UPDATE – 2011

EI-ACF FORCED LANDING, JANUARY 1, 1953, SPERNAL, ENGLAND.

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After dedicated research of the BA BOEING 777, JANUARY 17, 2008, HEATHROW, ENGLAND Accident Report dated 2010 concluded

FUEL ICING WAS THE CAUSE.

The investigation in England and America has proved the matter conclusively.

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Because we believed the water threat, to propeller aircraft and Jets, our efforts over decades were not alone to refute the EI-ACF finding, but to maintain our pursuit of the Water in Fuel hazard in Aviation world wide, and fuel icing specifically.

The Captain of EI-ACF presented his Water in Fuel judgement from experience to the Company and the Public Inquiries. 57 years later his opinion has been proven correct.

No Recommendations were issued following the Case of EI-ACF.

Extract: Paper delivered on February 24, 1951 by
Air Commodore Vernon Brown
O.B., O.B.E., MA, F.R.Ae.S., RAF(ret'd)
Chief Inspector of Accidents
Ministry of Civil Accidents

'The evidence must be found – it must be written down and most carefully studied. What is untenable or irrelevant is discarded and after the elimination of the impossible what remains must be the truth'.

Extract: Letter from Capt. T. J. Hanley to Captain Lamplugh, Underwriter and Principal Surveyor, British Aviation Insurance Company, in 1953:

I believe that Filter Icing stopped the engines. De Havillands have produced similar results in their laboratories at about the same temperatures with a certain amount of water suspended in the fuel. They have also produced the same results with the Comet in the air and I understand that the ARB are insisting on Filter De Icing on the Comet and Viscount. Yet such a possibility would not be admitted here. They would rather blame the pilot than fully investigate the affair and perhaps save lives thereby. I was really lucky to survive. During my long connection with Aviation I have seen too many good men die often due to a very slight cause. I hope that this lengthy letter is not too much of an imposition and that you will succeed in helping me join a company which will take Aviation seriously.

Yours sincerely

T. J. Hanley

Dublin High Court Accident Report EI-ACF, 1953.

#45 **The Court was reluctantly driven to reject the possibility of any accidental cause operating to the same complete effect and at the same time to two separate fuel feed sources**, if in fact two separate fuel feed sources were being drawn on when power was lost.

(See **Log of Descent and Testimony of Air Traffic Controller, Mr. Prior.)**

JUNE 1953.

The 1953 Court of Inquiry opinion has been inadvertently comprehensively proven incorrect.

Extract: **Heathrow Boeing 777 Accident Report, January 2010.**

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

1) Accreted ice from within the fuel system 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 the 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 -10^0 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.

JANUARY 2010.

Hanley Family Comment.

Capt. Tommy Hanley, during his Army career was responsible for management of aviation spirit and its possible water content.!! When fuel was delivered to the aerodrome the water content was measured, removed and fuel replaced by the equivalent amount.

In 1953, at both the Company and Public Enquiries he presented his special knowledge of the water in fuel hazard. His testimony was rejected. The Liverpool Police Report was withheld by the Court. The actual copy was delivered to our home by a State courier hours after the verdict against the crew was issued in the Press. (Three members of the family attended the Court for the eleven days.)

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Highly Recommended Reading.

A Report written by Captain Christian Roger relating to the Air France 1988 A320 Accident from his position as a professional pilot. He was leader of the French air force's aerobatics team and later a civilian pilot with Air France.

He was President of the French Airline pilot's Association.

Report Title: The scandal of the Airbus A320 crash at Habsheim, France

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In each of the cases cited the pilots survived.

EXTRACTS:

REPORT ON THE ACCIDENT TO BOEING 777-236ER, G-YMMM, AT LONDON HEATHROW AIRPORT ON 17 JANUARY 2008, ISSUED 1/2010 AND RECOMMENDATIONS.

1.6.6 Engine fire protection and detection

The aircraft has two engine fire extinguishers, each with cartridges which, when fired, can supply extinguishant to either engine. However, only one bottle can supply one engine at any one time. The extinguishers are operated by the pulling and twisting of the fire handles in the flight deck.

1.6.7 Flying controls

The Boeing 777 primary flight control system uses fly-by-wire flying controls consisting of ailerons, flaperons, elevators, movable horizontal stabiliser, rudder and spoilers.

1.6.7.1 Flaps

The Boeing 777 has trailing edge flaps, leading edge slats and Krueger flap high lift devices controlled via a flap lever in the flight deck. The flap lever has detent positions set at UP, 1, 5, 15, 20, 25, and 30.

1.6.8 Fuel System

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 6). The centre tank contains two override / jettison pumps (OJ) and each main fuel tank contains two boost pumps, identified as forward and aft. Each of the pump inlets is protected by a ¼ inch mesh screen and the pumps are 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 impeller and check valve, monitors the fuel pressure and triggers an advisory warning in the flight deck if the pressure rise across the pump drops below a value, of between 4 and 7 psi.

Fuel feed manifold

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, identified as forward and aft. 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 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.

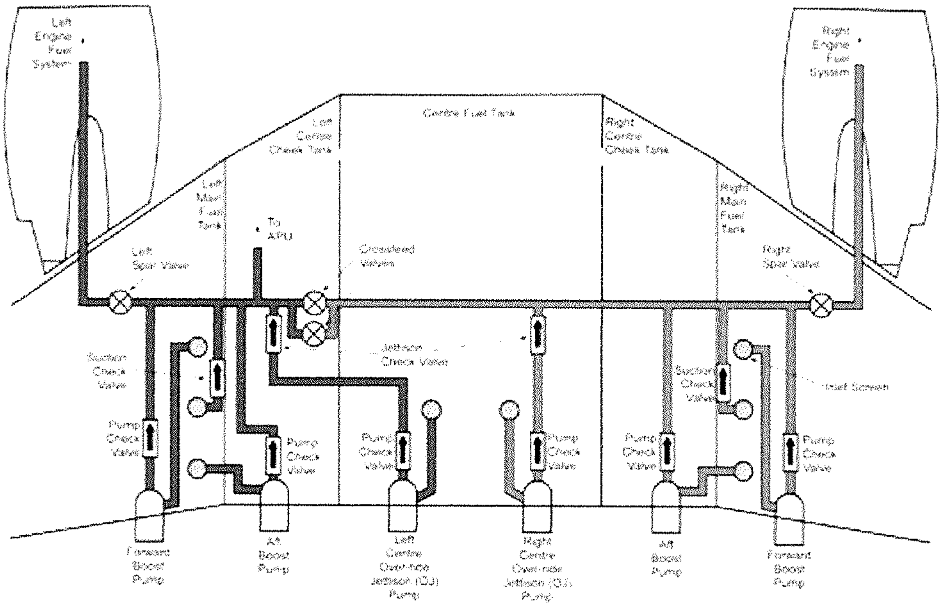

Figure 6

Simplified diagram of the airframe fuel system

Water scavenge

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 there are two in the centre tank. In the main fuel tanks the jet pumps draw fluid from the lowest sections of each tank and inject it close to the inlet of each aft boost pump. In the centre tank, fluid is drawn from the lowest section of the tank and injected close to the OJ inlets.

Centre tank fuel scavenge

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 contents are 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.

Fuel tank vent system

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.

Fuel delivery

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.

Engine low pressure stage of the Main Engine pump (Figure 7)

The airframe fuel system supplies fuel to the LP engine-driven pump, which forms part of the Main Engine Pump (MEP). This raises the fuel pressure (and fuel temperature slightly) and pumps the fuel through a Fuel/Oil Heat Exchanger (FOHE).

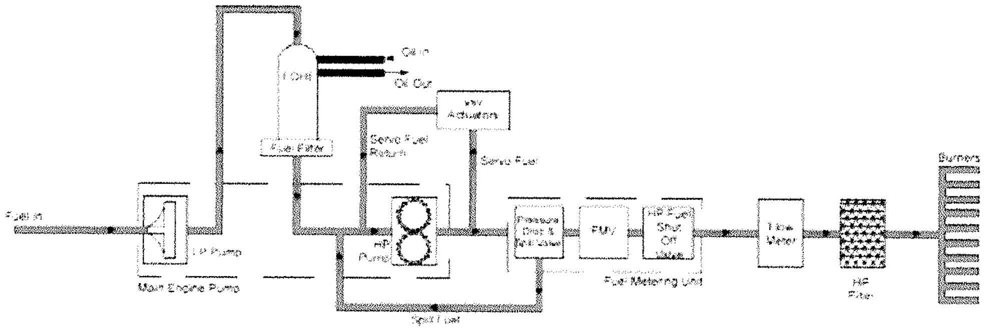

Figure 7

Simplified diagram of the engine fuel system

Fuel Oil Heat Exchanger (Figure 8)

The FOHE serves the dual purpose of cooling the engine oil and raising the temperature of the fuel so that ice does not affect the downstream components, including the LP filter and the Fuel Metering Unit (FMU). The FOHE is a hybrid cross-flow / counter-flow design and it includes a matrix of fine tubes. The fuel enters the top of the FOHE and passes through the tubes; the hot oil enters the FOHE main body and passes around the fuel tubes.

The temperature of the fuel after it has passed through the FOHE is considerably above its entry temperature. The FOHE matrix consists of over 1,000 small tubes that are crimped at various locations along their length to improve thermal transfer efficiency. The crimps at the inlet of the tubes are to a slightly smaller diameter than the remainder of the crimps to prevent small debris becoming lodged in the matrix. The tubes protrude by approximately 4 mm from the matrix top plate, which separates the fuel from the oil, and therefore extend into the fuel in the inlet chamber.

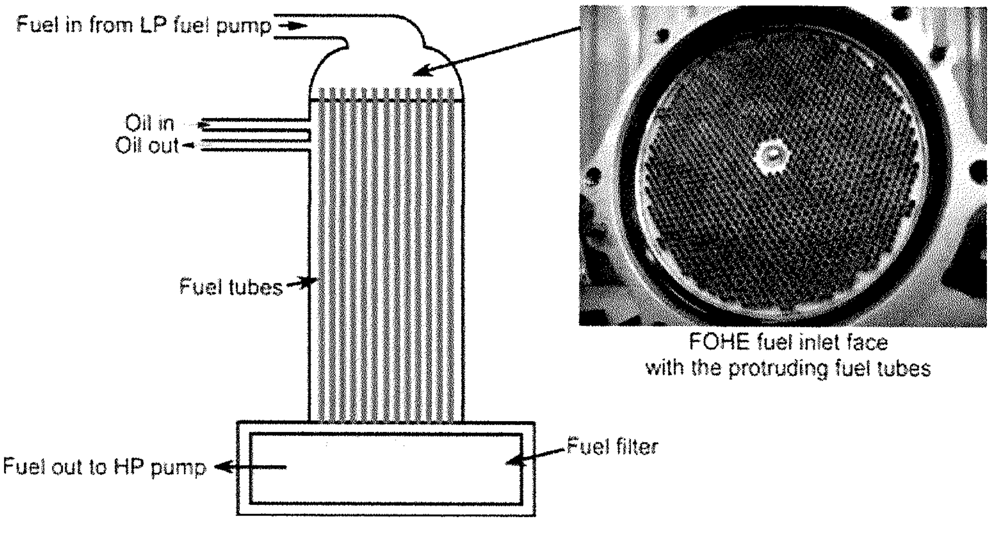

Figure 8

Fuel Oil Heat Exchanger (FOHE)

In the event that the oil becomes too viscous during engine start in cold conditions, the FOHE incorporates an oil pressure relief valve to bypass oil away from part of the matrix to reduce the time taken to heat the oil to operating temperatures. Under certain conditions the fuel flow may not be sufficient to keep the oil temperature within limits and therefore cooling is augmented by an Air Oil Heat Exchanger (AOHE), controlled by the Electronic Engine Control (EEC).

Low Pressure Fuel Filter

The LP filter is mounted directly below and downstream of the FOHE. It has a bypass that will operate should the fuel flow through the filter become restricted. When the LP filter begins to become restricted a differential pressure builds up across the filter and when this reaches a predetermined limit it operates a switch which then provides an indication to the flight crew of an impending filter blockage by displaying the message 'ENG FUEL FILTER L(R)' on the EICAS. The LP filter differential pressure switch operates before the bypass of the filter operates.

Engine High Pressure stage of the Main Engine Pump

After the LP filter, the fuel travels to the High Pressure (HP) pump of the MEP where its pressure is again raised, to the values needed for injection through the fuel spray nozzles in the combustion chamber.

Main Engine Pump (MEP) (Figure 9)

The MEP comprises a centrifugal LP stage and a gear-type HP stage (Figure 9). Both stages are housed in a single unit, although LP fuel is passed to the FOHE/ LP filter unit before being fed back to the HP stage. The pump is driven from the HP spool of the engine through the accessory gearbox. There are four phosphor-bronze plain bearings which mount the two gears of the HP stage and these are coated with a dry-film lubricant, although the fuel itself is the primary lubricant.

Fuel Metering Unit

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 FMU is attached to the MEP case but is a separate unit. It contains three torque motors, which direct servo fuel to regulate fuel for metering, overspeed protection and fuel shutoff; movement of the torque motors is controlled by the EEC. The FMV position is measured by a resolver, which feeds back this information to the EEC. Changes in pressure drop are caused by FMV position variations, so the FMU contains a pressure drop and spill valve to maintain a constant pressure drop across the fuel metering valve and spills excess fuel back to the HP pump inlet.

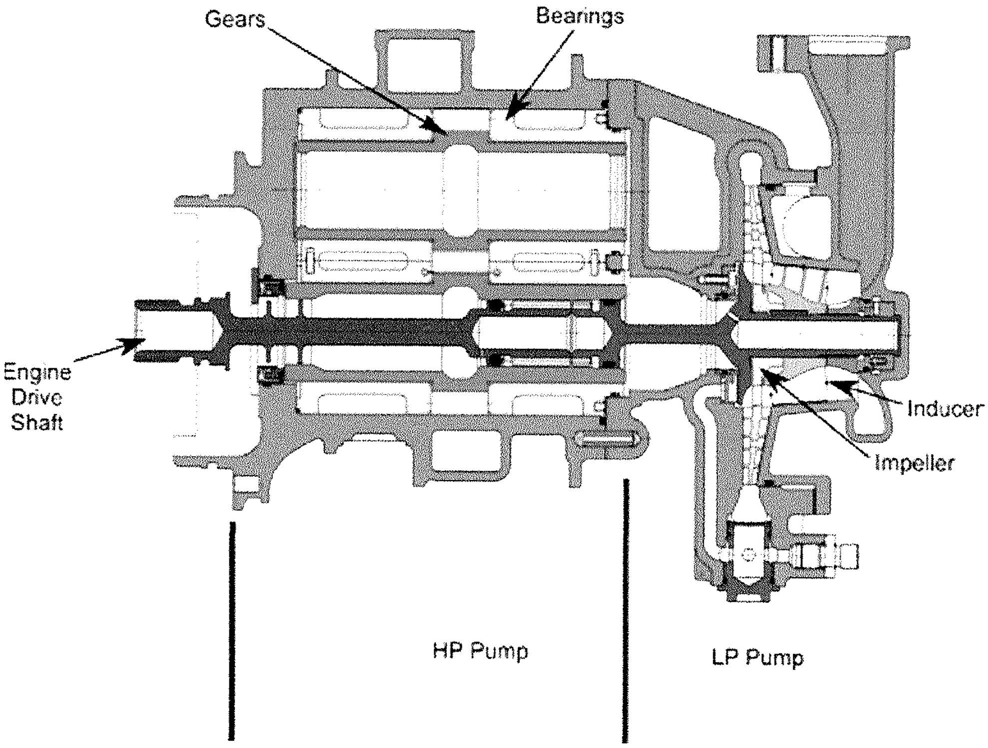

Figure 9

Main Engine Pump (MEP)

High-pressure fuel shutoff

To shut off the high-pressure fuel supply to the engine, the 'pressure raising and shutoff' valve in the FMU closes when the related engine run/cutoff switch is operated to CUTOFF, or the fire switch on that engine is pulled.

Engine burners and fuel flow meter

The fuel from the FMU is routed to the burners via a flowmeter and a coarse HP strainer. The ELDEC flowmeters are mass-flow (as opposed to volumetric) measuring devices and include a vane which is spun by the flow and sends an analogue signal to the EEC. The latter calculates the fuel mass flow and provides this information for display on the cockpit instrumentation. To prevent constant fluctuations of the displayed fuel flow, a time constant is introduced to 'slug' the changes and it is this conditioned signal which is recorded on the Digital Flight Data Recorder (DFDR).

1.6.8.1 Fuel temperature measurement

The fuel temperature indication system has a temperature probe located between ribs 9 and 10 in the left main tank. The probe is situated approximately 12.6 inches above the lower wing skin and is located 40 inches outboard of the aft boost pump inlet. The fuel in the left wing tank can be slightly colder than the right wing tank. This is because the right fuel tank contains two hydraulic fluid/fuel heat exchangers, which are used to cool the hydraulic fluid, whereas the left wing has only one.

Fuel temperature is displayed in white on the primary EICAS. The EICAS low temperature warning trigger automatically defaults to the freezing limit of Jet A, unless another temperature, such as the freezing point of Jet A-1, has been set in the Flight Management Computer (FMC) Control Display Unit (CDU). Once the fuel temperature reaches 3°C above the fuel freezing temperature (-37°C for Jet A and -44°C for Jet A-1) the fuel temperature indication turns amber and the FUEL TEMP LOW advisory message is displayed on the EICAS.

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 Total Air Temperature (TAT). Whilst the cheek tanks of the centre tank are situated in the wings, and are affected by aerodynamic cooling, the majority of the centre tank fuel is sandwiched between the cabin and the air conditioning packs. Consequently the fuel in the centre tank is considerably warmer than the fuel in the main tanks.

The aircraft manufacturer had previously undertaken tests on a B777-200, which has the same wing fuel system as the B777-200ER, to determine the effectiveness of the fuel temperature probe. During the test three racks of thermocouples, mounted vertically in the tank, were fitted along the span of the left main fuel tank. The test established that there is a temperature gradient along the wing span with the coldest fuel inboard and the warmest fuel outboard. This gradient occurs because the wing surface to fuel volume ratio results in the fuel in the outer sections of the wing cooling at a greater rate than the fuel in the inboard sections of the wing. However, a consequence of the wing dihedral and flexing in flight is that the cold fuel migrates towards the inboard sections of the wing. A comparison of the test data with the actual fuel probe temperatures revealed that there is a close correlation between the temperature of the fuel measured by the probe and that measured by the rack of thermocouples mounted adjacent to the probe.

1.6.8.2 Fuel spar valve control and indication

The spar valves are manually selected and electrically operated by the use of either the engine fuel control switches in normal operation or by the fire switches in the event of an engine fire. The operation of the engine fuel control switches, through a spar valve control relay, electrically commands the spar valve actuator to OPEN or CLOSE. The operation of the fire switch directly commands the spar valve actuator to CLOSE and isolates power to the spar valve control relay CLOSE coil.

The control wiring for the spar valve is fed via various connectors in the aircraft. In three locations the connectors contain wiring for both the OPEN and CLOSE command signals for both left and right spar valves. The signal wiring, from the engine fuel control switches to the spar valve control relay, routes through two common connectors D4017 and D4417, both located in the electrical bay. The fire switch signal wiring and the engine fuel control switch wiring to the relays both route through connector D1325 located in the cabin roof area.

In addition, connector D1304 for the right spar valve and D1313 for the left spar valve have OPEN and CLOSE signal wiring routed through them. Both of these connectors are located in a panel in the forward cabin roof area.

The wiring to the spar valves is routed along the wing rear spar in two separate looms. The valve OPEN signal wire, fire CLOSE signal wire and position indication wiring route in a loom that runs in the raceway located above the main landing gear attachment fitting. The engine fuel control switch CLOSE signal wire is routed in a separate loom that is lower down on the rear spar and routes initially outboard toward the engine strut, before routing back along the rear spar and into the spar valve connector.

The power supply to operate the spar valves is 28 V DC from the fuel Shut Off Valve (SOV) bus. This bus is normally supplied by the 28 V DC hot battery bus, however in the event of a loss of power from the aircraft's battery, there is an independent spar valve battery. This spar valve battery has its own charger and any failures are indicated by a status message on EICAS.

In 2002 Boeing issued a Service Bulletin (SB) 777-28-0025 to add additional wiring such that power was available to the engine fuel control relay following the operation of the engine fire switches. This modification was introduced to prevent the situation in which an open circuit of the CLOSE wire from the fire switch would prevent the spar valve from closing if the fire switches were operated prior to the engine fuel control switches. This SB had not been incorporated on G-YMMM at the time of the accident.

In 2005 the FAA mandated the SB via airworthiness directive AD 2005-13-20 requiring the installation of the modified wiring by July 2010.

Spar valve position indication

The 'fuel synoptic' page on EICAS indicates the position of the spar valve. In addition the fuel management maintenance page gives the command signal and actual position status indication for the valves.

The Overhead Panel ARINC 429 System (OPAS) monitors the position of the spar valve and the commands from the spar valve control relay. If there is a discrepancy between the spar valve control relay position and the spar valve actual position, then OPAS sends a fault message to AIMS to display a status message 'FUEL SPAR VALVE L(R)'. If the spar valve is in transit for more than 10 seconds an advisory message is indicated on EICAS.

The DFDR gives the spar valve position indication taken from AIMS based on signal information from OPAS. The DFDR gives four indications, OPEN, CLOSED, INVALID and FAILED. The FAILED indication shows on the DFDR if the valve is not in either the OPEN or CLOSE position for more than 5 seconds.

1.6.8.3 Fuel quantity

A Fuel Quantity Processor Unit (FQPU) receives signals from tank units and densitometers in the fuel tanks and uses these to calculate the fuel quantity in the each of the three fuel tanks. The FQPU then sends data to EICAS for the display of fuel quantity to the flight crew.

Each tank unit measures the fuel height at its location, through the use of an ultrasonic transmitter/receiver. The FQPU commands each tank unit's ultrasonic transmitter to send out a sonic pulse, the time for the pulse to be reflected from the fuel surface and return to the receiver directly relates to the fuel height in the tank.

The densitometers use a vibrating cylinder; the frequency of vibration is proportional to the fuel density.

Each tank has measuring sticks at various locations so that the fuel quantity can be manually checked on the ground. The sticks use a magnetic float which surrounds the measuring stick housing and rests on the fuel surface. When the measuring stick is moved from within its housing, the end of the stick 'catches' at the position of the magnetic float. The stick has graduations which give a direct reading of the height of fuel in the tank at that location. Fuel quantity in the tank can then be calculated using conversion tables, with reference to the aircraft's pitch and roll attitude, fuel density and the fuel heights measured at each of the stick locations. These were used to establish the fuel quantity onboard the aircraft following the accident see para 1.12.3.8.

Fuel on board G-YMMM

G-YMMM was refuelled with 71,400 kg of Jet A-1 at Heathrow approximately 1 hour 30 minutes prior to engine start for the outbound flight to Beijing. The Quick Access Recorder (QAR) recorded the fuel temperature in the left tank at 1130 hrs, 47 minutes prior to the start of the refuel, as 3°C. The aircraft landed at Beijing with 4,100 kg in the right main, 4,000 kg in the left main and 0 kg in the centre fuel tank. The temperature of the fuel in the left tank was recorded as 10°C on departing Heathrow and -20°C on arrival at Beijing. At Beijing the aircraft was refuelled with 71,401 kg of Jet A-1, at a temperature of 5°C, 30 minutes before the engines were started for the return flight to Heathrow. The total fuel load at the start of the return leg was recorded on the DFDR as 79,000 kg, with 28,900 kg in each of the main fuel tanks and 21,200 kg in the centre fuel tank. The temperature of the fuel in the left main tank at engine start was recorded as -2°C.

1.18.1.2 Water in aviation turbine fuel

Water is always present, to some extent, in aircraft fuel systems and may be introduced during refuelling or by condensation from moist air which has entered the fuel tanks through the tank vent system. The latter effect is greatest when a cold soaked aircraft descends into a warm moist air mass. The water in the fuel can take one of three forms: dissolved, entrained (suspended) or free water.

Dissolved water: Dissolved water occurs when a molecule of water attaches itself to a hydrocarbon molecule; the amount of water dissolved in fuel is a function of humidity, temperature and the chemical constitution of the fuel. As a general guide the dissolved water content of aviation turbine fuel in parts per million (ppm) is approximately numerically equal to the temperature of the fuel in degrees Fahrenheit. When warm fuel is cooled the dissolved water is released and takes the form of either entrained or free water.

Entrained (suspended) water: Entrained water is water that is suspended in the fuel as tiny droplets and may not be visible to the naked eye in concentrations below 30 ppm. At higher concentrations entrained water will give the fuel a cloudy or hazy appearance, depending upon the size and number of water droplets. Entrained water can be formed by the release of dissolved water as the fuel cools, by violently agitating water and fuel together, or if there is a surfactant in the fuel.

A surfactant acts to stabilise small water droplets so that they do not form large water droplets that would settle out on the bottom of the tank. The maximum amount of surfactant allowed in aviation turbine fuel is not directly specified in the fuel specification but is controlled by water separation testing as part of fuel delivery requirements.

Agitation can occur during refuelling, mixing of the water scavenge outlet with the bulk fuel, or as the fuel and water pass through the aircraft fuel pumps. Entrained water will settle out of the fuel, but the rate is dependent on the droplet size, the density of the fuel and the amount of fuel agitation. As a general rule, under static conditions, entrained water is considered to settle at a rate of about one foot per hour; however it is unlikely that on an in-service aircraft all the entrained water would have the opportunity to settle out of the fuel.

Free water: Free water is the water which is neither dissolved nor entrained and, as it has a higher density than the fuel, it takes the form of droplets, or puddles of water lying on the bottom of the fuel tanks. Free water can also be found in the fuel filters and stagnation points within the fuel delivery system.

1.18.1.3 Estimated water content of fuel on G-YMMM

Based on the temperature of the fuel, it was estimated that the fuel loaded at Beijing would have contained up to 3 litre (40 ppm) of dissolved water and a maximum of 2 litre (30 ppm) of undissolved water (entrained or free). In addition, it was estimated that a maximum of 0.14 litre 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.

1.18.1.4 Formation of ice in fuel

As water cools it freezes and forms ice as follows:

Dissolved water: Any water that is still dissolved in the fuel at low temperatures will not form ice because the water molecules are still chemically bonded to the fuel. Dust particles in the fuel could provide a nucleation point for the formation of water droplets that could then form ice. However, at low fuel temperatures the concentration of dissolved water is very low and therefore the amount of ice formed by this mechanism would be small.

Free water: Free water forms ice as it is cooled below its freezing point and within the aircraft fuel tanks the cooling mechanism is the effect of the TAT on the lower wing skin; it is the water closest to the wing skin which freezes first. From the examination of two other B777 aircraft, by the AAIB, it appeared that, in the main fuel tanks, ice forms around the rivets, access panels and structure adjacent to Rib 8 and it was very difficult to release some of this ice from the bottom of the tank. For the ice to release it is necessary to increase the temperature of either the fuel or the lower wing skin above the melting point of the ice.

At the point, in the accident flight, when the engines did not respond to the demand for an increase in power, the fuel temperature was -22°C and the TAT was 12°C. Photographs of G-YMMM taken as it crossed the airfield perimeter show the inboard sections of the lower wings skins, which form the main fuel tanks, covered in frost which indicates that the wing skin was very cold; therefore, there was no release mechanism for any ice that may have formed on the bottom of the fuel tank.

Entrained (suspended) water: Entrained water in fuel will freeze and form ice crystals, which turn the fuel cloudy. Because the density of the ice crystals is approximately the same as the fuel, the crystals will generally stay in suspension and drift within the fuel until they make contact with a cold surface. Due to impurities in the water the ice crystals will not start to form in the fuel until the temperature has reduced to around -1°C to -3°C. As the temperature is further reduced it reaches the 'Critical Icing Temperature' which is considered to occur between -9°C and -11°C. The 'Critical Icing Temperature', is the temperature at which the ice crystals start to stick to their surroundings. As the temperature is further reduced to -18°C, the ice crystals start to adhere to each other so that they become larger, with the risk of blocking small orifices.

The temperature range over which ice crystals in fuel adhere to surfaces, and each other, is sometimes called the 'sticky range'. From observations made during the sub-scale testing, the investigation defined the 'sticky range' as being between -5°C and -20°C.

1.18.1.5 Generation of ice in testing

When water freezes it can form a number of different ice crystal structures, which determine the physical properties of the ice. During this investigation very hard, dense ice was found in the bottom of the aircraft main fuel tanks and occasionally, during the testing, a thin layer of what appeared to be rime ice formed around the outlet of the boost pump check valve housings. However, for the most part, during the icing tests, the ice which formed within the fuel system pipes was very soft and could be easily moved around. Temperature variations did not appear to affect the type of ice that was formed. When the ice was melted it was found to contain a mixture of fuel and water.

To overcome the difficulties in maintaining the water concentration in cold fuel, the aircraft manufacturer fitted an acrylic 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 water, which would then adhere to the inside of the pipes. During 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.

1.18.1.6 Fuel waxing

As fuel is cooled beyond its freezing point it is the long straight chain (heavier) hydrocarbons which first form wax crystals. These wax crystals have a similar density to liquid fuel and, therefore, remain suspended in the fuel. This mixture of fuel and wax crystals can normally be pumped by the aircraft boost pumps into the fuel system until the fuel temperature reaches its 'pour point', which is much colder than the fuel freezing point.

Previous testing by the aircraft manufacturer has established that there is a vertical thermal gradient (stratification) in fuel tanks and other research has established that it is the fuel adjacent to the lower wing skin which will wax first and form a layer that lines the bottom of the tank. This layer of wax then acts as an insulator which serves to reduce the rate of cooling of the bulk fuel. However, in flight there are a number of factors which tend to equalise the vertical temperature gradient of the fuel in the tank. These include fuel sloshing and circulation of the fuel as a result of the flow into the boost pumps, action of the water scavenge systems and migration of the cold fuel from the outer to inner sections of the wing tanks.

In previous testing undertaken by the aircraft manufacturer on a B777-200, which has the same wing fuel system as the B777-200ER, it was established that during feed from the centre fuel tank, stratification of the fuel in the main fuel tanks occurred as TAT reduced. During the test, ten thermocouples mounted vertically in the tank close to the fuel temperature probe recorded the temperature as varying from -17°C at the bottom of the tank to -3°C near the top of the tank. When the boost pump was turned ON, so that the flow was sufficient to provide the motive flow for the water scavenge system and internal pump cooling, the stratification diminished and the vertical temperature variation adjacent to the temperature probe reduced to around 3°C.

1.18.1.7 Entrapped air in aviation fuel

Jet fuel contains dissolved air and the amount depends on the temperature of the fuel and the altitude. As the airplane climbs to cruising altitude, and the ambient pressure decreases, air is liberated from the fuel as bubbles that rise to the surface. As the flight progresses the rate of effervescence decreases as the fuel comes into equilibrium with the atmospheric and fuel temperature conditions. This condition is called fuel weathering. Since the accident flight was in descent, fuel was in a weathered condition and the liberation of entrapped air was not considered to be an issue.

1.18.2 Other relevant events

1.18.2.1 Incident to Boeing 777-200ER (N862DA)

On 26 November 2008, a Boeing 777-200ER powered by Rolls-Royce Trent 800 engines, registered N862DA was being operated from Pudong International Airport, Shanghai, People's Republic of China to Atlanta-Hartsfield International Airport, Atlanta, Georgia, USA. Whilst in cruise at FL390, the right engine suffered an uncommanded reduction in engine power.

Subsequent examination of the right engine HP pump revealed the presence of severe cavitation damage, in a similar location to, but worse than, that found on the HP pumps removed from G-YMMM. Data from the DFDR revealed an increase in the combined scavenge oil temperature and a reduction in the oil pressure following a step climb from flight level FL350 to FL370. The step climb occurred approximately 9.5 hours into the 13.5 hour flight and the fuel flow was increased from about 6,900 pph to around 10,900 pph to accomplish the climb. The engine power reduction occurred 55 minutes after the step climb and during a small increase in power commanded by the autothrottle. The fuel flow to the right engine was restricted to approximately 5,000 pph. The power reduction persisted for 23 minutes despite several autothrottle commands for increased thrust.

The engine thrust levers were retarded to idle as the aircraft descended to a lower altitude. During this descent the engine recovered, the fuel flow returned to that demanded and the oil temperature reduced.

The fuel temperature at the time of the rollback was -22°C, which was the lowest fuel temperature experienced during the flight.

Preliminary conclusions issued by the NTSB in their recommendations document SB-09-11 issued on 11 March 2009, were that the FOHE on the right engine had become restricted with ice, thus reducing the fuel flow and causing the engine to rollback. This resulted in the increased oil temperature as the cooling efficiency of the oil by the fuel had been compromised. Once the engine had been commanded to idle fuel flow during the descent, the oil temperature dropped and the fuel flow was restored. This led to the conclusion that the restriction was temporary and that it had been cleared through the reduction of engine power to idle.

1.18.2.2 Accident to USAF B52D

On 11 February 1958 a Boeing B52D crashed in South Dakota, USA. During a go-around engines 1, 2 and 5 had an uncommanded reduction in engine power. During the subsequent approach, power was gradually lost from all the engines, despite the selection of full thrust.

The aircraft struck the ground some 3,500 ft short of the runway threshold fatally injuring three of the crew. Despite a significant post-crash fire, ice was discovered within the aircraft fuel system.

A subsequent inquiry attributed the engine power loss to icing of the engine fuel pump screens, causing a restricted fuel flow to the engines. Contributory factors were excess water/ice in the fuel tanks and no bypass on the fuel pump screen.

1.18.3 Literature

Since the early 1950s considerable research has been carried out on the issue of fuel system icing by various organisations, resulting in several substantial reports. Some of this literature is freely available; some reports are proprietary or have government, military or export constraints.

This early research established that it is possible for ice to form from dissolved water, alone, in aviation turbine fuel and this can then block filters and small orifices. A number of different types of ice were observed, and 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.

Two documents produced by the Society of Automotive Engineers (SAE) detail succinctly the issue and findings of this research at that time and advises the aerospace industry on suggested procedures to test aircraft fuel systems and components for icing.

The SAE initially produced Aerospace Information Report (AIR) 790 in 1964; this was intended to provide information on ice formation in aircraft fuel systems.

With regard to testing AIR 790 states:

> *'Test set-ups should represent actual aircraft conditions as closely as practicable. The component or system installation should be representative of that in the aircraft in configuration and location relative to aircraft features which might influence the performance... '*

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.

4 Safety Recommendations

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

4.1 **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.

4.2 **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.

4.3 **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.

4.4 **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.

4.5 **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.

4.6 **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.

4.7 **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.

4.8 **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.

4.9 **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

4.10 **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.

4.11 **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.

4.12 **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.

4.13 **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.

4.14 **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.

4.15 **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.

4.16 **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.

4.17 **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.

4.18 **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.

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Presence of water

Tests for water

The requirement in the fuel specification is that the fuel should be clear, bright and free of water and sediment. Apart from the appearance test there is no fuel specification test to detect the presence of entrained or dissolved water in the fuel. Therefore, during the investigation a Karl Fischer test (ATSM D6304), which uses a chemical method to establish the total amount of water (dissolved and entrained) in the fuel, was carried out on a number of samples.

Shell Water Detector Capsules were used to check for the presence of water in the fuel loaded onto the aircraft at Beijing and the bulk fuel removed from the aircraft after the accident at Heathrow. These detectors only detected undissolved water, that is entrained and free, and change colour when the undissolved water content reaches 30 ppm.

Results of tests for water

With the exception of some of the fuel drained out of the main tanks and the samples taken from the engine fuel filters and housings, all the remaining samples passed the appearance tests.

The bulk fuel was removed from the aircraft on 23 January 2008 and stored in a clean bowser. The fuel was then allowed to settle before it was tested on 30 January 2008 by the AAIB using a Shell Water Detector capsule. The sampled fuel, taken from the bowser sump, was bright and clear with no visual sign of free water. The water detector capsule did not change colour indicating that the entrained water content was less than 30 ppm.

Small water droplets were observed in the fuel samples taken from the engine fuel filters and housings. The amount of water was too small to measure and so was classified by reference to the QinetiQ fuel appearance table as being 'small'. Figure 59 is a reconstruction of the QinetiQ description of 'small' using water coloured with food dye.

As a comparison, fuel samples were taken from the engine fuel filters and housings of another of the operator's aircraft, G-YMMN, on 15 October 2008 after it had completed a 13 hour flight from Singapore to Heathrow. Similar quantities of water were found in the engine filter and housings.

Figure 59

Reconstruction of a '*small*' amount of dyed water in aviation turbine fuel

Samples of fuel taken from the left main tank fuel sump, APU fuel line and the right engine Variable Stator Vane (VSV) actuator were tested by QinetiQ using the Karl Fischer test. The samples contained no visual free water, but had a total water content (dissolved and entrained) of between 35 to 40 ppm. As a comparison, fuel samples taken from the engine fuel filters and housings on G-YMMN on 15 October 2008 were found to have a total water content of 45 to 50 ppm. Given the accuracy of the Karl Fischer test these results are considered to be very similar and QinetiQ have advised that they are typical for aviation turbine fuel.