the fact that the FDR records oil temperature and pressure at intervals of 64 seconds. The QAR samples at a faster rate - every two seconds - but, because of data buffering issues (outlined in the initial Interim Bulletin), QAR data was lost immediately after the left engine rolled back. It was concluded that no meaningful trend of oil temperature could be discerned at that time.

The data has been re-examined with respect to oil pressure. This showed that both left and right engines' oil pressure generally follow each other until the start of the final acceleration, which resulted in first the right and then the left engines rolling back. The left engine oil pressure rose, as expected, as the engine accelerated: the right engine oil pressure, however, started to decrease, even though the engine was also accelerating prior to its rollback. Whilst, this observation was based only on a few data points, it can be inferred that this was due to an oil temperature increase caused by a restricted FOHE and that the blockage occurred at, or close to, the start of the final acceleration. Unfortunately, the loss of QAR data so close to the left engine rollback meant that it was not possible to draw a similar conclusion for this engine.

Most likely scenario

Based on the available data, testing, and the analysis contained in the AAIB initial interim report, the investigation has established, that with a relatively low fuel flow, ice would start to form on the inside of the

Footnote

8 Aviation fuel contains dissolved air some of which dissipates out of the fuel as the fuel temperature and fuel tank pressure decreases. This condition is called weathering, which is the condition of the fuel on G-YMMM at the time of the accident.

9 The icing of inlet screens is unlikely to have occurred on the accident flight.

fuel feed pipes that pass through the main fuel tank whilst the centre tank was supplying fuel to the engines. When the main fuel tanks started to supply fuel to the engines, the temperature of the fuel in the main tanks was approximately -21°C (-6°F) and reduced over the following 5 hours to a temperature of -34°C (-29°F). During this period the rate that the ice accumulated in the pipes located in the main fuel tanks would have reduced as the fuel temperature moved out of the 'sticky range'; however it is likely, due to the warmer environment in the strut (engine pylon), that ice would have accumulated in the fuel feed pipes located in this area. Towards the end of the flight the rate that ice accumulated in the fuel feed pipes would change as the TAT and the fuel temperature increased.

It is considered that, in the later stages of the approach, the engine accelerations, and perhaps a combination of other factors such as turbulence, aircraft pitch changes and an increase in the strut temperature, could have contributed to a sudden release of soft ice in the fuel feed system for both engines. This ice would have travelled through the fuel feed pipes, where it could have formed a restriction on the face of the FOHE sufficient to cause the subsequent engine rollbacks.

Whilst this is considered to be the most likely cause of the engine roll backs on G-YMMM, and is consistent with data from the incident to N862DA, it has not been possible, due to limitations in the available recorded data, to totally eliminate the possibility that a fuel restriction, from ice, formed elsewhere in the fuel system which, in addition to an FOHE restriction, contributed to the engine roll backs on G-YMMM. It should be noted that extensive testing and data analysis has not identified any features elsewhere in the aircraft fuel system which would have caused a large enough concentration of ice to accumulate and cause a restriction.

In summary, the investigation has established that it is possible for sufficient ice to build up within the fuel feed system, such that its sudden release would cause a restriction at the FOHE sufficient to cause an engine rollback. Therefore:

Safety Recommendation 2009-028

It is recommended that Boeing and Rolls-Royce jointly review the aircraft and engine fuel system design for the Boeing 777, powered by Rolls-Royce Trent 800 engines, to develop changes which prevent ice from causing a restriction to the fuel flow at the fuel oil heat exchanger.

In response to Safety Recommendation 2009-028 Boeing and Rolls-Royce have stated that:

> 'Boeing and Rolls-Royce have accepted the above recommendation. To mitigate the potential for a future fuel system ice accumulation and release event, to cause a blockage at the inlet to the FOHE, Rolls-Royce have developed a modification to the FOHE. The modification will improve the FOHE's capability in the event of a fuel system ice release event.'

To ensure that changes as a result of Safety Recommendation 2009-028 are introduced onto in-service aircraft in a timely manner:

Safety Recommendation 2009-029

It is recommended that the Federal Aviation Administration and the European Aviation Safety Agency consider mandating design changes that are introduced as a result of recommendation 2009-028, developed to prevent ice from causing a restriction to the fuel flow at the fuel oil heat exchanger on Boeing 777 aircraft powered by Rolls-Royce Trent 800 engines.

The tests that have been carried out were all related to the Boeing 777 and Trent 800 fuel system. It is unknown if other airframe-engine combinations are susceptible to this phenomenon; therefore Recommendation 2008-048 was made to EASA and the FAA in the initial interim report to address this concern.

Anti-ice additives in aviation fuel

Ice in aviation turbine fuel is an industry-wide problem and currently the mechanism by which it accumulates and is released within an aircraft and engine fuel system is not fully understood.

The military, and some business jet operators, have used anti-icing additives in aviation turbine fuel as a means of preventing ice from forming within the aircraft and engine fuel systems. The widespread use of such additives would reduce the risk from ice in fuel. However, its introduction worldwide would not only require changes to the infrastructure and ground fuel handling systems, but it could also lead to increased aircraft maintenance. Moreover, unlike the Boeing 777, not all aircraft are currently cleared to use existing anti-icing additives.

Despite the difficulties, the use of an anti-icing additive could significantly reduce, or even eliminate, ice formation in aviation turbine fuel. Therefore, to clarify the current issues:

Safety Recommendation 2009-030

It is recommended that the Federal Aviation Administration and the European Aviation Safety Agency conduct a study into the feasibility of expanding the use of anti-ice additives in aviation turbine fuel on civil aircraft.

Future industry activity

The formation of ice in aircraft fuel systems from dissolved and entrained water in aviation turbine fuel is well documented and is largely based on observations and conclusions made during research projects undertaken in the 1950s. This research formed the basis of the SAE Aerospace Information Report (AIR) 790 and SAE Aerospace Recommended Practice (ARP) 1401, which advises the aerospace industry on suggested procedures to test aircraft fuel systems and components for icing.

This early research established that it is possible for ice to form from dissolved water, alone, in aviation turbine fuel which can then block filters and small orifices. A number of different types of ice were observed which was described as being 'slush ice' and 'soft white ice', which when melted contained between 10% and 30% water. During this period the United States Air Force (USAF) undertook research into the formation of ice in fuel and observed that not all the water droplets form ice crystals, but some of the water remains as supercooled droplets. The research concluded that the type of ice is dependent on a number of factors including the rate of cooling, water droplet size and the agitation of the fuel. It was also noted that the variation in fuel composition between batches of fuel affects the concentration and size of the water droplets and the amount of subsequent icing.

A solution to the early icing problems was to produce a remedy for the specific problem: fuel heaters and filter bypasses were introduced and the optimum mesh size for the boost pump inlet screens was determined. The USAF, like other military organisations, introduced Fuel System Icing Inhibitor (FSII), which can help to prevent the formation of ice.

Little is known about the properties of ice formed in aviation turbine fuel and, during the extensive testing undertaken by the manufacturer in this investigation, there was 'randomness' in the formation of ice, with poor repeatability between batches of fuel with similar compositions.

Given the physical size of the Boeing 777 it was not practical to undertake a 'one pass' test of the fuel through a full scale system. Instead, as is current industry practice, for the tests cited in this report, part of the fuel system was tested by circulating the fuel through an external heat exchanger and storage tank. However, due to the cloudiness of the fuel it was not possible to visually monitor the formation of ice, nor was it always possible, using pressure sensors and temperature-measuring equipment, to determine whether ice was present. Consequently, it was not possible to detect the release and movement of ice through the fuel system without first draining out the fuel and then dismantling the system. Circulation of the fuel also makes it difficult to maintain the water concentration at levels experienced in flight. It is known, from previous research, that agitation and the rate of cooling of the fuel can affect the type of ice formed, and therefore there is uncertainty regarding the similarity of the properties of the ice generated during rig tests to the ice generated in flight.

In the testing of fuel systems at cold temperatures there are two aspects which need to be considered: fuel waxing and fuel icing. Whilst fuel waxing is determined by the temperature of the fuel, the risk from fuel icing is more complex. This investigation has established that the phenomenon, where ice can accumulate and then release, appears to be dependent on the time that the fuel temperature is in the 'sticky region', low fuel flow, environmental factors and aircraft attitude. It is considered that a combination of these factors would lead to the quantity of ice accumulating within the fuel system reaching a critical level.

Whilst the guidelines in SAE ARP 1401 and SAE AIR 790 recommend that ice testing should be carried out at various flow rates, and with the fuel temperature in the 'sticky range', they do not address the risk from ice accumulating throughout the fuel system and subsequently releasing. Consequently, there is no published guidance on the environmental conditions, or how much of the fuel system needs to be assembled in a test rig, to accomplish these fuel icing tests.

The investigation has established that the risk from fuel system icing is complex and is dependent on a number of interactions that are not fully understood. Much of the current industry guidance is based on research undertaken over 50 years ago and since that time civil aircraft have become larger, fly for longer periods and incorporate new technology and materials. In order to improve guidelines for the design and testing of aircraft fuel systems it will be necessary for the aviation industry, led by the regulatory authorities, to undertake a number of co-ordinated research projects. The first step would be to understand how ice forms in aviation turbine fuel and the properties of this ice. Therefore:

Safety Recommendation 2009-031

It is recommended that the Federal Aviation Administration and the European Aviation Safety Agency jointly conduct research into ice formation in aviation turbine fuels.

Research is also required to establish how ice accumulates in a fuel system and to establish the factors that may cause it to be released in a sufficient concentration to restrict the fuel flow. The results of this research can then be used to further develop the industry guidance on fuel system design, materials, and the development of test procedures for aircraft fuel systems. Therefore:

Safety Recommendation 2009-032

It is recommended that the Federal Aviation Administration and the European Aviation Safety Agency jointly conduct research into ice accumulation and subsequent release mechanisms within aircraft and engine fuel systems.

Further AAIB investigation

The investigation continues, including examination of the crashworthiness aspects of the accident, and further analysis is being carried out on fuel and engine data from other Boeing 777 aircraft. A final 'Inspector's investigation' report, ordered by the Chief Inspector of Air Accidents and covering all safety aspects of the accident, will be published in due course.

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