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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	

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

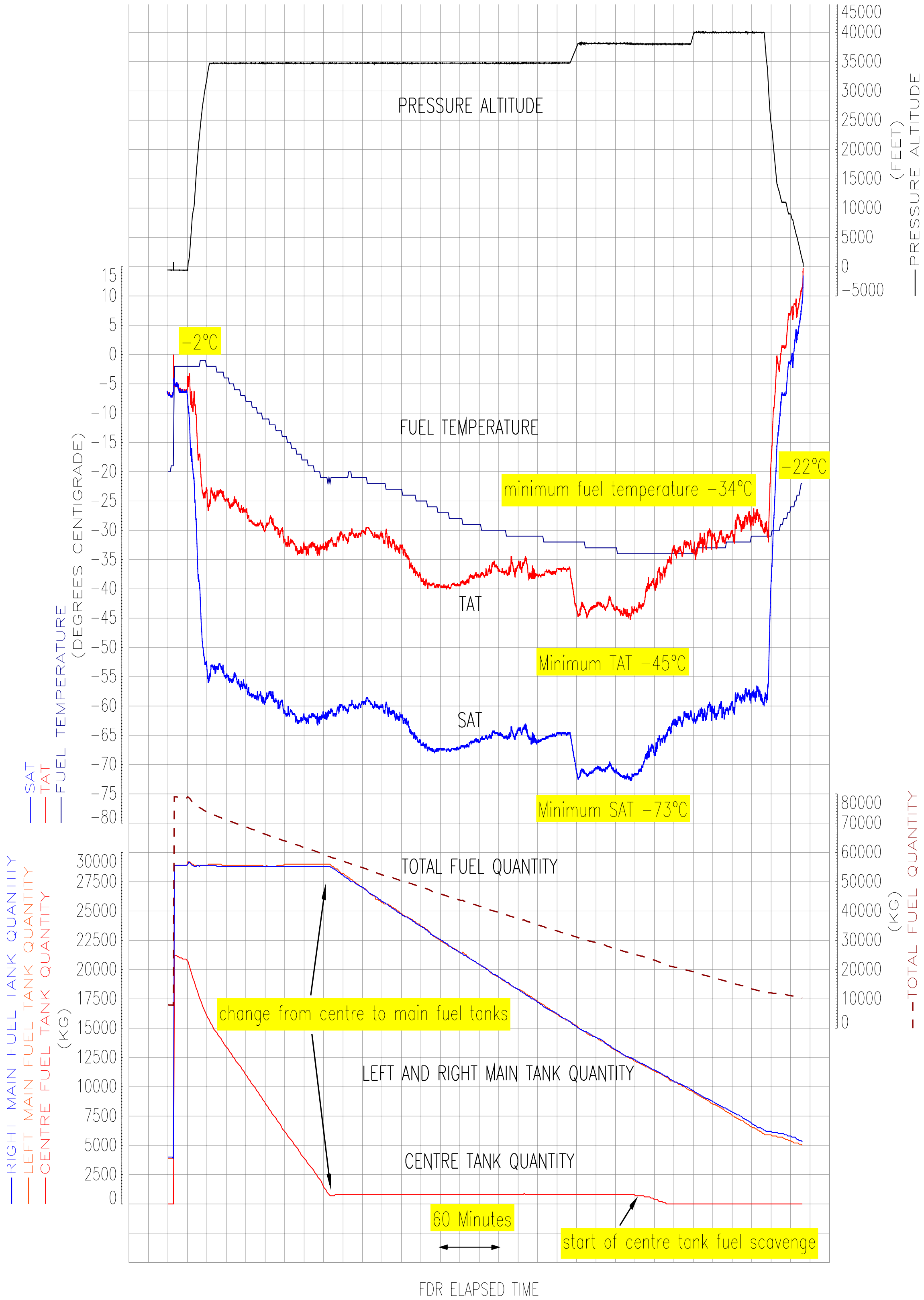

Figure 1

Temperatures

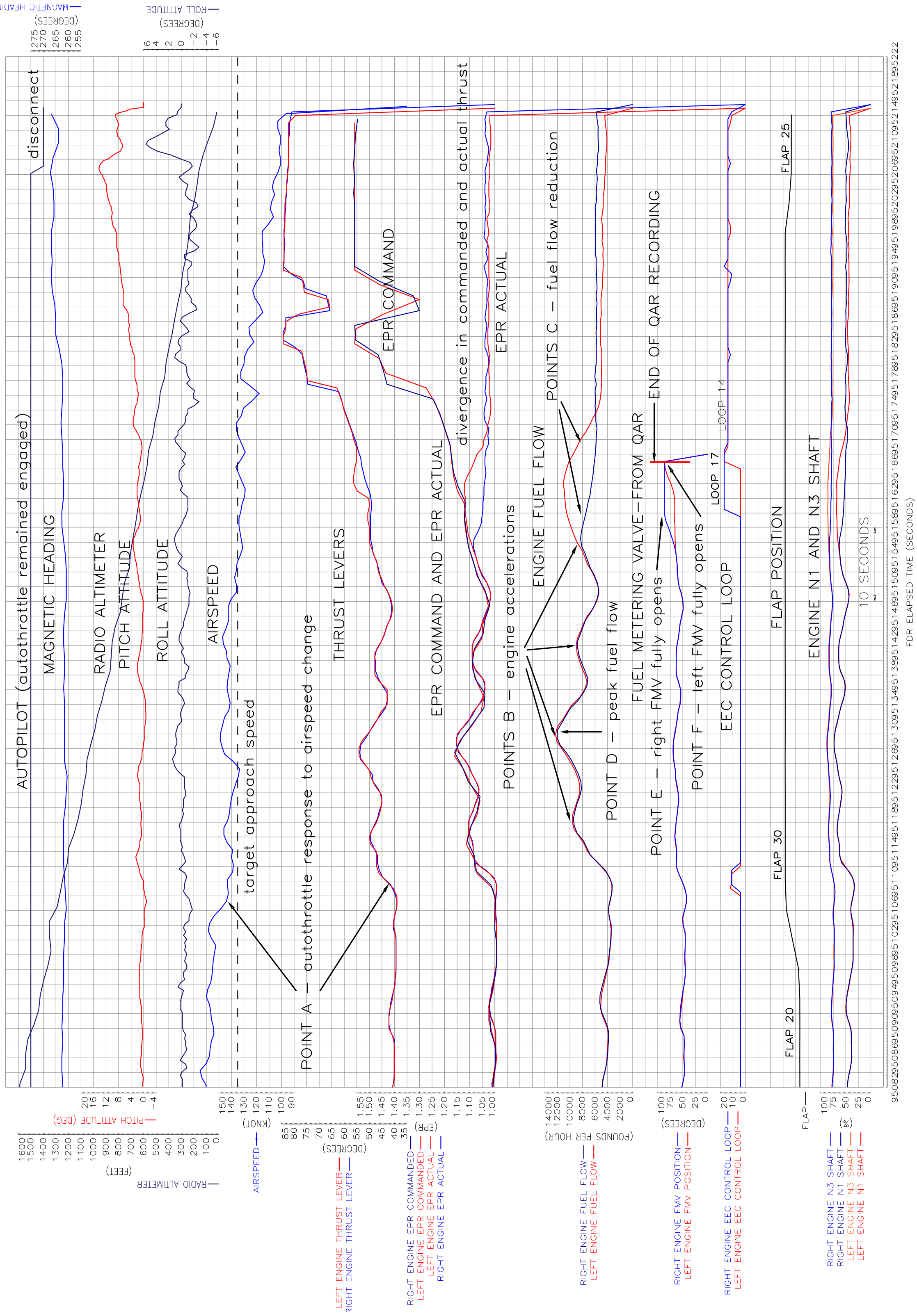

Figure 2

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.

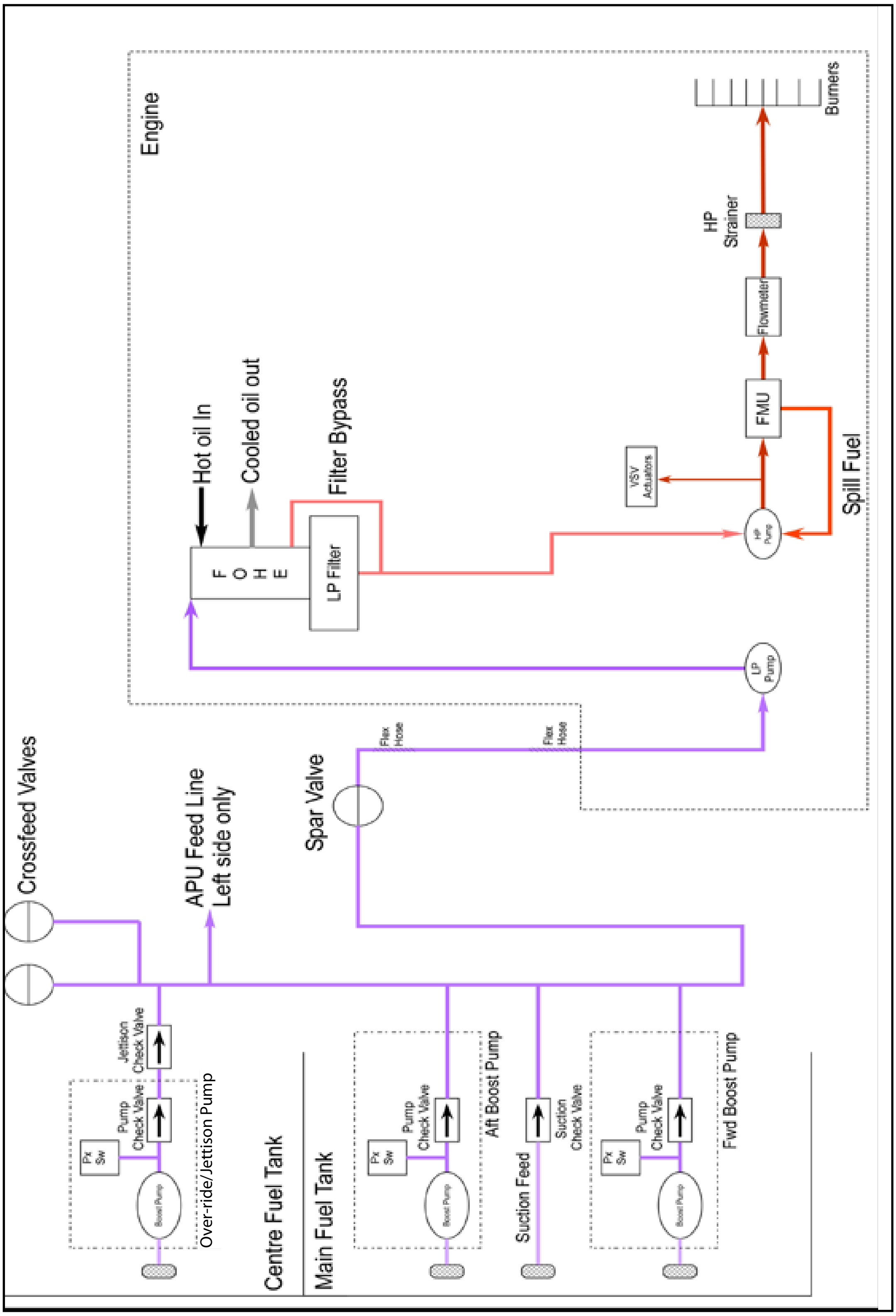

Figure 3

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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