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

Footnote

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

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.

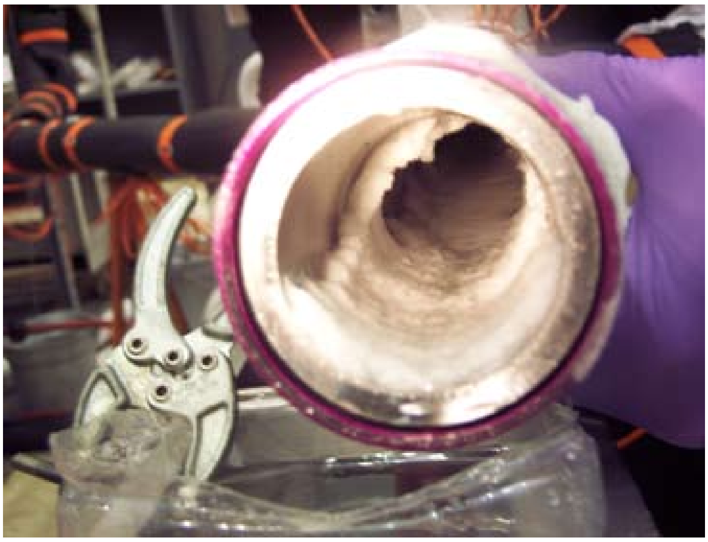

Figure 1

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.

- 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 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

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[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.

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.

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

Footnote

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

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 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),

Footnote

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

[6] SAE ARP 1401 and SAE AIR 790.

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

-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.

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 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

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[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.

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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