AIRCRAFT ACCIDENT REPORT No 1/2010

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REPORT ON THE ACCIDENT TO BOEING 777-236ER, G-YMMM, AT LONDON HEATHROW AIRPORT ON 17 JANUARY 2008

Registered Owner and Operator	British Airways PLC
Aircraft Type	Boeing 777-236ER
Serial No	30314
Nationality	British
Registration	G-YMMM
Place of Accident	London Heathrow Airport
Date and Time	17 January 2008 at 1242 hrs All times in this report are UTC

Synopsis

The Air Accidents Investigation Branch (AAIB) was notified at 1251 hrs on 17 January 2008 of an accident involving a Boeing 777-236ER aircraft registration G-YMMM at London Heathrow Airport. The investigation commenced immediately and the AAIB team consisted of:

Mr R Tydeman
Investigator-in-Charge January 2008 - October 2008
Mr R D G Carter
Investigator-in-Charge from November 2008
Mr P A Sleight
Engineering - Deputy IiC & Lead Engineer
Ms A Evans
Engineering - Chair Crashworthiness Group
Mr B D McDermid
Engineering - Chair Fuel and Fuel System Group
Mr S W Moss
Engineering - Chair Powerplant Group
Mr R Parkinson
Engineering - Chair Aircraft Group
Mr M W Ford
Flight Data Recorders - Chair Data Group
Mr A Severs
Operations - Lead Operations
Mr P E B Taylor
Operations - Chair Evacuation Group

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, appointed an Accredited Representative and was supported by a team which included additional investigators from the

NTSB, the Federal Aviation Administration (FAA) and Boeing; Rolls-Royce, the engine manufacturer, also participated fully in the investigation. The operator co-operated with the investigation and provided expertise as required. The Civil Aviation Authority (CAA) and the European Aviation Safety Agency (EASA) were kept informed of developments.

On 28 November 2008, a Boeing 777-200ER suffered an in-flight engine rollback; an investigation by the NTSB was initiated with Mr P A Sleight, from the AAIB, assigned as the UK accredited representative.

Prior to this Final Report the AAIB published an Initial Report, on 18 January 2008, a subsequent update on 23 January 2008, Special Bulletins on 18 February 2008 and 12 May 2008, and Interim Reports on 4 September 2008 and 12 March 2009.

Eighteen Safety Recommendations have been made.

Whilst on approach to London (Heathrow) from Beijing, China, at 720 feet agl, the right engine of G-YMMM ceased responding to autothrottle commands for increased power and instead the power reduced to 1.03 Engine Pressure Ratio (EPR). Seven seconds later the left engine power reduced to 1.02 EPR. This reduction led to a loss of airspeed and the aircraft touching down some 330 m short of the paved surface of Runway 27L at London Heathrow. The investigation identified that the reduction in thrust was due to restricted fuel flow to both engines.

It was determined that this restriction occurred on the right engine at its Fuel Oil Heat Exchanger (FOHE). For the left engine, the investigation concluded that the restriction most likely occurred at its FOHE. However, due to limitations in available recorded data, it was not possible totally to eliminate the possibility of a restriction elsewhere in the fuel system, although the testing and data mining activity carried out for this investigation suggested that this was very unlikely. Further, the likelihood of a separate restriction mechanism occurring within seven seconds of that for the right engine was determined to be very low.

The investigation identified the following probable causal factors that led to the fuel flow restrictions:

1. Accreted ice from within the fuel system[1] released, causing a restriction to the engine fuel flow at the face of the FOHE, on both of the engines.

2. Ice had formed within the fuel system, from water that occurred naturally in the fuel, whilst the aircraft operated with low fuel flows over a long period and the localised fuel temperatures were in an area described as the 'sticky range'.

3. The FOHE, although compliant with the applicable certification requirements, was shown to be susceptible to restriction when presented with soft ice in a high concentration, with a fuel temperature that is below -10°C and a fuel flow above flight idle.

4. Certification requirements, with which the aircraft and engine fuel systems had to comply, did not take account of this phenomenon as the risk was unrecognised at that time.

Footnote

[1] For this report 'fuel system' refers to the aircraft and engine fuel system upstream of the FOHE.

Findings

Conduct of the flight

1. The crew were properly licensed and rested to conduct the flight.

2. The aircraft had been loaded with 71,401 Kg of Jet A-1 fuel at Beijing and the total fuel load at the start of the accident flight was 79,000 kg. This was sufficient fuel to complete the flight.

3. The left main fuel tank temperature at takeoff was -2°C, this was not unique and data mining revealed that a small percentage of B777 flights had a fuel temperature below 0°C at takeoff.

4. During the flight from Beijing the fuel temperature reached a minimum of -34°C and the minimum TAT reached was -45°C. These temperatures experienced during the flight were unusual but were within the operating envelope of the aircraft and were not unique.

5. During the flight two step climbs were completed in VS mode which required relatively low fuel flows and contributed to low average fuel flows for the flight.

6. Data mining showed that the accident flight was unique amongst 175,000 flights as having a low cruise fuel flow and a high fuel flow during approach while at a low fuel temperature.

7. The flight from Beijing had been uneventful until the final approach to Runway 27L at London Heathrow.

8. The co-pilot took control of the aircraft from the commander at 800 ft in accordance with the operator's procedures.

9. At 720 ft agl the right engine suffered an uncommanded reduction in engine power to 1.03 EPR and seven seconds later the left engine suffered an uncommanded reduction in engine power to 1.02 EPR.

10. The right engine fuel flow reduced to 6,000 pph and the left engine fuel flow reduced to 5,000 pph, levels above those required by an engine at flight idle.

11. Both the left and right engine FMVs moved to full open and the EECs entered LIC 17, with no effect on the fuel flow.

12. Data mining did not reveal any flight, other than the G-YMMM accident flight and the N862DA incident flight, that had indicated an EEC LIC 17 or had a genuine FMV position versus fuel flow mismatch.

13. The fuel temperature at the time of the engine rollback was -22°C. This was also the fuel temperature at which the rollback occurred on the N862DA incident flight.

14. The flight crew became aware of a possible problem with the thrust 48 seconds before touchdown.

15. The co-pilot intended to disconnect the autopilot at 600 ft but became distracted by the engine rollback, so the autopilot remained engaged.

16. The loss of engine power led to a reduction in airspeed as the autopilot attempted to

follow the ILS glideslope, leading to a nose-high pitch attitude.

17. Thirty-four seconds before touchdown the flight crew became concerned about the reduction in airspeed below the target approach speed and attempted manually to increase engine thrust to compensate; there was no response from the engines.

18. At 240 ft agl the commander retracted the flap from FLAP 30 to FLAP 25 which increased the distance to touchdown by about 50 metres; if left at FLAP 30 the touchdown would have still been within the airfield boundary.

19. At 200 ft agl the stick shaker activated and as a touchdown short of the runway was inevitable the commander transmitted a 'MAYDAY' call three seconds before touchdown.

20. At the operation of the stick-shaker, the co-pilot pushed forward on the control column and the autopilot disconnected.

21. The aircraft struck the ground within the airfield boundary at a recorded normal peak load of 2.9g, and a descent rate of about 1400 fpm (~25 ft/s), at 1242:09 hrs, 330 m short of Runway 27L and slid 372 m before coming to rest.

22. During the latter stages of the approach the commander attempted to start the APU, but the start sequence was not completed.

23. The landing gear attachments were disrupted during the initial impact, the left MLG collapsed and the right MLG separated from the aircraft.

24. The nose landing gear collapsed and the lower side of the aircraft and engines were severely disrupted during the ground slide.

Evacuation and survivability

25. There was insufficient time for the flight crew to brief the cabin crew or issue a 'brace brace' command.

26. The evacuation alarm was perceived by the cabin crew as sounding 'faint' in the cabin.

27. The evacuation alarm was later found to operate satisfactorily, except at Door 1L which was silenced due to a stuck reset switch.

28. There is no minimum performance specification for the evacuation alarm as it is an optional fit to the aircraft. However, sound level checks met BS EN 1SO 7731.

29. The commander initially announced his evacuation call over the VHF radio, but when ATC informed him of this, the call was repeated over the cabin PA system.

30. The cabin crew initiated the evacuation, all the escape slides deployed satisfactorily and all the passengers evacuated the aircraft.

31. The passenger in seat 30K suffered a broken leg as items from the right MLG penetrated the fuselage during the ground slide.

32. 34 passengers and 12 cabin crew suffered minor injuries, mainly to the back and neck.

33. The evacuation was conducted efficiently with clear instructions from the cabin crew.

34. Some passengers attempted to retrieve personal items during the evacuation.

35. There was no fire; however there was a significant fuel leak and an oxygen leak from disrupted passenger oxygen bottles. The AFS were on site within 2 minutes of the initial touchdown.

36. The operator's evacuation check list split the actions between the commander and co-pilot and was on a placard on the control column. The commander operated the engine run/cutoff switch and the co-pilot the engine fire switches. The engine fire switches were operated first.

37. The evacuation check list from the aircraft manufacturer required the operation of the engine run/cutoff switch to CUTOFF prior to pulling the fire switch.

38. The spar valves remained OPEN following the accident despite the operation of the fire switches and engine run/cutoff switch to CUTOFF. This allowed 6,750 kg of fuel to leak out of the engines until the valves were manually closed.

39. The spar valves remained OPEN due to the wiring damage caused by the separation of the MLGs, which also caused the left spar valve circuit breaker to trip.

40. The wiring to the right spar valve from the engine run/cutoff switch remained intact. Pulling the fire handle isolated the run/cutoff relay and removed the ability of the run/cutoff switch signal to CLOSE the spar valve.

41. SB 777-28-0025 introduced a means of shutting the spar valve from the engine run/cutoff switches, even if the fire switch has been pulled. This SB had not been embodied on G-YMMM.

Crashworthiness - cabin

42. Exit sign lenses at Doors 3L and 3R detached during the accident due to the lack of positive retention.

43. Glass fragments from the indirect ceiling fluorescent tubes were found on the cabin floor.

44. The light fittings met the regulatory requirements for emergency landing loads, but these requirements did not allow for flexing of the surrounding structure.

45. Nine of the 32 Business economy video monitors detached from the seat backs, in the impact, due to wear of the support detent and spring.

Crashworthiness – structure

46. Both MLGs partially separated at initial impact with a vertical descent rate of 25 ft/s.

47. The left MLG attachments separated as designed.

48. On the right side a section of rear spar web ruptured during the detachment of the right

MLG and thus left a large breach in the right wing rear spar and centre fuel tank.

49. The right MLG had moved aft, causing the shock strut to contact the truck beam leading to the separation of the forward truck beam and two front wheels.

50. Two of the right MLG inboard wheels contacted the fuselage behind the MLG bay, disrupting the RAT and the passenger oxygen bottles, leading to an oxygen leak.

51. Simulation of the accident showed different behaviour depending on the type of impact surface.

52. Certification requirements for landing gear design do not specify differing impact surfaces.

Aircraft examination

53. The aircraft had been adequately maintained and had a valid certificate of airworthiness.

54. There were no recorded technical defects with the aircraft, prior to departure from Beijing, that would have contributed to the accident.

55. The left engine fuel valve circuit breaker had tripped due to the wiring disruption to the underside of the engine during the ground slide.

56. The Ram Air Turbine had not deployed prior to the initial impact.

57. The forward cross-feed valve was found OPEN and the switches for the cross-feed valves on the overhead fuel panel were also in OPEN.

58. The operation of the forward cross-feed valve was after the power had been lost to the DFDR during the accident ground slide. Prior to this point it was CLOSED.

59. The loose fuel scavenge union in the left fuel tank was not a factor in this accident.

60. The manufacturing debris found in the fuel tanks was not a factor in this accident.

61. The right suction check valve was found to stick OPEN, but was not a factor in this accident.

62. There was no evidence that HIRF or EMI were factors in this accident.

63. There were no pre-existing defects with the engines and the engine control systems operated correctly.

Fuel

64. There was 10,500 kg of fuel remaining on the aircraft at the time of the engine rollback, 5,100 kg in the left main fuel tank and 5,400 kg in the right main fuel tank.

65. The fuel onboard G-YMMM was consistent with Jet A-1 and met the Defence Standard 91-91 and ASTM D1655.

66. The fuel sampled from G-YMMM contained 35 to 40 ppm of water, which was similar to that found on other aircraft that had flown similar routes.

67. The fuel had not, at any time during the flight, cooled to a temperature at which it would suffer from fuel waxing.

68. The operator had the highest practicable frequency of fuel sumping for the Boeing 777. The frequency and efficiency of the fuel tank sumping was not a factor in this accident. The aircraft had been last sumped on the 15 January 2008.

69. The centre tank water detection messages, recorded during taxi in Beijing, were most likely 'nuisance' messages.

70. The centre tank fuel scavenge system was not a factor in this accident.

71. The water scavenge system was not a factor in this accident.

Recorded data

72. The DFDR did not record FMV position; however it was recorded on the non-protected QAR.

73. The QAR buffer caused the loss of 45 seconds of data prior to the accident.

Restriction to fuel flow

74. The FMV positions and the recorded fuel flows showed that both engines had suffered restrictions in the fuel delivery system to the engine.

75. The left and right HP pumps had signs of fresh cavitation, indicating that the restriction was recent and upstream of the pump.

76. The aircraft fuel boost pump had not indicated a low pressure during the flight.

77. Testing and analysis of the engine response has shown that aeration of the fuel had not occurred.

78. The restriction was downstream of the forward boost pump connection into the fuel manifold and upstream of the HP pump.

79. There was no remaining evidence of a physical restriction in the fuel system.

80. The fuel spar valves had remained open throughout the flight and there was no indication of an uncommmanded movement of a spar valve, either recorded or reported by the flight crew.

Engine testing

81. Engine tests and analysis suggested that a restriction could have been in place prior to the final series of four acceleration/deceleration cycles, during the approach, if the restriction was sited 25 feet or more from the strut interface.

82. The engine tests used fixed restrictor plates, warm, unweathered fuel and did not consider the dynamics or properties of ice in the system.

83. It was concluded that the restriction most probably occurred at the face of the FOHE just prior to the final acceleration cycle.

Fuel system testing

84. Ice can form within the fuel system feed pipes with normal concentrations of dissolved and entrained water present in aviation turbine fuel.

85. Ice can form on the inside of fuel pipes when warm fuel at a temperature of +5°C flows through cold pipes.

86. There is a 'sticky range' between -5°C and -20°C, when ice crystals in aviation fuel are most likely to adhere to their surroundings.

87. The ice is most 'sticky' at -12°C.

88. Ice does not appear to stick to the inside of the fuel pipes when the fuel temperature is at -35°C or below.

89. Ice that accumulated in the fuel system, during testing, was always soft and mobile.

90. The properties of the ice generated during testing may not be the same as the properties of the ice generated in flight.

91. Increasing the fuel flow can cause accreted ice to be released from the walls of the fuel pipes.

92. Ice released from within the fuel pipes could form a restriction at the face of the FOHE.

93. Tests demonstrated that water when injected into a cold fuel flow at concentrations of the order of 100 times more than certification requirements could form a restriction at the face of the FOHE.

94. Sufficient ice can accumulate in the Boeing 777 fuel system, which, when released, could form a restriction on the face of the FOHE.

95. It was not possible to restrict the fuel flow through the FOHE when fuel temperature in the main tank was warmer than: -15°C at a flow of 6,000 pph, and -10°C at a flow of 10,000 pph.

96. Reducing the fuel flow to idle always cleared any ice restriction on the face of the FOHE and therefore restored full fuel flow capability.

97. The FOHE was the only component in the fuel system that could be demonstrated to collect sufficient ice to cause the fuel restrictions observed during the accident flight.

98. The minimum fuel temperature of -34°C was not critical to the formation of ice in the fuel system.

99. A temperature below 0°C at takeoff has little effect on ice accumulation compared to during flight.

100. FSII is a means of preventing ice formation in fuel systems.

101. Research from the 1950s identified the problem of ice formation in fuel systems from dissolved or entrained water, but did not identify the scenario of accumulated ice release and subsequent restriction to fuel flow.

102. There are no published guidelines on environmental conditions or fuel rig size required to accomplish tests on the susceptibility of a fuel system to ice.

103. Current certification requirements do not address the scenario of ice accumulation and release within fuel systems.

The engine rollbacks

104. Ice probably began to accumulate in the fuel feed pipes whilst the warm centre tank fuel flowed through cold fuel pipes that pass through the main fuel tank at the start of the flight.

105. Ice would have continued to accumulate in the fuel feed pipes as the fuel was later fed from the main fuel tanks, but the rate of ice accumulation reduced as the fuel temperature dropped from -20°C down to its minimum temperature of -34°C.

106. The rate of accumulation of ice in the fuel pipes in the strut area may have been greater due to the warmer environment, whilst the localised fuel temperature was in the 'sticky range'.

107. Ice accumulation rates changed as the fuel temperature and TAT rose toward the end of the flight.

108. During the later stages of approach, the accumulated ice in the fuel system was probably released due to the final set of engine accelerations and possibly a combination of turbulence, aircraft pitch changes and an increase in strut temperature.

109. The ice would have travelled through the fuel feed system and formed a restriction on the face of the FOHE sufficient to cause the subsequent engine rollbacks.

110. The recorded drop in oil pressure on the right engine, which occurred close to the start of the final acceleration, was consistent with a restriction of the fuel flow at the face of its FOHE.

111. The recorded oil pressure data for the left engine ceased before it could provide any meaningful data for a positive determination of a restriction at its FOHE.

112. For the left engine, the investigation concluded that the restriction most likely occurred at its FOHE. However, due to limitations in available recorded data, it was not possible totally to eliminate the possibility of a restriction elsewhere in the fuel system, although the testing and data mining activity carried out for this investigation suggested that this was very unlikely.

113. For the left engine, the likelihood of a separate restriction mechanism occurring within seven seconds of that for the right engine is very low.

114. In response to AAIB Safety Recommendation 2008-047, Boeing introduced operational changes to mitigate the risk from fuel icing in the B777 powered by Trent 800 engines.

115. In response to the findings of this investigation Rolls-Royce developed a modified version of the FOHE and this was approved, and mandated, by the EASA.

Safety Recommendations

Safety Recommendations made previously in S1/2008 published 18 February 2008

Safety Recommendation 2008-009

Boeing should notify all Boeing 777 operators of the necessity to operate the fuel control switch to CUTOFF 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.

Safety Recommendations made previously in Interim Report published on 15 September 2008.

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.

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.

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 systems.

Safety Recommendations made previously in Interim Report 2 published on 12 March 2009.

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.

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.

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.

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.

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.

Safety Recommendations made in this report

Safety Recommendation 2009-091

It is recommended that the European Aviation Safety Agency introduce a requirement to record, on a DFDR, the operational position of each engine fuel metering device where practicable.

Safety Recommendation 2009-092

It is recommended that the Federal Aviation Administration introduce a requirement to record, on a DFDR, the operational position of each engine fuel metering device where practicable.

Safety Recommendation 2009-093

It is recommended that Boeing minimise the amount of buffering of data, prior to its being recorded on a QAR, on all Boeing 777 aircraft.

Safety Recommendation 2009-094

It is recommended that Boeing apply the modified design of the B777-200LR main landing gear drag brace, or an equivalent measure, to prevent fuel tank rupture, on future Boeing 777 models and continuing production of existing models of the type.

Safety Recommendation 2009-095

It is recommended that the Federal Aviation Administration amend their requirements for landing gear emergency loading conditions to include combinations of side loads.

Safety Recommendation 2009-096

It is recommended that the Federal Aviation Administration, in conjunction with the European Aviation Safety Agency review the requirements for landing gear failures to include the effects of landing on different types of surface.

Safety Recommendation 2009-097

It is recommended that the Federal Aviation Administration require that Boeing modify the design, for the Boeing 777, of the indirect ceiling light assemblies, their associated attachments, and their immediate surroundings to ensure that the fluorescent tubes, or their fragments, will be retained in a survivable impact.

Safety Recommendation 2009-098

It is recommended that the Federal Aviation Administration and the European Aviation Safety Agency, review the qualification testing requirements applied by manufacturers to cabin fittings, to allow for dynamic flexing of fuselage and cabin structure.

Safety Recommendation 2009-100

It is recommended that the European Aviation Safety Agency mandate MSB4400-25MB059 Revision 3 to require the inspection and replacement of the video monitor fittings on the Recaro seat model 4400.