5mm Crack Leading to an Engine Fire – Lessons Learnt

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Synopsis

On 27 June 2016, a Boeing 777-300ER aircraft departed Singapore for Milan. About two hours into the flight, the right engine indication showed a low oil quantity.

Subsequently, the flight crew felt a vibration in the control column and cockpit floor. The flight crew decided to return to Singapore.

Shortly after landing in Changi Airport, a fire was observed to have occurred in the vicinity of the aircraft's right engine. After the aircraft came to a stop on the runway, a fire developed under the right wing. The airport rescue and firefighting service extinguished the fire. Damage to the aircraft included heat damage to the core of the engine, portions of the engine cowlings, the wing area directly behind and outboard of the right hand engine.

The Transport Safety Investigation Bureau conducted the investigation into this occurrence with the assistance of the U.S. National Transportation Safety Board, the U.S. Federal Aviation Administration, and the aircraft and engine manufacturers.

The information in this paper details the findings and other aviation safety aspects deliberated during this investigation.

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Background of Flight

1 A Boeing 777-300ER aircraft departed Singapore Changi Airport at 0224 hrs for Milan on 27 June 2016. The aircraft carried two sets of operating crew, i.e. four pilots in total.

2 As the aircraft was climbing to its cruising altitude, the flight crew encountered weather which required them to perform weather avoidance manoeuvres. About 30 minutes into the flight, when the aircraft had climbed to 30,000 feet, the flight crew noticed that the oil quantity parameter in the Engine Indicating and Crew Alerting System (EICAS) showed 17 units for the left engine but only 1 unit for the right engine. The flight crew also noticed from the EICAS display that the right engine oil pressure was fluctuating between 65 and 70 psi while the oil temperature for the right engine was 10°C higher than the left engine. However, both the oil pressure and temperature parameters were within the normal operating range[1].

3 The flight crew looked through the available manuals but was unable to find an appropriate procedure that addressed the low engine oil quantity situation.

4 At 0304 hrs, the Pilot-in-command (PIC) contacted his company's engineering control centre for assistance via satellite communication (SATCOM). The PIC informed the engineer on duty of the engine parameters and asked if it was safe to continue with the flight. The engineer informed the PIC that since the oil pressure was within the normal operating range, there could be a faulty oil quantity indication. The engineer advised the PIC to continue with the flight but monitor the right engine oil parameters. The engineer told the PIC that he would also contact the company's technical services personnel for advice.

5 After being briefed by the engineer on the situation, the technical services personnel believed that it was a faulty oil quantity indication. As the aircraft had just departed and was not far from Singapore, the technical services personnel recommended that the aircraft return to Singapore.

6 According to the flight crew, as they were passing waypoint VPG at approximately 0320 hrs, the First Officer performed a routine fuel quantity check. After comparing the TOTALIZER fuel quantity[2] with the planned fuel remaining quantity[3], it was determined that the fuel consumption was better than expected as the fuel on board was 600 kg more than the expected value.

[1] Typically, when there an oil leakage situation, the oil quantity will decrease. At a sufficiently low quantity, there may be a noticeable increase in oil temperature and, eventually, a noticeable decrease in oil pressure.

[2] The TOTALIZER fuel quantity is the remaining quantity of fuel determined by the fuel quantity indicating system. The quantity is calculated based on feedback from sensors in the fuel tanks.

[3] The planned fuel remaining quantity is the expected amount of fuel remaining at various waypoints based on the expected fuel consumption, taking the flight plan into consideration.

7 At 0328 hrs, the engineer sent a message via the Aircraft Communication and Reporting System (ACARS) to the flight crew informing them about the recommendation by the technical services personnel for the aircraft to return to Singapore and requesting them to contact the engineering control centre.

8 The PIC contacted the engineering control centre and a conference call among the PIC, the engineering control centre and the technical services personnel was held, which lasted for about 20 minutes. The PIC informed the rest that the flight crew had been monitoring the right engine oil parameters for 50 minutes and other than the indicated low oil quantity, the parameters appeared normal. It was jointly assessed that the flight could continue to Milan with the proviso that the flight crew monitor the right engine oil parameters and contact the engineering control centre for assistance if needed.

9 Shortly after the conference call ended, the flight crew felt an unusual vibration in the control column and cockpit floor. The flight crew tried to diagnose the problem by changing the engine power settings and found that the vibration disappeared when the power of the right engine was reduced. At about the same time, the flight crew caught a momentary wisp of burnt smell in the cockpit but the smell disappeared quickly.

10 At 0404 hrs, the PIC informed the engineering control centre about the vibrations which the flight crew experienced whenever the right engine was operated at higher power settings. In the ensuing conference call among the PIC, the engineering control centre and the technical services personnel, it was assessed that there was no need to shut down the right engine and decided that the aircraft would return to Singapore with the right engine operating at idle power. In the midst of the conference call, the In-flight supervisor (IFS) informed the flight crew that there was a burnt smell detected in the cabin. In response, the flight crew turned off the right engine bleed system[4].

11 According to the cabin crew, the smell was particularly strong in the business class cabin, in the forward part of the aircraft. The cabin crew distributed wet towels for the passengers to hold over their nose and breathe through it.

12 After the conference call ended, the flight crew reduced the right engine to idle power and proceeded to turn the aircraft around to return to Singapore. For the return journey to Singapore, the flight crew adopted the procedure for single engine operation, including a descent to 17,000 feet before reducing the right engine to idle power.

13 When the IFS informed the flight crew that the burnt smell in the cabin was still present, the right air conditioning pack and recirculating fans were switched off. Shortly after, the smell in the cabin subsided.

14 At 0521 hrs, the flight crew received a FUEL DISAGREE message on the EICAS. The flight crew performed the FUEL DISAGREE checklist. The FUEL DISAGREE checklist suggested four scenarios in which a fuel leak should be

[4] The engine bleed system routes air from the compressor section of the engine for various uses, including air conditioning.

suspected and when the flight crew should perform the FUEL LEAK checklist. One such scenario is when the TOTALIZER fuel quantity is less than the CALCULATED[5] fuel quantity.

15 The flight crew observed from the display of the flight management system that TOTALIZER fuel quantity was about 79 tonnes and the CALCULATED fuel quantity was about 83 tonnes.

16 However, the flight crew did not perform the FUEL LEAK checklist. According to the flight crew, they believed the CALCULATED fuel quantity was no longer accurate in view of the following:

(a) Input changes had been made to the flight management system after the right engine was set to idle power[6].
(b) They were no longer on the planned flight route.
(c) They had 600 kg more fuel than expected when they last performed a routine fuel check (see paragraph 6).

17 Thus, the flight crew performed their own fuel calculation by subtracting the amount of fuel consumed from the total amount of fuel at the start of the flight. The fuel consumed was calculated by multiplying an average fuel flow value (that the flight crew determined) by the duration of the flight. They arrived at a figure of about 79 tonnes. As this tallied well with the TOTALIZER fuel quantity figure, the flight crew concluded that the FUEL DISAGREE message was a spurious one and that there was no need to proceed with the FUEL LEAK checklist.

18 Several times on the return journey and as the aircraft approached Singapore, the flight crew was queried by the Air Traffic Control (ATC) if they needed any assistance. The flight crew replied that, other than the need to fly at the lower altitude of 17,000 feet, no assistance was needed as all other operations were normal.

19 Prior to landing, the flight crew jettisoned about 41,500 kg of fuel to bring the aircraft to below its maximum landing weight.

20 At 0649 hrs, the aircraft landed on the runway. About 20 seconds after the thrust reversers on both engines were deployed, the occupants in the cabin heard two loud bangs, accompanied by two flashes, originating from the right engine area. At the same time, the flight crew heard a soft thud. The Airport Rescue and Firefighting Service (ARFF) personnel who were monitoring the aircraft's arrival informed the Control Tower on seeing the fire at the right engine. The Control Tower informed the flight crew of the fire and instructed the aircraft to stop at the intersection between the runway and rapid exit taxiway E7. The flight crew did not receive any fire warning in the cockpit.

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[5] The CALCULATED fuel quantity is determined by the flight management computer by subtracting the fuel used (calculated basing on fuel flow figures as measured by sensors in the engines) from the total fuel quantity at the start of the flight.

[6] As there was no option on the flight management system to reflect that the right engine was operating at idle power, the flight crew decided to select the option indicating that one engine was inoperative. This was to configure the flight management system to compute navigational and performance parameters based on single engine operation.

Response to Fire

21 The ARFF which was on standby with four foam tenders and one water tender, entered the runway as soon as clearance to enter the runway was given by the Control Tower. The first foam tender arrived on scene after 57 seconds and started discharging foam at the right engine.

22 When responding to the fire, the Fire Commander (FC) of the ARFF requested the Control Tower to ask the flight crew to switch the aircraft radio to the emergency channel for communication between the FC and flight crew.

23 Subsequently, the FC and PIC established communication on the emergency channel and the key exchanges were as follows:

Time	Party Speaking	Content
06:51:50	PIC	*how is it looking…Is the fire contained*
06:51:53	FC	*…we are still trying to contain the fire…the fire is pretty big…will like to advise… disembarkation*[7] *on your port side*
06:52:05	PIC	*Okay evacuate*[8] *from the port side confirm*
06:52:09	FC	*…still trying to contain the fire…still some random fire on your right hand engine but we are keeping it under control*[9]
06:52:24	PIC	*…do you need us to evacuate from the port side*
06:52:29	FC	*…Singapore 368 standby*[10] *standby*
06:52:33	PIC	*Okay standby for your instructions Singapore 368 standby for your instructions*

24 Jet fuel that was discharged from the right engine onto the tarmac fuelled a fire that impinged on the underside of the right wing near the right engine area.

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[7] The FC was confident that the ARFF would be able to bring the fire under control and the occupants of the aircraft could then disembark from the aircraft. According to the FC, he knew the difference between evacuation (via escape slides) and disembarkation (via stairs). He specifically used the term "disembarkation" as he did not think that an evacuation was necessary.

[8] According to the PIC, he knew the difference between evacuation and disembarkation. He was trying to ask the FC for input on the evacuation aspect.

[9] According to the FC, when he mentioned that the fire was under control, it was based on his assessment that there was no risk of the fire spreading.

[10] The FC said the reason he asked the PIC to stand by was that he was on the left side of the aircraft where his view of the fire was blocked by the fuselage, and he decided to move to the right side of the aircraft to reassess the situation before giving the PIC a reply.

25 The ARFF managed to bring the fire under control and put out the visible fire in the right engine area and on the ground at 0653 hrs. However, ARFF personnel, using infra-red detector, found heat signature within the internal section of the engine and they continued to monitor the situation. The key exchanges between the FC and PIC at that point were as follows:

Time	Party Speaking	Content
06:54:08	FC	*…we have kept the fire under control. We will like to advise disembarkation on your port side*
06:54:20	PIC	*okay you want us to disembark through the slides or are you going to provide mobile stairs*
06:54:38	FC	*…we will like to advise disembarkation on your on your port side*
06:54:48	PIC	*okay you want us to disembark on the port side through the emergency slides can you confirm that*
06:55:14	PIC	*…can you just confirm that we need to evacuate through the left through the emergency slides*
06:55:33	FC	*negative negative negative we will like to advise disembarkation disembarkation no evacuation no evacuation*
06:55:42	PIC	*okay disembarkation through mobile steps understand understand…*

26 About three minutes later, the fire appeared again at the forward section of the right engine. It was immediately put out by the ARFF.

27 There was no fire warning in cockpit when the flight crew were informed of the ongoing fire by the FC. The flight crew eventually discharged both the bottles of fire extinguishing agent into the right engine when they were queried by the FC if they had discharged the bottles.

28 Eventually, after the FC had assessed the situation to be safe and that the fire was brought under control, the occupants of the aircraft disembarked via mobile stairs.

Damage to Aircraft and Engine

29 The right wing and engine area of the aircraft sustained extensive damage. The most extensive damage to the right wing was in the vicinity of the right engine. Fire damage was also observed on the underside of the right wing, outboard of the engine.

30 The fan section, variable bleed valves and high pressure compressor of the right engine sustained varying degrees of heat damage.

Cause of Fuel Leak

31 During the initial post occurrence examination of the right engine, fuel was found in the booster spool cavity, oil tank, all bearing sumps, accessory and transfer gearboxes. These were areas of the engine where fuel should not be present during normal operation.

32 The main fuel oil heat exchanger (MFOHE), a component that is used by both the engine fuel and oil system, was examined for the presence of an internal leak. The MFOHE contains a series of tubes. Fuel flows in these tubes, while oil used for lubricating the engine flows around the tubes **(Figure 1).** This allows oil to be cooled through heat transfer to the fuel through the tubes. The design of the MFOHE is such that the oil and fuel flow paths will not cross and the oil and fuel will not come into contact with each other.

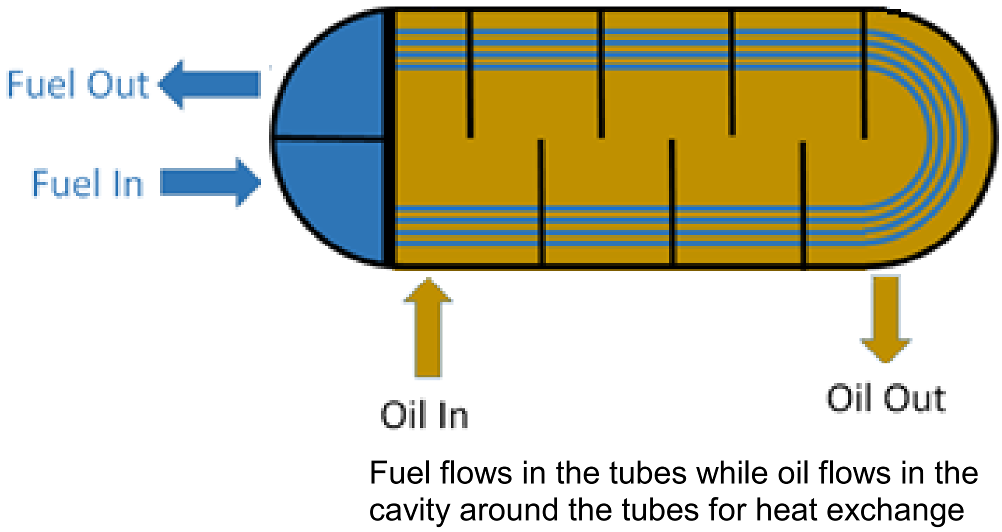


Figure 1: Schematic diagram of MFOHE

33 The MFOHE was removed from the engine and preliminary pressure tests performed on it confirmed an internal leak between the oil and fuel flow paths.

34 The MFOHE was sent to the engine manufacturer's facility where a computer tomography scan was performed on the MFOHE. The scan results showed that there was a cracked fuel tube which was displaced.

35 The MFOHE was then sent to the MFOHE manufacturer's facility for further examination. In a test performed to simulate the operation of the MFOHE at idle engine power setting, the leak rate from the displaced cracked tube was found to be about 31 pounds per minute.

36 A portion of the MFOHE casing was removed. One of the fuel flow tubes was found cracked and displaced (**Figure 2**).

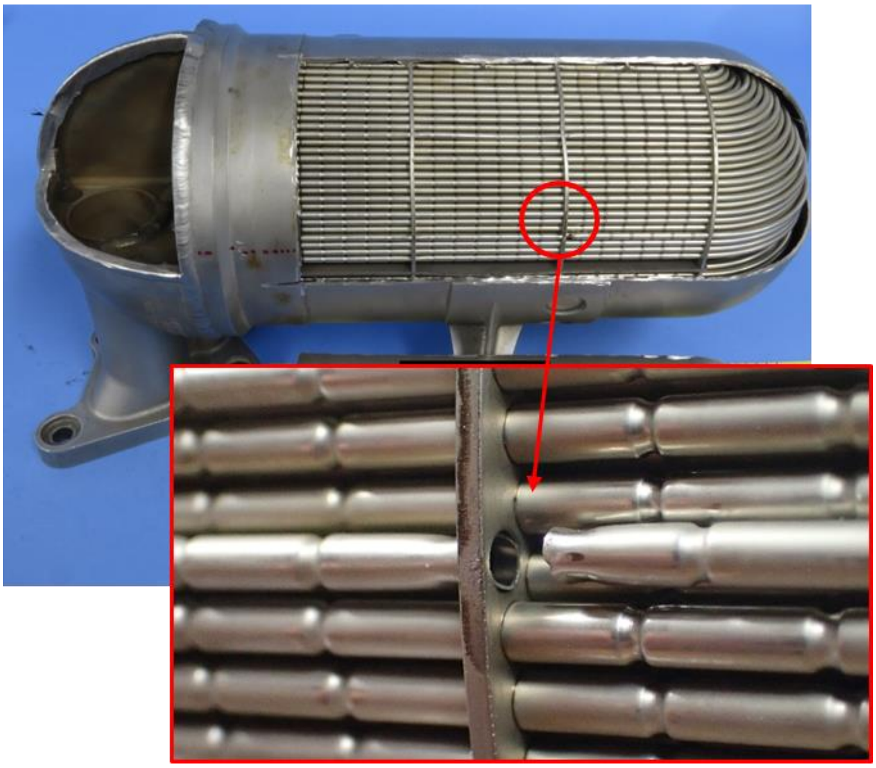


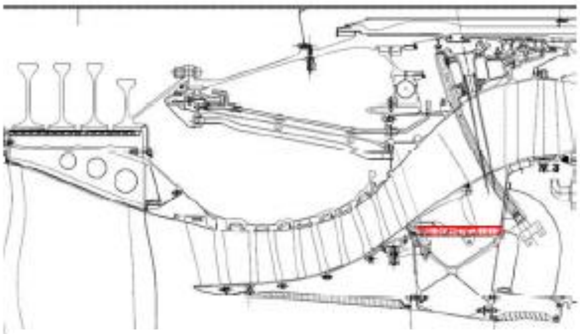
Figure 2: View of cracked tube in MFOHE

37 The cracking of a tube in the MFOHE allowed fuel in the fuel flow path of the MFOHE to flow into the oil flow path in the MFOHE. The investigation has not revealed other sources of fuel leak.

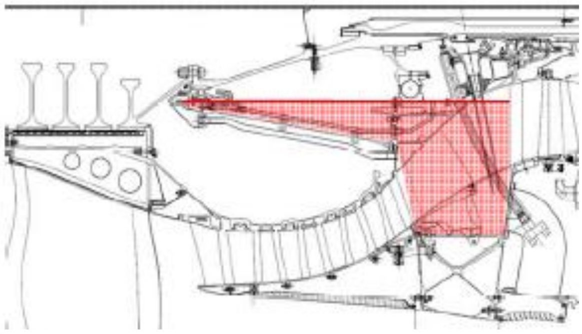
38 During all phases of the engine fuel pump operation, fuel is delivered at pressures between 400 and 1600 psi. In comparison, the pressure within the engine oil system is about 100 psi. As such, when the fuel carrying tube in the MFOHE cracked, the higher pressure fuel entered the engine oil distribution system.

39 During the normal operation of the engine oil system, a small amount of oil will collect in the A Sump[11]. However, when fuel leaked into the oil system, it filled the A Sump until its maximum storage capacity. The additional quantity of leaked fuel overflowed into the booster spool cavity and started to collect there (**Figure 3**).

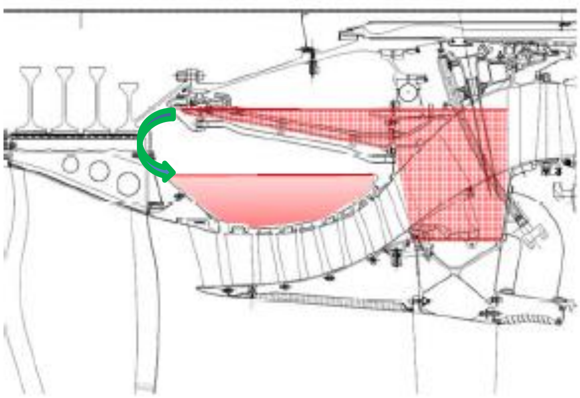
[11] During normal operation, oil in the A Sump will be contained and prevented from leaking by labyrinth seals and surrounding air pressure providing the constant seal (see Figure 3a). With fuel leaking into the A Sump and reaching its maximum storage capacity, the fuel pressure build-up in the A Sump overcomes the air pressure and the fuel leaks out.



a: Normal operation with small amount of oil collecting in A Sump (shaded area



b: Maximum storage capacity of A Sump reached due to fuel leak



c: Fuel leaked into the booster spool cavity

Figure 3: Process of fuel filling the A sump and booster spool cavity

40 Once the booster spool cavity was filled up to the aft lip, the excess fuel leaked through a gap between the spool and aft stage booster vane into these areas (**Figure 4**):

- High Pressure Compressor (HPC) through the core airflow
- Fan duct when the Variable Bleed Valve (VBV) doors are open at engine idle power

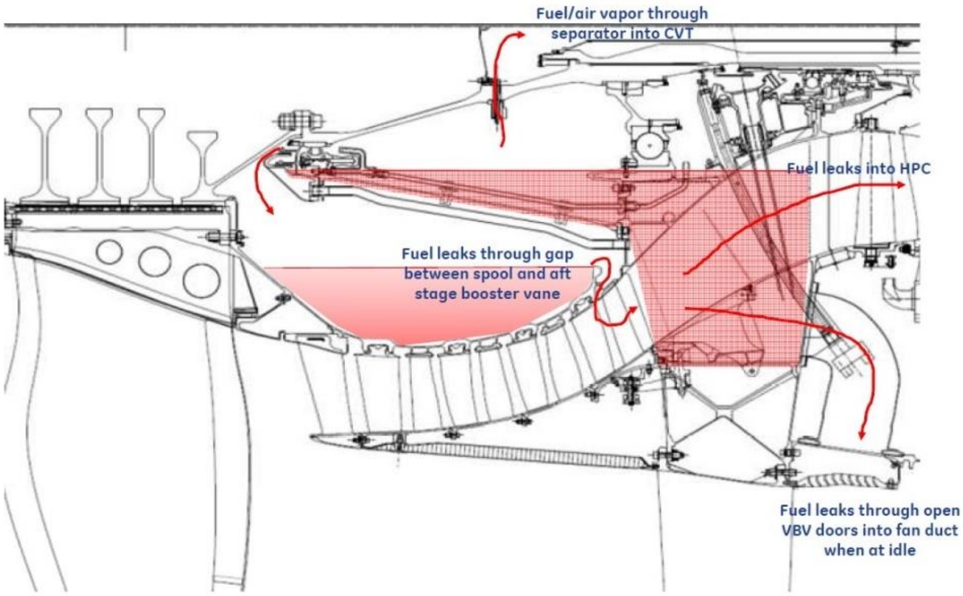


Figure 4: Leak path for fuel

41 The oil tank and various engine drain points are areas where one would usually expect to find only oil. Instead, fuel was found in those locations. Similarly, residual fuel was found in the various engine sumps. In addition, the gearboxes and the engine bearings, which are usually coated in oil, were found to be dry. These observations suggest that engine oil was displaced from the engine and fuel, in place of oil, was distributed throughout the engine oil system.

42 Engine oil lubricates and cools the engine bearings and gearboxes, and helps in lowering vibration at the engine bearings. Fuel is not as efficient as oil for engine lubrication. Therefore, when oil had been displaced by fuel in the occurrence engine, oil temperature increased. The temperature increase was a result of fuel in the oil system which was not able to cool the engine bearings and gearboxes as efficiently as oil.

43 The vibration detected by the flight crew when operating the right engine at a higher power setting was likely due to the fuel that collected in the booster spool cavity. This cavity is a dome shape space and rotational forces would have caused the fuel to be spun against the inner wall of the booster spool cavity as the engine was operating. The rotating fuel created imbalance that resulted in vibration. At higher engine power settings, the vibration would have been more pronounced as compared with the engine at idle operation. This was consistent with the flight crew's observation that the vibration seemed to disappear when engine was at reduced power setting.

44 For the remainder of the return journey back to Singapore, fuel leaked through the core of the engine and the fan duct. As engine was operating at idle power, the VBVs were open (see paragraph 40), allowing the leaked fuel into the VBV ducts and the fan duct, where it could accumulate in the honeycomb core material behind the perforated walls of the thrust reverser duct.

Fire Initiation and Propagation

45 The investigation team determined that the fire was a result of hot surface ignition[12] of leaked fuel at the area behind the turkey feather seal of the core exhaust nozzle. Based on recorded video footages and recorded data from the aircraft, the investigation team believed that the fire first started after the thrust reversers were deployed during the landing.

46 There was no fire during airborne segment of the aircraft's return journey to Singapore. This was due to the high velocity of the airflow over the exterior of the engine which prevented both the ignition and sustained combustion of the leaked fuel.

47 As the aircraft arrived to land, fuel was still leaking from the engine through various leakage areas (**Figure 4**). When the thrust reversers were deployed, the velocity of airflow over the core exhaust nozzle was significantly reduced. The area aft of the turkey feather seal, which is a protrusion on the core exhaust nozzle, would have experienced the most significant disruption of airflow. In addition, the accumulated fuel in the fan duct was also distributed over a wide area of the lower surface of the wing.

48 The investigation team believed that, with the disrupted airflow, the mixture of accumulated fuel on the core exhaust nozzle and fuel in the airflow would have been sufficiently heated to the point of ignition. Subsequently, the fire propagated through these following areas of the engine:

- Fan duct
- Thrust reverser blocker doors
- Booster
- HPC
- VBV

49 As the engine was spooling down, the excess fuel that had been collected in the booster spool cavity was discharged through the fan duct and flowed onto the runway and caught fire.

50 The fuel that was distributed over a wide area of the lower surface of the wing also caught fire.

Design of MFOHE

51 The MFOHE was designed and manufactured by a component manufacturer who supplied it to the engine manufacturer. It was designed to have unlimited service lifespan, i.e. periodic replacements would not be needed. The engine manufacturer did not require any periodic inspection of the internal portion of the MFOHE during its service lifespan.

[12] Hot surface ignition is the ignition of fuel on hot surfaces in the presence of ventilated airflow.

52 The manufacturing process involves crimping, a process where a force is applied to achieve a slight deformation of a material. The purpose of the crimping is to deform the cross-sectional shape of the tubes so that the tubes cannot slide freely through the round holes of the support plates. This prevents the support plates from moving during assembly (Figure 5).

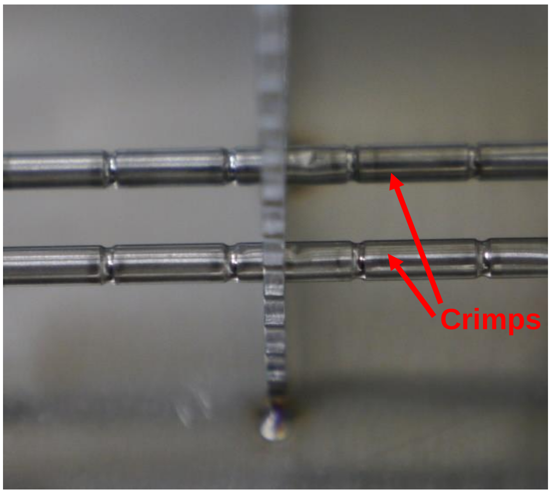


Figure 5: Crimps on tubes

History of MFOHE Leakage

53 According to the MFOHE manufacturer, prior to December 2013, there had been nine instances of leaking MFOHEs on GE90-115B engines that were returned to the MFOHE manufacturer for repair. The causes of the leakages in these nine MFOHEs, which would have required destructive examination, were not determined.

54 Between December 2013 and February 2014, the MFOHE manufacturer received three MFOHEs from GE90-115B engines that were suspected to be leaking. The engine and MFOHE manufacturers jointly decided to conduct destructive examination of these three units. It was found that two MFOHEs had a partially cracked tube. The cracks were at the crimped areas of the tubes. At that point, the cracks were attributed to the stress concentrations created at the support plate hole edges resulting from the crimping operation. The third unit had a tube with a pinhole leak.

55 In April 2014, the engine and MFOHE manufacturers conducted a review of the manufacturing operations. Improvements to the manufacturing process were made in May 2014. The improvements included using a standardised crimping tool to eliminate the variation in the crimps due to the use of hand tools. In addition, the crimped fuel tubes that have a history of cracking will be welded close at assembly.

56 The MFOHE manufacturer received another MFOHE unit from a GE90-115B engine suspected to be leaking that was removed from service in June 2014. This unit was manufactured before the improved manufacturing process was implemented. Destructive examination revealed a partially cracked crimped tube, in the same location as the previous two units examined.

57 In August 2014, a B777-300ER aircraft installed with GE90-115B engines and operated by another operator, experienced after landing and engine shutdown, a small, candle-wicking-like fire emanating from its left engine centre vent tube[13]. Teardown of the MFOHE revealed that fuel had entered the oil system through a cracked tube. This MFOHE was manufactured before the improved manufacturing process was implemented.

58 The cause of the crack in the August 2014 event was determined by the engine and MFOHE manufacturers to be the variation in the crimp on the tube that resulted in contact between the support plate and crimped tube. The contact resulted in stress concentration that could have led to crack initiation.

59 The August 2014 occurrence led the engine manufacturer to introduce a diagnostics programme to monitor oil consumption trends. After an aircraft has landed, the aircraft operator will send the engine data related to the preceding flight to the engine manufacturer for analysis by the diagnostic programme. Should the diagnostics programme detect any abnormal oil consumption trend related to a suspected fuel leakage into the oil system, the operator will be alerted by the engine manufacturer.

60 In a failure analysis test conducted by the engine manufacturer in September 2016, it was further discovered that unintended diffusion bonding[14] occurred during the manufacturing process of the MFOHE when elevated heat was applied. It was identified that the diffusion bonding occurred at the areas where there was close contact between the tubes and the support plates.

61 During normal operation of the MFOHE, stress was introduced at the fused area which ultimately led to the tube cracking. It was also determined that crimping increased the likelihood and severity of diffusion bonding to occur.

Resolution for Cracked Tube Problem

62 As part of its airworthiness control system, the U.S. Federal Aviation Administration (FAA), the regulatory authority for U.S. aeronautical products, requires engine manufacturers to identify unsafe conditions and implement corrective actions.

63 The FAA offered a process known as Continued Airworthiness Assessment Methodologies (CAAM) to help engine manufacturers identify potential unsafe conditions associated with their products. CAAM also helped engine manufacturers determine if the potential unsafe conditions were likely to exist or develop in other products of the same type design.

64 The engine manufacturers may use CAAM to:

- Assess the risk associated with the unsafe conditions
- Develop and prioritise appropriate corrective actions to address the unsafe conditions
- Assess the effectiveness of the corrective actions

[13] The centre vent tube allows air in the oil system to be vented.

[14] Diffusion bonding is a process whereby similar or dissimilar metals can join under high temperature and pressure through the transfer of atoms at the interface between the metals.

65 Under the CAAM process, each occurrence would be accorded a severity level. The severity ranges from Level 1 (minor) to Level 5 (catastrophic). The determination of the CAAM level was based on the actual damage and consequences in the occurrence. The CAAM level of a possible future occurrence was then assessed and used to determine the urgency to implement corrective actions. The unsafe conditions identified and the corrective actions determined had to be approved by FAA before being implemented.

66 The small candle wicking fire occurrence in August 2014 was categorised as a CAAM Level 2 event by the engine manufacturer[15].

67 Following its investigation into the August 2014 event, the engine manufacturer issued Service bulletin (SB) 79-0034 in December 2014 to address the issue of fuel leakage into the oil system. The SB required the MFOHE to be removed from the engine no later than the next occasion when the engine was in an engine shop for engine shop maintenance[16]. The deadline for compliance with the SB was set in accordance with the CAAM consistent with a Level 2 criticality.

68 As required by SB 79-0034, the MFOHEs were to be sent back to the MFOHE manufacturer to check for leakages. Should a leakage be detected, the openings at the entrance and exit of the leaking tube would be welded close to prevent fuel from flowing into it. Crimped tubes that had a history of cracking will also be welded close, regardless of whether the MFOHE was found leaking.

69 In response to an immediate safety recommendation made by the investigation team, the deadline for compliance with the SB was brought forward. The actions called for by the SB were performed on all affected MFOHEs by July 2017.

Timeliness of Safety Improvement Implementation

70 At the time of the occurrence, the actions called for by SB 79-0034 had not yet been performed on the occurrence engine. The engine had last undergone an engine shop maintenance in March 2014, before the SB was issued.

71 Had the SB been incorporated in the occurrence MFOHE, the fuel leak would not have occurred and the fire event would have been avoided.

72 Despite the engine manufacturer following the CAAM, which was provided by the FAA, a fuel leak in the MFOHE due to a cracked tube recurred and resulted in a more severe consequence of an uncontrolled fire.

[15] CAAM Level 3 (Serious Consequences) events include uncontained or uncontrolled fire that might result in impinging flames onto the wing or fuselage. As the small fire in the August 2014 event did not fit this description, the less critical CAAM Level 2 was used by the engine manufacturer.

[16] Engine shop maintenance refers to the process where an engine is removed for maintenance at a specific facility that includes performance restoration, replacement of life-limited parts, and inspection and maintenance of the entire engine, and its components and sub-assemblies.

73 This occurrence suggests that there is room for civil aviation authorities to review and enhance, if necessary, their control system to ensure that corrective actions can be implemented more expeditiously to prevent the recurrence of unsafe conditions.

74 Undoubtedly, implementation of safety improvement measures often results in additional costs and operational constraints for stakeholders in the aviation industry. In such situations, civil aviation authorities will have to balance the needs of promoting growth of the aviation industry and to ensure the safety of the flying public.

Decision Making During Abnormal Situation

75 In the initial communication, the FC advised the PIC "*…we are still trying to contain the fire…the fire is pretty big…will like to advise… disembarkation on your port side*". As the commander of the aircraft, the PIC was aware that the decision to evacuate lay with him and that he could order an evacuation even if the FC advised a disembarkation. Although the PIC was the only person actively communicating with the FC, the rest of the flight crew members were listening to the communication and the decision not to evacuate was reached collectively.

76 Making a decision to evacuate is not always straightforward:

- On the one hand, the operator's flight crew training manual recommends that in a situation that a persistent smoke or a fire which cannot positively be confirmed to be completely extinguished, the safest course of action typically requires the earliest possible descent, landing and evacuation. The manual also recommends that pilots should utilise all available sources of information in making a decision regarding evacuation. The manual also highlights that key factors to be considered include the urgency of the situation (e.g. possibility of significant injury or loss of life if a significant delay occurs). The manual also recommends that, in case of doubt, an evacuation should be considered.

- On the other hand, the operator's flight crew training manual also recognises that fire may be spreading rapidly from spilled fuel or other flammable materials, which may endanger the people who have left the aircraft or are still on the escape slides.

77 The flight crew will have to balance the pros and cons of a decision to evacuate given the situation picture that they have. So, it cannot be overemphasised that the flight crew need to exhaust all possibilities and all available resources to try to build up a situation picture that is as accurate as possible.

78 In this occurrence, there were a number of resources that were not used by the flight crew but which could have been of help:

- <u>Taxiing camera system</u>

The aircraft was equipped with a system of cameras installed at various locations on the aircraft to assist the flight crew in their taxiing. If switched on, the system could have provided real time video images of the exterior of the fuselage.

There was one camera installed on the leading edge of the right horizontal stabiliser. This camera could provide the flight crew with a vantage view of the fire.

According to the flight crew, they would usually switch on this camera system when they are taxiing the aircraft, as required by the operating procedures. However, in this occurrence, they did not switch on the system because they had not reached the taxiing phase as they had been instructed by ATC to stop at the intersection between the runway and rapid exit taxiway E7.

- Cockpit escape window

  The flight crew could have opened the cockpit escape window[17] on the right side to find out the situation outside. Extending the upper body out of the right escape window would allow a person to obtain a view of the fire situation at the right wing and engine area[18].

- Cabin crew

  The cabin crew members could have had a view of the fire situation at the right wing and engine area through the cabin windows. The flight crew could have asked the cabin crew what they could see.

  According to the PIC, the flight crew were aware that cabin crew members were a source of information throughout the occurrence. However, the flight crew were not able to attend to every call from the cabin crew as they had to prioritise their tasks. In terms of obtaining information on the fire, they gave priority to the task of communicating with the FC as he was the subject matter expert and would have a better assessment of the fire from his location outside the aircraft.

79 Admittedly, the situation that the flight crew faced was a stressful one. In trying to decide whether to evacuate, they were further disadvantaged as there was no indication of fire from the aircraft's fire detection system. The fire detection elements were shielded from the fire by the engine cowlings and there were no fire detection elements located outside the engine cowling. There was also no guidance in the manuals available to the pilots when there is a reported fire but the aircraft fire detection systems did not indicate so.

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[17] Flight crews may use a cockpit escape window to exit an aircraft when they are unable to escape otherwise.

[18] In performing this manoeuvre, the flight crew must ensure their safety is not compromised by smoke or heat entering the cockpit.

80 In that situation, the flight crew depended on the FC as the sole source for information collection and it may have slipped their mind to consider alternative ways of gathering information. Research has shown that decision making under stress may become less systematic and more hurried, and that fewer alternative choices are considered[19]. The flight crew's behaviour was consistent with the research findings.

81 It is recognised that it may not be possible for an operator to practise its pilots on checklist response for all possible emergency and abnormal situation scenarios. It is therefore all the more critical that pilots develop the ability to always consider alternatives and other resources when they encounter a situation that is not dealt with by any checklist.

Execution of Infrequently Used Checklist

82 The FUEL DISAGREE message that the flight crew encountered was a result of the fuel leak after the tube had cracked in the MFOHE. The FUEL DISAGREE checklist suggested four scenarios in which a fuel leak should be suspected and thus the FUEL LEAK checklist should be performed. One such scenario is when the TOTALIZER fuel quantity is less than the CALCULATED fuel quantity. Given that the TOTALIZER fuel quantity was about 79 tonnes and the CALCULATED fuel quantity about 83 tonnes, the flight crew should have concluded that they had to proceed on to the FUEL LEAK checklist[20].

83 As mentioned in paragraphs 16 and 17, the flight crew's own assessment and fuel calculation put the remaining fuel quantity at about 79 tonnes, which tallied well with the TOTALIZER fuel quantity figure. This gave the flight crew the confidence that the TOTALIZER fuel quantity was accurate and they were not experiencing a fuel leak. They decided that the FUEL DISAGREE message was a spurious one and that, therefore, there was no need to conduct a fuel leak check.

84 During the initial training to operate this aircraft, the operator provides training to all its pilots to understand the requirements of the FUEL DISAGREE checklist. However, in this case, the flight crew appeared to have misinterpreted certain requirements of this checklist even though they have undergone the training.

85 As part of its recurrent training for the pilots, operators may wish to consider including periodic refresher training on the requirements of the checklists that are used infrequently. This will increase the likelihood that checklists will be executed as intended.

Conclusion

86 This occurrence brought several interesting issues into consideration. Other than having to determine the cause and propagation of the fire, other factors such as

[19] See research paper titled "Effects of Acute Stress on Aircrew Performance: Literature Review and Analysis of Operational Aspects" authored by Dismukes, R. et al. published in August 2015.

[20] The FUEL LEAK checklist includes steps to quantify the magnitude of the fuel leak. For leaks of sufficient magnitude, the checklist directs the crew to shut down the affected engine.

regulatory requirements, risk management processes, recurrent training for flight crews and human performance were considered in this investigation.

87 In conclusion, the experience and lessons learnt through this investigation will benefit the stakeholders in the aviation industry as they continue to seek the optimal balance between ensuring safety, maintaining operating efficient and profitability.

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