

## **Fuel Icing – Trent 800-Powered 777 Airplanes**

Reference 1: AAIB Interim Report 2, “Accident to Boeing 777-236ER, G-YMMM at London Heathrow Airport on 17 January 2008”, dated 12 March 2009  
[http://www.aaib.gov.uk/publications/interim\\_reports/interim\\_report\\_2\\_\\_boeing\\_777\\_236er\\_\\_g\\_ymmm.cfm](http://www.aaib.gov.uk/publications/interim_reports/interim_report_2__boeing_777_236er__g_ymmm.cfm)

Reference 2: NTSB Safety Recommendation Letter, dated 11 March 2009,  
[http://ntsb.gov/Recs/letters/2009/A09\\_17\\_18.pdf](http://ntsb.gov/Recs/letters/2009/A09_17_18.pdf)

Two recent events involving engine thrust rollbacks (uncommanded reduction in thrust) on Trent 800-powered 777-200 airplanes have been attributed to a fuel flow restriction at the inlet face of the engine fuel oil heat exchanger (FOHE) caused by water ice in the fuel. The first event occurred on January 17, 2008. The airplane, a 777-200ER (G-YMMM, Reference 1), suffered a dual-engine rollback to a thrust level above idle while on final approach and crashed short of the runway at London Heathrow. No fatalities occurred but the airplane was declared a total loss.

The second event was a single engine thrust rollback that occurred on November 26, 2008 on a 777-200ER airplane (N862DA, Reference 2). During level cruise at 39,000 feet, the right engine rolled back, again to a thrust setting above idle but below commanded thrust. The crew accomplished a descent to 31,000 feet and performed the Engine Response Non-Normal Checklist (NNC), causing the engine to recover and operate normally for the remainder of the flight.

Investigation into these events and subsequent laboratory testing has shown that ice can form from normal amounts of water in the fuel and can accumulate on the inside of the aircraft fuel system tubes. The current understanding is that this ice can release and travel through the fuel feed tubes resulting in a restriction at the inlet face of the engine FOHE. As presented in the References, detailed information related to these events has been released by the investigating authorities; the UK Air Accident Investigation Branch (AAIB) and the US National Transportation Safety Board (NTSB), including AAIB Interim Reports, and NTSB safety recommendation letters to the FAA and EASA. Boeing and Rolls-Royce have also distributed all-operator communications. A redesigned FOHE, that will better tolerate ice released from the fuel system, has been certified for Trent 800 powered airplanes.

This document provides information on fuel icing and how it occurs, information on the events, corrective action, and why corrective action is not being considered for 777 airplanes powered by GE90 or PW4000 engines. It is intended as background information for airline engineering and flight operations engineering departments and is intended only to complement the previously released AAIB, NTSB, Boeing and Rolls-Royce reports and communications.

### What is fuel icing?

Water is present in all jet fuel and is uploaded into the aircraft during each refueling. A typical water concentration in a nominal fuel upload at 70 deg F (21 deg C) would be on the order of 70ppm (parts per million). Ice will form normally from this water as the fuel temperature cools below 0 degrees C. The water is present in fuel in three different forms: dissolved water; suspended free water; and settled free water. As fuel temperature decreases, dissolved water will come out of solution and become suspended free water. It is the suspended free water or ice crystals that can freeze to the interior of the fuel system tubing. On long range high altitude flights, dissolved water transitioning to suspended water is expected as the fuel tank temperatures decrease.

For a 777-200 or -300 airplane with full left, right and center tanks, the typical expected amount of dissolved and suspended free water (assuming a typical concentration in uploaded fuel of 70ppm) in a fuel load would be on the order of 7 liters. Figure 1 shows water in a fuel sample from the Boeing laboratory showing dissolved, suspended and settled water. Dissolved water at any concentration level cannot be seen; the fuel is clear and bright. Suspended free water at concentrations below 30ppm is also clear; above that concentration the fuel becomes hazy.

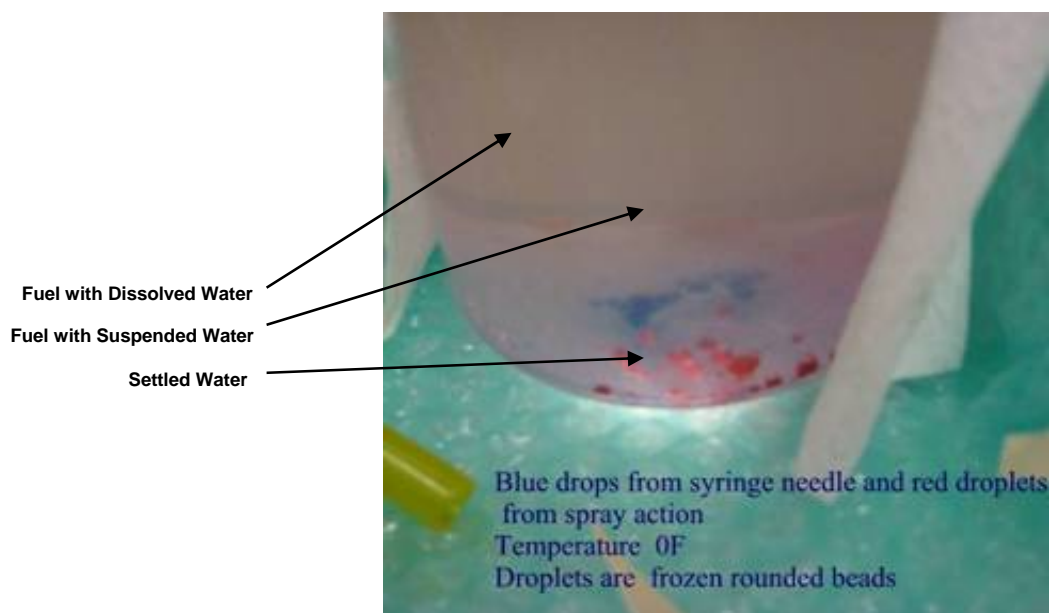


Figure 1 – Fuel Sample showing dissolved, suspended free water and settled free water

### Why does regular sumping not remove all water from the airplane fuel tanks?

An airplane's water scavenge system and periodic sumping are intended to prevent excessive water build-up and microbial growth within the tanks. However, these

measures cannot remove all water present in the tanks as more water is added with each new fuel loading.

Water scavenge and water sumping will target settled water only; water scavenge returns settled free water (not ice) to suspended free water, allowing it to be consumed by the engines; tank sumping removes settled water from the tanks. Dissolved water and suspended water are not addressed by either water scavenge or tank sumping. Finally, neither system will remove ice frozen to the interior of the fuel tank.

**Are there fuel system messages that could be an indicator of fuel icing?**

There are no fuel system messages that can warn the crew of water icing in fuel. Questions have arisen on the use of the water detection and low fuel temperature messages in this manner. Neither message correlates with the presence of hazardous water ice in fuel.

Water detection messages are maintenance level messages that may indicate the presence of settled water at the bottom of the tanks, but, as noted above, settled water will tend to freeze at the bottom of the tank and not enter the fuel system. In addition, 777 operators have reported nuisance fuel system water detection messages as discussed below:

- L MAIN WATER, R MAIN WATER, or CENTER TANK WATER R messages are often displayed on the Fuel Quantity Maintenance Page. Boeing Maintenance Tip 777 MT 28-023 addresses the above water detection messages on the fuel quantity maintenance page. As noted in the Maintenance Tip, bubbles can form on the fuel surface during refueling and become trapped at the top of the still well in the water detector as the fuel surface rises, causing the noted WATER messages to be displayed on the fuel quantity maintenance page after refueling. Normal aircraft vibration associated with fuel pump operation, engine start, aircraft movement, etc., can dissipate the bubble(s), and extinguish the message. These messages are typically nuisance messages and will normally disappear as the aircraft begins taxiing. Display of these messages is not in any way related to fuel icing events and should not be interpreted as a precursor to a fuel icing event.

The FUEL TEMP LOW message indicates that the fuel is cooling to within 3 deg C of the specified fuel freezing (or waxing) point, and is not related to water icing in the fuel. There have been several nuisance erroneous FUEL TEMP LOW messages reported:

- Several 777 operators have reported intermittent uncommanded autothrottle advances to the CRZ or CLB thrust limit. The A/T then immediately retards the throttle to the commanded thrust position. On some occasions, the flight crews have reported the FUEL TEMP LOW message being coincident with the throttle lever movement. The investigation is in work at Boeing and is thought to be related to the FMC. The FUEL TEMP LOW messages set during these intermittent A/T excursions are nuisance messages that are not related to fuel

icing or actual low fuel temperatures. The root cause of the uncommanded A/T advances is under investigation.

**What is the suspected role of fuel icing in the accident or the subsequent single engine rollback event**

The investigation into the January 2008 accident and the subsequent November 2008 single engine rollback event has established that it is possible for sufficient ice to build up within the fuel feed system, such that it's sudden release would cause a restriction at the face of the Fuel Oil Heat Exchanger (FOHE). The AAIB Interim Report 2 concluded that the most likely scenario for the accident flight was that ice formed on the inside of the fuel feed tubes. Testing has shown that ice can form around the internal circumference of the tubes (ice formation is similar to plaque or scaling on the internal circumference of a household water pipe) as shown in Figure 2a. 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.

It should be noted that ice formation is not considered unique to the 777 airplane. This phenomenon of fuel line icing would be expected to occur on any airplane type exposed to cold enough temperatures for a significant length of time.

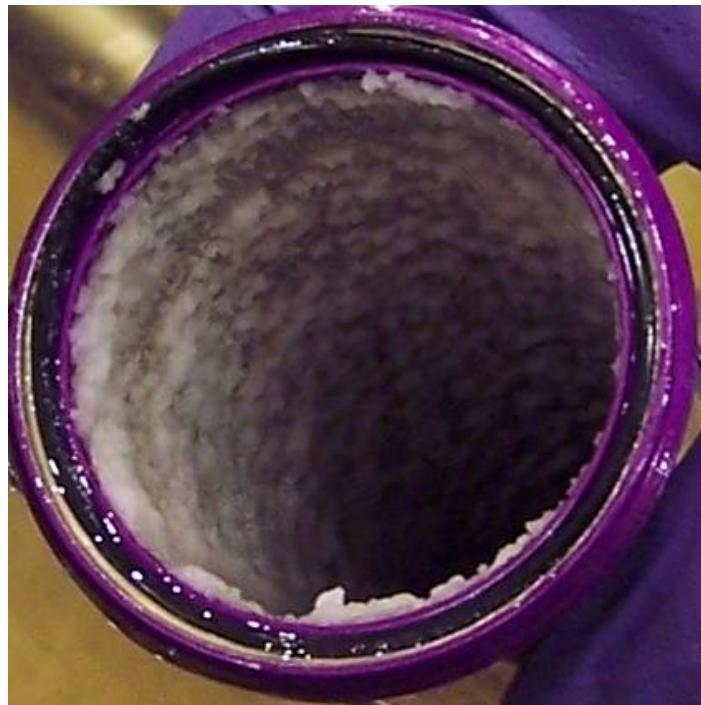


Figure 2a Ice forming inside the fuel system tubing

Figure 2b shows ice accumulation on the inlet of the FOHE (from laboratory testing at Boeing's fuels lab). Testing has identified that the current FOHE can become blocked by soft ice and that a fuel restriction can result at fuel tank temperatures of -15°C and below.



Figure 2b – Ice Accumulation on Inlet to FOHE

**How much ice is required to cause a blockage at the FOHE?**

In order for ice to cause a rollback, more than 95% of the FOHE's fuel flow tubes must be blocked. As noted in the AAIB Interim Report 2, testing has established that as little as 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. This concentration is not considered realistic. Fifty ml of water, injected at a more representative concentration, yielded restricted fuel flows in the test rig similar to those seen on the airplanes.

**If some degree of fuel icing is always to be expected, what was unusual about the accident flight?**

Boeing and Rolls-Royce reviewed their databases covering all 1.2 million flights of the Trent 800-powered 777 fleet, looking for specific characteristics and flags in the data which would indicate other rollbacks that could have been caused by ice but went unnoticed at the time. None were found. Therefore, ice-induced rollbacks are extremely rare. In fact, even in the laboratory, it was difficult to cause ice to form in the fuel system reliably and water had to be directly injected into the inlet to create fuel system icing on demand. Therefore, it is apparent that a random element may play a role in creating a

significant amount of ice in the fuel system. However, some contributing factors are known.

Both flights were colder than average. During the accident flight, the fuel temperature reached a low of -34 degrees C during cruise, and warmed to only -22 degrees C on approach, both of which are unusually cold for the 777 fleet. However, the second event only reached a minimum fuel temperature of -22 deg C, which, while colder than average, is not unusual.

On the accident flight, all step climbs were conducted using lower power settings (vertical speed). Therefore, many hours were spent at low fuel flows, allowing ice to build up in the system. Laboratory testing has shown that ice can accumulate within the tank and fuel system over many hours at low power settings. Periodic high fuel flows, such as used in VNAV step climbs, help keep the system clear of large amounts of ice. The cruise rollback flight did conduct all step climbs using VNAV. In fact, a step climb released enough ice to cause the oil temperature to begin to rise. But it should be noted that the amount of ice was smaller than on the accident flight, and only one engine rolled back, nearly an hour after the initial ice release.

Conducting step climbs at full thrust will prevent hazardous amounts of ice from forming in the system. Small amounts of ice hitting the FOHE will not block it, and will be melted when the thrust is reduced to idle for descent. In the unlikely event that enough ice is released to block an FOHE, the Engine Response non-normal checklist has been shown to be effective in restoring full thrust capability

**Why does pulling the throttle to idle clear ice from the FOHE?**

Lab testing has proven that reducing the fuel flow to idle will almost immediately clear any ice that has accumulated on the inlet face of the FOHE. This is because at idle, the (cold) fuel flow is reduced by 80% but (hot) oil flow is only reduced by about 20%. This change in the mass flow ratio of the two fluids changes the thermal balance of the FOHE and allows the heat from the hot oil to overpower the cold from the fuel flow and melt the ice.

**Why are only Trent 800 Powered 777 Airplanes affected by ice in the fuel and; why is interim action and/or design changes not required for other 777's?**

As noted above, the likely scenario of the accident and the single engine rollback event has been determined to be a sudden release of ice that had built up in the airplane fuel system, which, when released, travelled through the fuel feed pipes and resulted in a restriction on the face of the engine FOHE. Operators have questioned whether GE90- and PW4000-powered 777 airplanes are susceptible to a similar type of event and, if so, if the interim flight operations procedures and/or a system or FOHE redesign are required for GE90- or PW4000-powered airplanes.

It is important to note that both the 777 and the Trent 800 engine, including the FOHE, met all certification requirements at the time, including stringent fuel icing requirements. However, the possibility of large amounts of extremely concentrated ice presenting to the system components was unknown and not considered in the tests. The design of the FOHE is very robust and has an excellent history of reliability. However, each manufacturer will approach a design in a different way, and there are differences between the three engine types on the 777.

Figure 3 provides a simplified schematic of the Fuel Metering Unit (FMU) spill fuel return for the three 777 engine types (note that GE90-94B and GE90-115B are considered one engine type for the purposes of this comparison since the spill flow return configuration is identical between these two engine types).

The engine fuel pump on all engines is sized to provide excess fuel flow to the engine for all engine thrust ranges from idle to maximum takeoff thrust. All three engine types use a fuel metering valve (FMV) to regulate the fuel flow supplied to the engine based on the commanded thrust level. The excess fuel flow provided by the pump that is not required for the engine thrust level (referred to as spill flow) is recirculated and reintroduced upstream of the FMV where it mixes with fuel coming from the airplane fuel tanks. Spill flow from the FMV has already been heated by upstream heat exchangers and pumps and will always be at a significantly higher temperature than the colder fuel coming from the airplane fuel tanks. Spill flow will decrease as thrust increases, but some amount of spill fuel is always available for recirculation.

On the Trent 800 engine the spill flow is reintroduced downstream of the FOHE resulting in fuel from the fuel tank hitting the face of the FOHE without any significant heat addition. On both the PW4000 and the GE90 engines, the warm spill flow is reintroduced upstream of the FOHE resulting in much warmer fuel hitting the face of their heat exchangers. As shown in Figure 3, the PW4000 engine's IDG Oil Cooler could act as the first restriction point if ice is released upstream. However, this component includes a bypass valve that permits uninterrupted fuel flow should the primary flow path become obstructed. Similarly, the GE90 fuel system includes a strainer, which could act as the 1st restriction point. Although this component is located upstream of the spill return, the bypass valve again permits uninterrupted fuel passage should a restriction occur. Consequently, the opportunity for fuel flow restriction due to ice accumulation on the face of the FOHE is comparatively less for the PW4000 and GE90 engines and Boeing has determined that no action is required to address fuel icing on PW4000- and GE90-powered 777 airplanes.

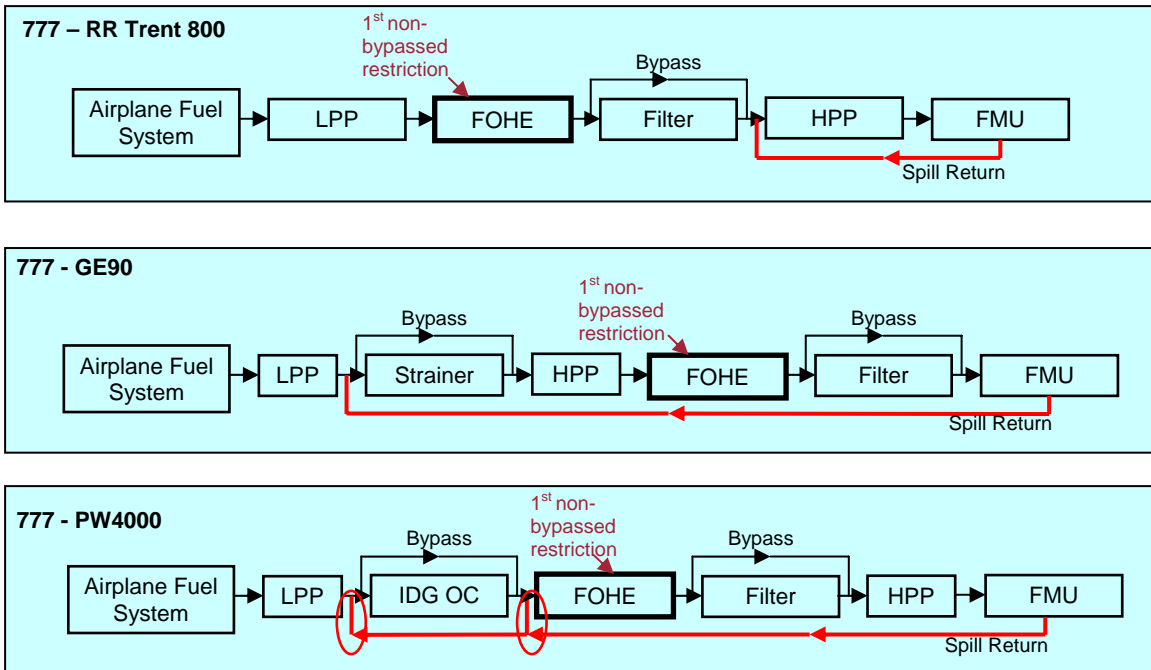


Figure 3 – Comparison of FMV Spill Flow Return for 777 Engine Types (LPP-Low Pressure engine fuel Pump, HPP-High Pressure engine fuel Pump, FOHE-Fuel Oil Heat Exchanger, FMU-Fuel Metering Unit, IDG OC-Integrated Drive Generator Oil Cooler)

**The AAIB Interim Report also recommends that the investigation findings be reviewed to consider the implications on other airframe / engine model combinations (beyond the 777 airplane). What is the status of the review of other Boeing airplanes?**

As the possibility of this scenario became known, Boeing began evaluating the susceptibility of all of its products to fuel system icing. At this time, all Boeing aircraft models have been reviewed in accordance with the AAIB recommendations. This review included all active airplane models (current and post-production; both Boeing and heritage McDonnell Douglas). Note that the conclusions stated below have not yet been validated by the FAA and EASA.

The Boeing review determined that the majority of airplane / engine combinations are not considered at risk from fuel system icing based on our current understanding of the threat condition and an analysis of the engine fuel system architecture, and no action is required or planned for these models. Several engine / airplane combinations require further analysis and/or testing once the threat condition has been fully defined. However, based on our current understanding of the threat condition and these engine fuel system architectures, these combinations are considered low risk. As such, interim action was found not to be required for these combinations that are still under review.

**What are the symptoms of the fuel icing event – how will the indicated engine parameters respond?**

Firstly, the fuel temperature would have to be less than -15 deg C for an ice blockage of the FOHE to occur. Laboratory testing has shown that, at cruise fuel flows, the FOHE can melt any amount of ice presented to it at fuel tank temperatures above -15 deg C. Note that -10 deg C was used as the trigger temperature in the interim mitigation procedures in order to provide a 5 deg C margin for conservatism.

There are flight deck indications of a rollback due to fuel icing. Depending on the size of the blockage, fuel flow on the affected engine(s) will reduce to a level below commanded thrust. On both event aircraft this was approximately 5000 pounds per hour (pph)). The other engine performance parameters will rollback to a level consistent with this fuel flow (this is above idle but well below typical cruise thrust settings and should correspond to an indicated (or actual) EPR of between 1.05 and 1.10). If autothrottle is engaged, then both throttles would move forward to try to compensate for the reduction in thrust (moving the command EPR bug up). If thrust is insufficient to maintain airspeed, a gradual deceleration may occur. Thrust Asymmetry Compensation will automatically introduce rudder as needed to maintain attitude.

The EICAS display for a single (right) engine thrust roll back event is illustrated in Figure 4a below. The most obvious characteristic is that the indicated (or actual) EPR will drop below the commanded level, causing a large command EPR arc sector to appear on the EPR indicator of the affected engine. Although this large EPR command sector (or shortfall between commanded EPR and indicated EPR) is typical of any scenario where the EEC is commanding a higher EPR than the engine is actually delivering (including normal engine transient conditions where a higher thrust has been commanded but the engine is still spooling up), a fuel icing event will be evident due to the persistence of the large command sector (i.e. a standing command arc) and the magnitude of the EPR shortfall even with the thrust levers remaining stationary. Periodic fluctuations (every 20-30 seconds) in indicated EPR may also be seen.

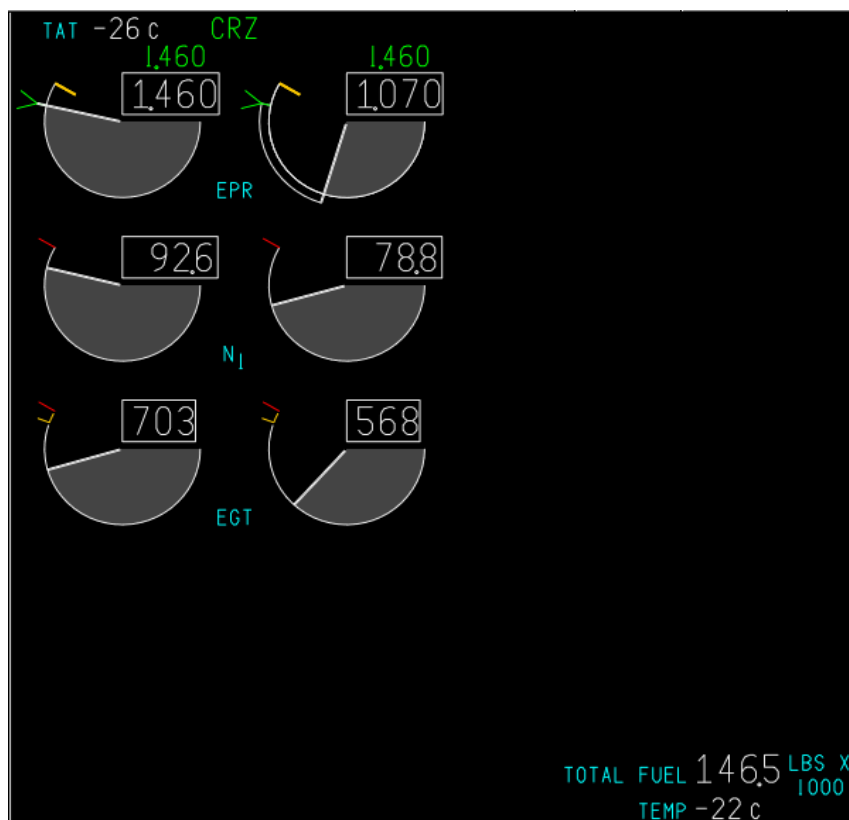


Figure 4a – Primary EICAS Display (Fuel Icing Scenario, Right Engine)

Because the affected engine(s) are not producing commanded thrust, it would be expected that the “ENG THRUST L (R)” EICAS caution message should be displayed. However, because of the specific characteristics of these rollbacks, the message may not appear, and in fact did not in the two events described.

In both rollback events, EPR did not drop sub-idle, it stayed above idle (in the vicinity of 1.1 EPR) corresponding to approximately 5000 lb/hr fuel flow. There are no other readily identifiable engine failure modes that will cause the engine to drop to this EPR below the commanded EPR and remain there.

The mismatch between indicated and commanded EPR can differentiate this event from that of a blockage of the airplane TAT or engine probes due to probe icing or debris in the probe. In that case, the EEC is presented with incorrect temperature data and limits the commanded EPR to a lower value. The engine responds in kind, and the indicated EPR matches the commanded EPR. The EICAS display for a TAT probe icing event affecting both engines is illustrated in Figure 4b below.

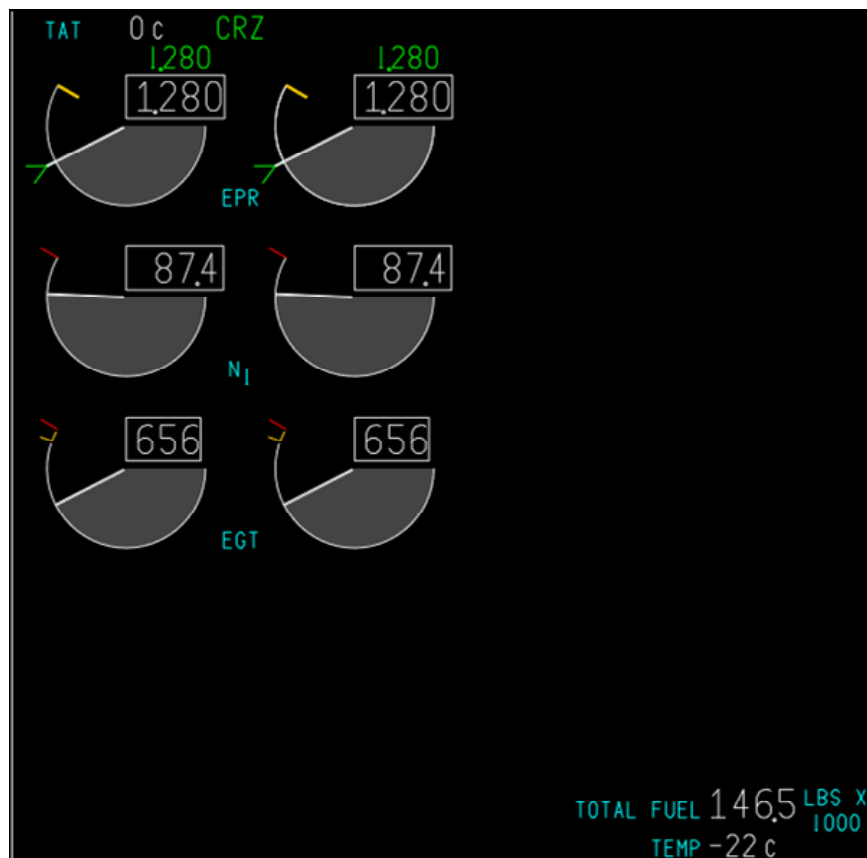


Figure 4b – Primary EICAS Display (TAT Failure Scenario, dual engine)

Even though in the second rollback event the uncharacteristic oil temperature rise on the right engine provided a clue as to the blockage location at FOHE, oil temperature is not a reliable indication of this scenario. There are many other reasons for oil temperature to vary, both during a given flight and between engines, including fuel temperature, TAT, power level, age of engine, oil cooler configuration, etc.

**What should I do to prevent fuel system icing from restricting fuel flow through the FOHE, and why?**

Interim flight operations procedures to prevent fuel system icing from restricting fuel flow through the FOHE have been mandated via FAA AD 2009-05-11, which became effective on 20 march 2009. This AD supersedes previous AD 2008-19-04. AD 2009-05-11 requires that the limitations section of the AFM be revised to include the following statement (this may be done by inserting a copy of the AD in the AFM):

## "STEP CLIMBS AND INITIAL DESCENT

Perform all step climbs using VNAV or maximum climb thrust. During initial descent, maintain idle thrust for a minimum of 30 seconds.

## COLD FUEL OPERATIONS

On ground, after refueling, check fuel temperature if fuel temperature indication is operative. If fuel temperature is 0 degrees C or colder or if fuel temperature indication is inoperative, verify that a record exists certifying that the approved fuel circulation procedure was performed.

Do not do the following paragraph and balance the fuel at the same time. Balance the fuel before or after performing the following paragraph.

In flight, within 2 hours of top of descent, but not less than 15 minutes before top of descent, check fuel temperature. If fuel temperature is colder than -10 degrees C, perform a step climb using maximum climb thrust. If a step climb using maximum climb thrust cannot be accomplished, select or verify CLB thrust on the thrust limit page and verify cruise speed is set to 0.84 Mach or less. Manually advance thrust levers to maximum (autothrottles may be overridden). After reaching maximum climb thrust, hold for 10 seconds or until reaching 0.86 Mach, whichever occurs first. Check engines to ensure they have achieved maximum climb thrust and operate normally."

Boeing has revised all 777/Trent 800 AFM's to incorporate the above requirements. Boeing has also released Flight Crew Operations Manual (FCOM) Bulletin "Cold Fuel Operations Procedures for RR Trent 800 Series Equipped 777 Airplanes" dated 28 January 2009. This bulletin provides details of the changes to the operating instructions, a revised Engine Response Non-Normal Checklist and a revised Cold Fuel Operations Supplementary Procedure which addresses the above requirement accomplish a maximum climb thrust step climb within 2 hours of top of descent, but not less than 15 minutes before top of descent, when fuel temperature is colder than -10 deg C

### **What should I do if I suspect restricted fuel flow due to icing, and why?**

If the engine(s) rollback or fail to achieve commanded thrust and fuel system icing is suspected (fuel temperature is below -10 deg C and indicated EPR is less than commanded), perform the Engine Response Non-Normal Checklist:

**Engine Response**

[RR Engines]

Condition: One or both engines do not reach commanded thrust or roll back, and fuel system icing is suspected (Indicated EPR is below commanded EPR and fuel temp is below -10 degrees C).

Objective: To clear ice from the fuel system by reducing engine fuel flow while descending, then checking for proper engine response.

- 1 Select a lower altitude on the MCP.
- 2 FLCH switch . . . . . Push
- 3 Thrust levers (both) . . . . . Idle
- 4 WING ANTI-ICE selector . . . . . OFF
- 5 ENGINE ANTI-ICE selectors (both) . . . . . OFF
- 6 Maintain idle thrust for 30 seconds.
- 7 If thrust asymmetry compensation is inoperative, manual control inputs are required to compensate for asymmetric thrust conditions.
- 8 Left thrust lever . . . . . Advance to maximum
- 9 Check for normal engine indications. Engine may accelerate very slowly especially at high altitudes. The time from idle to maximum thrust may be as long as 30 seconds.
- 10 Left thrust lever . . . . . Retard to idle
- 11 Right thrust lever . . . . . Advance to maximum

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▼ Engine Response continued ▼

- 12 Check for normal engine indications. Engine may accelerate very slowly especially at high altitudes. The time from idle to maximum thrust may be as long as 30 seconds.
- 13 Right thrust lever . . . . . Retard to idle
- 14 WING ANTI-ICE selector . . . . . AUTO or ON
- 15 ENGINE ANTI-ICE selectors (both) . . . . . AUTO or ON
- 16 Resume normal operation.



By pulling the thrust levers to idle, the amount of cold fuel entering the FOHE is reduced, allowing the hot oil to melt the ice blockage. In the laboratory this occurs within a matter of seconds, and the procedure was successfully conducted on the single engine rollback event in November, 2008. It must be emphasized that the lower the fuel flow, the faster the ice will melt, so it is important to ensure the thrust levers are pulled fully back to the idle stop. It is this characteristic that will prevent an engine from flaming out in this situation. As the fuel flow reduces towards idle, the blockage will self-clear, and normal operation will resume.

**What Design Changes are being Pursued to Address Fuel Icing in Trent 800 Powered Airplanes**

Testing has shown that the current FOHE is susceptible to ice accumulation at the inlet due to the protrusion of the heat transfer tubes from the end plate surface and inlet crimps on the heat transfer tubes (see Figure 5).

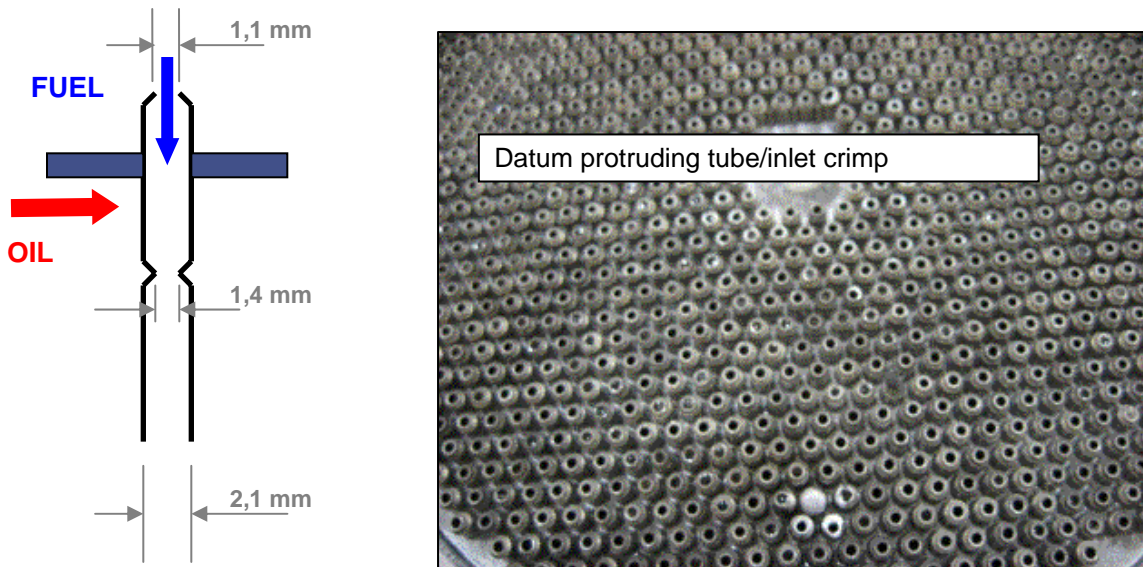
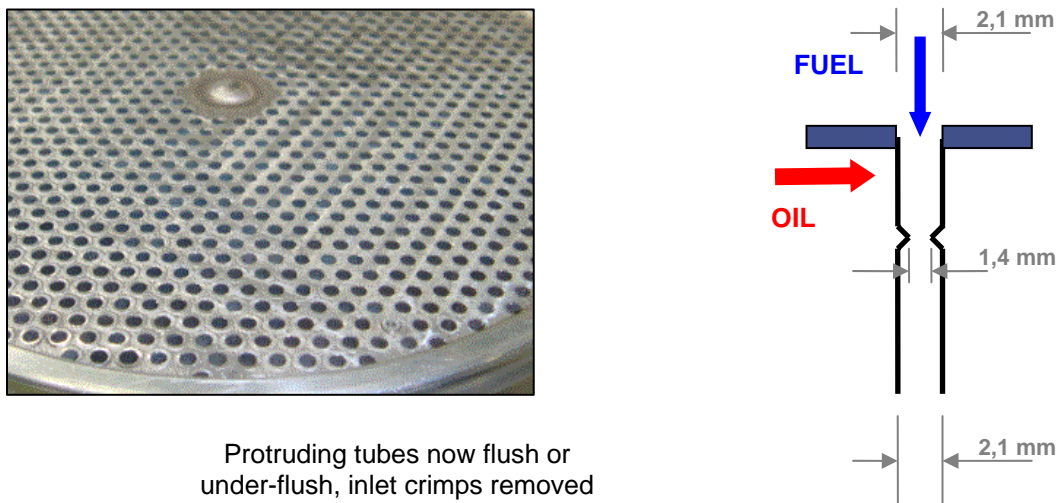


Figure 5 – Current Production Standard of FOHE

Boeing and Rolls-Royce have worked with the FAA and EASA to certify a redesigned FOHE that demonstrated a significantly more robust capability to handle ice released from the fuel system. The redesigned FOHE incorporates changes to make the heat transfer tubes flush with the end plate surface and to remove the inlet crimps (see Figure 6). Testing has demonstrated that the redesigned FOHE can withstand a soft ice release event at fuel temperatures below -44 deg C.



Protruding tubes now flush or under-flush, inlet crimps removed

Figure 6 – Proposed FOHE Redesign

Following European certification of the redesigned FOHE for the Trent 800 engine by EASA, the FAA certified the redesigned FOHE on July 9, 2009 for use on the 777. On 13 July, 2009, EASA issued an airworthiness directive (AD) mandating the installation of the new FOHE on the Trent 800 engine (AD No.: 2009 – 0142). It is expected that FAA will adopt this AD for US 777 operators. The EASA AD requires all Trent 800 engines be upgraded before 1 January, 2011 or within 6000 flight hours beginning 10 July, 2009, whichever occurs first.

The new FOHE is incorporated on in-service airplanes by Rolls-Royce Service Bulletin 79-AG257 dated 24 June 2009 (published 10 July 2009) and Boeing Service Bulletin 777-72A0030, dated 10 July 2009.

**Will the interim procedures be removed once the new FOHE is installed?**

The intent is that incorporation of the redesigned FOHE will be approved as closing action for the interim cold fuel ground and flight operations procedures. Boeing and Rolls-Royce will be discussing this with the FAA & EASA as the new FOHE's are deployed to the fleet. Our current goal is to remove the requirement for the Interim Mitigation Procedures once an operator's entire 777-Trent 800 fleet is retrofitted with the new FOHE.